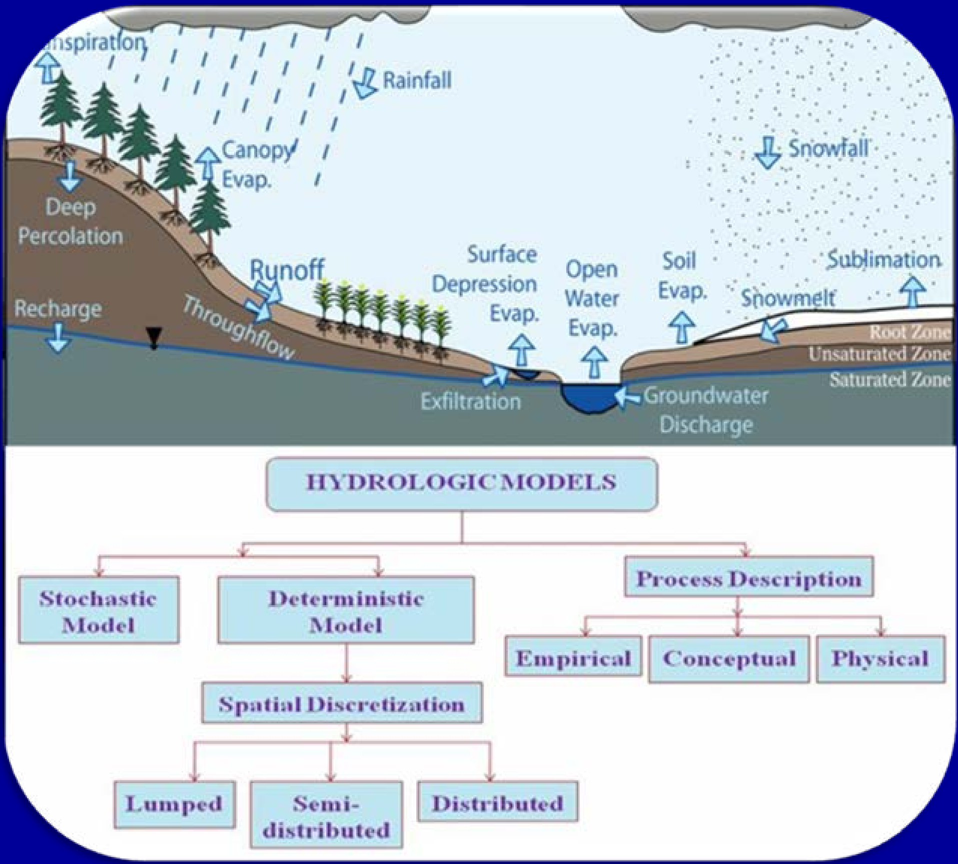
HYDROLOGIC MODELING

Current Status and Future Directions



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Forward

The report titled "Hydrological Modeling – Current Status and Future Directions", has been prepared as a guiding document for the activity of the 'Centre of Excellence for Hydrologic Modelling' under National Hydrology Project (NHP). The report has brought out a comprehensive review of surface water, ground water, water quality and systems models developed and successfully adopted for solving water management problems world over. Some of those models are generic, process based, less data driven and have proven effective and capable to simulate conditions prevalent in India. It is, therefore, desirable that the potential of adopting some of the models which have open access, be examined in detail. Some models are open source while others are not available free. Some of the open source models are very robust and have been tested widely.

The report covers the basics about various modeling components, issues related to modeling and different models used to deal with Surface water modeling, Groundwater modeling, Water Quality modeling, snowmelt-runoff modeling, soil erosion and sediment transport modeling and water resources systems modeling. All these domain modeling descriptions have been presented through 6 chapters; Chapter 1 presents hydrological modeling concepts in detail and reviews surface water modeling tools used in rainfall-runoff modeling, flood modeling and urban water hydrology; Chapter 2 provides basic theory used in ground water models development and tools and techniques along with description of groundwater modeling software. Snow/glacier melt runoff models are discussed in Chapter 3, while Chapter 4 is about soil erosion and sediment transport modelling. Basic concepts used in water quality modeling and different water quality modeling approaches are presented in Chapter 5. Finally, in Chapter 6, simulation and optimization techniques used in water resources systems and models based on these techniques are discussed. Each chapter concludes with a summary and way forward of modeling tools for wide application in India.

It is hoped that the report would be useful for the water resources professionals and would also provide guiding material for the future activities of the "Centre of Excellence for Hydrologic Modeling" that has been setup under NHP at NIH.

A large team of NIH scientists have put in considerable efforts to bring out this review report. I compliment all those who were involved in preparation of the report. Many experts reviewed the report and their help is gratefully acknowledged. We plan to periodically revise and improve the report to keep it updated and freely disseminate it through NIH/NHP web channels.

(Sharad K Jain)
Director, NIH

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ABSTRACT

Hydrological modeling is an indispensable tool for obtaining a better understanding of hydrological processes, their interactions, and prediction. Hydrologic models are simplified, conceptual representations of real-world system, commonly through mathematical equations, developed with the aim to understand hydrological processes, predict their future behavior, and to manage water resources, both in terms of quantity and quality of water. Hydrologic models help faster and logical decision making.

A large number of hydrologic models ranging from simple to highly complex have been developed world over and are available for solving wide ranges of domain problems. Each model has its own merits, limitations, data requirement and complexities in use. Water professionals are interested in estimation of response of water systems to hydro-meteorological inputs and intervention to plan, construct, and operate water resources development projects. Some models are comprehensive and derived based on the physics of underlying hydrological processes. Keeping in view the hydro-climatic regions, topographic variability in India, and data availability, a group of models need to be identified for wider use. Selection of an appropriate model for an application requires consideration of the suitability of the model to the catchment conditions, data requirements and availability, model assumptions, complexity, and its accuracy and validity. Therefore, a model user must fully understand these aspects before using a model. If necessary and possible, suitable modification may be incorporated in a model to make them more useful for Indian river basins. Reliable data at a range of spatial and temporal scales are critical to calibrate and validate the hydrological models.

An important area of surface water modeling is contribution of snow and glacier melt in snowfed catchments. In mid and high latitude mountain ranges, for example, seasonal snow cover exerts a strong influence on runoff variability whereas glaciers are the dominant source of water during the dry season at low latitudes. Improved understanding of snow and glacier melt runoff studies will help better management of water resources in rivers fed by these two.

Groundwater, one of the India’s most important natural resource, is under constant threat of exploitation with increasing population and economic development. Proper understanding and modeling of subsurface water movement has been an enduring challenge for hydrologists and practitioners. Current modeling efforts are plagued by the complex heterogeneity within the subsurface, reconciliation with spatial and temporal scales, and lack of supporting data.

Water quality management including soil erosion and transport is a critical component of overall integrated water resources management. Water quality modelling can give answers to a large number of management questions related to prospective social, economic, environmental, technical and political issues of future scenarios based on past and present conditions. Decisive use of water quality modelling as a tool for policy evaluation & decision, water quality management, risk assessment, and water quality conservation is yet to pick up momentum in India.

Data challenges continue to plague modeling efforts, particularly in India. Complex models

have too many parameters that need to be estimated accurately and independently for the models to be used at their full and correct potential. Most efforts rely on calibration and corroboration exercises that are fraught with uncertainty. Field-scale experiments are time-consuming and costly. State-of-art data acquisition techniques need to be applied for reliable modeling and impact studies. There is a need to devise low-cost and rapid ways to accurately determine hydrogeologic parameters. Geographical information systems (GISs) are increasingly being included in planning and management models. Most of the current models have been linked with GIS database.

Assessing the potential impacts of climate change on surface and ground water regime is yet another long-term challenge that confounds both researchers and managers. Developing new models that account for uncertainties and provide more realistic assessment of predictive capabilities is needed for devising effective management practices. Uncertainties in modeling and in defining climate change scenarios make it difficult to assess the state of future groundwater resources. Methods for quantifying and reducing these uncertainties need to be derived using advanced mathematical techniques, and modeling strategies.

This document reviews the hydrologic and water resources modeling and management challenges in India covering surface and sub-surface water, snow and glacier melt water, water resources systems, water quality aspects, and sediment transport, and also reviews the most promising models developed to solve wide ranges of problems covering all those hydrological domains. A critical appraisal of the most widely used domain models including their characteristics has been elaborated in this document to help readers choose which models have what capability, limitations, data requirements and complexities.

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CHAPTER-1 SURFACE WATER MODELLING RAINFALL-RUNOFF MODELLING, FLOOD MODELLING AND URBAN HYDROLOGY

Anil K. Lohani, Ravindra V. Kale, Purna C. Nayak, Sharad K. Jain and Rakesh K. Jaiswal

CHAPTER-2 SUBSURFACE WATER MODELING – FLOW AND CONTAMINANT TRANSPORT

Narayan C. Ghosh, Chandra P. Kumar, Anupma Sharma, Surjeet Singh and Mathew K. Jose

CHAPTER-3 SNOW/GLACIER MELT RUNOFF MODELLING

Sanjay K Jain, Renoj J. Thayyen and Manohar Arora

CHAPTER-4 SOIL EROSION AND SEDIMENT TRANSPORT MODELLING

Jaivir Tyagi, Pushpendra K. Singh and Archana Sarkar

CHAPTER-5 SURFACE WATER QUALITY MODELLING

Narayan C. Ghosh, Pushpendra K. Singh, Sumant Kumar, Bekal K. Purandara and Mukesh K. Sharma

CHAPTER-6 WATER RESOURCES SYSTEMS MODELING – STATUS AND FUTURE DIRECTIONS

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CONTENTS

Title	Page No.

CHAPTER 1

SURFACE WATER MODELING: RAINFALL-RUNOFF MODELING, FLOOD MODELING AND URBAN HYDROLOGY

The aim of a model is, of course, precisely not to reproduce reality in all its complexity. It is rather to capture in a vivid, often formal, way what is essential to understanding some aspect of its structure or behavior…. We select, for inclusion in our model, those features of reality that we consider to be essential to our purpose… the ultimate criteria, being based on intensions and purposes as they must be, are finally determined by the individual, that is, human modeler. - Joseph Weizenbaum (1976).

1.1 Introduction

Hydrologists are mainly concerned with evaluation of catchment response in order to plan, develop, manage and operate various water resources schemes. There is continuous circulation of water between earth and atmosphere. This is signified by different phases in the "Hydrologic Cycle" which is the fundamental principle of hydrology. The hydrological processes are stochastic in nature and exhibits high spatial and temporal nonlinearity and non-stationarity. The measurement of each and every variable in space and time is not possible to understand and predict the behavior of hydrological systems. Therefore, hydrological modeling is considered as the heart of hydrological studies. The aim of hydrological modeling studies is to solve as well as manage various hydrological problems.

Since the second half of the 19th century, rainfall-runoff modeling has emerged as effective tool in response to many engineering problems: water availability assessment, reservoir storage and spillway design, storm water system design in urban area, agricultural land reclamation, drainage systems design, flood protection and flood forecasting, and climate change impact studies etc. Presently, plethora of conceptual and physical based rainfall-runoff models involving various hydrological processes are available to simulate and evaluate the rainfall-runoff process and design floods which play an important role in water and environment resources management.

Hydrological models build based on the dominant hydrological processes are necessary to accomplish various tasks in the planning and operation of integrated water resources management projects. The project planning phase requires models for estimation of water levels (stage) or flow discharges and for developing flood inundations and flood hazard maps based on design scenarios instead of real time runoff. Therefore, the selected model should appropriately consider the hydro-morphological characteristics of the landscape as well as operational hydrological scale. The project's operational phase requires models to determine operational rules, e.g., reservoir operations. Real-time hydrological forecast models are needed to plan and operate various water resources projects. The foreseen impacts of global climate changesare temperature rise, variation in precipitation pattern and intensity and increase in frequency as well as intensity of extreme events such as cloud bursts, heavy precipitation events, high floods with concurrent intense landslides and soil erosion which cause loss of human lives and livelihood, damage to infrastructures and agricultural crops and deterioration of health and environmental conditions. In order to handle these issues effectively and efficiently, the proper understanding of the hydrological system and forecasting of the seadverse hydrological events are of utmost importance which requires immediate up-gradation of the relevant research areas in the hydrology sector with heuristic computational and operational methodologies, database management system and, state-of-the-art hydrological modeling tools. Recently, the technological innovation, in the field of geo-informatics, cutting edge techniques such as Geographical Information System (GIS) and Remote Sensing (RS) enables the extensive use of hydrological modeling tools for hydrological analysis and modeling of natural phenomena with enhanced prediction accuracy and flexibility.

1.2 Brief History of Hydrological Models

A model represents the physical, biological and/or chemical catchment characteristics and simulates the natural hydrological processes. It is not an end in itself but is a tool in a larger process which is usually a decision problem. It aids in making decisions, particularly where data or information are scarce or there are large numbers of options to choose from. It is not a replacement for field observations. Its value lies in its ability, when correctly chosen and adjusted, to extract the maximum amount of information from the available data. The obtained information on the watershed and atmospheric characteristics can be used as inputs in the hydrological models to estimate runoff quantity and quality. The major inputs required for the hydrological models are climatic variable; such as, precipitation, maximum and minimum air temperature, relative humidity, wind speed and atmospheric pressure, watershed characteristics; such as, drainage network and its characteristics, watershed topography, characteristics of groundwater aquifer, spatio-temporal time series of groundwater levels, hydraulic storage and conveyance structures, soil properties, soil moisture content, vegetative cover and water quality parameters. However, the number of input parameters required for the execution of the specific hydrological model depends on the degree of simplicity or complexity involved in the conceptual construction of that particular hydrological model. In hydrological model literature, the model which gives simulation results close to reality using minimum input parameters and with less complexity is considered as the best hydrological model by following the principle of parsimony.

Development of hydrological modeling encompasses the Rational method (Mulvany, 1850) to the recent grid based physically based distributed models. Mulvany, in year 1850, proposed the Rational Method which is based on the concept of time of concentration and its relation to the maximum runoff. This method is physically based only in case of small sized (impervious) watersheds having dominant kinematic flow process and can be used to estimate peak flow but not flood volume. This method was extensively applied for the design of sewers system. Another milestone in the hydrological modeling is marked by the unit hydrograph (UH) model developed by Sherman (1932). Conceptually, the UH model is based on the principle of superposition of effects which represent the response of a linear, contributory, dynamic stationary system. Accordingly, in the UH model the flood hydrograph at the catchment outlet can be predicted by assuming that the spatially uniform rainfall occurring at constant time intervals. Based on the continuous and discrete time impulse responses of a linear system, instantaneous unit hydrograph (IUH) and the finite period unit hydrograph (TUH) models were developed. The development of IUH model is proved to be helpful in classifying the physically based and data driven models. If the ‘shape’ of the IUH is defined *a priori* on physical ground by set of linear or linearised differential equations and the model parameters are predicted from catchments physical characteristics instead of the historical input-output data, then IUH is a physical interpretation of phenomenon (Kalinin and Milyukov 1957). If the ‘shape’ of the IUH/TUH cannot be defined *a priori* on physical ground rather the historical input-output data are used to define shape as well model parameters, the resulting model is data driven model (e.g., Clark Unit Hydrograph; Clark, 1945). However, the IUH/TUH model extensions to large catchments (including pervious catchments) have difficulties in physical interpretations, so the non-linear or threshold-type IUH approach has been developed. In year 1960, the IUH models are developed which used interconnected conceptual elements to represent the individual component of hydrological cycle that enabled better physical interpretation of the catchment physical process responsible for runoff generation. The Stanford watershed, SACRAMENTO, SSARR, and TANK models are some of the hydrological models which are built-in following the principles of IUH.

During 1970s, the conceptual hydrological models were developed based on the simple lumped basin parameter and geomorphologic instantaneous unit hydrograph (GIUH) approach. The development of these conceptual models lead to the development of the variable contributing area models (e.g., Xinanjiang and the Probability Distribution, ARNO, VIC, TOPMODEL models etc.) which assume that the rainfall-runoff process mainly governed by the saturated area dynamics and thus, simple monotone function can be used to relate it to the soil moisture storage. The period from mid 1980s onwards is marked as digital era in hydrological modeling as evaluation and improvement of physically based models following a blueprint for a distributed physically based model by Freeze and Harlan (1969) has been undertaken. The development of physically-based models was based on the use of physical knowledge of surface and subsurface phenomenon. In these models, the various flow sub-systems such as surface and saturated and unsaturated subsurface flows in a computational grid are coupled by using representative partial differential equations and suitable boundary conditions. Further, all coupled flow subsystems in the computational grids are numerically integrated to produce catchment response as well as predictions at various locations. This concept led to the development of SHE (Systeˈme Hydrologique Europeeˈn) and other models. Beven (1989) expressed reservation about problems in hydrological prediction by using physically based models which includes the lack of physical based theory applicable in all aspects of the surface and subsurface processes, constraints in the real applications, and equifinality and dimensionality issues in the physically based models. The main strength of the physically based models as advocated by Grayson et al. (1992) is that these models can be used for the data analysis, verification of physical processes based on the collected field data to understand the physical processes existing in nature and their interactions, and to understand our limitations in the description of the physical processes.

During 1990 to 2000, the hydrological modeling studies were mainly focused on the issues related to climate change, environment and natural disasters. Maidment (1993) proposed GIS based spatially distributed modeling methodology to arrive at single hydrograph at the catchment outlet by routing flow through cell-by-cell raster structure.

Maidment's work provided impetus to various distributed models in hydrology, e.g., Precipitation-elevation Regressions on Independent Slopes Model (PRISM), General Circulation Models (Atmospheric- "GSMs"), European Soil erosion Models (EUROSEM), etc. Many researchers have attempted to apply spatially distributed unit hydrograph (UH) with spatially variable rainfall including the use of Soil Conservation Services Curve Number (SCS-CN) as a loss method with suitable GIS environment which ultimately resulted in successful simulation of hydrograph obtained from actual measurement (Muzik 1996). By this time, the remote sensing (RS) methods had emerged as the significant tool in the hydrological modeling. Further, the soft computing tool like artificial neural network (ANN) was introduced for rainfall-runoff modeling (e.g. Dawson and Wilbey, 1998; Dawson and Wilbey, 2001). This decade is also marked with pioneering research in the coupling of Digital Elevation Model (DEMs) analysis and raster-based hydrologic modeling, such as,extraction of drainage network from DEM data (Tarboton et al., 1991; Fairfield and Leymarie, 1991; Zhang and Montgomery, 1994; Tarboton, 1997); hydrological, geo-morphological and biological modeling application through digital terrain modeling (DTM) (Quinn et al., 1991) and raster based models for flood inundation simulation (Bates and De Roo, 2000).

Twenty-first century started with significant advancement in GIS, RS, inbuilt library functions, and other modern technologies in hydrological modeling which seems to be well established although constant evolution and revolution of the hydrological modeling with use of modern technologies are still flourishing and finding new applications to meet continuously growing demands. Since 2001, the scientists are bringing new ideas based on previous research work and tools in the hydrological modeling, widening applications from small field scale to watershed, basin, national and global level. Various researchers have reviewed hydrological models (e.g., Xu, 1999: Singh and Frevert, 2002; Todini, 2007; Todini, 2009; Vargas-Castaneda et al. 2015; Paniconi, and Putti, 2015; Chalkias et al., 2016).

1.3 Classification of Hydrological Models

There is no single way to classify the hydrological models. Based on the criteria of interest to describe and discuss strength, capability and limitations, the hydrological models can be classified in different ways. Based on the description of physical process, the hydrological models can be classified into three groups: (1) empirical (data driven models), (2) conceptual, and (3) physically based. Based on the spatial representation: (1) lumped, and (2) distributed. Based on the aspect of randomness: (1) deterministic, and (2) Stochastic (Džubáková, 2010, Singh and Frevert, 2002, ESCAP, 2016). Hydrologic models can also be classified as (a) lumped and distributed parameter models, (b) conceptual and hydrodynamic models, (c) models with fitted, physically determined or empirically derived parameters, and (d) event and continuous simulation models (Todini 1988; Knapp et al., 1991).

In case of empirical (or data driven) hydrological models the mathematical correlation is based on the observed data analysis rather than the physical processes in the catchment. The empirical models which also known as "black box" models are again classified into four categories: (1) unit hydrograph based/ linear model (2) Linear regression and gauge to gauge correlation models (3) Auto regressive (AR) models (e.g., ARX, ARMAX), and (4) Hydro-informatics based models those based on concept of working neurons (e.g., ANN, WANN, fuzzy logic, and genetic algorithms, OE, Box-Jenkins, and state-space models). In case of the conceptual hydrological models, the physically based system is conceptually represented based on simple principles (e.g., SSARR, TANK model, HBV, XINANJIANG, UBC, NAM, SACRAMENTO, and Symhyd models). Due to representation of the catchment as a series of interconnected storage components and empirical equations for computing the various fluxes the conceptual models are also referred as soil moisture accounting (SMA) models. The model parameters are obtained through model calibration. Although the significant hydrograph features can be accurately forecasted by using the conceptual models, they should be applied cautiously especially when they are required to apply for the hydrologic predictions falling outside the range of calibration data.

The physically-based hydrological models build on sound mathematical ground attempt to represent the natural phenomenon by physical laws governing the conservation of mass and momentum/energy (e.g., overland flow and channel flow simulation carried out by using 1D and 2D Saint-Venant equations; unsaturated zone flow simulated by 1D, 2D and 3D Richard’s equation and its approximations and groundwater flow simulation by using Boussinesq’s equation etc). The suitable numerical schemes are used to solve theses physical law expressed by partial differential at each spatial and temporal grid and thus catchment response is computed at each grid point. Lumped models use an aggregated description of catchment by using representative values of parameters and state variables based on calibration process and thus catchment response is computed only at the outlet. Therefore, most of such models are not suitable for analyzing the impacts of climate and land use changes on the hydrological regime. To overcome this limitation, some hydrological models use the lumped parameters for each homogeneous sub-basin (i.e., Hydrologic Response Unit) within the whole catchment area known as semi-distributed models (e.g., SWAT model). In another class of hydrological models the catchment area is divided into elementary grid net and water routed from one grid to another in downslope direction and such model structure referred as the fully distributed model (e.g., the Mike-SHE model). The deterministic models attempt to express the computational domain by mathematical relations based on physical laws and do not consider randomness, while, stochastic hydrological model has at least one random variable which is implicitly presented in the model input. If the model components are described by a mix of deterministic and stochastic components, the model is called stochastic-deterministic or hybrid model.

The classification shown in Fig. 1.1 is derived mainly from Fleming (1975) and Woolhiser (1973). Not all models fit easily into this classification but it is general with respect to fundamental principles. Two main groups of mathematical models emerge from Fig. 1.1: those which involve optimization and those which do not. Here, optimization strictly refers to decision making rather than optimization of model parameters. The non optimizing models are generally associated with the assessment of hydrological data and are used to quantify the physical processes. Methods involving optimization are concerned with the problem of selecting the "best" solution among a number of alternatives. Non optimizing models are divided into two fundamentally different approaches, the deterministic and the statistical. Although the deterministic and the statistical models are fundamentally different, a strong interplay between the two approaches exists, mainly because the processes involved in the hydrological cycle are partly causal and partly random. Hence, some deterministic models contain random functions to relate processes, while some statistical models contain casual or deterministic functions as part of their structure. The interplay between the two approaches also includes the subsequent analysis of the information gained from the different models. For example, a deterministic model using a conceptual representation of the hydrological cycle may be used in producing a record of streamflow at a gauging station. This record may then be analysed by statistical methods to produce a flood frequency curve for that site. Conversely, a statistical model involving the generation of rainfall data by a stochastic model could provide input to a conceptual model producing information which is then analyzed statistically. Over last few decades, such interplay of model has occurred increasingly and joint stochastic-deterministic modeling framework has emerged as a very important modeling tool to address numerous hydrological problems such as spatial variability accounting in modeling framework and assessment of uncertainties in the hydrological modeling.

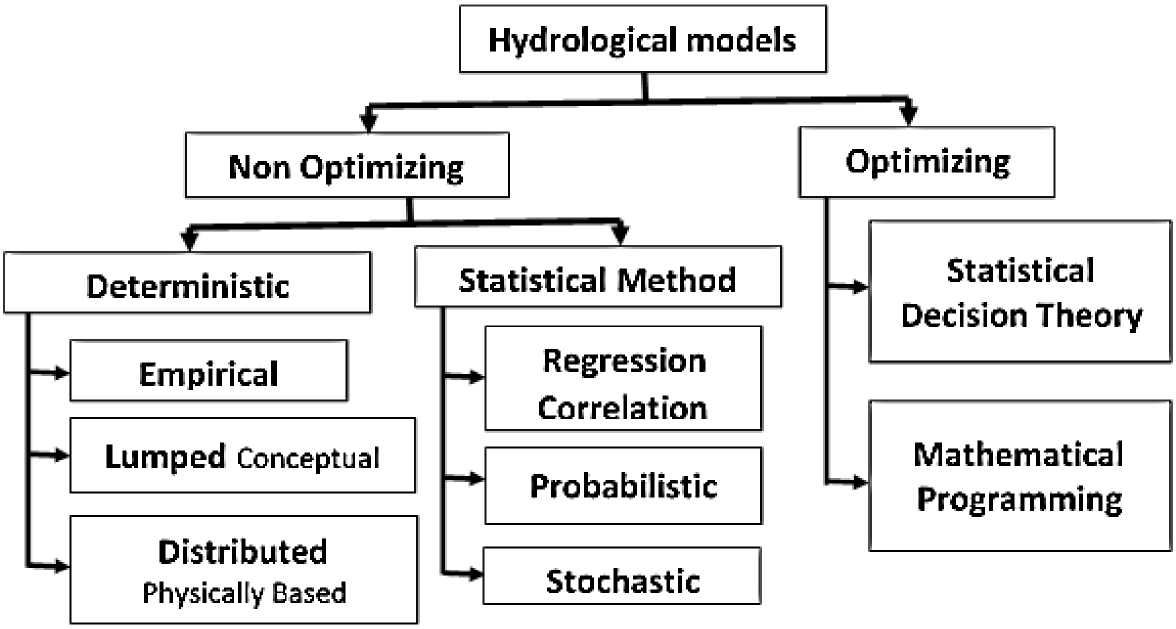
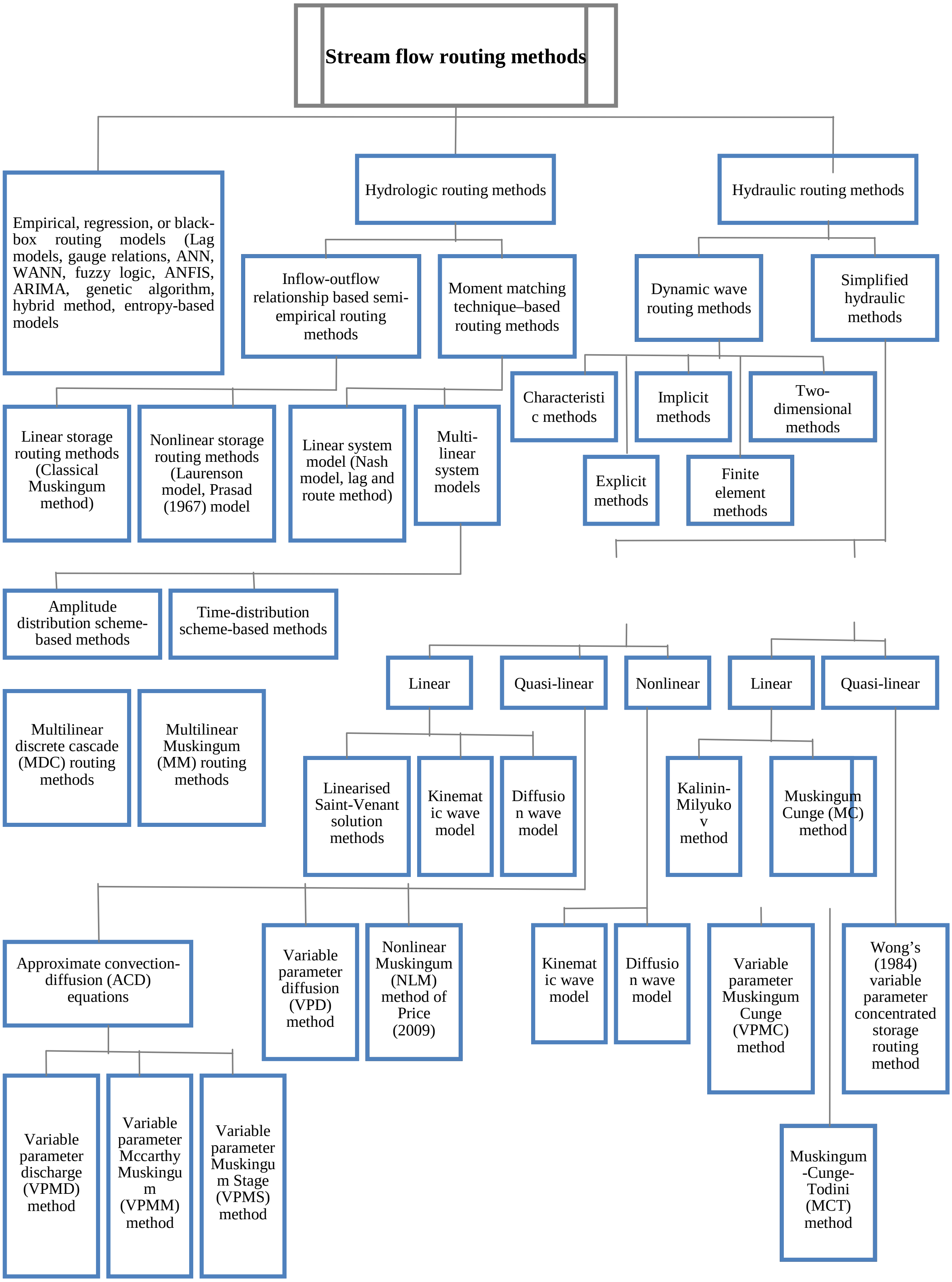


Figure 1.1: Classification of Hydrological Models

Beside these classifications, hydrological models can be classified as those designed for operation and planning (Jajarmizadeh et al., 2012). As stated earlier, models can be classified by considering spatial representation, as models based on (a) rectangular grids, (b) sub-catchment, and (c) hydrological response unit (Plate, 2009). Further, these models can also be classified as: (1) event and continuous simulation precipitation-runoff models, steady and unseady channel flow models, reservoirs regulating models, and flood frequency analysis models (Vargas-Castaneda et al. 2015).

Flood routing through channel/ river is important component in hydrological models which signifies the attenuation and translation of flood hydrograph from upstream to downstream. Now-a-days, 1D and 2D flood routing models are available which can be used for flood forecasting in the rivers. Perumal and Sahoo (2009) and Perumal et al. (2013) have given a classification of the available flood routing models, as shown in Fig. 1.2.



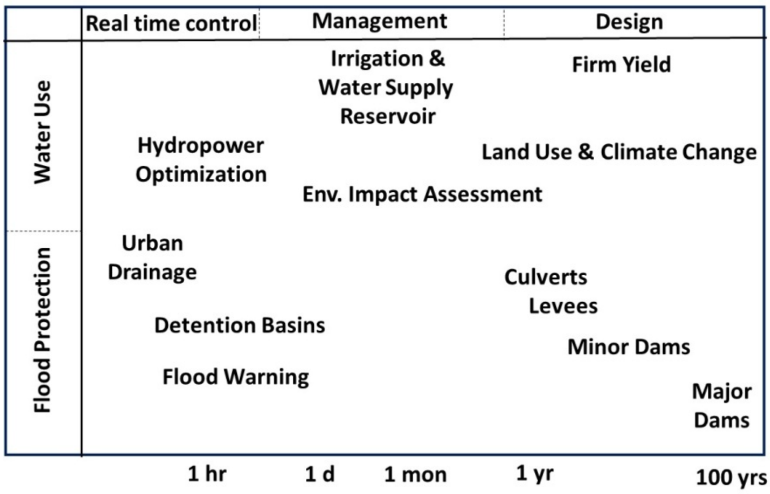
Source: Perumal and Sahoo, 2009; Perumal et al. 2013

Figure 1.2: Classification of flood routing methods

1.4 Temporal and spatial scale in hydrological modeling

1.4.1 Hydrological processes and observational scales

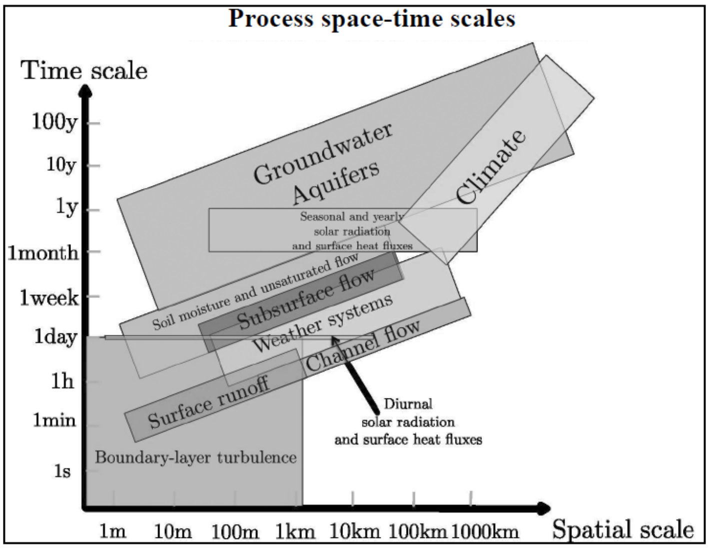
Hydrological models are used in two different ways: (1) predictive modeling to solve location specific hydrologic problem, and (2) investigative modeling to enhance our understanding about hydrological processes. Surface hydrologic process are often viewed or analyzed at the scale of watersheds; the scale at which water resources management occurs. The area of watershed varies from a few hectares to thousands of square kilometre. The temporal scales in hydrology vary from sub-hourly to decadal and beyond. Usually, the conceptual hydrological model is developed based on important hydrological process in the watershed area and then use calibration process to fit the developed mathematical model with historical observed data. The developed model assumed to be suitable to be used in predictive mode when the outputs of the model are close to the observed data during validation process. However, conditions are always different in space and time which creates problems in hydrological modeling studies. The process are observed or modelled at very short time scale but predictions are required at very large time scales. Fig. 1.3 explains the time-scale range required for real-time control, water resources management and design for which hydrological models are required to be used. It is noted that the time-scales associated with these phases varies from minute to hundreds of year. Therefore, transfer of information across various scales is achieved by some sort of extrapolation or interpolation by adopting suitable transfer functions. The process of transferring the information is called *scale* and associated problems are called scale issues (Bloschl and Sivapalan, 1995).



Source: Bloschl and Sivapalan, 1995

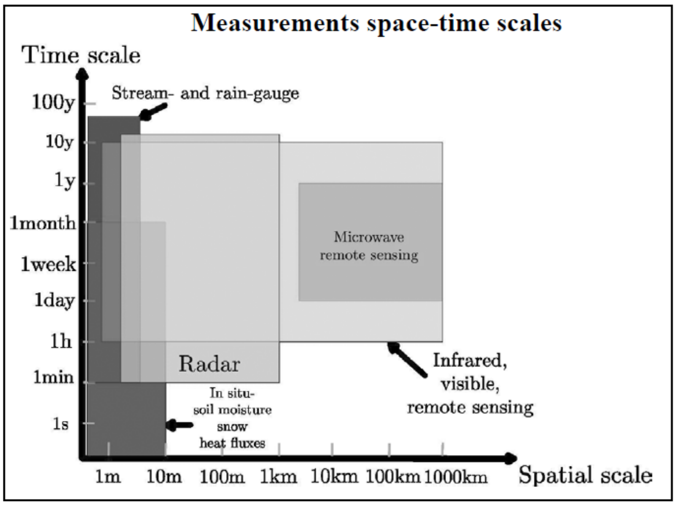
Figure 1.3: Range of time-scales for hydrological problems

In hydrological modeling the discrepancy between the hydrological physical process scale and observational scale plays important role in the restricting the development of theories so that observational scale is accurately related to modeling scale. Further, heterogeneity and variability in catchment makes the scaling issues in hydrological modeling very challenging task. The range of scales at which hydrological processes occur is very wide, e.g., floods in river system occur over a million square kilometrewhereas unsaturated flow occur in the one meter soil profile. However, flash flood occurs for several minute duration whereas ground water flow in aquifers occurs over hundreds of years. As shown in Fig. 4, based on observed data and heuristic considerations, a characteristic time-scale (response time of a catchment) *versus* a characteristics space scale (e.g., square root of catchment area) can be plotted as a shaded region for particular hydrological process (Bloschl and Sivapalan, 1995; Gentine et al., 2012). The spatial and temporal observational scales (as depicted in Fig. 1.5) generally do not match with hydrological process scales or modeling scales as revealed from comparison of Fig. 1.4 and Fig. 1.5. The overlapping grey shades in Figs. 1.4 and 1.5 represents the overlapping space-time scales of different processes and observations.



Source: Bloschl and Sivapalan, 1995; Gentine et al., 2012

Figure 1.4: Spatial and temporal scale of hydrological processes



Source: Gentine et al., 2012

Figure 1.5: Spatial and temporal scale of observations

Precipitation (weather system) is the primary delivery system of water to earth. As depicted in Fig. 1.4, the precipitation phenomenon spatially range from cells at scale of a few km to synoptic system at 1000 km and temporally at scale of several minutes to more than a day. Similarly to atmospheric processes, hydrological processes also occur at different space scale (See Fig. 1.4). The infiltration excess or Horton overland flows (which most likely occur in arid climate during high rainfall) occur as point phenomenon and response time is few minutes. The saturation excess runoff (usually occurs in humid climate and thin soil) response is generally slow and it is spatially aggregated phenomenon to be operative requires specific saturated catchment area. Subsurface flow has significantly slower response time varying from day to longer time for same catchment size and to be operative requires certain catchment area. The ground water controlled flows response time scale varies from some months to hundreds of years. Channel flow response time scale varies from the small channel initiation area to the scales of large river basins.

1.4.2 Hydrological Modeling (Working) Scale

The choice of hydrological model depends on characteristics of landscapes. Plate (2009) recommended the use different precipitation-runoff models for four different kinds of landscapes: (1) high mountain area, (2) foothill areas with or without vegetation, (3) large flood plains, and (4) urban areas. Beside these criteria, the selection of hydrological scale of area is important criterion. According to Bloschl and Sivapalan (1995), the hydrological modeling (working) scale partly related to the scale of the physical hydrological process (see Fig. 1.4) and partly to the working scale of the hydrological model to be applied (see Fig. 1.3). Depending upon the study area characterization and the hydrological problem being addressed, working scale of hydrological models may vary spatially and temporally. Typical modeling scales in space are (Dooge, 1982; 1986): the local scale ($\approx$1 m^2); the hillslope reach scale (100 m^2); the catchment scale (10 km^2); and the regional scale (1000 km^2). Typical modeling scales in time are: the event scale (several minutes to 1 day); the seasonal scale (1 year); and the long term scale (100 years). For application of hydrological models, hydrological units are classified as a macro and micro hydrological unit. Area of macro and micro hydrological units varies from 0.5 to 1130 lakh hectares and 0.001 to 0.5 lakh hectares, respectively. Base map scale of macro hydrological unit varies from 1:10M to 1:250000 and micro hydrological unit varies from 1:4000 to 1:50000. Classification of hydrological units for macro and micro watershed is given in in Tables 1.1 and Table 1.2, respectively.

Table 1.1 Spatial Scale of Hydrological Unit (Macro)

Hydrologic Unit (Macro)	Spatial (in 100,000 hectare)	Base Map Scale
Region	270-1130	1:10 M
Basin	10-50	1:4M or 1:6 M
Catchments	10-50	1:1 M
Sub-catchment	2-10	1:25,0000
Watersheds	0.5-2	1:25,0000

Table 1.2 Spatial Scale of Hydrological Unit (Micro)

Hydrologic Unit (Micro)	Spatial (in 100,000 hectare)	Base Map Scale
Sub-watershed	0.1-0.5	1:50000
Milli-watershed	0.01-0.1	1:15000
Micro-watershed	0.001-0.01	1:10000or 1:8000
Mini-watershed	0.000001-0.001	1:4000

It may be noted that hydrological modeling scales are defined both by catchment area, the local dominant physical processes and how these processes are represented in the hydrological model (Plate, 2009). In the hydrological modeling, overland flow occurring over catchment is relatively significant as compare to the concentrated flow in the channel network. A detailed description is given by Plate (2009) on how the hydrological scale has been handled in the hydrological modeling.

As depicted in Fig. 1.6, smallest scale in hydrological modeling associated with area element ‘a’ (approximately 1 m^2). Runoff due to overland flow or baseflow from this elementry area ‘a’ is concentrate into nearby channel. Similarly, the runoff response of such elementary area in the sub-area A_j concentrate in the channel draining this area with characteristic time called as time of concentration, t_c. The runoff from n number of sub-areas i.e., $j = 1, 2, 3...n$ is simulated through the drainage network joining these sub-areas up to the river gauging point with characteristic time called as routing time, t_f . The selection of hydrological modeling (working) scale is obtained by using t_c/t_f ratio as an appropriate indicator. Different hydrological scales in models application are described next.

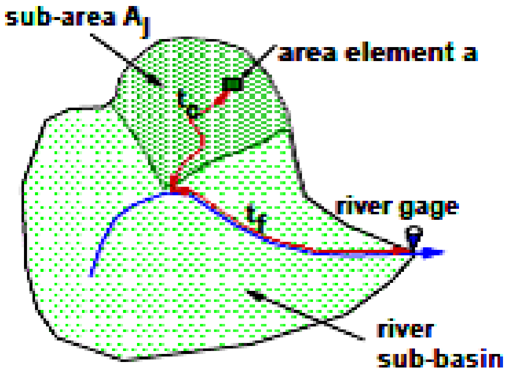


Figure 1.6: Flow concentration time in hydrological basin.

1.4.2.1 Point scale

At the point scale(i.e., the scale of elementary area ‘a’) (see Fig. 1.6) the physical processes occurs mainly in the vertical direction and thus, the routing time, t_f is meaningless. Further, the infiltration, depression storage (micro-topography), interception losses due to evapotranspiration and overland flow generation are the dominant physical processes at this scale. These physical processes are governed by the natural features like soil, topographic and vegetative cover characteristics. Therefore, these natural features plays important role in generation of local runoff at this scales. It can be noted that factors such as macro-pores, local depressions, and frost phenomenon during snow melt strongly influence the infiltration process and thus runoff production process at the point scale. As these hydrological processes are characterized by high non-linearity and local variability, thus potential variability of these processes isusually accounted for identical areas such as agriculture field or forest area having identical soil characteristics.

1.4.2.2 Micro-scale

Micro scale models are developed using the point scale models as building blocks. Subdivision of the catchment area into various homogenous contributing area is carried out by combining the elementary area 'a' with identical infiltration behaviour. For any sub-area A_j the initialization of runoff generation and area average value of time of concentration t_c for individual contributing area required to be computed. If t_f/t_c is small, the detailed accounting of each of these processes is recommended in precipitation-runoff models. The micro-scales hydrological models are basically physically based models developed to simulate runoff from hill slopes particularly applied where extreme high rainfall have impact on soil erosion or solute transport.

1.4.2.3 Meso-Scale

The meso-scale models are developed using the conceptual precipitation-runoff models depending on system function (Plate, 2009). To capture the spatial variability, the large catchment can be sub-divided into small sub-catchments which are interconnected by the well-defined stream networks. Runoff from each sub-catchment can be computed by conceptual models such as unit hydrograph. However, more detailed physically based models for runoff processes in small area can be used. In plain areas, unit hydrograph/conceptual models can be used. However, if there is lack of observed input data, hydrologists usually apply unit hydrograph models for the large catchments. On other hand where useful input data available to execute the hydrological models based on micro-scale or grid based models, including fully hydraulic models (1D or 2D models based St. Venant equation or its approximations or simplified hydrological models) of the channel network can be used. Coupling of the sub-basin overland flow routing model with river routing models are important particularly where the geological and topographical properties are different in different parts and rainfall also varies spatially and temporally leading to variable runoff formation in the catchment. As it is well known that the extreme rainfall causes very minor flood in the large catchment but very high peak flood (flash flood) in local area, yet, temporal variability of rainfall is very important when rainfall occurs over large area and under this condition the catchment size does not have significant impact on runoff generation. For large spatial scales, the spatial rainfall distribution as well as temporal distribution of area averaged rainfall field need to be considered, which requires the subdivision of catchment with local area averaged rainfall inputs. Such approach is very important for hydrological models applied for flash flood forecasting. However, hydrologic models applied for design purpose actual areal distribution of rainfall has least importance. The meso-scales models are suitable to apply for hydrological prediction where the magnitude of t_c and t_f are of same order. This approach used for the catchment area ranging from a few 10s km^2 to a few 100s km^2.

1.4.2.4 Macro-Scale

When the ratio t_c/t_f decreases asymptotically to 0 in large catchment, i.e. river flow processes dominates the overland runoff processes, the application macro-scale hydrological models are required. In macro-scales, the catchment sizes ranges from about 1000 to many thousand km^2. On this scale, simplified relationships between rainfall-runoff given by exponential (linear reservoir) or runoff coefficients can be used to model the surface runoff from sub-catchment. However, as river flow processes are dominant, the hydraulic river routing methods are required to be used to predict the large discharges and flood level for effectively management of floods by planning appropriate flood protection measures.

In case of all hydrological models, the temporal scale is selected partly based on the hydrological process and observation scale and partly on the selected spatial modeling scale so that the modeling time interval should not exceed the time of concentration of flow for that particular spatial modeling scale.

1.5 Hydrological Processes and Runoff Routing considered in Runoff Assessment

In hydrological cycle, the water is in continuous circulation between the atmosphere, earth surfaces and underground strata through vertical and horizontal flow movements (Fig.1.7). The visible components of such hydrologic cycles are precipitation and runoff whereas other components like infiltration, evapotranspiration, percolation, groundwater recharge and discharge are not visible components. The water exchange between these components is very simple to schematize, however quantification of all the interaction among these components is difficult to visualize.

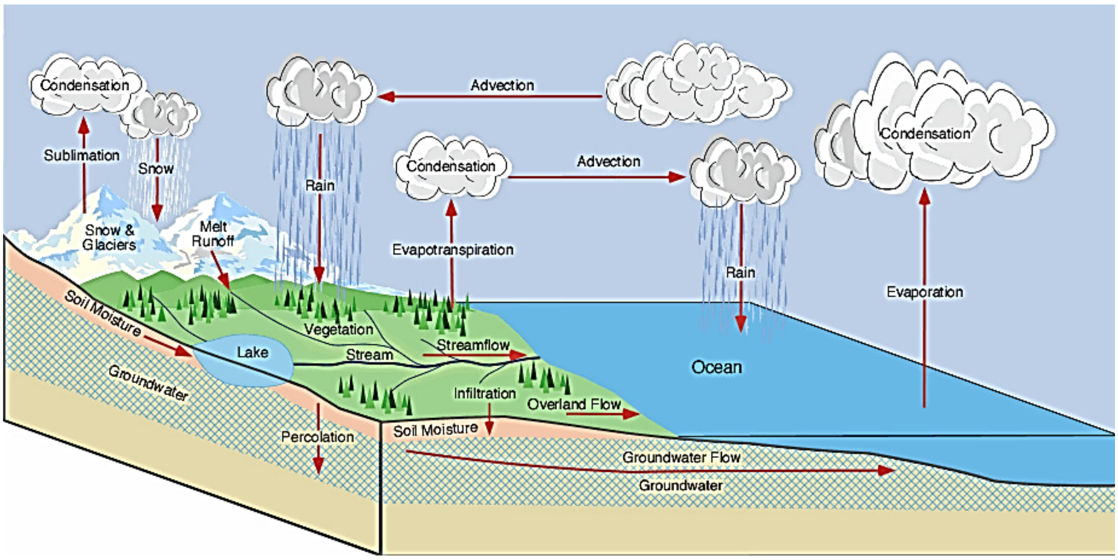


Figure 1.7: Vertical and horizontal movement of water in hydrological cycle

1.5.1 Physical processes considered in hydrological model

The hydrological problems to be addressed plays very important role in the consideration of the physical processes (component) in the hydrological model (see Fig. 1.8) as some of the physical processes are considered relevant while others are considered of secondary importance. A typical hydrological model may account various modules such as (1) spatial variation in land use and management, soil properties, climate, topography, geology, and (2) addition processes for overland flow routing, stream flow routing, floodplains, aquifers, ponds, reservoir and their regulations, water regulating structures, wetlands, and their interaction with adjoining fields. The representation of various physical processes into a typical hydrological model using various physically based methods, conceptual or empirical methods is presented in Table 1.3.

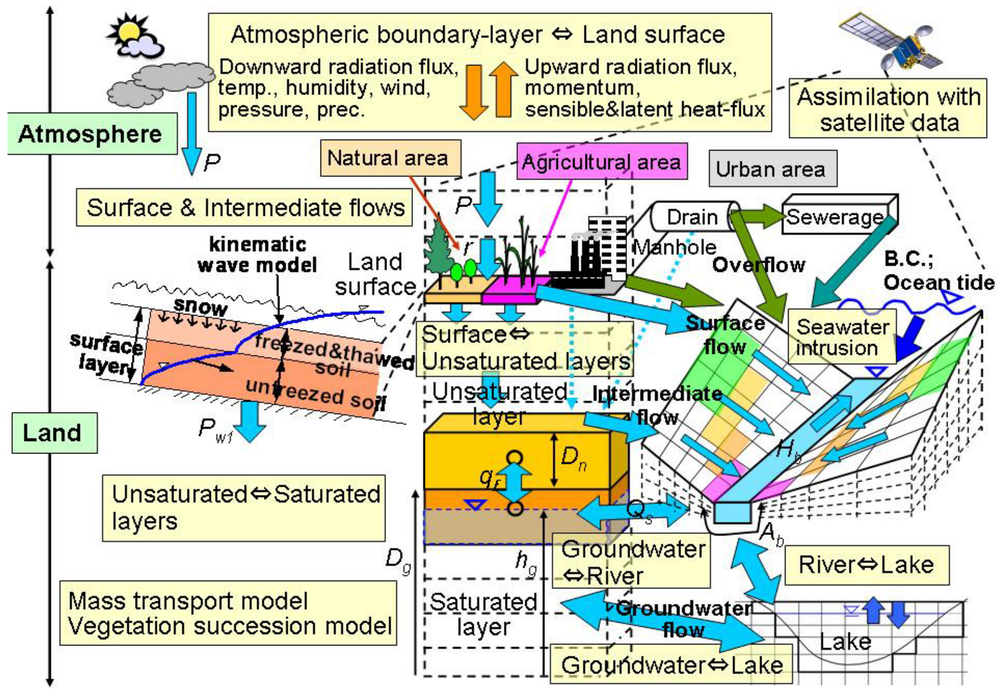


Figure 1.8: Typical physical processes considered in the hydrological models.

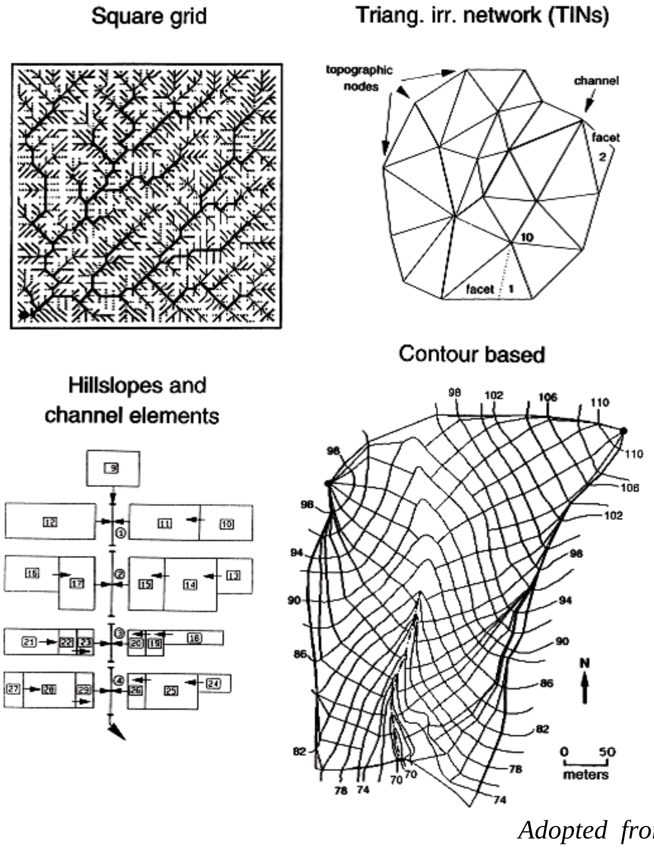
Table 1.3 Physical processes, their representation in hydrological models using different methods.

Physical Process	Physically based models	Empirical/conceptual/measured
Precipitation/ climatic parameters		• Rain gauge point data, • Radar and numerical weather data • Daily max. and min. temperature, Relative humidity, wind speed, vapor pressure, dew point temperatures, sunshine hour, cloudiness factor, evapo-transpiration • Area averaged or spatially distribute climatic parameters • Gridded climatic data
Snow melt and accumulation	• Energy balance equation as a function of air temperature and precipitation	• Temperature index method • ETH snow melt component • A radiation-temperature index model • Degree day method
Interception and Infiltration	• Richards equation (1D/2D/3D) • Green-Ampt equation • Kinematic wave equation • Philip-two term equation • Smith-Parlange method	Interception • Linsley equation • Maximum interception storage capacity • Modified Rutter model • Von Hoyningen-Huene method • Vegetation coveragedescribed in terms of Leaf-Area-Index • Shuttleworth and Calder method • Equivalent of water depth method (Snow interception) Infiltration • Infiltration capacity method • SCS method • SCS-CN

		• Exponential decaying method • HEC • Linear parabolic model • Algebraic equations • One layer deficit constant method • Multi-layer Soil-Moisture Accounting (SMA)model
Evapotranspiration (ET)	• Penmann-Monteith • Morten method	• Observed ET data (pan) • Soil-Moisture Accounting (SMA)model • Blaney-cradle method • Priestley-Taylor method • Thornthwaite and Mather method • Hargreaves equation • Kristensen-Jensen model • Leaf-Area Index for estimation of actual ET from potential ET (PET)
Groundwater flow (baseflow)	• 2D or 3D finite difference groundwater flow model • Non-linear Boussinesq method • Model based on continuity equation,Darcy's law and several simplifications	• Recession method • Constant rate method • Linear reservoir method • GW Routing using response function as in HBV model • Algebraic e.g. Horton equation • Algebraic equations
Flow over porous bed	• Kinematic wave • Dynamic wave • Volume balance	• SCS model
Surface runoff	• Kinematic wave (1D/2D) • Diffusion wave (1D/2D) • Dynamic wave (1D/2D) • Simplified methods	• Rational method • Unit Hydrograph • SCS method • Clark's method for IUH • Linear reservoir routing method • Conceptual models • Nash's conceptual model
Channel routing	• Kinematic wave • Diffusion wave • Dynamic wave • Muskingum –Cunge method • Simplified flood routing methods	• Muskingum method • Straddle stagger method • Pulse method • Modified Pul's method • Hydrograph analysis • Linear reservoir routing method • Storage routing methods
Reservoir routing		• Modified Pul's method • Goodrich method • Fourth order Runge-Kutta method • Storage discharge lake routing method
Solute transport	• Model based on Advection dispersion Fickian model	• Algebraic equations
Sediment transport	• Kinematic • Dynamic • Einstein bed load	• Sediment graph models • Regression equations

1.5.2 Spatial hydrological model structure: spatial discretization

Here some general features of spatial hydrological models and their advantages and limitations in building a suitable model for a particular application are discussed. During the processes representation within hydrological model, selection of resolution for the spatial discretization and conceptualization of process is important task. Usually, the hydrological processes can be parameterized at one resolution and explicitly resolved at another resolution. However, the landscape and climatic heterogeneity makes the hydrological processes representation complicated. One should properly select the spatial discretization between land cover with various soil types, soil profiles and soil horizons, geological formation, and soil matrix and macro pores at smaller scales. Ideally, each level of spatial discretization should correspond with a different process conceptualization. The complexity involve in the selection of proper level of spatial discretization in hydrological model usually leds to user specific varied discritization, as well as to processes conceptualization. In hydrology, the significance of topography and easily avilable digital terrain data often dictates the size and type hydrological model elements based on the way by which the topography is represented in the model structure. There are three ways to represent terrain data digitally as contour data (x and y coordinates of points of equal elevation), gridded elevation data, and irregularly spaced x, y, z data (Grayson Bloschl, 2000). These three types of digital data representation used to construct four type of computational grids to simulate spatial hydrological response (see Fig. 1.9).



Adopted from Grayson Blöschl, 2000

Figure 1.9: Schematic diagram of the element geometry of the four process-oriented rainfall runoff models

The most common form of computational grid used in the hydrological model build up is square grid, e.g., MIKE-SHE and TOPAKAPI model, etc. However, some researchers consider this as a "reductionist" approach arguing that the parameters in the equations estimated from calibration process rather than actual field observation. Another criticism about the use of square grid is that they do not handle heterogeneity properly due to non-organization of continental surface in pixels and thus, parameter estimation task is more difficult. To overcome this problem, some researchers suggested spatial discretization with use of contour data to construct a mesh of elements bounded by adjacent contours (iso-contours of elevation) and orthogonal trajectories (streamlines), e.g., THALES or TOPOG model. Some other researchers suggested Triangulated Irregular Network (TIN) based hydrological models which develop a flow mesh from the triangular facets derived by joining adjacent data points. Some model do not directly use digital elevation data but rather use a subjective discretization of a catchment, e.g., KINEROS model. Each of these approaches has its own advantages and disadvantages as summarized in Table 1.4.

Table 1.4 Approaches used for the explicit terrain representation

Approach	Advantages	Disadvantages
Gridded elements	• DEMs often available as grids • Computationally simple to set up dynamic models • Many models available for use • Multiple approaches exist in literature from simple D8 which sends all the water to the downslope neighbouring element that has the greatest elevation drop, to more realistic D∞, multiflow direction algorithm. • Simple to overlay other spatial information	• Flow directions not straightforward to define • Uniform density of points means inefficiently large number of elements if detail is to be maintained in key areas of the terrain • Use of more sophisticated approaches rather than D8 approach, depends on the quality of original DEM
Contours and streamlines	• More naturally suited to the routing of surface flow • Able to assume 1-D flow in each element	• Setting up of flow mesh • Requires specialized software –software must also be designed to avoid the inefficiency of large elements in gullies and small elements in divergent areas • Does not allow flow to crossstreamlines which is likely in nature • Few models are designed for this structure
TIN facets	• Most efficient methods for representing terrain • Least number of elements for most of terrain detail as mesh is dense where elevation is changing rapidly whereas sparse in flatter area.	• Flow paths are difficult to represent and hence flow routing is not trivial • Data are not common (except direct from field survey) • Few models are designed for this structure
Conceptual elements of hill slopes and stream segments	• Based on the assumption that it is only those features preserved in the conceptual elements (e.g. average slope, flow path length, area) are really important to model response • Some models are based on the concept of hydrologic similarity and can be defined using for instance the topographic index (e.g. TOPMODEL), some models are based on the concept of Hydrological Response Units (HRU's) (e.g. SWAT model) and others are based on concept of Representative Elementary Area (REA) • This structure enable to assume 1-D flow in each element • Lead to a small number of elements - faster model running times	• Discretisation generally done manually • One of the drawback of HRUs is that the mapping induces merging of smaller unit into larger ones by applying smoothing filters. • In case of REAs, flow routines and the hierarchical structure of the river network were not taken into account. Further, global mass, momentum and energy balance law formulated at sub-catchment scale remains unchanged for whatever modeling scale required to be defined for each scale. • Uncertainty about the validity of the main assumption in some applications • Few models are designed for this structure

1.6 Model Calibration and Validation

Hydrological models are increasingly being used to support decisions for better management and operational strategies of water resources and hence, calibration, validation and uncertainty analysis of these models are necessary before using them in research and/or real-world applications. Calibration and validation of hydrological models, however, is a challenging task. Recently, Cornelissen et al. (2013) have studied four different types of models (WaSiM, SWAT, UHP-HRU and GR4J) that vary in complexity, spatial resolution, and process representation to differentiate between effects caused by model choice and also to improve the understanding of hydrological processes and to provide new insight into the influence of land use and climate change on discharge behavior. It was reported that the variation between simulation qualities of the models can be attributed to uncertainty in input data, calibration strategy, parameterization, and difference in model structure, output data for model validation (Breuer et al., 2009; Cornelissen et al., 2013; Huisman et al., 2009). In remote regions which are minimally gauged, the calibration and validation of hydrological models is really a tough task.

Model calibration refers to the adjustment of parameters of a particular model using historical input-output records to reproduce the observed response of the catchment within the range of accuracy specified in the performance criteria. Calibration is performed by carefully selecting model parameter values, adjusting them within their recommended ranges, and comparing predicted output variables with observed data for a given set of conditions (Arnold et al., 2012). A successfully calibrated model is able to replicate observed data within an adequate level of accuracy and precision.

Model validation refers to the judgment on the calibrated model performance to simulate the response with sufficient accuracy for a period other than the calibration period.

Distributed hydrological models are structured to enable the spatial variations in catchment characteristics to be represented by providing data for a network of grid points. Often model applications require several thousands of grid points, each of which is characterized by several parameters and variables. In this way distributed models differ fundamentally from conceptual and lumped models, where a catchment is considered as one unit characterized by, typically, a few tens of parameters and variables. Thus, the number of parameters and variables in a distributed model is often two or three orders of magnitude higher than it would be for a lumped model of the same area (Beven, 1989, 1996). Obviously, this generates different requirements to lumped and distributed models with regard to parameterization, calibration and validation procedures.

The problems related to initialization, calibration and validation of distributed models are excellently summarized by Rosso (1994): "*In principle, spatially distributed models can accept experimental data at each grid element or calculation node. In practice, because of heterogeneity of parameter values, differences between measurement scales and model grid scales, and experimental constraints, the specification of parameter values is very difficult. These constraints also apply to the validation of distributed model predictions by using measurements of internal system response. Conventional strategies for distributed model validation typically rely on the comparison of simulated model variables to observed data for* *specific points representing either external boundaries or intermediate locations on the model grid. Traditional validation based on comparing simulated with observed outflows at the basin outlet still remains the only attainable option in many practical cases. However, this method is poorly consistent with spatially distributed modeling".*

Refsgaard and Storm (1996) emphasized that a rigorous parameterization procedure is crucial to avoid methodological problems in model calibration and validation. The following points are important in parameterization (Refsgaard and Storm, 1996).

- The parameter classes (soil types, vegetation types, climatological zones, soil layers, etc.) should be selected so that it becomes easy, in an objective way, to associate parameter values. Also, the parameter values in the different classes should, to the highest possible degree, be assessable from available field data.
- It should explicitly be evaluated which parameters can be accessed from field data alone and which need some kind of calibration. For the parameters subject to calibration, physically acceptable intervals for the parameter values should be estimated.
- The number of calibration parameters should be kept low, both from practical and methodological points of view. This can be done, for instance, by fixing a spatial pattern of a parameter but allowing its absolute value to be modified in calibration.

1.6.1 Calibration methods

An appropriate model calibration is important in hydrologic modeling studies to reduce uncertainty in model simulations (Engel et al., 2007). An ideal model calibration can be carried out (1) using data that includes wet, average, and dry years (Gan et al., 1997), (2) using multiple evaluation techniques (Willmott, 1981; ASCE, 1993; Legates and McCabe, 1999; Boyle et al., 2000), and (3) calibrating all constituents to be evaluated.For model calibration, the methods which have been commonly used include: (i) manual parameter estimation by using 'Trial and Error' procedure, (ii) automatic parameter estimation using numerical optimisation procedures, and (iii) a combination of (i) and (ii). In manual parameter estimation, the modeller's knowledge on the model and impact of each parameter on the simulation results are used to calibrate parameters. Change in parameters is made primarily by comparing simulated versus observed values. The calibration is terminated when the user subjectively determines that the set accuracy criterions have been met fully. Another method is automated calibration (Gupta et al., 2000) in which various computer algorithms are used to achieve the best fit simulated values with observed values. The algorithms contain strategies for varying the values of user specified parameters in an attempt to obtain an optimal fit by applying limits on the range over which parameter can varying to provide more physically realistic results. The quality of the reproduction can be determined by a single statistical objective function, such as minimizing the daily root mean square error, or a series of steps with use of different groups of parameters and different objective functions at each step (Hogue et al., 2000) or multiple objective functions to find out a group of parameter sets that will produce good results based on several criteria (Gupta et al., 1998).

Automatic optimization has been primarily used for the calibration of individual watersheds, mainly headwater drainages. There are limited strategies available for using automated optimization over entire river basins. However, selection of an appropriate criterion is greatly complicated by the variation in the sources of error. It further depends on the objective of the simulation (e.g., to simulate flood peaks or hydrograph shape) and on the model output variable, e.g., phreatic surface level, soil moisture content, stream discharge or stream water level. No single criterion is entirely suitable for all variables and even for a single variable it is not always easy to establish a satisfactory criterion.

Both statistical and graphical model evaluation techniques are used for model calibration. The quantitative statistics are divided into three major categories: Strength of the linear relationship between simulated and measured data is determined by the standard regression statistics. Dimensionless techniques providea relative model evaluation assessment and error indices quantify the deviation in the units of the data of interest (Legates and McCabe, 1999).

Moriasi et al. (2007) recommended both graphical techniques and quantitative statistics in model evaluation. Model evaluation statistics includes slope and y-intercept of the best fit regression; pearson's correlation coefficient (R) and coefficient of determination (R^2).

Kling-Gupta efficiency (KGE) (Gupta et.al., 2009) provides improved model diagnoses for different ranges of streamflow and processes, and a better understanding of the balance between correlation and mean/variance biases. The Kling-Gupta efficiency (KGE) measure is computed using either streamflow series, hydrological regime curves, or flood and low-flow samples. The modified KGE dimensionless statistics (Kling et.al. 2012) is given as:

$$KGE = 1 - \sqrt{(r-1)^2 + (\beta-1)^2 + (\gamma-1)^2}$$

Timing	Magnitude	Variability

Where,

$$\beta = \frac{\mu_s}{\mu_0}$$

$$\gamma = \frac{CV_s}{CV_0} = \frac{\sigma_s/\mu_s}{\sigma_0/\mu_0}$$

r is the correlation coefficient between simulated and observed runoff (dimensionless), β is the bias ratio (dimensionless), γ is the variabilityratio (dimensionless), μ is the mean runoff in m3/s, CV is thecoefficient of variation (dimensionless), σ is the standard deviationof runoff in m^3/s, and the indices s and o represent simulated andobserved runoff values, respectively. KGE, r, β and γ have their optimum at unity.

This scheme is based on a preliminary search in a parameter library, a sequential calibration using different representative objective functions based on the KGE measure, a hierarchical calibration of a parsimonious version and a full version of the model and the computation of Pareto fronts. This calibration scheme provides a good balance between automatic calibration and the expert knowledge of watershed and model properties.The commonly used criterion for performance evaluation is presented in Table 1.5.

Table 1.5 Criteria for evaluating the performance of the hydrological model and their corresponding classifications.

Statistical Criterion	Value	Classification of performance	Reference
Nash-Sutcliffe coefficient $NSE = 1 - \frac{\sum_{i=1}^{n}(O_i - S_i)^2}{\sum_{i=1}^{n}(O_i - \overline{O})^2}$	0.75 < NSE < 1.00 0.65 < NSE ≤ 0.75 0.50 < NSE ≤ 0.65 0.4< NSE ≤ 0.50 NSE ≤ 0.4 0.4 < NSE < 0.70	Very good Good Satisfactory Acceptable Unsatisfactory Acceptable	Boskidis et al., 2012;Moriasi et al., 2007
Percent bias RSR-$\frac{\text{RMSE}}{\text{STDEV}_{\text{obs}}} = \left[\frac{\sqrt{\sum_{i=1}^{n}(O_i - S_i)^2}}{\sqrt{\sum_{i=1}^{n}(O_i - \overline{O})^2}}\right]$	PBIAS<±10 ±10≤PBIAS<±15 ±15≤PBIAS<±25 PBIAS≥±25	Very good Good Satisfactory Unsatisfactory	Moriasi et al., 2007
Root mean Square error RMSE = $\left[\frac{\left(\sum_{i=1}^{n} S_i - O_i\right)^2}{n}\right]^{0.5}$	Value below half the standard deviation	Satisfactory	Singh et al., 2004
Ratio of the RMSE to the Standard deviation of the observations RSR-$\frac{\text{RMSE}}{\text{STDEV}_{\text{obs}}} = \left[\frac{\sqrt{\sum_{i=1}^{n}(O_i - S_i)^2}}{\sqrt{\sum_{i=1}^{n}(O_i - \overline{O})^2}}\right]$	0.00≤RSR≤0.50 0.50≤RSR≤0.60 0.60≤RSR≤0.70 RSR>0.70	Very good Good Satisfactory Unsatisfactory	Moriasi et al., 2007
Pearson's correlation coefficient (r) and coefficient of determination (R2)	r=0 r=1 r=-1 0≤R2≤1	No linear relationship exists. A perfect positive linear relationship exists A perfect negative linear relationship exists. Higher values indicating less error variance, and typically values greater than 0.5 are considered acceptabl	Santhi et al., 2001, Van Liew et al., 2003
Best-fit regression line between simulated data and measured data $y = mx + c$	slope m=1 and intercept c=0	model perfectly reproduces the measured data	Willmott, 1981.
Index of agreement (dimensionless) $d = 1 - \frac{\sum_{i=1}^{n}(p_i - O_i)^2}{\sum_{i=1}^{n}(\lfloor P_i - \bar{O}\rfloor + \lceil O_i - \bar{O}\rceil)}$	d=1 d=0	perfect agreement between the measured and predicted values no agreement at all	Willmott, 1981
Persistence model efficiency (PME)	PME = 1. PME≥0	optimal value minimally acceptable	Gupta et al., 1999
Prediction efficiency (Pe) P_e is the coefficient of determination	P_e	determines how well the probability	Santhi et al.,2001

(R2) calculated by regressing the rank (descending) of observed versus simulated constituent values for a given time step.		distributions of simulated and observed data fit each other.It may not account for seasonal bias.	
Performance virtue statistic (PV_k) PV_k is the weighted average of the NashSutcliffe coefficients, deviations of volume, and error functions across all flow gauging stations within the watershed of interest	$-\infty \leq PV_k \leq 1.0$	indicating that the model exactly simulates A negative value indicates that the average of observed values is better than simulated values	Wang and Melesse, 2005
Daily root-mean square (DRMS): The daily root-mean square (DRMS), which is a specific application of the RMSE, computes the standard deviation of the model prediction error (difference between measured and simulated values).	DRMS	The smaller the DRMS value, the better the model performance	Gupta et al., 1999
Peak percent thresholdstatistics of prediction betweentop u%and l% data (PPTS(l,u)). The term PPTS(l,u) is the average absolute relative error in prediction of flows lying in the band of top u% and l% data. For computation of the PPTS(l,u), the observed data are arranged in descending order	PPTS of top 5 to 10% data PPTS of lowest 5 to 10% data	Useful for flood comparing flood forecasting model Useful for low flow forecasting models	Lohani et al., 2014

(where i – time series of the measured and simulated data sets; n - number of the measured and simulated data variables; O_i-- observed data;S_i – simulated data; $\overline{O}$ – mean of the observational data)

1.6.2 Model validation

For the model validation, various statistical indices and graphs based on the observed and computed output are used. It is apparent that quantitative assessments of the degree to which the model simulations match the observations are used to provide an evaluation of the model's predictive abilities. Frequently, evaluations of model performance utilize a number of statistics and techniques, usually referred to as 'goodness of fit' statistics. Many of the principal measurements that are used in the hydrological literature have been critically reviewed by Legates and McCabe (1999). Still, there is diversity in using global goodness of fit statistics to determine how well models forecast flood hydrographs. As a single evaluation measure is not available, Sudheer and Jain (2003) suggested a multi-criteria assessment with various goodness of fit statistics. These measures can be grouped into two types: relative and absolute. Relative goodness of fit measures are non-dimensional indices which provide a comparison of the performance of one model against another. In contrast, absolute goodness of fit statistics are measured in the units of the actual measurement. Nayak et al. (2005) provided specific information about model performance during high flow, which is of critical importance in a flood forecasting context. Gupta et al. (2008), proposed split model evaluation in three complementary phases: (a) quantitative evaluation of model performance; (b) qualitative evaluation of model performance; (c) qualitative evaluation of model structure and scientific basis for hydrologic and environmental modeling. In the following section, commonly accepted performance and scientific validation procedures are briefly discussed.

1.6.3 Performance validation

1.6.3.1 Statistical and graphical performance indices

The typical approach adopted to evaluate model performance requires the comparison between simulated outputs on a set of observations that were not used for model calibration. This procedure coincides with the so-called split sample test in the classic hierarchical validation scheme proposed by Klemeš (1986), as well as with the first level of the theoretical scheme of Gupta et al. (2008). However, an ordinary split-sample test is not sufficient for a rigorous and comprehensive model validation. Therefore, Klemes (1986) has proposed differential split-sample test, as latter tests will most often be associated with a higher degree of uncertainty than former tests. Many criticisms have been addressed to traditional lumped indices for their lack of diagnostic power or inability to capture differences between different model or parameter sets leading to ambiguous situations characterized by equifinality. As a result, more powerful evaluation tool like multi-objective methods that combines different (weighted) performance metrics into one overall objective function (e.g., Gupta et al., 1998) have been proposed. Another notable issue is that metric interpretation in not always straight forward. A differential split-sample test is, from a theoretical point of view, weaker than the traditional split-sample test, where data from the specific catchment are used.

Graphical techniques including scatter plots between observed and computed also allow a subjective and qualitative validation. Despite the plethora of exiting goodness-of-fit metrics, visual inspection still represents a fundamental step in model validations

1.6.3.2 Performance indexes for model selection

The performance indexes or information criteria provide a quantitative and aggregate estimate of model reliability and are generally expressed as a function of the simulation errors. Some metrics have a statistical foundation, as the likelihood functions (Beven et al., 2001; Romanowicz and Beven, 2006), the AIC (Akaike Information Criterion), the BIC (Bayesian Information Criterion) and the KIC (Kashyap Information Criterion). The last three statistic criteria account for the mathematical complexity of the model by including the number of model parameters in the metric computation. AIC and BIC are based on the maximum likelihood estimates of the model parameters. The model with the lowest BIC is preferred. It is based, in part, on the likelihood function and it is closely related to the Akaike information criterion (AIC). Both BIC and AIC attempt to resolve this problem by introducing a penalty term for the number of parameters in the model; the penalty term is larger in BIC than in AIC.

1.6.4 Advanced techniques and general guidelines for model calibration and validation

During the past decades, general methodologies related to hydrological model calibration and validation have been subjected to considerable discussion (e.g., Jain, 1993; Sudheer et al., 2007; DiBaldassarre et al., 2016). Efficient calibration methods have been implemented in several software packages (e.g., MICA (Markov Chain Monte Carlo analysis) (Doherty, 2003b); PEST (Doherty, 2005; Tonkin and Doherty, 2009), UCODE (Poeter and

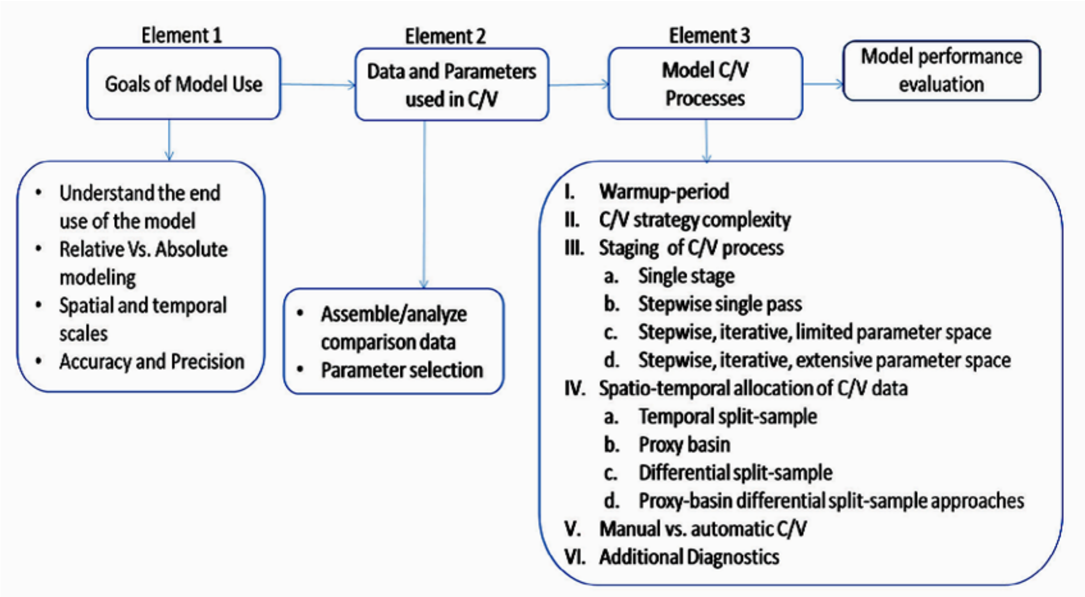
Hill, 1998) and OSTRICH (Matott, 2005)). Vrugt et al. (2009) have used the Differential Evolution Adaptive Metropolis (DREAM) algorithm to calibrate model parameters.

Despite mathematical objectivity, some subjectivity is unavoidable: through defining the conceptualization of the inverse problem and making a set of decisions related to regularization, parameter bounds, observation weighting strategy, etc. (Fienen, 2013). The inverse modeling tool PEST (Doherty, 2010) uses an iterative, nonlinear regression approach that involves simultaneous adjustment of multiple model parameters and evaluation of model fit by the sum of weighted squared residuals between field observations and simulated values. In addition to providing sophisticated estimates of the parameter values that provide the best possible fit for a given calibration problem, inverse modeling provides a method for comprehensive model analysis through statistical measures such as the variance/covariance index, parameter correlations, confidence intervals, sensitivities, identifiability, and predictive uncertainty analysis (Moore and Doherty, 2005). Recently, Necpa′lova′ et al. (2015) have reported simultaneous calibration of 67 DayCent model parameters using multiple observation types through inverse modeling using the PEST software.

Wallner et al. (2012) compared a variety of manual (lumped, one-factor, distributed, and regionalization) and automatic (parameter estimation (PEST), dynamically dimensioned search (DDS), and shuffled complex evolution (SCE)) calibration strategies. They found that the DDS automatic algorithm gave the best results overall. Other studies have assessed different strategies for parameter optimization (Blasone et al., 2007), automatic calibration (Kim et al., 2007), and parameterization (Pokhrel and Gupta, 2010; and Daggupati et al., 2015). Ramsankaran et al., (2012) proposed Physically Based Distributed (PBD) model using the Ordered-Physics-based Parameter Adjustment (OPPA) method for calibration.

Many hydrological models are reported on model calibration and validation but, there is no unanimity on methodology to compare modeling results from different studies because there are no universally accepted guidelines (Moriasi et al., 2012). Most of this scientific discussion has been of a principal nature and only a few authors, such as, Moriasi et al. (2012), Biondi et al. (2012) and Daggupati et al. (2015) have attempted to outline general rigorous operational procedures.

Daggupati et al. (2015) attempted to develop a generalized structure and process (organized into three major strategy elements) to assist modelers in developing a calibration and validation (C/V) strategy for hydrological as well as water quality modeling applications by surveying literature (e.g., Moriasi et al., 2012) (See Fig. 1.10). Readers may refer the work of Daggupati et al. (2015) for more detailed discussion of these strategy elements. According to these authors, although, there is wide difference between calibration and validation processes, while planning calibration and validation strategy, modelers must take care of the modeling application’s goals, end users’ needs and constraints of the use and the associated considerations, including absolute or relative predictions, spatial and temporal scales, and levels of accuracy and precision required.



Source: Daggupati et al., 2015

Figure 1.10: Elements of calibration and validation (C/V) strategy for hydrologic modeling.

1.6.5 Guidelines for model performance validation

1. Provide clear and unequivocal indications about model performance in real world applications.
2. Apply the validation procedure by using independent information with respect to what was used for model calibration.
3. Perform validation and discussion of data reliability, and possibly implement a combined validation of models and data.
4. Use graphical techniques and several numerical performance indices to evaluate different aspects of model performance. Among the available graphical techniques, the use of scatter plots of observed versus simulated values is suggested for their immediate readability. The use of the logarithmic scale should be properly justified.
5. When dealing with probabilistic simulations, use rigorous techniques that test several attributes of forecast quality.
6. When presenting results, do not focus only on a few cases (e.g., a single intense flood event), but consider a statistically significant number of cases including those where the model didnot return satisfactory results. Indications about worst performance should be provided, discussing the possible reasons that are responsible for the obtained performance level.
7. If possible, extend the validation to model input and state variables.
8. If possible, validate the model over different temporal and spatial scales.
9. Evaluate the opportunity to apply jack-knife techniques to create confidence intervals (Shao and Tu, 1995; Castellarin et al., 2004; Brath et al., 2003).

1.7 Uncertainty Analysis

Aconcerning query in hydrology is how far different models constitute reality with their necessary estimates of hydrological processes and parameters at the element scale. An analysis of this question reveals a number of issues such as the problems of nonlinearity, scale, uniqueness, equifinality and uncertainty (Beven, 2001). Hydrologic modeling has benefited from significant developments over the past two decades, including dramatic growths in computational power, ever increasing availability of distributed hydrologic observations, and improved understanding of the physics and dynamics of the hydrologic system. This has led to the building of higher levels of complexity into hydrologic models, and an advance from lumped, conceptual models toward semi-distributed and distributed physics-based models. Paradoxically, while these advances reflect our growing understanding, they have also increased the need for concrete methods to deal with the increasing uncertainty associated with the models themselves, and with the observations required for driving and evaluating the models. It is now being broadly recognized that proper consideration of uncertainty in hydrologic predictions is essential for purposes of both research and operational modeling (Wagener and Gupta, 2005). From the management point of view, uncertainty refers to the lack of exact knowledge, regardless of what is the cause of this deficiency (Refsgaard et al., 2007). Each decision or set of decisions has associated gains or losses which are usually dependent on several random factors and thus highly uncertain (Fenton and Neil, 2012).

Although the hydrological model can be trusted as a suitable tool to make prediction for decision through model simulation, there is always uncertainty about the soundness of model structure (conceptual basis) even the models has passes the validation test. Under such circumstances, compensating error in conceptual model (model structure) with errors in parameter values could be right choice rather it is for wrong reason. It would be possible to find many other models that can pass the validation test, and that it would not be possible before hand to identify one of these models as the best one in all respects. Having realised this equifinality problem the relevant question is what should be done to address it in practical situations. Typically, uncertainty is present on every step of the hydrological model analysis. In decision making, hydrological model analysis should aim to provide the decision maker with as realistic picture of the current knowledge and its deficiencies as possible, by utilising all the relevant information available. Uncertainty is often expressed in the form of probability distribution that indicates different scenarios of possible outcomes.

Uncertainty in the hydrologic system can be commonly divided into four categories according to their basic nature: aleatory uncertainty (i.e., inherent randomness and natural variability); epistemic uncertainty (resulting from imperfect knowledge); semantic /linguistic uncertainty (i.e., uncertainty about what statements or quantities in the relevant domain actually mean) and ontological uncertainty (i.e., uncertainty associated with different belief systems) (Baldassarre et al., 2016; Beven, 2016). The first is typically seen as irreducible, whereas the latter three can be quantified and reduced. Basically, four sources of uncertainty occur in deterministic simulation, the disagreements between recorded and simulated output resulting from:

1. Random or systematic errors in the input data, e.g., precipitation, temperature, soil moisture or evapotranspiration used to represent the input conditions in time and space for the catchment.

2. Random or systematic errors in the recorded output data, e.g., water level or discharge data used for comparison with the simulation output.
3. Errors due to non-optional parameter values.
4. Errors due to incomplete or biased model structure.

Input uncertainty is often related to imprecise or spatially interpolated measurements of model input or initial conditions, such as elevation data, land use data, rainfall intensity, temperature and initial groundwater levels. Other uncertainties in distributed models may also arise due to the large number of unknown parameters and the errors in the data used for parameter calibration. An additional uncertainty emerges when applying calibrated hydrological models under the future condition which differs from the condition in the calibration period. Since the issue of identifying and understanding the transferability of hydrological model parameters to a contrasted climate has not been well resolved, significant uncertainty could emerge from the choice of the calibration periods that represents specific climatic characteristics. Unfortunately, the assessment of this uncertainty is usually ignored in the impact analysis. Previous findings (Brigode et al., 2013; Wilby, 2005; Wang, et al., 2015) prove the need of routinely carrying out the uncertainty assessment of the transferability of hydrological models in the context of climate change impact studies.

To calculate for these uncertainties, various uncertainty-analysis techniques have been developed and applied to different catchments in the world since two decades. The need for developing new or modified approaches may be related to fact that the typical use of frequency response based approaches (e.g.,Yanget al., 2007a) and Bayesian approaches (e.g.,Yanget al. 2007b) which only consider parameter uncertainty and (independent) measurement error while neglecting input and model structure uncertainty leads to unrealistic prediction uncertainty bounds.

Regardless of the large number of proposed techniques, rarely more than one technique has been applied in the same case study in the literature and few studies only reported on comparison between different uncertainty analysis techniques applied to simple hydrological models (e.g., Nkonge et al., 2014). To fill this gap, Yang et al. (2008) have furnished comparison among existing important techniques for uncertainty estimation. Yang et al. (2008) have studied the advantages and disadvantages of the five techniques namely Generalized Likelihood Uncertainty Estimation (GLUE) (Beven and Binley, 1992), Parameter Solution (ParaSol) (Van Griensven and Meixner, 2006), Sequential Uncertainty Fitting (SUFI-2) (Abbaspour et al., 2004; 2007), Bayesian inference based on Markov chain Monte Carlo (MCMC) (e.g., Vrugt et al., 2003 and Yang et al., 2007a), and Bayesian inference based on importance sampling (IS) (e.g., Kuczera and Parent, 1998) in practical applications of complex hydrological models. Note that these uncertainties analysis techniques are different in their philosophies and leave the user some freedom in formulating the generalized likelihood measure, objective function, or likelihood function, a literal comparison between the techniques is not possible. For the sake of ready reference of readers, these five techniques are briefly presented here in the following section.

1.7.1 Commonly used uncertainty estimation techniques

1.7.1.1 Generalized Likelihood Uncertainty Estimation (GLUE)

GLUE is an uncertainty analysis technique instigated by importance sampling and regional sensitivity analysis (Hornberger and Spear, 1981). In GLUE, parameter uncertainty accounts for all sources of uncertainty, i.e., input uncertainty, structural uncertainty, parameter uncertainty and response uncertainty, because 'the likelihood measure value is associated with a parameter set and reflects all these sources of error and any effects of the covariation of parameter values on model performance implicitly' (Beven and Freer, 2001). Also, from a practical point of view, 'disaggregation of the error into its source components is difficult, particularly in cases common to hydrology where the model is non-linear and different sources of error may interact to produce the measured deviation' (Gupta et al., 2005). In GLUE, parameter uncertainty is described as a set of discrete 'behavioral' parameter sets with corresponding 'likelihood weights'.

1.7.1.2ParaSol and modified ParaSol

ParaSol is based on a modification to the global optimization algorithm SCE-UA (Duan et al., 1992). The idea is to use the simulations performed during optimization to derive prediction uncertainty because ''the simulations gathered bySCE-UA are very valuable as the algorithm samples over the entire parameter space with a focus on solutions nearthe optimum/optima'' (Van Griensven and Meixner, 2006).

1.7.1.3 Sequential Uncertainty Fitting (SUFI-2) procedure

In SUFI-2, parameter uncertainty is described by a multivariate uniform distribution in a parameter hypercube, while the output uncertainty is quantified by the 95% prediction uncertainty band (95PPU) calculated at the 2.5% and 97.5% levels of the cumulative distribution function of the output variables (Abbaspour et al., 2007). Latin hypercube sampling is used to draw independent parameter sets (Abbaspour et al., 2007). Similarly, GLUE, SUFI-2 represents uncertainties of all sources through parameter uncertainty in the hydrological model. SUFI-2 allows its users several choices of the objective function (such as, NS coefficient). In literature, the weighted root mean square error (RMSE) (Abbaspour et al., 2004) and the weighted sum of squares SSQ (Abbaspour et al., 2007) were used.

1.7.1.4 Bayesian inference

Scientific hypotheses typically are expressed through probability distributions for observable scientific data. These probability distributions depend on unknown quantities called parameters. In the Bayesian paradigm, current knowledge about the model parameters is expressed by placing a probability distribution on the parameters, called the "prior distribution". Posterior prediction uncertainty is usually represented by quantiles of the posterior distribution. The crucial point of applying this technique is the formulation of the likelihood function. If the statistical assumptions for formulating the likelihood function are violated, the results of Bayesian inference are unreliable. Unfortunately, when formulating likelihood functions in hydrological applications, it is oftenassumed that the residuals between measurements and simulations are independently and identically (usually normally) distributed. However, this assumption is often violated. To avoid this problem, the likelihood function by combining a Box–Cox transformation with a continuous-time autoregressive error model. This model extends earlier works with discrete-time autoregressive error models in hydrological applications (e.g., Kuczera, 1983; Duan et al., 1988; Bates and Campbell, 2001). More details are given by Yang et al. (2007a). Two generic Monte Carlo approaches to sample from the posterior distribution are Markov chain Monte Carlo and Importance Sampling (Gelman et al., 1995; Kuczera and Parent,1998). Both techniques can be used as implemented in the systems analysis tool UNCSIM (Reichert, 2005; http://www.uncsim.eawag.ch).

1.7.1.5 Markov Chain Monte Carlo (MCMC)

MCMC methods are a class of algorithms for sampling from probability distributions based on constructing a Markovchain that has the desired distribution as its equilibrium distribution. The simplest technique from this class is the Metropolis algorithm (Metropolis et al., 1953; Gelmanet al., 1995).

1.7.1.6 Importance sampling (IS)

Importance sampling is a well-established technique for random sampling from a probability distribution (Gelmanet al., 1995; Kuczera and Parent, 1998). The idea is to draw randomly from a sampling distribution f_{sample} and calculate weights for the sampling points to make the weighted sample from the posterior distribution. The computational efficiency of this procedure depends strongly on how close the sampling distributionis to the posterior distribution. Hence, the choice of the sampling distribution is crucial (Gelman et al., 1995).

1.8 Flood Modeling

Floods are caused by variety of factors, both natural and man-made. Some obvious causes of floods are heavy rains, melting snow andice, and frequent storms within a short time duration. Major causes of floods in India include intense precipitation leading to flash flood, inadequate capacity within riverbanks to contain high flows, and silting of riverbeds. Other factors are landslides leading to obstruction of flow and change in the river course, retardation of flow due to tidal and backwater effects, poor natural drainage, cyclone and heavy rainstorms/cloud bursts, snowmelt and glacial outbursts, and dam break flow. The primary purpose of the flood flow analysis is to estimate the flood water level for a given flood runoff. The types of flood flow change mainly depend on the topography of the river and flood plains. Various approaches are therefore conceivable for flood flow analysis depending on its flood flow types. These are given below:

- Flood flow with small overbankflow
- Flood flow with steep slope overbank flow
- Flood flow with mild slope overbank flow
- Inundation due to local runoff

Some special flood problems in India are briefly described here.

1.8.1 Dam Break Flows

Flooding due to dam break is a mega-disaster as it is associated with huge loss of life and property. An unusual high peak in a short duration and presence of a moving hydraulic shock/bore make it a different process compared to natural floods. In India failure of dams such as Machhu and Panshet had generated dam break floods. Sometimes, blockage of water due to deposits caused by landslide takes place. When this natural blockage fails due to increased pressure of water at upstream end, huge flooding occurs.

1.8.2 Flash Floods

Flash floods are characterized by sudden rise and recession of flow of small volume and high discharge which causes damages because of suddenness. They generally take place in hilly region where the bed slope is very steep. Typical examples are flash flood of Arunachal Pradesh and flash flood of Satluj in 2000.

Floods in coastal areas may also be caused by cyclones. Coastal areas of Andhra Pradesh, Orissa, Tamilnadu, and West Bengal frequently experience heavy floods. The flood due to the super cyclone combined with heavy rainfall during October 1999 in the coastal region of Orissa is an example. During past 110 years (1891-2000), over 1,000 tropical cyclones and depressions, originating in the Bay of Bengal and Arabian Sea, moved across India. Passage of such storms over a river basin leads to severe floods.

1.8.3 Real-Time Flood Forecasting

Real-time forecasting is one of the most effective non-structural flood management measures. To formulate flood forecasts in the real time, the observed meteorological and hydrological data are transmitted to the forecasting station through the means of data communication which include telephones and network of telemetry stations, etc. The techniques available for real-time flood forecasting may be broadly classified in three groups: (i) deterministic modeling, (ii) stochastic and statistical modeling and (iii) computational techniques like Artificial Neural Network (ANN) and fuzzy logic. Depending on the availability of hydro-meteorological data, basin characteristic, computational facilities available at the forecasting stations, warning time required and purpose of forecast, different flood forecasting techniques are used. Some of the commonly used techniques include: (i) simple relation developed correlating the stage-discharge data, (ii) co-axial correlation diagram's developed utilizing the stage, discharge and rainfall data etc., (iii) event based hydrological system models for small to moderate sized catchments, (iv) network model consisting of the sub-basins and sub-reaches for the large sized catchments, and (v) hydrologic models (at selected places). The application of the computing techniques such as ANN and fuzzy logic are currently in the development stage and being mostly used by the academicians and researchers (Lohani et al. 2006, 2007, 2011, 2012, 2014, Kar et al. 2015, 2017). A comprehensive review of varies hydrometric data based methods for real time forecasting has been discussed by Perumal and Sahoo (2009 and 2010) who have also described flood forecast systems implemented by various agencies.

1.8.4 River Bank/Bed Erosion and Sediment Transport

Many natural rivers have mobile bed. Depending on the flow properties, there may be aggradations and/or degradation in the river banks and beds. A river erodes its banks due to various reasons, causing loss of arable and productive land, and deterioration of the river flow regime. Deforestation of upper catchment and hills lead to increased sediment load in rivers. River erosion causes a loss to the land resources. The river behaviour causes new riverine landmass to be built up, but these become productive after many years and cannot compensate the land-loss due to erosion. Rivers in Brahmaputra-Barak and Ganga basins are prone to severe erosion. The channel configuration of the river undergoes large changes in response to variations in the flow regime and the pattern of sediment transport. The geomorphic response of fluvial systems to large flood events has long been the focus of geomorphological research. Establishing and quantifying the processes that link flow dynamics, sediment transport and erosion is always challenging.

1.8.5 Urban Flood Modeling

United Nations projects that 60% of the world's population will live in cities by 2030. Skyscrapers, paved roads, storm water drains, sewer drains and illuminated light system etc. are the symbol of urban areas. Various practices are employed to mitigate the adverse effects of urbanization on storm water runoff. The natural rainfall-runoff process is altered in an urbanized area. Part of the land surface is covered by impervious material due to urbanization. A typical urban land cover consists of impervious rooftops, streets, and parking lots etc. allowing far less surface infiltration and retention. The natural water courses are cleared, altered, deepened, and straightened to improve their conveyance capacities. New man made drainage facilities added to the existing drainage system. As a result of these factors, storm water runoff increases causing flooding. If the water stagnates, then there is a likelihood of spreading water borne diseases, which may affect the health of the people.

In recent years higher intensity of rainfall in short duration is observed more likely due to climate change even reducing the number of rainy days in a year. On top of this the landuse changes, topographical modification, unplanned garbage disposal obstructing natural and man-made drainage system in an urban area adds to the menace.

Mumbai went under water on 26-27 July, 2005 as torrential rains plunged the financial capital into a black hole, jeopardizing all the modern-day lifelines that the metropolis took for granted. Over 21 hour burst, Santa Cruz in northwestern Mumbai clocked as much as 944.2 mm of rainfall - the highest recorded since 1974 (annual rainfall 2500 mm). Mumbai airport stayed closed. Train services disrupted and many cancelled. ATMs of banks with Mumbai bases stopped functioning. Communication links were snapped, forcing thousands to sleep over in offices, stay stuck in cars or walk for miles. Several children were also marooned in schools through the night. Most networks of cellphones simply fell silent because of power failure. A handful of commuters were lucky to reach home after walking for 14 hours walking on rail tracks and wading chest-deep through water. The Fireman tied ropes to lamp-posts and a chain of people held onto it to get through water. Many people died in the city. The heavy downpour of 380 mm for 3 hours between 14.30 PM to 17.30 PM on 26 July was more than 125 mm/hr which is 5 times more than the intensity of rain for which old drains were designed causing disruption and losses.

Chennai city often faces the problem of floods in many areas during rainy season.

Heavy rain associated with cyclonic activity resulted to catastrophic flooding in Chennai during 1943, 1978, 1985, 2002 and 2005. In 2005, a 100 years return period rainfall of 40 cm in a day caused heavy inundation in and around the Chennai city and its suburban areas and more than 50,000 persons had to be evacuated from the existing low lying areas. The horror of Chennai floods in 2015 is still fresh in the mind of people. Flooding of less catastrophic nature also occurs regularly in low-lying areas of the city and its suburbs. The causative factors of this menace are inadequate drainage of major rivers and other drainage systems.

Patna has been facing acute drainage problem due to its topography. According to historians and archaeologists, ancient Patna was once washed away because of floods of rivers Ganga, Sone and Punpun accompanied with the continuous rains for 17 days in the catchments. In the recent past also, Patna was heavily flooded in the year 1975-76 and there was a severe water logging in the year 1990 and 1997 in the town. Small boats could be seen on the roads. Due to topographical condition of Patna, storm water does not flow under gravity to river Ganga or Punpun during the period of flood. Pumping is away to dispose the rainwater of the town. Rapid development of new unplanned colonies and their commercial activities without proper drainage system has aggravated the problem of water logging.

Recently, in 2016 severe flooding crippled the millennium city of Gurugram. Intense rain for only two hours paralysed life in Gurugram with knee-deep standing water on the roads, halting the traffic and forcing authorities to shut down schools and offices declaring a holiday. It is a reality of unsustainable urban development that population growth and visionless race for infrastructure is disturbing the natural equilibrium and worsening quality of life for urban residents.

In order to overcome the inundation, the storm water drainage system has to be properly designed based on short duration rainfall data (15 min) alongwith detailed topographical and existing and projected landuse information. Estimation of surface runoff due to rainfall events is a key factor in drainage system network design. Municipal authorities should reassess the drainage network especially along the roads and highways in the context of natural drainage pattern within the micro-watershed. Based on field data, a suitable mathematical model can be setup to evaluate storm water flooding phenomena at micro and macro level. The model can predict runoff hydrographs based on the input hyetograph and the physical characteristics of the sub catchment. A mathematical model can generate expected and extreme scenarios apriori which can be a guiding factor for the planners and decision makers. Flood hydrology of urban areas includes estimation of design rainfall, peak flow and remedial steps to combat the flooding and drainage problems.

In small basins, the design discharge is often estimated from rainfall intensity-duration-frequency curves for the locality. For a given recurrence interval, the design concept is to choose a storm from the rainfall intensity-duration curve such that it produces the maximum peak discharge. This maximum peak discharge is the design discharge. A number of hydrologic models are used to evaluate the effect of urbanisation on peak discharges.Table 1.6 presents several formulae for calculation of peak discharge in urban catchment.

A number of urban hydrology models are available for finding out the engineering solutions to problems street flooding, out-of-bank flows, combined sewer overflows, and nonpoint sources pollutant management. The selection of an urban hydrologic model is a matter of experience in assessing the needs of a particular design project. A brief listing of the most commonly used models is presented in Table 1.7 (Hydrology Handbook, 1996).

Table 1.6 Formula for computation of Design discharge for urban catchment

Sl	Method/Author	Date	Formulae
Peak Discharge Computation			
1	Rational Method		$Q = CiA$ Q = peak discharge, A = catchment area, i = average rainfall intensity, C = coefficient
2	Unit Hydrograph Methods/ Sherman(1932),USDA,SCS, 1969, USDA SCS, (1986)	1932	Synthetic Unit Hydrograph, Clark unit Hydrograph, SCS dimensionless curvilinear unit hydrograph
3	Regression Equation/Sarma et al.	1969	$q_p = 2.441A^{0.723}(1+U)^{1.516}P_E^{1.113}T_R^{-0.403}$ qp = peak discharge (m^3/Sec), A = drainage area (km^2), U = imperviousness as decimal fraction, P_E = excess rainfall depth (cm),T_R = rainfall excess duration (hrs)
4	Peak Discharge for a permeable plane/Wong and Li	1997	$$Q_p = \frac{WLC_p}{3.6\times10^6}\left[\frac{a_p^{1/b_p}}{7\left(\frac{n_pL}{\sqrt{S}}\right)C_p^{-0.4}}\right]^{\frac{b_p}{1-0.4b_p}}$$ W = width of the overland plane, L = length of the overland plane, C_p = runoff coefficient of the plane, n_p = Manning resistance coefficient of the plane surface, S =slope of the plane in the direction of flow and a_p and b_p are the respective values of a and b in $i = at_r^{-b}$ for t_r (rainfall duration) = t_{cp} (time of concentration)
5	Peak discharge for a plane with down stream portion urbanisation/ Wong and Li	1997	$$Qd = \frac{W(C_pL_p + C_iL_i)}{3.6\times10^6}\left\{\frac{a_d^{1/b_d}}{7\left[\left(\frac{n_pL_p}{\sqrt{S}}\right)C_p^{-0.4} + \left(\frac{n_i}{\sqrt{S}}\right)^{0.6}\left(\frac{(C_pL_p + C_iL_i)^{0.6} - (C_pL_p)^{0.6}}{C_i}\right)\right]}\right\}^{\frac{b_d}{1-0.4b_d}}$$ a_d and b_d are the respective values of a and b in $i = at_r^{-b}$ for t_r (rainfall duration) = t_{cd} (time of concentration) $$Q_i = \frac{WL_iC_i}{3.6\times10^6}\left[\frac{a_i^{1/b_i}}{7\left(\frac{n_iL_i}{\sqrt{S}}\right)C_i^{-0.4}}\right]^{\frac{b_i}{1-0.4b_i}}$$ where subscript *'p'* denotes the properties that relate to the impermeable portion, and subscript '*i*' denotes the properties that relate to the permeable portionand a_i and b_i are the respective values of a and b in $i = at_r^{-b}$ for t_r (rainfall duration) = t_{ci} (time of concentration) The greater of the two peak discharge is the maximum discharge of the plane.
6	Peak discharge for a plane with upstream portion urbanisation/ Wong and Li	1997	

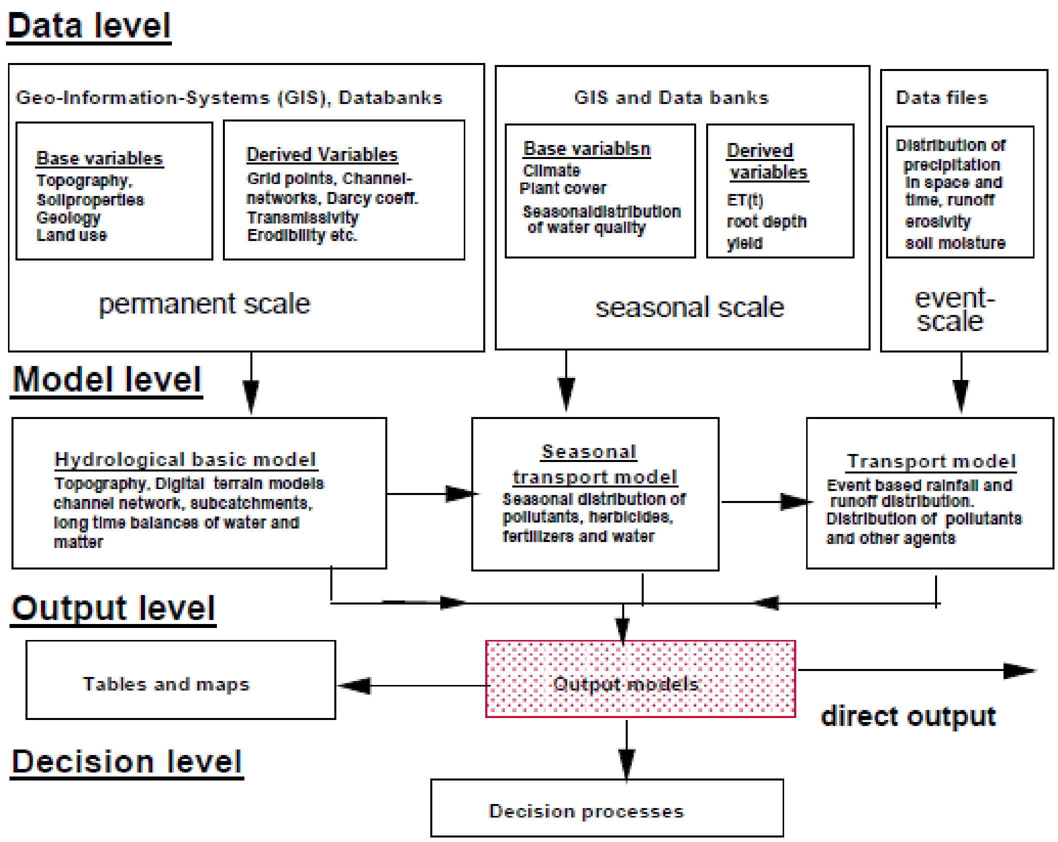
Sl	Method/Author	Date	Formulae
			$Q_{mu} = \frac{W(C_i L_i + C_p L_p)}{3.6\times10^6}\left\{\frac{a_u^{1/b_u}}{7\left[\left(\frac{n_i L_i}{\sqrt{S}}\right)C_i^{-0.4} + \left(\frac{n_p}{\sqrt{S}}\right)^{0.6}\left(\frac{(C_i L_i + C_p L_p)^{0.6} - (C_i L_i)^{0.6}}{C_p}\right)\right]}\right\}^{\frac{b_u}{1-0.4b_u}}$ a_u and b_u are the respective values of a and b in $i = at_r^{-b}$ for t_r (rainfall duration) = t_{cu} (time of concentration)

Table 1.7 Common urban hydrology models

Model Name	Agency Name	Precip. Excess method	Hydrograph synthesis method	Channel or sewer routing method	Detention basin method	Runoff quality
TR 20	USDA Soil Conservation Service, Washington, DC	Curve number and SCS soil-cover complex	SCS dimensionless unit hydrograph(UH)	Attenuated kinematic wave	Storage-indication routing	No
HEC-1	Hydrologic Engrg. Centre, US Army Crops. Of Engrs. Davis, CA 95616	SCS Curve Number; Holtan eq.; variable loss rate	SCS UH, Snyder UH, Clark UH, Kinematic overland flow	Muskingum; Muskingum-Cunge; Kinematic	Storage-indication routing	No
HYMO	USDA/ARS; also Ontario Provincial Govt., Ottawa	SCS Curve Number	SCS UH	Convex routing method	Storage-indication routing	No
ILLUDAS	Illinois State Water Survey, Champaign, IL 61820	Holtan eq.; SCS Curve Number	Time -area UH	Kinematic by Manning's eq.	Storage-indication routing	Yes
SWMM	US EPA, Centre for exposure Assessment, Athens, GA 30613	Hortan; modified Hortan; SCS Curve Number	Kinematic overland flow	Kinematic by Manning's eq.; also by complete dynamic eqs. In EXTRAN	Storage-indication routing	Yes
PSRM/QUAL	Penn State U. dept. Civil Engrg. University Park, PA 16801	Hortan; SCS Curve Number	Kinematic overland flow	Muskingum	Storage-indication routing	Yes
DR3M	US Geological Survey Urban Studies Program Austin, TX	Phillips eq.	Kinematic overland flow	Kinematic by mannings eq.	Storage-indication routing	Yes
KINEROS	USDA Agricultural Research Services, Washington, DC	Smith and Parlange	Kinematic overland flow	Kinematic by Manning's eq.; Chezy or Darcy-Weisbach eq.	Storage-indication routing	Sediment only

1.9 Data Requirement for Rainfall-runoff and Flood Modeling

Hydrological rainfall-runoff models require the input data which is associated with three different time scale (see Fig. 1.11). The data level consists of permanent, seasonal and event scale based data. The permanent scale data consist of geometric and geological properties of catchment topography, geology, soil composition, river network and gradually changing features like land use, forest cover, road network, settlements, large scale climate etc. Seasonal data consist of seasonal agriculture activities, seasonal climate and water quality data etc. and the event scale data consist of rainfall, climate, water management data (e.g., irrigation, reservoir operation etc.), runoff, soil moisture, erosivity etc.The data requirement of hydrological rainfall-runoff models generally depends upon the purpose, as planning require historical data whereas forecasting requires real time event data for short interval. Before undertaking rainfall-runoff modeling, it is a general requirement to assess both the quantity and quality of available data. Generally, the available data prescribe the type of model to be used more than the problem itself. A general inventory of data frequently available or needed is given below:

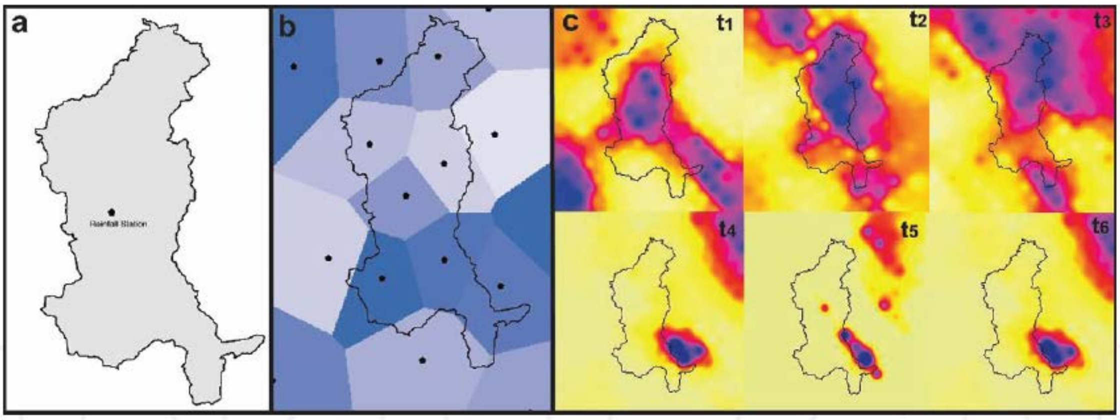


Source: Plate, 2009

Figure 1.11: Data levels for hydrological models.

1.9.1 Rainfall characteristics and Other Metreological Data

The hydrological rainfall-runoff model can incorporate various types of rainfall data (Fig. 1.12). Usually data obtained from meteorological stations is used. Determination of the average amount of rain that falls on basin/subbasins during a given storm is a fundamental requirement for many rainfall-runoff models. A number of techniques for estimating mean areal rainfall have been developed. Rainfall hyetographs are needed for each subbasin. Some of the subbasins may not have a recording raingauge and may involve extrapolation of rainfall data from neighbouring subbasins. The mean areal rainfall hyetograph is to be determined for a subbasin having more than one raingauge. Sometimes, only standard/storage-type raingauges are available in some watersheds. In such watersheds the rainfall amounts then need to be properly distributed in time so that a rainfall hyetograph can be prescribed. Nowadays, the use of radar data for record rainfall or the use the data from atmospheric simulation model has provided the ability to incorporate the spatial and temporal variation of rainfall into the hydrological modeling. Apart from precipitation data, some conceptual or physically based model require metreological data such as temperature, evaporation, humidity rainfall-runoff gridded estimates of weather parameters derived from actual meteorological observations are one potential alternative data source.



Source: Chalkias et al., 2016

Figure 1.12: Most common types of rainfall data that used in the hydrological rainfall runoff model:(a) single station rainfall, (b) semi-spatiotemporal data, and (c) atmospheric simulation data (t_1-t_6) are time snapshot of 3 hrs cumulative rainfall, blue and yellow colour indicates high and low cumulative rainfall, respectively.

1.9.2 Infiltration and other loss characteristics

Generally, in most of the cases, no data are available on soil infiltration, interception, depression storage, and antecedent soil moisture. If data do exist in part or full, maximum advantage must be taken to estimate infiltration and other loss functions. If no information is available on antecedent soil moisture, then an antecedent precipitation index can be used to get an estimate of the antecedent soil moisture. Soil type and landuse vegetation complex can be used to estimate infiltration parameters.

1.9.3 Streamflow characteristics

Generally, streamflow may be available in terms of the stage at the watershed outlet and at some other gauges within the watershed. Appropriate rating curves developed for the site can be used to convert stages into discharges.

1.9.4 Watershed characteristics

Topographic map is the most commonly available source of data from which many useful geomorphic parameters, such as, watershed area, subbasin areas, elevations, slopes, channel lengths, channel profiles, centroid, etc, can be extracted and many others can be computed. Landuse map is another useful map which provides data on areas of land-use practice, soil types, vegetation, forest areas, lakes, urban development, etc.

Table 1.8 lists the data required for hydrological model development. In case data is not available from national agencies and neighboring countries, the global data sets as shown in Table 1.4 can be used. Satellite radar altimetry data having revising time interval of 35 days for knowing water level variation in large water bodies can be very useful.

Meteorological forecast data is required after hydrological model setup. Various centers provide global, regional, national, and local weather forecasts. The Weather Research and Forecasting model is one of the best to use for this purpose.

Table 1.8 Input data for hydrological modeling and alternative sources.

<table>
<tr><th>Type of data</th><th>Data Source</th></tr>
<tr><td colspan="2">1. Spatial data</td></tr>
<tr><td>Digital elevation model (DEM)</td><td>• Cartosat-1:DEM: http://bhuvan.nrsc.gov.in/data/download/...,
• Shuttle Radar Topography Mission (SRTM) at 90m resolution: http://srtm.csi.cgiar.org/SELECTION/inputCoord.asp or http://earthexplorer.usgs.gov/
• Shuttle Radar Topography Mission (SRTM) at 30m resolution: http://earthexplorer.usgs.gov/
• Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) at 30m resolution:http://gdem.ersdac.jspacesystems.or.jp/download.jsp
• Interferometric Synthetic Aperture Radar (IFSAR) at 5m resolution:https://lta.cr.usgs.gov/IFSAR_Alaska</td></tr>
<tr><td>Land use and Land Cover</td><td>1. European Space Agency (ESA) CCI Land Cover dataset http://www.esa-landcover-cci.org/
2. MODIS Land Cover Type product (MCD12Q1) http://earthexplorer.usgs.gov/
3. BHUVAN Land Use Land Cover (250K) http://bhuvan.nrsc.gov.in/gis/thematic/index.php
• Land cover database http://glovis.usgs.gov/</td></tr>
<tr><td>Soil database:
Soil physical properties (Texture, bulk density, available water capacity, saturated conductivity, soil albedo, organic carbon, etc.) for different soil profiles</td><td>• NBSSLUP and Soil and Land Use Survey of India:http://slusi.dacnet.nic.in/
• FAO soils portal: http://www.fao.org/soils-portal/soil-survey/soilmaps-and-databases/en/
• Soil and Terrain Database (SOTER): http://www.isric.org/data/datadownload
• Soil Grid data:https://soilgrids.org
• Soil-Plant-Air-Water (SPAW) model:
• http://hydrolab.arsusda.gov/SPAW/SPAWDownload.html</td></tr>
<tr><td>Location of observation stations</td><td>India-WRIS
www.india-wris.nrsc.gov.in/</td></tr>
<tr><td colspan="2">2. Meteorological observation data</td></tr>
<tr><td>Climatic Database:

Daily/Sub-daily rainfall and metrological data (Precipitation Temperature, wind speed, relativehumidity, solar radiation etc.)</td><td>• Indian Metrological Department (IMD) : Station data and gridded rainfall and temperature data
• Asian Precipitation – Highly-Resolved Observational DataIntegration Towards Evaluation (APHRODITE) Water Resourcesdaily and monthly precipitation at 0.25° x 0.25° and 0.50° x 0.50°resolution from 1951-2007: http://www.chikyu.ac.jp/precip/index.html
• Climate Research Unit (CRU) monthly precipitation andtemperature data at 0.50° x 0.50° resolution from 1901-2014:https://crudata.uea.ac.uk/cru/data/hrg/cru_ts_3.23/cruts.1506241137.v3.23/
• Santa Clara University daily and monthly precipitation andtemperature data at 0.50o x 0.50o resolution from 1960-1999:http://www.engr.scu.edu/~emaurer/global_data/
• Tropical Rainfall Measuring Mission (TRMM) daily rainfall data at0.25° x 0.25° resolution from 1998:http://disc2.nascom.nasa.gov/Giovanni/tovas/TRMM_V6.3B42.2.shtml
• NASA global climate data:http://eosweb.larc.nasa.gov./sse
• http://globalweather.tamu.edu/home/view/
• NICRA data: http://www.nicra-icar.in/
• http://www.indiawaterportal.org/data/metdata
• SWAT Global data: http://eosweb.larc.nasa.gov./sse</td></tr>
<tr><td colspan="2">3. Hydrological (at least 30-year data) and hydraulic data</td></tr>
<tr><td>Discharge</td><td>India-WRIS (www.india-wris.nrsc.gov.in/)</td></tr>
</table>

1.10 Hydrological Modeling Softwares for Rainfall-Runoff and Flood Modeling

Table 1.9 provides a list of hydrologic rainfall-runoff models along with the web addresses from where these models can be downloaded. This list is compiled from Singh and Woolhiser (2002) and Vaergas-castaneda et al. (2015) with our own inputs.

Table 1.9 The list of commonly used rainfall-runoff models.

Model	Components	Access	Web Page
HSPF (Hydrological Simulation Program-Fortran) [Arnold et al. 1998]	Runoff, water quality, simulations in permeable and impermeable areas.	Public	water.usgs.gov/software/HSPF/
USDAHL (USDA Hydrograph Laboratory) Holtan et al.	Lumped model for event simulation	Public	http://babel.hathitrust.org/cgi/pt?id=uvax030378420;view=1up;sep=3
USGS-PRMS (USGS-Precipitation Runoff Modeling System) [Markstrom et al. 2015]	Model for continuous simulation and by events.	Public	http://wwwbrr.cr.usgs.gov/projects/SW_MoWS/PRMS.html
TAUDEM (Terrain Analysis Using Digital Elevation Models) [Yıldırım(2015), Wallace et al. (2010)]	Model for Hydrologic analysis.	Public	hydrology.usu.edu/taudem/taudem5/downloads.html
HEC-HMS(Hydrologic Engineering Center-Hydrologic Modeling System) [Chu & Steinman, (2009)]	Semi-distributed model for event simulation.	Public	http://www.hec.usace.army.mil/software/nec.hms/download.aspx
RORB (Runoff routing Bruce)[Mein, R. and Nathan R (2005)]	Lumped model for event simulation	Public	eng.monash.edu.au/civil/research/centres/water/rorb
SWMM Storm Water Management Model) [Kazezyilmaz-Alhan & Medina (2007)]	Semi-distributed model for continuous simulation.	Public	https://www.epa.gov/water-research/storm-water-management-model-swmm#downloads
MD_SWMS (Multidimensional Surface Water Modeling System) [McDonald, Nelson et al.(2006)]	System for multidimensional modeling of surface water.	Public	http://iric.org/en/downloads.htm
TOP MODEL	Distributed model for continuous simulation.	Public	http://www.lancaster.ac.uk/lec/
MIKE-SHE (Mike –Systems Hydrologique Europee)[Roblero, (2013)]	Distributed model for continuous simulation of surface and groundwater flow.	Private	www.mikebydhi.com/download/mike-by-dhi-2014/mike-she
ARNO (Tuscany Regional Government in Italy) [Todini (1988)]	Semi-distributed model for continuous simulation.	Public	http://www.researchgate.net/publication/222499511_The_ARNO_rainfallrunoff_model
WAT FLOOD (Department of Civil Engineering University of Waterloo Waterloo, Ontario, Canada)	Semi-distributed model for continuous simulation.	Public	www.civil.uwaterloo.ca/watflood/downloads/watflood_downloads.html
SHETRAN (Systeme Hydrologique Europe-Transport) [Ewen,J. Dunn, S et al.(1990)]	Distributed model for Simulating water amount and quality.	Public	research.ncl.au.uk/shetran/Downloads.php
SWAT (Soil and Water Management Tool)[Arnold et al. (1998), Arnold and Fohrer (2005)]	Distributed model for continuous simulation.	Public	www.swat.tamu.edu
HYDRO TEL.[Turcotte *et al.*(2000)]	Distributed model for continuous simulation.	Public	https://hydrotel.codeplex.com/releases
ANSWERs 2000 (Areal Nonpoint Source Watershed Environment Response Simulation.[Beasley	Distributed Modelfor simulating runoff, infiltration, nutrients and contaminants.	Public	http://ww2.bse.vt.edu/ANSWERS/Download.php

Model	Components	Access	Web Page
and Huggins (1982)]			
AGNPS (Agricultural Non-Point Source Pollution Model) U.S. Department of Agriculture,	Distributed Model for simulating runoff, infiltration, erosion and contaminants.	Public	www.nrsc.usda.gov/wps/portal/nrcs/detailfull/national/water/?cid=stelprdb1043535
Ann-AGNPS [Scott E. Nezdhw. and Robert A. Young1993].	Distributed Model for simulating sediments, nutrient and pesticide transport.	Public	www.nrsc.usda.gov/wps/portal/nrcs/detailfull/national/water/?cid=stelprdb1043535
GSSHA-CASC2D (GSSHA-Cascade of planes. 2-Dimensional) (USACE ERDC)	Distributed model for simulating soil moisture, channel flow, erosion and sediment transport.	Private (Free 14-Day trail version)	www.aquaveo.com/software/wms-gssha
KINEROS 2 (Kinematic Runoff and Erosion Model 2) Research Hydraulic Engineer, USDA-Agricultural Research. [Woolhiser, et al., 1970]	Distributed Model forsimulatingoverland flow, channel flow,sediment transport, infiltration and erosion.	Public	www.tucson.ars.ag.gov/kineros/
AGWA (Automated Geospatial Watershed Assessment) [Miller et al., 2007; Semmens et al., 2008]	The AGWA tool is an interface to automate the parameterization and execution of SWAT and KINEROS2	Public	http://www.epa.gov/esd/land-sci/agwa/
WEPP (Water Erosion Prediction Project) USDA (ARS)	Distributed model for simulatingsurface flow, water balance, plant growth, erosion etc.	Public	www.ars.usda.gov/News/docs.html?docid=10621
HBV (Hydrologiska Byrans Vattenbalansavdelning) [Bergström, S 1992]	Lumped Model for Continuous simulation.	Public	http://www.geo.uzh.ch/en/units/h2k/services/hbv-model
EPIC &APEX (Environemental Policy Integrated Climate-Agricultural Policy/Environmental eXtender Model) [Wang, X., A. Kemanian, J.R. Williams.(2011)]	Cropping systems model for estimating soil productivity. Model for water, sediment, nutrient and pesticide transport.	Public	epicapex.tamu.edu/model-executables/
CHEQUEAU (Centre Quebecois des Sciences de I'Eau)	Distributed model for continuous simulation.	Public	ete.inrs.ca/ete/publications/cequeau-hydrological-model
LASCAM (Large-Scale Catchment Model) [Sivapalan et al. (1996a,1996b, 1996c) Viney and Sivapalan (1999) and Viney et al. (2000)]	Model for predicting the impact of land-use and climate change.	Private	www.cwr.uwa.edu.au/software1/downloads/login/login.php
SAFRAN-ISBA-MODCOU (SAFRAN–(Interactionsol-bioshere-atmosphere-MODCOU)	Models for analysis of atmosphere variables, energy exchange and hydrology.	Public	http://www.cnrm-game-meteo.fr/spip.php?article424&land-fr&lang=fr
DHSVM(Distributed Hydrology Soil Vagetation Model)	Distributed model for large watersheds.	Public	www.hydro.washington.edu/Lettenmaier/Models?DHSVM/
DWSM (Dynamic Watershed Simulation Model)	Model for simulate runoff and water quality in events.	Private	woolpert.com
SEFM (Stochastic Event Flood Model)	Model for event simulation.	Private	www.mgsengr.com/Dam_Safety.html
BWBM (Bochum Water Balance Model)	Distributed model for continuous simulation of soil moisture and runoff.	Public	http://hydrologicmodels.tamu.edu/Adjusted_Apr_2010/Precipitation_runoff_models_49/Distributed_models_17/BOCHUM.pdf
IWFM (Integrated Water Flow	Lumped Model for continuous	Public	http://baydeltaoffice.water.ca.g

Model	Components	Access	Web Page
Model)	simulation of surface water and groundwater.		ov/modeling/hydrology/IWFM/
OWLS (Object Watershed Link Simulation)	Distributed model for continuous simulation of different hydrology cycle 40omponent.	Public	hydromodel.com
RRMT (Rainfall-Runoff Modeling and Monte-Cario Analysis Toolboxes)	Rainfall-runoff model in Matlab environment.	Public	http://www.imperial.ac.uk/environmental-and-water-resource-engineering/research/software/
HYMOD	Conceptual lumped model for rainfall-runoff.	Public	https://github.com/jdherman/hymod
MPE (Model paraPronosticode Escurrimientos) [Domínguez-Mora et al. (2008) Méndez-Antonio et al. (2014)]	Distributed-parameter model for runoff forecasting.	Public Mexico	http://aplicaciones.iingen.unam.mx/SAPII/Buscarplublicaion.aspx.
WaSim-ETH	The grid-based **Wa**ter Flow and Balance **Si**mulation **M**odel WaSiM is a well-established physically based, distributed hydrologic modeling tool for investigating the spatial and temporal variability of hydrological processesin complex river basins	Public	http://www.wasim.ch/en/
Spatial Processes in Hydrology (SPHY) [Terink et al., 2015]	It is distributed leaky bucket type of model which integrates most of hydrological processes, has flexibility to be applied in a wide range of applications at various scale.	Public	www.sphy.nl
IHACRES	Simulation of stream flows from basins of various sizes,Unit hydrograph approach for lumped modeling	Public	http://www.toolkit.net.au/tools/IHACRES
Water and Energy Transfer between Soil, Plants and Atmosphere.(WetSpa) [Liu et al. 2004]	The model is physically based and simulates hydrological processes, e.g., precipitation, snowmelt, interception, depression, surface runoff, infiltration, evapotranspiration, percolation, interflow, groundwater flow, etc. continuously both in time and space, for which the water and energy balance are maintained on each raster cell. It issuitable for studying the impact of land use change on the hydrological behaviours of a river basin	Public	http://www.vub.ac.be/WetSpa/
Water Modeling System (WMS)	Provide the link between spatial terrain data (GIS)and hydrologic models, including models like HEC-1, TR-55, TR20, GSSHA-CASC2D etc.	Private	http://www.aquaveo.com/software/wms-watershed-modeling-system-introduction

As can be seen from Table 1.10, the land surface and hydrologic communities have made substantial progress in understanding the spatial presentation of fluxes of water and energy. Their efforts have led to the development of well-known hydrological models, such as, VIC (Liang et al., 1994, 1996), SWAT (Neitsch et al., 2009), TOPKAPI-ETH (Finger et al., 2011; Ragettli and Pellicciotti, 2012; Ragettli et al., 2014, 2015), LISFLOOD (Van Der Knijff et al., 2010), SWIM (Krysanova et al., 2015, 2000, 1998), HYPE (Lindström et al., 2010), mHM (Samaniego et al., 2010), PCR-GLOBWB (van Beek and Bierkens, 2008; Bierkens and van Beek, 2009;Wada et al., 2010; SpernaWeiland et al., 2010), MIKE-SHE (Refshaard and Storm, 1995; Oogathoo et al., 2008; Deb and Shukla, 2011) and GEOtop (Rigon et al., 2006; Endrizzi et al., 2014, 2011), amongst others. All these models are different from each other based on the number of hydrologic processes incorporated, their file of application, scale of application and way of implantation. Terink et al. (2015) has provided comprehensive comparison of these models which is given in Table 1.10 as follows:

Table 1.10 Advantage (+) and disadvantage (-) of some well-known hydrological models. A categorization is made between (i) processes that are integrated. (ii) field of application, (iii) scale of application, and (iv) implementation.

	SPHY	**TOPKAPI-ETH**	**SWAT**	**VIC**	**LIS-FLOOD**	**SWIM**	**HYPE**	**mhM**	**MIKE-SHE**	**PCRGLOBWB**	**GEO-top**
Processes Integrated											
Rainfall-runoff	+	+	+	+	+	+	+	+	+	+	+
Evapotranspiration	+	+	+	+	+	+	+	+	+	+	+
Dynamic Vegetation growth	+	-	+	+	+	+	A	NA	+	+	-
Unsaturated zone	+	+	+	+	+	+	+	+	+	+	+
Groundwater	+	-	+	+	+	+	+	+	+	+	+
Glaciers	+	+	-	-	-	+	+	-	-	-	+
Snow	+	+	+	+	+	+	+	+	+	+	+
Routing	+	+	+	+	+	+	+	+	+	+	+
Lakes Incorporated into routing scheme	+	-	+	+	+	+	+	NA	+	+	-
Reservor Management	-	-	+	-	-	+	+	NA	-	+	-
Field of application											
Climate change impacts	+	+	+	+	+	+	+	+	+	+	+
Land use change impacts	+	+	+	+	+	+	+	+	+	+	+
Irrigation planning	+	-	+	+	-	+	+	-	+	-	+
Floods	-	-	-	-	c	-	+	-	+	+	+
Droughts	+	+	+	+	+	+	+	+	+	+	+
Water supply and demand	-	-	+	-	-	-	+	NA	-	-	-
Scale of Application											
Catchment scale	+	+	+	+	-	-	+	-	+	-	+
River basin scale	+	+	+	+	+	+	+	+	+	-	-
Mesoscale river basin	+	-	+	+	+	+	+	+	+	+	-
Global scale	-	-	-	+	+	-	-	-	-	+	-
Farm level	+	-	-	-	-	-	+	-	-	-	-
Country Level	+	-	-	-	-	+	+	-	-	-	-
Fully distribted	+	+	-	+	+	-	-	+	+	+	+
Sub-grid Variability	+	-	-	+	-	-	-	+	-	+	+
Flexible Spatial resolution	+	+	-	+	+	-	-	+	+	+	+
Hourly resolution	-	+	+	-	+	-	+	+	+	-	+
Sub-daily resolution	-	-	-	+	+	-	+	NA	+	-	-
Daily Resolution	+	+	+	+	+	+	+	NA	+	+	-
Implementation											
Open source	+	-	+	+	-	-	+	-	-	-	+
Forcing with remote sensing	+	+	-	+	+	-	+	NA	-	-	+

	SPHY	TOPKAPI-ETH	SWAT	VIC	LIS-FLOOD	SWIM	HYPE	mhM	MIKE-SHE	PCRGLOBWB	GEO-top
GIS compatibility	+	+	+	-	+	+	+	+	+	+	+
Modular set up	+	-	-	+	+	+	+	+	+	-	-
Computational efficient	+	+	+	-	+	+	+	+	-	+	+
Climate forcing requirement	+	+	-	b	-	-	+	+	-	-	-
Flexible output reporting option	+	+	-	+	+	+	+	NA	+	-	+
Graphicaluser-interface in GIS	a	-	+	-	-	+	-	-	+	-	-

[a] Currently in development; [b] More climate variables are required if the model is run in energy balance mode; [c] Only if run in combination with LISFLOOD; NA: Information not available.

Kauffeldt et al. (2016) technically reviewed 24 large scale models to provide guidance for model selection for the European Flood Awareness System (FEAS), as example of an operational continental flood forecast system. The list of model which have been applied over large-scale basins, continental or global domain are provided in Table 1.10. Kauffeldt et al. (2016) attempted to provide selection criteria for hydrological model based on:

1. Availability of model code,
2. Existing user community,
3. Input data requirements,
4. Flexibility to grid structure,
5. Possibility of calibration with suitable tools,
6. Flexibility in resolution,
7. Facility of introducing discharge observation stations (data assimilation), and
8. Existing large domain model set-up.

Based on the comparison of model listed in Table 1.11, Kauffeldt et al. (2016) concluded that the LISFLOOD model is suitable for operational flood forecasting within EFAS. However, the code is not yet open source which may be unsuitable for other users outside JRC. Out of 24 models, they found ten models namely, CLM (calibration would be complex), G2G (only executable available), GWAVA (only executable available), LaD (Code no longer maintained or developed), LPJml (discharge calibration not advisable), Mac-PDM (code available, but lacks documentation and instruction), MATSIRO (difficult to downscale), MPI-HM (calibration not advisable), WASMOD-M (code not available) and WaterGAP (code not available). According to them, all remaining model found to be suitable for the application. Further, JULES, H-TESSEL and ORCHIDEE are not calibrated, so they are required to run without calibration or calibration mechanism can be developed. In H08 and NOAH-MP, there is no calibration tool available which required to be developed. SWAT requires a high number input which can be difficult to obtain with sufficient details and also not justifiable to gather and prepare all the needed input data for flood forecasting. In addition, SWAT, E-HYPE and SWMI typically run for sub-basin rather than regular grids and there is need to develop some tools to make model outputs comparable within the ensemble. The sub-bsin approach has the advantage of using natural boundaries and with that a more correct representation of the actual watershed characteristics. TOPLATS and VIC do not offer full flexibility in the resolution within the 1-10 km span. Models Overall mHM and WBMplus models found relatively most suitable in EFAS system. They concluded that many of the assessed models are under development thus can be considered suitable in the future (Table 1.11).

Table 1.11 Comparison of hydrological models applied for large-scale basins, continental or global domain [adapted from Kauffeldt et al. (2016)].

Model	Main Ref. and domain of application	Availability of Code	User Community	Input data Requirement	Flexibility to grid Structure	Possibility ofcalibration	Flexibility in resolution	Facilityto Introduce discharge obs. Stations	Pan European model set up?
CLM (Community Land Model)	Technical: (Oleson et al., 2013), Global: (Lawrence et al., 2011; Oleson et al., 2008)	Open Source http://www.cesm.ucar.edu/models/clm/	Active working group > 100 members, user base broader	netCDF <6h,~2/0.1^o S,R,SR,LW,SP,Q, T,W,aerosol, CO_2	Regular or irregular spectral girds	In the theory, but complex. No tools available	5-10 km, but higher resolution possible. Routing 0.1-0.5 deg.	In place	Set up for global application, but can be run for any domain
E-HYPE (European Hydrological Predictions for the Environment)	Technical: (Lindstr€om et al., 2010; SMHI, 2013a,b), Europe: (Donnelly et al., 2014; Donnelly et al., 2013)	Open source and Free training courses http://hype.sourceforge.net	Main collaborations outside SMH1:UFZ (Germany) and IRSTEA (France) Result used by a broader group.	Text files D, Median 215 km^2 P,T	Sub-basin structure, but can be run on grid	Calibrated to 104 gauging stations. Several tools including, typically stepwise procedure against differed types of data.	Sub-basin structure of varying size.	>8,500 gauging stations including (v3 vaildated for ~1,000),updating (or interpolation) to observations possible	Existing
G2G (Grid - to - Grid)	UK: (Bell et al., 2007a,b; 2009; Price et al., 2012)	Only executables	The Flood Forecasting Centre (England & Wales), Scottish Flood Forecasting Services, zEnvironment Agency and NaturalRes. Wales, CEH, SEPA, Scottish Marine.	BIL/ASCII 15 min, 1km P, T, PET	Runs with grid structure	Variety of tools available, both manual and automatic.	Flexible has been tested for 50m up to 25km	Observed discharge is used for dataassimilation, comparisons and calibration	Offline pan-European model set up, can be dome for operational forecasts.
GWAVA (Global Water Availability Assessment Method)	Technical: (Meigh et al., 1999), Global: (Haddeland et al., 2011), Africa: (Meigh et al., 2005, 1999)	Only Executables and training courses available outside CEH	Water resource team in CEH Wallingford	Specialbinary, ASCII D/M, 0.5/5' P,PET, T	Runs with grid structure	Inbuilt calibration algorithm to obs. Q	Lower Limit currently approx. 10 km due to model assumptions	In Place	Existing
H08	Technical: (Hanasaki et al., 2008a), Global: (Hanasaki et al., 2010, 2008a,b), Thailand: (Hanasaki et al., 2014)	Open Source http://h08.nies.go.jp/h08/	National Institute of Environmental Studies, Thai Meteorological Dept. Princeton University, ISI-MIP, EU-WATCH	Plain binary format 6h, 1^o/0.5^o R, S, T, Q, W, SP, SW, LW	Runs with grid structure	No Tools provided.	Flexible	N tools provided	Set up for global application, high res, model set up for Thailand
H-TESSEL (Hydrology Tiled ECMWF Scheme for Surface Exchange over land	Technical: (ECMWF, 2014), Global: (Balsamo et al., 2009)	Free of charge license for education and research through OpenIFS. Manual and documentation online.	ECMWF	GRIB? 1h, >0.25^o R,S,T,Q. SP,W,SW,LW	Runs with grid structure	Typically not calibrated	Flexible	No Tools provided	Existing
JULES(Joint UK	Technical: (Best et al.,	Open Source https://jules.jch	Large Community of	ASCII/netCDF/bin	Runs with grid	Typically not calibrated	Depends on input data	No tools provided	Existing

Model	Main Ref. and domain of application	Availability of Code	User Community	Input data Requirement	Flexibility to grid Structure	Possibility ofcalibration	Flexibility in resolution	Facilityto Introduce discharge obs. Stations	Pan European model set up?
Land Environment Simulator)	2011), Global: (Cox et al., 1999; Essery et al., 2003)	mr.org/	over 100 users and developed in the UK and abroad	ary 1h,1-50km R,S,T,W, Q,LW,SW,SP	structure				
LaD (Land Dynamics Model)	Technical: (Milly and Shmakin, 2002), US: (Xia, 2007)								
LISFLOOD	Technical: (Burek et al., 2013; van der Knijff and de Roo, 2008), Europe: (Thielen et al., 2009), Elbe: (van der Knijff et al., 2008)	Only Executables	Principally only within the JRC. However, various groups within JRC are using it.	PCRaster grid/tables 6h/D, 5km P,PET,T	Runs with grid structure	Dedicated calibration tools exist	Depends on input data	Tools exist to shift real world station coord, to large scale drainage grid of the model	Existing
LPjml (Lund-Potsdam-Jena managed land)	Technical: (Sitch et al., 2003), Global: (Gerten et al., 2004; Rost et al., 2008; von Bloh et al., 2010)	Currently only provided to collaborators	Academic	Binary, ASCII D, 0.5^o P,T,LWnet, SW	Runs with grid structure	Problematic if discharge iscalibrated due to dynamic linking to veg. growth, irrigation etc.	Currently 0.5^o, but depends on input data. Some processes not turned for <10 km	No tools provided	Existing
Mac-PDM (Macro-scale Probability-Distributed Moisture Model.)	Global: (Gosling and Arnell, 2010), Europe: (Arnell, 1999)	Available in principle, but lacks documentation and user manual	Included in CIAS	Test D/M, $0.5^{o/20\ km}$ P,T,W,Q, LWnet, SW	Runs with grid structure	No tools provided	Depends on input data	No tools provided	Feasible (has been done before)
MATSIRO (MinimalAdvanced Treatments of Surface Interaction and Runoff)	Technical: (Takata et al., 2003), Global: (Hirabayashi et al., 2005; Koirala et al., 2014)	Provided upon request for academic and scientific purposes	Small user group based on mailing list	Binary 1h, $0.5^o/1^o$ R,S,T,W, Q,LW,SW,SP	Runs with grid structure	No tools provided	In theory, but some parameters are calibrated for 50-250 km resolution	No tools provided	Set up for global application
mHM (mesoscale Hydrologic Model)	Technical:(Samaniego et al., 2014a), Upper Neckar: (Samaniego et al., 2010a; Samaniego et al., 2010b), Germany (Samaniego et al., 2013), United States (Kumar et al., 2013), Pan-Europe (Samaniego et al., 2014b), Global	Open source http://www.ufz.de/index.php?en=31389	Developers and users at UFZ and partner organizations, developments ongoing	netCDF4/ASCII 1h/D, 1-$100km^2$ P,T, PET	Runs with grid structure at three res. Level.	MCMC, SCE. SA, DDS, Sensitivity analysis	Flexible, can be changed without recalibration.	Each basin can have as many as needed (internal or basins outlet)	Set up for >280 pan-EU basins

Model	Main Ref. and domain of application	Availability of Code	User Community	Input data Require ment	Flexibility to grid Structure	Possibility ofcalibratio n	Flexibility in resolution	Facilityto Introduce discharge obs. Stations	Pan European model set up?
MPI-HM (Max Planck Institute – Hydrology Model)	Global: (Hagemann and Dümenil, 1997; Hagemann and Gates, 2003; Stacke and Hagemann, 2012)	Provided given a scientific license in signed	Small user group	SR V binary format D, 0.5^o P,T	Runs with grid structure	Model is not calibrated and developers advice against	Currently $0.5^{o,}$ routing is not flexible	For comparison purposes, no tools provided	Set up for global application. Earlier version has been set up for Europe.
NOAH-MP (NOAH Land Surface Model – Multi-Physics)	Technical: (Yang et al., 2011a), Global: (Yang et al., 2011b), Mississippi: (Cai et al., 2014), Local: (Niu et al., 2011),	Open Source http://jsg.utexas.edu/noah-mp/	The University of Texas, NCAR, NOAA, NASAother universities and Institutes	netCDF 3h, 0.5^o P,T,SW, LW, Q,SP, W	Runs with grid structure	No tools provided	Depends on input data	No tools provided	Set up for US and global domain
ORCHIDEE (Organizin gCarbon and Hydrology inDynamics Ecosystems)	West Africa: (d'Orgeval et al., 2008), Global: (de Rosnay and Polcher, 1999; Krinner et al., 2005; Ngo-Duc et al., 2007a)	Open Source http://labex.ipsl.fr/orchidee/	Dedicated Project team from Institute Pierre Simon Laplace and other labs.	netCDF, ASCII 15 min/3h, $0.5^o/1^o$ P,T,W,SR,Q and CO_2	Runs with grid structure	N/A	Depends on input data	No tools provided	Set up for global application.
PCR-GLOBWB (van Beek and Bierkens, 2008)	Technical: (van Beek and Bierkens, 2008), Global: (van Beek et al., 2011), Rhine-Meuse: (Sutanudjaja et al., 2011)	Currently being prepared to become open source	UtrechtUniversity, Deltares, eWaterCycle, UNESCO-IHE, Alterra, Netherlands Environmental Assessment Agency	NetCDF(default) support of PCRaster D, 0.5^o/5' >=3F,S P,T,PET, alt T, W, GR, Q	Regular Cartesian grid (but can also be run on equidistant grid)	Ens, Kalman Filter technique with >3000 gauges. Being extended to consider RS data	Yes, currently runs at 5' globally, but down to 30" for some applications	In Place	Set up for global application or specific basins/countries, but can be set up fro Europe.
SWAT (Soil and Water Assessment Tool) (Arnold et al., 2012; Neitsch et al., 2011)	Technical: (Arnold et al., 2012; Neitsch et al., 2011), Africa: (Schuol et al., 2008)	Open Source http://swat.tamu.edu/	Very active including annual international conferences and online user group.	ArcGIS vector/grid D, sub-basin: 1 ha-3,000km^2 P, Tmin, Tmax	Sub-basin structure, but can be run on grid.	Automatic with SWATCUP and manual using GIS interface	Depends on the definition of and sub-basins.	In place	Set up for US and Africa
SWIM (Soil and Water Integrated Model) (Krysanova et al., 2000)	Technical: (Krysanova et al., 2000) Elbe: (Hattermann et al., 2005; Krysanova et al., 2005, 1998), Africa: (Aich et al., 2014), Central Asia: (Wortmann et al., 2014)	Provided upon request	Small, mainly the Potsdam Institute	ASCII D, sub-basin: 1,000-500,000km^2 P,T,SR,Q	Sub-basin structure, but can be run on grid	Tools available	Depends on the definition of hydrotopes and sub-basins.	No tools provided	Feasible, has been setup for large basins
TOPLATS (TOPMODEL-Based Land Surface-Atmosphere Transfer Scheme)	German Dill catchment: (Bormann, 2006), Field experiment sites: (Famiglietti and Wood, 1994; Pauwels	Open Sources http://github.com/chaneyn/TOPLATS.git	Terrestrial Hydrology Group at Princeton University	netCDF-4 1-3hr,10m-1km P,T,LW, SW,SP,Q,W	Runs with grid structure	Tools Available: LHS and SCE	10 m -1 km, coarser is not recommended due to model assumptions	In place	Set up for the US. Given data requirements it is feasible to set up for Europe.

Model	Main Ref. and domain of application	Availability of Code	User Community	Input data Requirement	Flexibility to grid Structure	Possibility ofcalibration	Flexibility in resolution	Facilityto Introduce discharge obs. Stations	Pan European model set up?
	and Wood, 1999; Peters-Lidard et al., 1997)								
VIC (Variable Infiltration Capacity) (Gao et al., 2009; Lohmann et al., 1998, 1996)	Technical: (Gao et al., 2009; Lohmann et al., 1998, 1996), Global: (Nijssen et al., 2001), Quasi-global: (Wu et al., 2014)	Open Source https://github.com/UW-Hydro/VIC	Active global user group, developments ongoing	ASCII/Binary 1h-D, 6-222km P, Tmin, Tmax, W	Runs with grid structure	Tools available	Smaller than 6 km should be done with caution	No tools provided	Set up for the global domain, but bas been set up for Europe previously
WASMOD-M(Water and Snow Balance MODeling System – Macro-scale) (Widen-Nilsson et al., 2009, 2007)	Global: (Wid_en-Nilsson et al., 2009, 2007)	Not available	Hydrology groups at Uppsala University/Oslo University	.mat-files D/M, 0.25/0.5° P,T,PET	Runs with grid structure	MC-approach, but no automatic tools available.	Currently only 0.25/0.5°, but can be changed with other input.	No tools available	Set up for global applications/Central America
WaterGAP (Water – a Global Assessment and Prognosis) (Alcamo et al., 2003; D€oll et al., 2003)	Global: (Alcamo et al., 2003; D€oll et al., 2003), Europe: (Verzano et al., 2012)	Not Available	Apart from developed, only in terms of model output.	Binary D/M, 0.5°/5' P,T, cloud/GR, LW	Runs with grid structure	Calibrated againstmean annual discharge	10 km and 50 km versions available	Included : for 5' model gaugingStation >= 3,000 km^2 &for 0.5° model >= 10,000 km^2	Set up for global applications
WBMplus (Water Balance Model) (Wisser et al., 2010)	Global: (Wisser et al., 2010), South America: (V€or€osmarty et al., 1989), US: (V€or€osmarty et al., 1998)	Open Source	Currently limited to a handful	>200 formats works D, 0.5° P,T	Any kind of network: basin, polygon, etc.	Calibration tool available	Yes, currently runs at resolution from 250 m to 2°	Yes, automatic procedure available for evaluation at > 600 GRDC stations	Set for up global Applications

1. Input data requirements lists: file format, typical temporal & spatial resolution and minimum forcing variables.

✓: Fulfilled
×: Not fulfilled
O: Fulfilled to some extent
N/A: Information not available
D: Daily
M: Monthly
P: Precipitation
R: Rainfall
S: Snowfall
PET: Potential evapotranspiration

T: Air temperature
Tmin: Minimum air temperature
Tmax: Maximum air temperature
SP: Surface Pressure
SW: Shortwave radiation (downward)
LW: Longwave radiation (downward)
LWnet: Longwave radiation (net)
SR: Solar radiation
GR: Global radiation
W: Wind speed

Q: Humidity
Cloud: Cloud cover
MC: Monte Carlo
MCMC: Monte Carlo Markov Chain sampling
DDS: Dynamically Dimensioned Search
SA: Simulated Annealing
SCE: Shuffled Complex Evolution
LHS: Latin Hypercube Sampling

1.11 Remarks

To address water resources problems that our country is facing today, we require improved tools based on strong scientific principles and advanced technologies. Such improved modeling framework should facilitate a holistic view of water resources as well as cooperation among the other discipline (such as hydrology, cryosphere, ecology, water chemistry, biological science, earth science, atmospheric science, agricultural science, remote sensing, sustainable development, social sciences, economics, management, and sensor and communication technologies) involved in the water resources management. The role of distributed hydrological modeling framework should be seen in this context. Further, the land surface does not behave in a lumped manner. However, conceptual models are easier to implement, while more physical models can better represent the real world (e.g., Wilby, 2005). In a global river flow management perspective, both types of models can yield reliable results. Further, with advancement of hydrological and allied sciences, the focus is shifting from micro scale (local scale) to macro scale (regional/global scale), from short to longer time scale, from individual hydrologic process to an integrated analysis of hydrologic cycle (Montanari et al., 2015).

On the basis of the present knowledge, available technology, and the likely future developments, five types of models are likelyto bewidely used in the near future: (1) distributed models (e.g., MIKE-SHE, SPHY, KINEROS, CAS2D, WaSiM-ETH**,** VIC, MIKE-FLOOD, MIKE-11, HEC-RAS etc.) (2) Lumped/lumped conceptual model (e.g.,SWAT, TOPMODEL, HSPF, SWMM, NAM, WEPP etc.) (3) real-time updating models (e.g., TOPAKAPI) (4) data driven soft computing models and (e.g., ANN, WANN, AR, ARMA etc. (5) Decision Support Systems (e.g., WEAP, Aquaris, RIBASIM etc.).

From the comprehensive survey of literature, it is evident that application of physically-based, spatially-distributed hydrologic simulations over large catchments or watersheds has historically been hindered by high computational demands (Wood et al., 2011). With new monitoring and modeling techniques and increasing opportunities for data and knowledge sharing from hydrological research likely provide innovative means to improve water management strategies to ensure sustainable development. Recently, the advanced computational facilities enabled scientists to apply hydrological models over large river basins (or at the continental scale) that typically resulted in coarser spatial resolution of the domain, limited temporal extent of the simulation and/or conduct strictly deterministic runs that do not account for uncertainties. While useful, macro-scale approaches have a more limited physical basis as compared to distributed models for catchment or micro scale which do not typically preserve the available land surface and meteorological data in a catchment. Parameter estimation and calibration of hydrologic models inherently possess an additional set of significant challenges including nonlinearity, data errors, data insufficiency, correlation among parameters, irregular response surfaces that may be insensitive to select model parameters, and single or multi-objective nature of the models.

Proper calibration and validation of hydrological models is necessary before using them. To ascertain the reliability of hydrological models in providing decision about water management and system operation problems, uncertainty analysis as well as the sensitivity analysis must be carried out. Although, many studies have focused on model calibration, validation and uncertainty analysis, well designed framework for such analysis is not presently available. In the uncertainty assessments, it is very important to go beyond the traditional statistical uncertainty analysis. Thus, aspects of scenario uncertainty and ignorance should generally be included and in addition the uncertainties originating from data and models often need to be integrated with socio-economic aspects to form a suitable basis for the further decision process. There is need of uncertainty measures which could provide an estimate of confidence limits on model results and would be of value in the application of these results in risk and policy analyses.

A major challenge in the hydrological modeling is to find efficient ways to analyze the extensive output of distributed parameter hydrological models and to present the results in a transparent way to the intended end user. Successfully setting up and running distributed parameter models as part of a learning process about system dynamics requires developing new approaches where continued observation and modeling go hand in hand. Thus, a challenge for future large-scale modeling is to set up models in a flexible manner such that: 1) different processes/compartments can be switched on or off; and 2) finer-scale models can be nested within large-scale models so that the information available at larger scales (or in the environment of the nested area) can also be taken into account. In addition, further work on scaling behavior and parameterization of sub-scale variability is needed. Such approaches would enable modelers to use appropriate process descriptions and complexity for different regions, scales or goals of a study. To decrease uncertainty related to model structure, a better understanding about which processes are most relevant at what spatial scales, and how process conceptualizations are related to scale is necessary. The challenge of "optimal" data collection requires considerations of practicality and cost, as well as more specific considerations of how to reconcile typically conflicting information from different data types (e.g., Gupta et al., 1998), and how to consider data with varying spatial support.

In India, there are numerous challenges that advocate the intensive use of hydrological models to solve real-life problems in holistic manner. A number of hydrological models are available for rainfall-runoff modeling, flood forecasting and urban flood modeling. Keeping in view the different hydro-climatic regions and topography in our country, region/catchment specific models need to be identified by carrying out detailed model comparisons. Further, suitable modification may be incorporated in modeling software/models for making them more useful for Indian catchments. For this purpose, collection of reliable data at a range of spatial and temporal scales are critical to improve our understanding of hydrologic processes and in testing and validating the downscaling techniques and hydrological models that are being developed.

1.12 Way Forward

While planning hydrological modeling studies in future, following ideas need to beconsidered:

1. New monitoring techniques, and in particular, remotely sensed data, are offering exciting opportunitiesfor observing hydrological processes across a wide range of spatial and temporal scales. Therefore, innovative ideas and comprehensive models are needed to make use of ever increasing information. Further, the adoption of high performance computational means, distributed hydrologic modeling may be feasible at the large watershed scale.
2. Presently, most of the techniques for formulating the real time flood forecasts are based on statistical approach. For some pilot projects, network model and multi-parameter hydrological models are used. There is a need for significant improvement of the real time flood forecasting systems in India.

3. The frequent occurrence of flash floods in the Hindu Kush Himalayan region poses a severe threat to lives, livelihoods, and infrastructure, both in the mountains and downstream. Forecast lead-time is the very important in flash flood modeling and to improve it accurate weather prediction is required. Therefore, the major challenges that lie ahead are to explore the advances in weather prediction for flood forecasting and available information at any location particularly during extreme storms. More research, interdisciplinary co-operation and stakeholder involvement is needed to improve forecast reliability and to decide on "if, when and where" to issue flood warnings.
4. The uneven distribution of rainfall coupled with growing urbanisation, encroaching upon and filling up natural drainage channels and urban lakes for buildings are the cause of urban flooding. Advances in urban flood modeling and short duration data collection are required to develop emergency action plans for flood management in rapidly growing urban areas.
5. Most catchments of the world are ungauged. For pursuing rainfall-runoff modeling of ungauged catchments there are two drivers: (i) operational and (ii) academic. The operational driver include design applications (of spillways, culverts, and embankments), forecasting applications (flood warning and hydropower operation), and catchment management applications (water allocation, climate impact studies), the academic drivers are geared toward understanding the catchment functioning and how the individual processes combine to produce catchment response. As in ungauged catchments, no runoff data are available for calibrating model parameters, so alternative methods/model structures are need to be developed. Furthermore, some guidelines for selecting the model structure in ungauged catchments may also be prepared.
6. Requirements for designing simulation tools vary greatly depending on the type of the basin being studied. Model calibration and operational implementation are technically complex operations. Therefore, scientific manpower must be updated with new concepts and latest techniques. Further, the recent modeling strategy has been technologically driven with the aim of converting distributed data of different types into useful information for decision-making at the scales that current computing power will allow, whilst looking towards the 'hyper resolution' scales of the future (Wood et al., 2011). There is need of high performance computational facilities to implement advanced hydrological modeling tools.
7. Guidelines should be created advising model users which tool is appropriate for which kind of hydrological situation as well as application, of sensitivity and uncertainty analysis. In this case, like climate models, ensembles of global, regional or small catchment scale hydrology models should be analyzed, as such comparisons allow for characterizing the uncertainty of model outputs and improving models.
8. Characterization of catchment and climatic heterogeneity and quantifying its effects are an emerging challenge to gain a better understanding of hydrological processes.
9. The interaction between anthropogenic activities and hydrologic system needs to be analyzed from new perspective to develop comprehensive picture of inherent feedback and evolving processes and better scenarios.

References

1. Abbaspour, K.C., Johnson, C.A., van Genuchten, M.T., (2004) Estimating uncertain flow and transport parameters using a sequential uncertainty fitting procedure. Vadose Zone Journal 3(4), 1340–1352.
2. Abbaspour, K.C., Yang, J., Maximov, I., Siber, R., Bogner, K., Mieleitner, J., Zobrist, J., Srinivasan, R., (2007). Spatially distributed modeling of hydrology and water quality in the pre-alpine/alpine Thur watershed using SWAT. J. of Hydrol., 333, 413–430.
3. Abbott, M. B., Bathurst, J. C., Cunge, J. A., O'Connell, P. E., & Rasmussen, J. (1986). An introduction to the European Hydrological System—Systeme Hydrologique Europeen, “SHE”, 1: History and philosophy of a physically-based, distributed modeling system. Journal of hydrology, 87(1-2), 45-59.
4. Aitken, A.P., 1973. Assessing Systematic Errors in Rainfall Runoff Model. Journal of Hydrology, 20, 121-136.
5. Ajami, N.K., Duan, Q.Y., Sorooshian, S., (2007) An integrated hydrologic Bayesian multimodal combination framework: confronting input, parameter, and model structural uncertainty in hydrologic prediction. Water Resources Research 43 (1), Art. No. W01403.
6. Albergel, C., R¨udiger, C., Pellarin, T., Calvet, J.-C., Fritz, N., Froissard, F., Suquia, D., Petitpa, A., Piguet, B., and Martin, E. (2008) From near-surface to root-zone soil moisture using an exponential filter: an assessment of the method based on in-situ observations and model simulations, Hydrol. Earth Syst. Sci., 12, 1323–1337, doi:10.5194/hess-12-1323-2008.
7. Arnold, J. G. & Fohrer, N. (2005) SWAT2000: Current capabilities and research opportunities in applied watershed modeling. Hydrological Processes, 19(3), 563–572. doi: 10.1002/hyp.5611
8. Arnold, J. G., Moriasi, D. N., Gassman, P. W., Abbaspour, K. C., White, M. J., Srinivasan, R., Santhi, C., Harmel, R. D., van Griensven, A., Van Liew, M. W., Kannan, N., Jha, M. K. (2012). SWAT: Model use, calibration, and validation. Trans. ASABE, 55(4), 1494-1508.
9. Arnold, J.G., Srinivasan, R., Muttiah, R.S., & Williams, J.R. (1998) Large-area hydrologic modeling and assessment: Part I. Model development. Journal of the American Water Resources Association. 34(1), 73-89. doi: 10.1111/j.1752 1688. 1998.tb05961.x
10. ASCE. (1993) Criteria for evaluation of watershed models. J. Irrigation Drainage Eng. 119(3, 429-442.
11. Aubert, D., Loumagne, C., and Oudin, L. (2003) Sequential assimilation of soil moisture and streamflow data in a conceptual rainfall runoff model, J. Hydrol., 280, 145–161, 2003.
12. Bates, B.C., Campbell, E.P. (2001) A Markov chain Monte Carlo scheme for parameter estimation and inference in conceptual rainfall–runoff modeling. Water Resources Research 37 (4), 937–947.
13. Bates, P.D., and De Roo, A.P.J. (2000) A Simple Raster-Based Model for Flood Inundation Simulation. Journal of Hydrology. 236(1–2), 54–77.
14. Bathurst, J.C., (1986) Physically-based distributed modeling of an upland catchment using the Systeme Hydrologique European. J. Hydrol., 87(1/2), 79-102.
15. Bayarri, M.J., Berger, J.O., Paulo, R., Sacks, J., Cafeo, J.A., Cavendish, J., Lin, C.-H., Tu, J. (2007) A framework for validation of computer models. Technometrics 49 (2), 138–154.
16. Beasley, D. B., Huggins, L.F., and Monke, E.J. (1980) ANSWERS: A model for watershed planning. Trans. of the ASAE 23(4):938-944.
17. Bergström, S. (1976) Development and application of a conceptual runoff model for Scandinavian Catchments. Department of Water Resources Engineering, University of Lund.Bulletin Series A No. 52.
18. Bergström, S. (1992) The HBV Model: Its Structure and Applications, Swedish Meteorological and Hydrological Institute (SMHI), Hydrology, Norrköping, 35.
19. Bergström, S. (1995) The HBV model (Chapter 13), in: Computer Models of Watershed Hydrology, edited by: Singh, V. P., Water Resources Publications, Highlands Ranch, Colorado, USA, 443–476.
20. Bergstrom, S., (1991) Principles and confidence in hydrological modeling. Nordic Hydrology 22, 123–156.

21. Betson, R.P., Tucker, R.L. and Haller, F.M. (1969) Using Analytical Method to Develop a Surface Runoff Model. Water Resources Research, Vol. 5, No. 1, 103-111.
22. Beven, K. (1989) Changing ideas in hydrology—The case of physically based models. Journal of Hydrology. 105(1–2), 157–172.
23. Beven, K. (1993) Prophecy, reality, and uncertainty in distributed hydrological modeling. Adv. Water Resour. 16(1), 41-51.
24. Beven, K. (2016) Facets of uncertainty: epistemic uncertainty, non-stationarity, likelihood, hypothesis testing, and communication, Hydrol. Sci. Journal, 61(9), 1652–1665.
25. Beven, K. and Binley, A. (1992) the future of distributed models: Model calibration and uncertainty prediction, Hydrol. Process., 6, 279-298.
26. Beven, K., (1989) Changing ideas in hydrology—the case of physically based models. Journal of Hydrology 105, 157–172.
27. Beven, K., Freer, J. (2001) Equifinality, data assimilation, and uncertainty estimation in mechanistic modeling of complex environmental systems using the GLUE methodology. Journal of Hydrology 249 (1–4), 11–29.
28. Beven, K.J., (1996) A discussion of distributed hydrological modeling. In: Abbott, M.B., Refsgaard, J.C. (Eds.), Distributed Hydrological Modeling. Kluwer Academic, pp. 255–278.
29. Bingeman, A.K, Kouwen, N. M. ASCE and Soulis, E. D. (2006) Validation of the hydrological processes in a hydrological model. Journal of Hydrologic Engineering, ASCE. 11 (5),451-463
30. Biondi, D., Freni, G., Iacobellis, V., Mascaro, G. and Montanari, A. (2012) Validation of hydrological models: Conceptual basis, methodological approaches and a proposal for a code of practice, Physics and Chemistry of the Earth 42–44 (2012) 70–76.
31. Birkinshaw, S.J., James, P. and Ewen, J. (2010) Graphical User Interface for Rapid Set-up of SHETRAN Physically-Based River Catchment Model. Environmental Modeling and Software, 25, 609-610.
32. Bloschl, G., and Sivapalan, M. (1995) Scale Issues in Hydrological Modeling: A Review, Hydrological Processes, Vol. 9, 251-290.
33. Boskidis, I., Gikas, G.D., Sylaios, G.K. and Tsihruntzis, V.A. (2012) Hydrologic and Water Quality Modeling of Lower Nestos River Basin. Water Resource Management, **26**, 3023-3051. http://dx.doi.org/10.1007/s11269-012-0064-7.
34. Boyle, D. P., H. V. Gupta, and S. Sorooshian. 2000. Toward improved calibration of hydrologic models: Combining the strengths of manual and automatic methods. Water Resources Res. 36(12): 3663-3674.
35. Brath, A., Castellarin, A., Montanari, A., (2003) Assessing the reliability of regional depth-duration-frequency equations for gaged and ungaged sites. Water Resour. Res. 39. doi:10.1029/2003WR002399.
36. Breuer,L.,Huisman,J.A.,Willems, P., Bormann, H., Bronstert, A., and Croke,B.F.(2009). Assessing the impact of land use change on hydrology by ensemble modeling (LUCHEM)I: Model intercomparison with current land use. Advances in Water Resources, 32,129–146.
37. Brigode, P., Oudin, L. and Perrin, C. (2013) Hydrological model parameter instability: A source of additional uncertainty in estimating the hydrological impacts of climate change? J. of Hydrol., 476, 410-425.
38. Carrigan, P.H., Jr., (1973) Calibration of U.S. Geological Survey Rainfall-Runoff Model for Peak Flow Synthesis - Natural Basins. Report No. U.S.G.S.-W.R.D.-73-026, U.S. Geological Survey-WRD, Reston, Va, U.S.A.
39. Castellarin, A., Galeati, G., Brandimarte, L., Montanari, A., Brath, A., (2004) Regional flow-duration curves: reliability for ungauged basins. Adv. Water Resour. 27, 953–965.
40. Chalkias, C., Stathopoulos, N., Kalogeropoulos, K. and Karymbalis, E. (2016) Applied Hydrological Modeling with the Use of Geoinformatics: Theory and Practice, Empirical Modeling and Its Applications, Prof. Dr. Md. Mamun Habib (Ed.), InTech, DOI: 10.5772/62824. Available from: http://www.intechopen.com/books/empirical-modeling-and-its-applications/applied-hydrological-modeling-with-the-use-of-geoinformatics-theory-and-practice.

41. Chu, X. and Steinman, A. (2009) Event and Continuous Hydrologic Modeling with HEC-HMS. Journal of Irrigation and Drainage Engineering, 135,119-124. doi: 10.1061/_ASCE_0733-9437_2009_135:1_119_
42. Clark, M. P., Rupp, D. E., Woods, R. A., Zheng, X., Ibbitt, R. P., Slater, A. G., Schmidt, J., and Uddstrom, M. J. (2008) Hydrological data assimilation with the ensemble Kalman filter: Use of streamflow observations to update states in a distributed hydrological model, Adv. Water Resour., 31, 1309–1324, doi: 10.1016/j.advwatres.2008.06.005.
43. Cornelissen, T., Diekkrüger, B., and Giertz, S. (2013). A comparison of hydrological models for assessing the impact of land use and climate change on discharge in a tropical catchment. Journal of Hydrology,498, 221–236.
44. Crawford, N.H. and Linsley, (1966) Digital Simulation in Hydrology. The Stanford Watershed Simulation Model `IV'. Technical Report No. 39, Department of Civil Engineering, Stanford Univ., Stanford, California.
45. Daggupati, P., Pai, N., Ale, S., Douglas-Mankin, K.R., R., Zeckoski, W., Jeong, J., Parajuli, P. B., Saraswat, D. and Youssef, M.A. (2015) A recommended calibration and validation strategy for hydrologic and water quality models, American Society of Agricultural and Biological Engineers, 58(6), 1705-1719, DOI 10.13031/trans.58.10712.
46. Dawson, C.W. and Wilby, R. (1998) An Artificial Neural Network Approach to Rainfall-Runoff Modeling. Hydrological Sciences Journal. 1998;43(1),47–66.
47. Dawson, C.W. and Wilby, R. (2001) Hydrological Modeling Using Artificial Neural Networks. Progress in Physical Geography. 2001;25(1):80–108.
48. DHI, (1988) Lecture notes and Exercises - Training course on Hydrological Computerized Modeling System (SHE).
49. Di Baldassarre, L., Brandimarte, G., and Beven, K. (2016) The seventh facet of uncertainty: wrong assumptions, unknowns and surprises in the dynamics of human–water systems, Hydrological Sciences Journal, 61:9, 1748-1758, DOI:10.1080/02626667.2015.1091460.
50. Dillaha, T.A and Beasley, D.B (1983) Sediment transport from disturbed upland watersheds. Trans. of the ASAE 26(6):1766-1772,1777.
51. Dillaha, T.A., Beasley, D. B. and L. F. Huggins, (1982) Using the ANSWERS model to estimate sediment yields on construction sites. J. Soil and Water Conservation 37(2):117120.
52. Doherty J. (2005) PEST: Model-Independent Parameter Estimation User Manual, 5th edn. Watermark Numerical Computing: Australia.
53. Doherty, J., (2003a) Ground water model calibration using pilot points and regularization. Ground Water 41 (2), 170-177.
54. Doherty, J., (2003b) MICA: Model-Independent Markov Chain Monte Carlo Analysis. Watermark Numerical Computing, Brisbane, Australia.
55. Doherty, J., (2010) PEST, Model-independent Parameter Estimation. User Manual (fifth ed., with slight additions). Watermark Numerical Computing, Brisbane, Australia.
56. Doherty, J.E., Hunt, R.J., (2010). Approaches to Highly Parameterized Inversion - a Guide to Using PEST for Groundwater-model Calibration. U.S. Geological Survey Scientific Investigations Report 2010-5169. USGS, Madison, USA.
57. Domínguez-Mora, R., Esquivel-Garduño, G., Méndez- Antonio, B., Mendoza-Reséndiz, A., Arganis-Juárez, M.L., & Carrizosa-Elizondo, E. (2008) Manual del Modelo para Pronóstico de Escurrimiento. Universidad Nacional Autónoma de México. Obtenido de: http:// eias.utalca.cl/isi/publicaciones/unam/pronostico_del_ escurrimiento.pdf.
58. Donigian, A. S., Jr. (2002) Watershed model calibration and validation: The HSPF experience. In Proc. WEF Natl. TMDL Science and Policy, 44-73. Alexandria, Va.: Water Environment Federation.
59. Dooge, J.C.I. (1982) Parameterization of Hydrologic Processes, in Eagleson, P. S. (Ed.), Land Surface Processes in Atmospheric General Circulation Models. Cambridge University Press, London. 243-288.
60. Dooge, J.C.I. (1986) Looking for hydrologic laws, Water Resources Research, 22, 46s-58s.

61. Douglas-Mankin, K.R., Srinivasan, R. and Arnold, J.G. (2010) Soil and Water Assessment Tool (SWAT) model: Current development and applications. Trans. ASABE 53(5): 1423-1431.
62. Downer, C.W., and Ogden, F.L. Gridded Surface Subsurface Hydrologic Analysis Users Manual," in preparation, U.S. Army Engineer Research and Development Center, Vicksburg, MS
63. Duan, Q.Y., Sorooshian, S., Gupta, V. (1992) Effective and efficient global optimization for conceptual rainfall–runoff models. Water Resources Research 28 (4), 1015–1031.
64. Duan, Q.Y., Sorooshian, S., Ibbitt, R.P. (1988) A maximum likelihood criterion for use with data collected at unequal time intervals. Water Resources Research 24 (7), 1163–1173.
65. Dunn, S., Savage, D. and Mackay, R. (1992) hydrological simulation of the Rede catchment using the Systeme Hydrologique Europeen (SHE). In Land Use Change: The Causes and Consequences, M.C. Whitby (Ed), HMSO, London 137-146.
66. Džubáková K. (2010) Rainfall-Runoff Modeling: Its development, Classification and Possible Application. ACTA, Geographica Universitat Comenianae, Vol. 54, 2010, No. 2, 173-181
67. Engel, B., Storm, D., White, M., Arnold, J. and Arabi. M. (2007) A hydrologic/water quality model application protocol. J. American Water Resour. Assoc. 43(5): 1223-1236.
68. EPA: Modeling at EPA, available at: http://www.epa.gov/epahome/ models.htm, 2014.
69. Ewen, J. (1990). Basis for the subsurface contaminant migration components of the catchment water flow, sediment transport, and contaminant migration modeling system SHETRAN-UK. NSS/R229, UK Nirex Limited.
70. Ewen, J., Parkin, G. and O'Connell, P.E. (2000) SHETRAN: Distributed River Basin Flow and Transport Modeling System. ASCE J. Hydrologic Eng., 5, 250-258.
71. Fairfield, J. and Leymarie, P. (1991) Drainage Networks from Grid Digital Elevation Models. Water Resources Research. 27(5), 709–717.
72. Fienen, M.N., (2013) We Speak for the Data. Groundwater. http://dx.doi.org/10.1111/ gwat.12018.
73. Finn, M.P., Usery, E.L., Scheidt, D.J., Beard, T., Ruhl, S., Bearden, M., (2002) AGNPS watershed modeling with GIS databases in Proceedings Second Federal Interagency Hydrologic Modeling Conference, Las Vegas, Nevada, 2002, Compact Disk.
74. Flanagan, D.C., Gilley, J.E. and Franti, T.G. (2007) Water Erosion Prediction Project (WEPP): development history, model capabilities, and future enhancements. Transactions of the ASABE50(5):1603-161
75. Fleming, G., (1975) Computer Simulation Techniques in Hydrology. Elsevier.
76. Fleming, M.J., (2010) Hydrologic Modeling System HEC-HMS Quick Start Guide V3.5
77. Gan, T. Y, E. M. Dlamini, and G. F. Biftu. 1997. Effects of model complexity and structure, data quality, and objective functions on hydrologic modeling. J. Hydrology 192(1): 81-103.
78. Gelman, S., Carlin, J.B., Stren, H.S., Rubin, D.B. (1995) Bayesian Data Analysis. Chapman and Hall, New York.
79. Grayson, R. and Bloschl, G. eds. (2000) Spatial Patterns in Catchment Hydrology: Observations and Modeling, Cambridge University Press.
80. Grayson, R.B., Moore, I.D. and McMahon, T.A. (1992) Physically based hydrologic modeling: 2. Is the concept realistic?Water Resour. Res., 28(10), 2659–2666, doi:10.1029/92WR01259.
81. Gupta, H.V., Beven, K.J., Wagener, T. (2005) Model calibration and uncertainty estimation. In: Anderson, M.G. (Ed.), Encyclopedia of Hydrological Sciences. John Wiley, New York, pp. 2015–2031.
82. Gupta Hoshin V., Kling Harald, , Yilmaz Koray K., , Martinez Guillermo F. (2009) Decomposition of the mean squared error and NSE performance criteria:Implications for improving hydrological modeling, Journal of Hydrology 377, 80–91. Gupta, H.V., Sorooshian, S., and Yapo, P.O. (1998) Toward improved calibration of hydrologic models: Multiple and noncommensurable measures of information. Water Resour.Res. 34(4), 751-763.

83. Gupta, H.V., Sorooshian, S., and Yapo, P.O. (1999) Status of automatic calibration for hydrologic models: Comparison with multilevel expert calibration. J. Hydrol. Eng. 4(2), 135-143.
84. Gupta, H.V., Wagener, T., Liu, Y., (2008) Reconciling theory with observations: elements of a diagnostic approach to model evaluation. Hydrol. Proc. 22, 3802–3813.
85. Hall, M.J. (1984) Urban Hydrology, Elsevier Applied Science Publisher, London & New York.
86. Hargreaves, G.H. (1981) Simplified method for rainfall intensities, Proc. Of American Society of Civil Engineers, J. Hydraul. Div., 104 (HY12), 1577-86.
87. Harmel, R. D., Smith, P. K., and Migliaccio, K. L. (2010) Modifying goodness-of-fit indicators to incorporate both measurement and model uncertainty in model calibration and validation. Trans. ASABE 53(1): 55-63.
88. Hassanizadeh, S.M., and Carrera, J., (1992) Editorial. Validation of Geo-Hydrological Models (special issue). Advances in Water Resources 15, 1–3.
89. Hokanson, H.L. (1978) Soil survey of Lyon County, Minnesota, United States Department of Agriculture, Washington, DC.
90. Hokanson, H.L., Anderson, W.W., Calkins, D.W., Hein, K.W., Lorenzen, F.D., Murray, J.J., Paulson, R.O., and Peterson, R.F. (1970) Soil survey of Lincoln County, Minnesota, United States Department of Agriculture, Washington, DC.
91. Hornberger, G.M., Spear, R.C. (1981) An approach to the preliminary-analysis of environmental systems. Journal of Environmental Management 12 (1), 7–18.
92. Houser, P.R., Shuttleworth, W. Famiglietti, Gupta, J. S., H. V., Syed K. H., and Goodrich D. C. (1998) Integration of Soil Moisture Remote Sensing and Hydrologic Modeling Using Data Assimilation. Water Resources Research. 34(12), 3405–3420.
93. Huggins, L. F. and Monke, E.J. (1966) The mathematical solution of the hydrology of small watersheds. Technical Report No. 1, Water Resources Research Center, Purdue University, West Lafayette, IN. 130.
94. Huisman, J. A., Breuer, L., Bormann, H., Bronstert, A., Croke, B.F., Frede, H.G., Willems, P. (2009). Assessing the impact of land use change on hydrology by ensemble modeling (LUCHEM) III: Scenario analysis. Advances in Water Resources, 32, 159–170.
95. Hunt, R.J., Doherty, J., Tonkin, M.J., (2007) Are models too simple? Arguments for increased parameterization. Ground Water 45 (3), 254-262.
96. Hydrology Hand Book (1996) American Society of Civil Engineers, 345, east 47th street, New York.
97. IAHR, (1994) Publication of guidelines for validation documents and call for discussion. International Association for Hydraulic Research Bulletin 11, 41.
98. Irrisoft: Database and on-line Applications in Irrigation, Drainage & Hydrology, available at: http://www.irrisoft.org, 2014.
99. Jackson, T.J., Le Vine D. M., Hsu A. Y., Oldak A., Starks P. J., Swift C. T., Isham J. D., & Haken M. (1999) Soil Moisture Mapping at Regional Scales Using Microwave Radiometry: The Southern Great Plains Hydrology Experiment, IEEE. Transactions on Geoscience and Remote Sensing. 37(5), 2136–2151.
100. Jain, S.K. (1993) Calibration of conceptual models for rainfall-runoff simulation, Hydrological Sciences Journal, 38:5, 431-441, DOI: 10.1080/026266693099492692.
101. James, L.D., (1972) Hydrologic Modeling, Parameter Estimation and Watershed Characteristics. Journal of Hydrology, Vol. 17, 283-307.
102. Kakar Y.P. (1981) Effect of electroplating waste on Ground water in Ludhiana, Punjab. National Seminar on Assessment, Development and Management of GroundWater Resources, CGWB, Minis. of Irrig., New Delhi, pp 435-446.
103. Kakar Y.P. (1983) Ground Water Pollution, Special paper in National Seminar on Assessment, Development and Management of Ground Water Resources, CGWB, Minis. of Irrig., New Delhi, pp 103-112.

104. Kar A.K., Lohani A.K. , Goel, N.K., Roy G.P., (2015) Rain gauge network design for flood forecasting using multi-criteria decision analysis and clustering techniques in lower Mahanadi river basin, India Journal of Hydrology: Regional Studies, 4 (Part B), 313-332.
105. Kar A.K., Lohani A.K., Goel N.K., Roy G.P. (2017) Development of a Fuzzy Flood Forecasting Model for Downstream of Hirakud Reservoir of Mahanadi Basin, India. In: Sharma N. (eds) River System Analysis and Management. Springer, Singapore, 211-218.
106. Kauffeldt, A., Wetterhall, F., Pappenberger, F., Salamon, P., and Thielen, J. (2016) Technical Review of Large-Scale Hydrological Models for Implementation In Operational Flood Forecasting Schemes on Continental Level,
107. Kavetski, D., Kuczera, G., Franks, S.W. (2006 b) Bayesian analysis of input uncertainty in hydrological modeling: 2. Application. Water Resources Research 42 (3), Art. No. W03408.
108. Kavetski, D., Kuczera, G., Franks, S.W. (2006a) Bayesian analysis of input uncertainty in hydrological modeling: 1. Theory. Water Resources Research 42 (3), Art. No. W03407.
109. Kazezyilmaz-Alhan, C.M., & Medina, M.A. (2007) Kinematic and diffusion waves: Analytical and numerical solutions to overland and channel flow. Journal of Hydraulic Engineering, pp.133(2). doi: 10.1061/_ASCE_0733- 9429_2007_133:2_217_
110. Kennedy, M.C., O'Hagan, A. (2001) Bayesian calibration of computer models. Journal of the Royal Statistical Society Series B, 63 (3), 425–464.
111. Kim, K., Whelan, G., Purucker, S.T., Bohrmann, T., F., Cyterski, M. J., Molina, M., Gu, Y., Pachepsky, Y., Guber, A. and Franklin, D.H. (2014) Rainfall–runoff model parameter estimation and uncertainty evaluation on small plots, Hydrol. Process. 28, 5220–5235.
112. Klemes, V., (1986) Operational Testing of Hydrological Simulation Models.Hydrol. Sci. J., 31(1), 13-24.
113. Kling Harald, Fuchs Martin, Paulin Maria (2012) Runoff conditions in the upper Danube basin under an ensemble of climate change scenarios, Journal of Hydrology 424–425, 264–277.
114. Kokkonen, T., Koivusalo, H., Jakeman, A., and Norton, J.: Construction of a Degree-Day Snow Model in the Light of the "Ten Iterative Steps in Model Development", in: Proceedings of the iEMSs Third Biennial Meeting: Summit on Environmental Modeling and Software, Environmental Modeling and Software Society, Burlington, USA, 2006.
115. Kouwen, N. and Garland, G. (1989) Resolution Considerations in Using Radar Rainfall Data for Flood Forecasting, Canadian Journal of Civil Engineering. 16:279-289
116. Kouwen, N., (1988) WATFLOOD: A Micro-Computer based Flood Forecasting System based on Real-Time Weather Radar, Canadian Water Resources Journal, 13(1):62-77.
117. Krause, P., Boyle, D.P. and Base, F. (2005), Comparison of different efficiency criteria for hydrological model assessment, Advances in Geosciences, 5, 89–97.
118. Kuczera, G. (1983) Improved parameter inference in catchment models. 1. Evaluating parameter uncertainty. Water Resources Research 19 (5), 1151–1162.
119. Kuczera, G., Kavetski, D., Franks, S., Thyer, M. (2006) Towards a Bayesian total error analysis of conceptual rainfall–runoff models: characterising model error using storm-dependent parameters. Journal of Hydrology 331, 161–177.
120. Kuczera, G., Parent, E. (1998) Monte Carlo assessment of parameter uncertainty in conceptual catchment models: The Metropolis algorithm. Journal of Hydrology 211 (1–4), 69–85.
121. Laflen, J.M., Lane, L.J. and Foster, G.R. (1991) WEPP—a next generation of erosion prediction technology. Journal of Soil Water Conservation 46(1): 34–38.
122. Larsen, L.G., Thomas, C.M., Eppinga, B. and Coulthard, T.J. (2014) Exploratory modeling: Extracting causality from complexity, Eos Trans. AGU, 95(32), 285–286.
123. Leavesley, G.H., Lichty, R.W., Troutman, B.M., and Saindon, L.G., (1983) Precipitation-runoff modeling system-User's manual: U.S. Geological Survey Water-Resources Investigations Report 83-4238, 207.

124. Leavesley, G.H., Restrepo, P.J., Markstrom, S.L., Dixon, M., and Stannard, L.G., (1996) The Modular Modeling System (MMS): User's manual: U.S. Geological Survey Open-File Report 96-151, 142.
125. Legates, D. R., and G. J. McCabe. 1999. Evaluating the use of “goodness-of-fit” measures in hydrologic and hydroclimatic model validation. Water Resources Res. 35(1): 233-241.
126. León, L.F., Soulis, E.D., Kouwen, N. and Farquhar, G.J. Modeling Diffuse Pollution with a Distributed Approach”, Journal Water Science and Technology, IWA 9(45),
127. Lindström, G., Gardelin, M., Johansson, B., Persson, M. and Bergström, S. (1997) Development and test of the distributed HBV-96 hydrological model. Journal of Hydrology, 201, 272-288.
128. Liu, Y., Weerts, A. H., Clark, M., Hendricks Franssen, H.-J., Kumar, S., Moradkhani, H., Seo, D.-J., Schwanenberg, D., Smith, P. van Dijk, A. I. J. M.,van Velzen, N., He, M., Lee, H., Noh, S. J., Rakovec, O. and Restrepo, P. (2012). Advancing data assimilation in operational hydrologic forecasting: progresses, challenges, and emerging opportunities, Hydrol. Earth Syst. Sci., 16, 3863–3887.
129. Liu, Y.B., De Smedt., F, Hoffman, L. and Pfister L., (2004) Assessing land use impacts on flood processes in complex terrain by using GIS and modeling approach, Environmental Modeling and Assessment, 9, 227-235.
130. Loague, K., and Green, R. E. (1991) Statistical and graphical methods for evaluating solute transport models: Overview and application. J. Contam. Hydrol. 7(1-2), 261-283.
131. Lohani A.K, Goel N.K. and Bhatia K.K.S. (2006) Takagi–Sugeno fuzzy inference system for modeling stage-discharge relationship, Journal of Hydrology, Elsevier, 331, pp 146-160
132. Lohani A.K, Goel N.K. and Bhatia K.K.S,(2007) Deriving stage-discharge-sediment concentration relationship using fuzzy logic, Hydrological Sciences Journal, 52(4), 793-807.
133. Lohani A.K, Goel N.K. and Bhatia K.K.S, (2011) Comparative Study of Neural Network, Fuzzy Logic and Linear Transfer Function Techniques In Daily Rainfall-Runoff Modeling Under Different Input Domains, Hydrological Processes. 25(2),175–193.
134. Lohani, A.K., Kumar Rakesh, Singh R.D. (2012) Hydrological Time Series Modeling: A Comparison Between Adaptive Neuro Fuzzy, Neural Network and Auto Regressive Techniques, Journal of Hydrology, Elsevier, 442-443 (6), 23-35.
135. Lohani A.K, Goel N.K. and Bhatia K.K.S. (2014) Improving real time flood forecasting using fuzzy inference system, A.K. Lohani, N.K. Goel, K.K.S. Bhatia, Journal of Hydrology, 509(13), 25–41.
136. Madsen, H., Rosbjerg, D., Damgard, J., and Hansen, F. S. (2003) Data assimilation into MIKE 11 flood forecasting system using Kalman filtering, Water Resources Systems – Hydrological Risk, Management and Development, IAHS Publ no. 281, 75–81, 2003.
137. Maidment D. R. (1993) Developing a spatially distributed unit hydrograph by using GIS applications of geographic information systems in hydrology and water resources management. In: Proceedings of EGU International Conference; 1993; Vienna, pp. 181–192.
138. Marjolein B.A., Asselt, V. and Rotmans, J. (2002) Uncertainty in integrated assessment modeling: From Positivism to Pluralism, Climatic Change 54: 75–105.
139. Markstrom, S.L., Regan, R.S., Hay, L.E., Viger, R.J., Webb, R.M.T., Payn, R.A., and LaFontaine, J.H., (2015) PRMS-IV, the precipitation-runoff modeling system, version 4: U.S. Geological Survey Techniques and Methods, book 6, chap. B7, 158 p., http://dx.doi.org/10.3133/tm6B7.
140. Marshall, L., Nott, D., Sharma, A. (2004) A comparative study of Markov chain Monte Carlo methods for conceptual rainfall–runoff modeling. Water Resources Research 40, W02501.doi:10.1029/2003WR002378.
141. Matott L.S. (2005) OSTRICH: An Optimization Software Tool: Documentation and User’s Guide, Version 1.6. State University of New York at Buffalo, Department of Civil, Structural and Environmental Engineering.

142. McDonald, Richard, Nelson, Jonathan, Kinzel, Paul, and Conaway, Jeff, 2006, Modeling surface-water flow and sediment mobility with the Multi-Dimensional Surface-Water Modeling System (MD_SWMS): United States Geological Survey, v. FS – 2005.
143. Mein, R. and Nathan, R. (2005) RORB Model Version 5, Monash University and SKM Pty.Ltd., Melbourne.
144. Méndez-Antonio, B., Soto-Cortés, G., Rivera-Trejo, F., & Caetano, E. (2014) Modelación hidrológica distribuida apoyada en radares meteorológicos. Tecnología y Ciencias del Agua, 5(1), 83-101. Obtenido de: http:// www.researchgate.net/publication/261798195_Modelacin_Hidrolgica_Distribuida_apoyada_en_radares_meteorolgicos
145. Metropolis, N., Rosenbluth, A.W., Rosenbluth, M.N., Teller, A.H., Teller, E. (1953) Equation of state calculations by fast computing machines. Journal of Chemical Physics 21 (6), 1087–1092.
146. Miller, S.N., Kepner, W.G., Mehaffey, M.H., Hernandez, M., Miller, R.C., Goodrich, D.C., Devonald, F.K. Heggem, D.T. and Miller, W.P. (2002) Integrating Landscape Assessment and Hydrologic Modeling for Land Cover Change Analysis. Journal of the American Water Resources Association, Vol. 38 No. 4, 915-929.
147. Miller, S.N., Semmens, D.J., Goodrich, D.C., Hernandez, M., Miller, R.C., Kepner, W.G., Guertin, D.P. (2007) The Automated Geospatial Watershed Assessment Tool. J. Environmental Modeling and Software. 22:365-377.
148. Montanari, A., Bahr, J., Bloschl, G., Cai, X., Mackay, D.S.,Michalak, A.M., Rajaram, H., and Sander,G. (2015) Fifty years of Water Resources Research:Legacy and perspectives for thescience of hydrology, Water Resour.Res., 51, 6797–6803, doi:10.1002/2015WR017998.
149. Moore, C., Doherty, J., (2005) Role of the calibration process in reducing mode predictive error. Water Resour. Res. 41 (5), W05020.
150. Moore, I.D., Grayson, R.B., and Ladson, A.R., (1991) Digital Terrain Modeling: A Review of Hydrological, Geomorphological, and Biological Applications. Hydrological Processes. 5(1), 3–30.
151. Moradkhani, H., Hsu, K.-L., Gupta, H., Sorooshian, S., (2005a) Uncertainty assessment of hydrologic model states and parameters: sequential data assimilation using the particle filter. Water Resources Research 41, W05012. doi:10.1029/2004WR003604.
152. Moradkhani, H., Sorooshian, S., Gupta, H. V., and Houser, P. (2005b) Dual state-parameter estimation of hydrological models using Ensemble Kalman filter, Adv. Water Resour., 28, 135–147.
153. Moriasi, D.N., Arnold, J.G., Van Liew, M.W., Bingner, R.L., Harmel, R.D. and Veith, T.L. (2007) Model Evaluation Guidelines for Systematic Quantification of Accuracy in Watershed Simulations. American Society of Agricultural and Biological Engineers, **50**, 885-900.
154. Moriasi, D.N., Wilson, B.N., Douglas-Mankin, K. R., Arnold, J.G.and Gowda, P.H., (2012) Hydrologic and water quality models: Use, calibration, and validation, American Soc. of Agril. and Bio. Engg., 55(4), 1241-1247.
155. Mujumdar, P.P., and Kumar, N., (2012) Flood in a Changing Climate: Hydrologic Modeling. Cambridge University Press.
156. Mukherjee, A.K., (1999) Environment and Sustainable Development, Technorama, Feb. 1999, 4-9.
157. Mulavany, T.J. (1850) On the use of self registering rain and flood gauges. Inst. Civ. Eng. Proc. (Dublin), 4, 1-8.
158. Muzik, I. (1996) Flood modeling with GIS-derived distributed unit hydrographs. Hydrological Processes. 1996, 10 (10),1401–1409.
159. Nagarajan, K., Judge, J., Graham, W. D., and Monsivais-Huertero, A. (2010) Particle Filter-based assimilation algorithms for improved estimation of root-zone soil moisture under dynamic vegetation conditions, Adv. Water Resour., 34, 433–447.
160. Nash, J.E., and Sutcliffe, J.V. (1970) River flow forecasting through conceptual models Part I—a discussion of principles. Journal of Hydrology. 1970;10(3), 282–290.

161. National Climatic Data Center. (NCDC). (2001) Annual Climatological Summary (2000): Tracy, Minnesota. National Climatic Data Center,http://lwf.ncdc.noaa.gov/servelets/ACS, July 17, 2001.
162. Neal, J. C., Atkinson, P. M., and Hutton, C. W. (2007) Flood inundation model updating using an ensemble Kalman filter and spatially distributed measurements, J. Hydrol., 336, 401–415.
163. Necpa′lov a′, M., Anex, R. P.,Fienen, M. N., Grosso, S. J. D., Castellano, M. J., Sawyer, John E., Iqbal, J.,Pantoja, J. L., and Barker, D.W. (2015) Understanding the DayCent model: Calibration, sensitivity, and identifiability through inverse modeling, Environmental Modeling & Software 66, 110-130.
164. Nelson, J.M., McDonald, R.R., and Kinzel, P.J., 2006, Morphologic evolution in the USGS surface-water modeling system: Proceedings of the 8th Federal Interagency Sedimentation Conference, April 2-6: Subcommittee on Sedimentation, CD_ROM, v. 8, p.-p.
165. Nkonge, L.K., Sang, J.K., Gathenya, J.M. and Home, P.G. (2014) Comparison of two calibration-uncertainty methods for Soil and Water Assessment Tool in stream flow modeling, Proceedings of 2014 International Conference on Sustainable Research and Innovation, Volume 5, 7th-9th May 2014.
166. Paniconi, C., and Putti, M., (2015) Physically based modeling in catchment hydrology at 50: Survey and outlook, Water Resour. Res., 51, 7090–7129, doi:10.1002/2015WR017780.
167. Pechlivanidis, I.G.and Arheimer, B. (2015) Large-scale hydrological modeling by using modified PUB recommendations: The India-HYPE case, Hydrol. Earth Syst. Sci., 19, 4559–4579.
168. Perumal, M., and Sahoo, B. (2009) Simplified flood routing methods in applied hydrology, Journal of Hydrological Research and Development, INCOH, Vol. 24, 37-88.
169. Perumal, M., and Sahoo, B. (2010) Real–time Flood Forecasting by a Hydrometric Data-Based Technique, Chapter–9, In: Natural and Anthropogenic Disasters: Vulnerability, Preparedness and Mitigation, M. K. Jha (editor), Capital Publishing Company, New Delhi, and Springer, The Netherlands, ISBN: 978-90-481-2497-8, 169–196.
170. Perumal, M., Sahoo, B., and Moramarco, T. (2013) Interpretations of the Muskingum flood routing method: a historical perspective, Proceedings of the Florisa Melone Memorial Conference, Oct. 10-11, 2013, Assisi, Italy.
171. Pietroniro, A., Prowse, T.D., Hamlin, L., Kouwen, N. and Soulis, E.D., 1996. "Application of a grouped response unit hydrologic model to a northern wetland region," International Journal of Hydrologic Processes, 10:1245-1261.
172. Planning Commission, Govt. of India (2011) report of working group on flood management and region specific issues for XII plan, 1-105.
173. Plate, E.J. (2009) Classification of Hydrological Models for Flood Management, Hydrology and Earth System Sciences, 13, 1939-1951.
174. Poeter E.P., Hill M.C. (1998) Documentation of UCODE: a Computer Code for Universal Inverse Modeling. U.S. Geological Survey Water-Resources Investigations Report 98-408: Denver, Colorado.
175. Pundarikanthan N.V., and Somasundaram, M.V. (1995) Using our limited water resources prudently, Yojana,53-56.
176. Quinn P., Beven K., Chevallier P., and Planchon, O. (1991) Prediction of hillslope flow paths for distributed hydrological modeling using digital terrain models. HydrologicalProcesses. 5(1), 59–79.
177. Rakovec, O., Weerts, A. H., Hazenberg, P., Torfs, P. J. J. F., and Uijlenhoet, R.(2012a) State updating of a distributed hydrological model with Ensemble Kalman Filtering: effects of updating frequency and observation network density on forecast accuracy, Hydrol. Earth Syst. Sci., 16, 3435–3449, doi:10.5194/hess-16-3435-2012.
178. Rakovec, O., Hazenberg, P., Torfs, P. J. J. F., Weerts, A. H., and Uijlenhoet, R. (2012b) Generating spatial precipitation ensembles: impact of temporal correlation structure, Hydrol. Earth Syst. Sci., 16, 3419–3434, doi:10.5194/hess-16-3419-2012, 2012b.

179. Ramsankaran, R., Kothyari, U.C., Ghosh, S.K., Malcherek, A. and Murugesan K. (2012) Geospatially based distributed rainfall-runoff modeling for simulation of internal and outlet responses in a semi-forested lower Himalayan watershed, Hydrol. Process. 26, 1405–1426.
180. Refsgaard, J.C. and Henriksen, H.J. (2004) Modeling guidelines—terminology and guiding principles, Advances in Water Resources 27 (2004) 71–82.
181. Refsgaard, J.C., (1996) Terminology, modeling protocol and classification of hydrological model codes. In: Abbott, M.B., Refsgaard, J.C. (Eds.), Distributed Hydrological Modeling. Kluwer Academic, pp. 17–39.
182. Refsgaard, J.C., van der Sluijs, J.P., Højberg, A.L., Vanrolleghem, P.A., (2007) Uncertainty in the environmental modeling process e a framework and guidance Environ, Model. Softw. 22, 1543e1556.Reichert, P. (2005) UNCSIM – A computer programme for statistical inference and sensitivity, identifiability, and uncertainty analysis. In: Teixeira, J.M.F., Carvalho-Brito, A.E. (Eds.), Proceedings of the 2005 European Simulation and Modeling Conference (ESM 2005), October 24–26, Porto, Portugal, EUROSIS-ETI. pp. 51–55.
183. Ricci, S., Piacentini, A., Thual, O., Le Pape, E., and Jonville, G. (2011) Correction of upstream flow and hydraulic state with data assimilation in the context of flood forecasting, Hydrol. Earth Syst. Sci., 15, 3555–3575, doi:10.5194/hess-15-3555-2011.
184. Roblero, H. R. (2013) Modelación hidrometeorológica de áreas con riesgo de inundación en la cuenca del río La Sierra, en los estados Chiapas y Tabasco, México. Tesis de maestro en ciencias. Colegio de Postgraduados. Obtenido de: www.biblio.colpos.mx:8080/.../Roblero_Hidalgo_R_MC_Hidrociencias_
185. Rodis, H.G. (1963) Geology and occurrence of groundwater in Lyon County, Minnesota, U.S. Geological Survey, Supply Paper 1619-N, U.S. Government Printing Office, Washington, DC.
186. Rosenbrock, K.H., (1960) An Automatic Method for finding the greatest or least value of a function. The Computer Journal, Vol. 7(3).
187. Santhi, C., Arnold, J.G., Williams, J.R., Dugas, W.A., Srinivasan, R. and Hauck, L.M. (2001) Validation of the SWAT model on a large river basin with point and nonpoint sources. J. American Water Resour. Assoc. 37(5), 1169-1188.
188. Sarma, P.G.S., Delleur, J.W., and Rao, A.R. (1969) A Program in Urban Hydrology, Part II, Tech. Rept. No. 99, Purdue University, Water Resources Research Centre, West Lafayette, IN.
189. Schaefli, B., Talamba, D.B., Musy, A. (2007) Quantifying hydrological modeling errors through a mixture of normal distributions. Journal of Hydrology 332, 303–315.
190. Schumann, G., Bates, P. D., Horritt, M. S., Matgen, P., and Pappenberger, F. (2009) Progress in integration of remote sensing derived flood extent and stage data and hydraulic models, Rev. Geophys, 47, RG4001, doi:10.1029/2008RG000274, 2009.
191. Seibert, J. and Vis, M. (2012). Teaching hydrological modeling with a user-friendly catchment-runoff-model software package. Hydrology and Earth System Sciences, 16, 3315–3325, 2012.
192. Seo, D.-J., Cajina, L., Corby, R., and Howieson, T. (2009) Automatic state updating for operational streamflow forecasting via variational data assimilation, J. Hydrol., 367, 255–275, doi: 10.1016/j.jhydrol.2009.01.019.
193. Seo, D.-J., Koren, V., and Cajina, N. (2003) Real-time variational assimilation of hydrologic and hydrometeorological data into operational hydrologic forecasting, J. Hydrometeorol., 4, 627–641.
194. Shao, J., Tu, D. (1995) The Jackknife and Bootstrap. Springer-Verlag, New York.
195. Shiiba, M., Laurenson, X., and Tachikawa, Y. (2000) Real-time stage and discharge estimation by a stochastic-dynamic flood routing model, Hydrol. Process., 14, 481–495.
196. Singh, J., Knapp, H.V. and Demissie, M. (2004) Hydrologic Modeling of the Iroquois River Watershed Using HSPF and SWAT. Illinois Department of Natural Resources and the Illinois State Geological Survey. Illinois State Water Survey Contract Report 2004-08. http://www.isws.illinois.edu/pubdoc/CR/ISWSCR2004-08.pdf
197. Singh, V.P. and Frevert, D.K., (2002) Mathematical Models of Large Watershed Hydrology, water Resources Publication.

198. Smith, R.E., (1992) Opus, An integrated simulation model for transport of nonpoint source pollutants at the field scale: Volume I, Documentation. ARS-98. Washington: USDA Agricultural Research Service. 120.
199. Santhi, C, J. G. Arnold, J. R. Williams, W. A. Dugas, R. Srinivasan, and L. M. Hauck. 2001. Validation of the SWAT model on a large river basin with point and nonpoint sources. J. American Water Resources Assoc.37(5): 1169-1188.
200. Smith, R.E., Goodrich, D.C., Woolhiser, D.A., and Unkrich, C.L. (1995) KINEROS - A kinematic runoff and erosion model, Chap. 20 of Computer Models of Watershed Hydrology, (Ed. by Singh, V. J.) Water Resour. Pub., Highlands Ranch, Colo., 697-732.
201. Sorooshian, S., Dracup, J.A. (1980) Stochastic parameter estimation procedures for hydrologic rainfall–runoff models – correlated and heterscedastic error cases. Water Resources Research 16(2), 430–442.
202. Stadnyk, T. A., Delavau, C., Kouwen, N. and Edwards, T.W.D. (2013) Towards hydrological model calibration and validation: simulation of stable water isotopes using the isoWATFLOOD model, Hydrol. Process. 27, 3791–3810.
203. Stroud, J. R., Lesht, B. M., Schwab, D. J., Beletsky, D., and Stein, M. L. (2009) Assimilation of satellite images into a sediment transport model of Lake Michigan, Water Resour. Res., 45, W02419, doi:10.1029/2007WR006747.
204. Sudheer, K.P., Chaubey, I., Garg, V.and Migliaccio, K.W. (2007) Impact of time-scale of the calibration objective function on the performance of watershed models, 21(25), 3409-3419.
205. Takeuchi, K., Blöschl, G., Savenije, H. H. G., Schaake, J., Sivapalan, M., Viglione, A., Wagener, T., and Young, G. (2013) Recommendations, in: Runoff Predictions in Ungauged Basins – Synthesis across processes, places and scales, edited by: Blöschl, G., Sivapalan, M., Wagener, T., Viglione, A., and Savenije, H. H. G., 384–387, Cambridge University Press, Cambridge, UK.
206. Tarboton, D.G. (1997) A New Method for The Determination of Flow Directions And Upslope Areas In Grid Digital Elevation Models. Water Resources Research. 33(2),309–319.
207. Tarboton, D.G., Bras, R.L., and Rodriguez-Iturbe I. (1991) On The Extraction of Channel Networks from Digital Elevation Data. Hydrological Processes. 5(1), 81–100.
208. Terink, W., Lutz, A. F., Simons, G.W.H., Immerzeel, W.W., and Droogers, P. (2015) SPHY v2.0: Spatial Processes in Hydrology, Geoscientific Model Development, 8, 2009-2034.
209. The United Nations Economic and Social Commission for Asia and the Pacific (ESCAP) (2016) Flood Forecasting and Early Warning in Transboundary River Basins: A Toolkit, UN, United Nations, Bangkok. http://www.unescap.org/resources/flood-forecasting-and early-warning-transboundary-river-basins-toolkit
210. Todini, E. (1978) Mutually Interactive State/Parameter Estimation (MISP) - in Chao-Lin Chiu (ed.) "Application of Kalman Filter to Hydrology, Hydraulics and Water Respurces", University of Pittsburgh, Penn, 135-151.
211. Todini, E. and Ciarapica L., (2001) The TOPKAPI model in Mathematical Models of Large Watershed Hydrology.
212. Todini, E. and Wallis, J.R., (1977) Using CLS for daily or longer period rainfall - runoff modeling - in Ciriani T.A., Maione U., Wallis J.R. (eds.) "Mathematical models for surface water hydrology" - John Wiley & Sons, London,149- 168.
213. Todini, E., (1988) Il modello afflussi deflussi del fiume Arno. Relazione Generale dello studio per conto della Regione Toscana, Technical Report, Bologna (in Italian).
214. Todini, E., (2007) Hydrological catchment modeling: past, present and future, Hydrol. Earth Syst. Sci., 11(1), 468-482.
215. Todini, E., (2009) History and Perspective of Hydrological Catchment Modeling, international Conference on “Water, Environment, Energy and Society (WEES-2009), New Delhi, 12-16 January 2009.
216. Todini, E. (1996) The ARNO rainfall-runoff model. J Hydrol., 175: 339-382.

217. Todini, E., Bossi, A., 1986. PAB (Parabolic and Backwater), an unconditionally stable flood routing scheme particularly suited for real time forecasting and control. J. Hydraul. Res., 24(5): 405-424.
218. Tommy, S.W., Wong, Y. Li. (1999) Theoretical assessment of changes in design flood peak of an overland plane for two opposing urbanisation sequences, Hydrological processes, Vo. 13, 1629-1647.
219. Tonkin MJ, and Doherty J. (2009) Calibration-constrained Monte Carlo analysis of highly-parameterized models using subspace techniques. Water Resources Research 45: W00B10. DOI: 10.1029/2007WR006678.
220. Toth, B., Pietroniro, A., Conley, F.M. and Kouwen., N. (2006) Modeling climate change impacts in the Peace and Athabasca catchment and delta I – hydrological model application. Hydrological Process 20, Special Northern Rivers Ecosystem Initiative Issue.
221. Tsang, C.F., (1991) The modeling process and model validation. Ground Water 29, 825–831.
222. Turcotte, R., Fortin, J.P., Rousseau, A.N., Massicotte, S. and Villeneuve, J.P. (2001) Determination of the drainage structure of a watershed using a digital elevation model and a digital river and lake network. J. Hydrol. 240, 225-242
223. UN/ISDR, (2004) United Nations Inter-Agency Secretariat of the International Strategy for Disaster Reduction (ISDR), living with risk: a global review of disaster reduction initiatives, United Nations Publications, Geneva.
224. USGS: Water Resources Applications Software, available at: http://water.usgs.gov/software/lists/alphabetical (last access: 30 April 2014), 2014.
225. van Griensven, A., and Bauwens, W.(2003) Multi-objective autocalibration for semidistributed water quality models. Water Resour. Res. 39(12): 1348-1356.
226. Van Griensven, A., Meixner, T. (2006) Methods to quantify and identify the sources of uncertainty for river basin water quality models. Water Science and Technology 53 (1), 51–59.
227. Van Liew, M. W., J. G. Arnold, and J. D. Garbrecht. 2003. Hydrologic simulation on agricultural watersheds: Choosing between two models. Trans. ASAE46(6): 1539-1551.
228. Vargas, C.G., Ibanez C.L.A., and Ramirez, R.A. (2015) development, classification and trends in rainfall-runoff modeling. Ingenieria Agricola Biosistemas, 7(1), 5-21, DOI: 105154/r.inagbi.2015.03.002.
229. Viney, N.R., & Sivapalan, M. (1995) LASCAM: The large scale catchment model. Perth: University of Western Australia, Centre for Water Research.
230. Vrugt, J.A., Diks, C.G.H., Bouten, W., Gupta, H.V., Verstraten, J.M. (2005) Towards a complete treatment of uncertainty in hydrologic modeling: combining the strengths of global optimization and data assimilation. Water Resources Research 41 (1), W01017. doi:10.1029/2004WR003059.
231. Vrugt, J.A., Gupta, H.V., Bouten, W., Sorooshian, S. (2003) A shuffled complex evolution metropolis algorithm for optimization and uncertainty assessment of hydrologic model parameters. Water Resources Research 39 (8), Art. No.-1201.
232. Wallace, R.M., Tarboton, D.G., Watson, D.W., Schreuders, K.A.T. and Tesfa, T. K. (2010) Parallel Algorithms for Processing Hydrologic Properties from Digital Terrain GIScience 2010, Sixth international conference on Geographic Information Science, Zurich, Switzerland, Extended abstract,http://www.giscience2010.org/pdfs/paper_229.pdf.Wang, L., Maskey, S., Ranasinghe, R., Vrijling, J.K., and Van Gelder, P.H.A.J.M(2015) Transferability and parameter uncertainty of hydrological models for estimating future mean and extreme discharges in the context of climate change, E-proceedings of the 36th IAHR World Congress, 28 June – 3 July, 2015, The Hague, the Netherlands.
233. Wang, X., and A. M. Melesse. (2005) Evaluation of the SWAT model's snowmelt hydrology in a northwestern Minnesota watershed. Trans. ASAE48(4): 1359-1376.
234. Wang, X., Kemanian, A., and Williams, J.R. (2011) Special features of the EPIC and APEX modeling package and procedures for parameterization, calibration, validation, and applications. 177-208. In Methods of Introducing System Models into Agricultural

Research. Ahuja, L.R. and L. Ma (eds.) Advances in Agricultural Systems Modeling 2. ASA • CSSA • SSSA, Madison, WI.
235. Wang, X., Williams, J.R., Gassman, P.W., Baffaut, C., Izaurralde, R.C., Jeong, J. and Kiniry. J.R. (2012) EPIC and APEX: model use, calibration and validation. Transactions of the ASABE 55(4):1447-1462.
236. Weerts, A. H. and El Serafy, G. Y. H. (2006) Particle filtering and ensemble Kalman filtering for state updating with hydrological conceptual rainfall-runoff models, Water Resour. Res., 42, W09403, doi:10.1029/2005WR004093.
237. Weerts, A. H., El Serafy, G. Y., Hummel, S., Dhondia, J., and Gerritsen, H. (2010) Application of generic data assimilation tools (DATools) for flood forecasting purposes, Comput. Geosci., 36, 453–463, doi: 10.1016/j.cageo.2009.07.009.
238. Weizenbaum, J., (1976) Computer Power and Human Reason: From Judgment to Calculation. W.H. Freeman: New York.
239. White, K.L. and Chaubey, I. (2005) Sensitivity Analysis, Calibration, and Validations for a Multisite and Multivariable SWAT Model. Journal of the American Water Resources Association (JAWRA) 41(5):1077-1089.
240. Wi, S., Yang, Y.C.E., Steinschneider, S., Khalil, A. and Brown, C.M. (2015) Calibration approaches for distributed hydrologic models in poorly gaged basins: implication for streamflow projections under climate change, Hydrol. Earth Syst. Sci., 19, 857–876.
241. Wilby, R.L. (2005) Uncertainty in water resource model parameters used for climate change impact assessment. Hydrological Processes, 19(16), 3201-3219.
242. William, A., Scharffenberg and Fleming, M.J. (2010) Hydrologic Modeling System HEC-HMS User's Manual V-3.5.
243. Willmott, C. J. 1981. On the validation of models. Physical Geography 2: 184-194.
244. Winsemius, H.C., Schaefli, B., Montanari, A. and Savenije, H.H.G. (2009) On the calibration of hydrological models in ungauged basins: A framework for integrating hard and soft hydrological information, Water Resour. Res., 45, W12422, doi:10.1029/2009WR007706.
245. Wood E.F., Roundy, J.K., Troy, T.J., Van Beek, L.P.H., Bierkens, M.F., Blyth, E., Whitehead, P. (2011) Hyperresolution global land surface modeling: meeting a grand challenge for monitoring Earth’s terrestrial water. Water Resou. Res., 47(5), W05301 DOI: 10.1029/2010WR010090.
246. Wood EF, Roundy JK, Troy TJ, Van Beek LPH, Bierkens MF, Blyth E, Whitehead P. 2011. Hyperresolution global land surface modeling: meeting a grand challenge for monitoring Earth’s terrestrial water. Water Resources Research 47(5): W05301 DOI: 10.1029/2010WR010090.
247. Woolhiser, D.A. (1996) Search for physically based runoff model - A Hydrologic El Dorado? ASCE Journal of Hydraulic Engineering, Vol. 122, No. 3, March, 122-129.
248. Woolhiser, D.A., (1973) Hydrologic and Watershed Modeling - State of the Art. Transactions of the ASAE, 16, 533-559.
249. Wu, J.Q., Dun, S., Elliot, W.J. and Flanagan, D.C. (2004) Modification and testing of the evapotranspiration (ET) routines in the WEPP model. Presented at the 2004 ASAE Annual International Meeting, August 1−4, 2004, Ottawa, Canada. St. Joseph, MI: ASAE
250. Xu, C., (2002) Hydrologic Models. Uppsala University, Department of Earth Sciences. 168p. Obtenido de:http://www.soil.tubs.de/lehre/Master.
251. Xu, C-Y., (1999) Climate Change and Hydrologic Models: A Review of Existing Gaps and Recent Research Development, Water resources Management, 13, 369-382.
252. Yang, J., P. Reichert, and K. C. Abbaspour (2007b), Bayesian uncertainty analysis in distributed hydrologic modeling: A case study in the Thur River basin (Switzerland), Water Resour. Res., 43, W10401, doi:10.1029/2006WR005497.
253. Yang, J., Reichert, P., Abbaspour, K.C., Xia, J., and Yang, H. (2008) Comparing uncertainty analysis techniques for a SWAT application to the Chaohe Basin in China, J. of Hydrol. (2008) 358, 1– 23.

254. Yang, J., Reichert, P., Abbaspour, K.C., Yang, H., (2007a). Hydrological modeling of the Chaohe Basin in China: statistical model formulation and Bayesian inference. Journal of Hydrology 340, 167–182.
255. Yıldırım, A.A., Watson, D.D., Tarboton and Wallace, R.M. (2015) A virtual tile approach to raster-based calculations of large digital elevation models in a shared-memory system,Computers & Geosciences, 82: 78-88,http://dx.doi.org/10.1016/j.cageo.2015.05.014.
256. Young, R.A., Onstad, C.A., and Bcscfi, D.D. (1986) Sediment Transport Capacity in Rills and Small Channels, in: Przc. Fourth Federal Interagency Sediment Data, Conf. Subcom, on Sedimentation of =he Interagency Advisory Corn. on Water > Vol 2. Wash. DC, 625-633.
257. Young, R.A., Onstad, C.A., Bosch, D.D. and Anderson, W. P. (1989) AGNPS: A Nonpoint Source Pollution Model for Z'raluating Agricultural Watersheds. JSWC, 44 (2): 168-173.
258. Young, R.A., Onstad, C.A., Bosch, D.D., and Anderson, W.P. (1995) AGNPS: An agricultural nonpoint source model, in Singh V.P. (ed.), Computer Models of Watershed Hydrology: Highlands Ranch, Colorado, Water Resources Publications, pp. 1011-1020.
259. Zhang, W., and Montgomery D.R., (1994) Digital Elevation Model Grid Size, Landscape Representation, and Hydrologic Simulations. Water Resources Research. 30(4), 1019–1028.
260. Zoppou, C. (2001) Review of Urban Storm Water Models, Environmental Modeling and Software, 16(2001), 195-231.

CHAPTER-2

SUBSURFACE WATER MODELING – FLOW AND CONTAMINANT TRANSPORT

2.1 Introduction

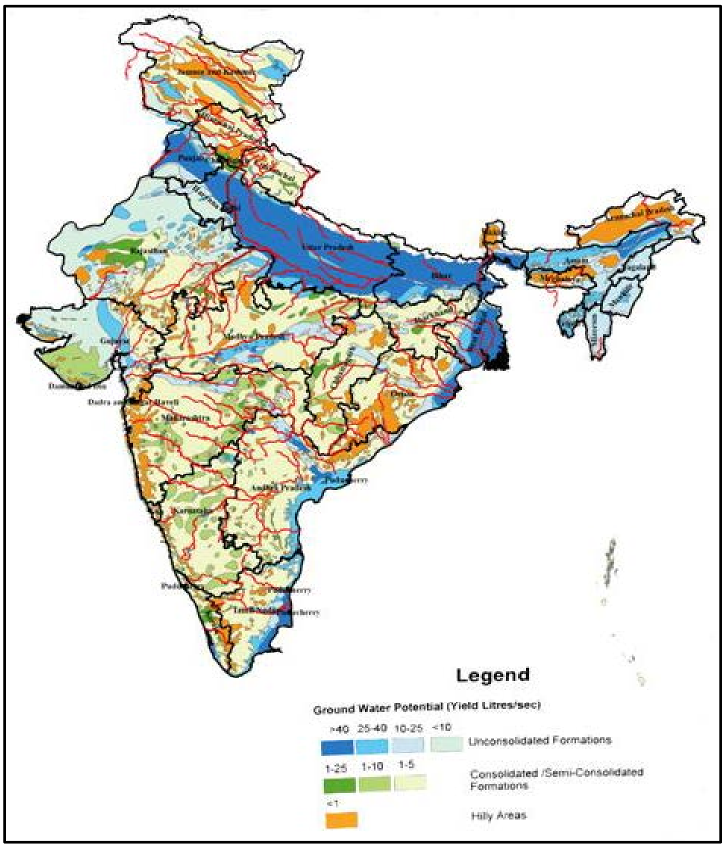
2.1.1 General

Groundwater is an integral part of a complex hydrological cycle that involves the continuous movement of water on earth (Alley et al., 2005). From occurrence as rainfall on earth until it moves out from the land masses, water available on earth as surface water, soil moisture and groundwater, interacts with one other and shapes the space-time distribution of groundwater.

Groundwater as it occurs in various aquifers (defined by their geometry and relationship to topography and the subsurface geology) namely, unconfined, confined, and perched aquifer are under continuous depressurization and expansion of water because of natural processes of recharge, discharge and movement, and extraction (pumping) by human interventions (Winter et al., 2013). The natural processes of groundwater movement that are governed by formational heterogeneity, permeability and potential gradient of flow, is generally slow; while the human interventions to the natural systems not only accelerate the processes but may also mismatch recharge and discharge component as well as geochemical/geo-environmental conditions. Groundwater levels depletion and quality deterioration, in many parts of the world including India, are examples of changing groundwater scenarios. Impact of climate change on groundwater is another emerging issue that poses a new challenge to the supply and demand management of groundwater resources. Groundwater potential plays a supplementary source of water to mitigate drought. Rising demands of, and increasing pressure on, groundwater driven by booming population growth and their allied demands for food and drinking water security pose other challenges on management of space-time availability and demand. These eventually call for the need of scientific tools and techniques, which are process based, robust, less complex, easy to handle, satisfy the hydrogeological settings, capable to simulate responses both local and regional scale with reasonable certainty, and can be used for policy evaluation, drought mitigation and for management of groundwater quality.

2.1.2 Hydrogeological settings of India

India with its varied hydro-geological settings (Fig.2.1) comprising; 12.5% as Himalayan highland province, 15.27% as Ganges-Brahmaputra alluvium province, 14.25% as Alluvium Sandstone composition and Precambrian sedimentary formation, 44.45%as Precambrian Crystalline province, 12.13% as Deccan trap province (Basalt), and 1.4% as Gondwana sedimentary province, of contiguous land areas of 3,188,111 sq. km. (CGWB,2006) supports 85% of rural domestic needs, 50% of urban and industrial needs and about 65% of irrigation water requirements (CGWB, 2011a; Planning Commission, 2011).



Source: CGWB, 2006

Figure 2.1: Hydrogeological map of India with superimposed major river networks

Usages of groundwater in India have increased at a very rapid pace by the advent of tube wells as the groundwater extraction structures. The data of the Minor Irrigation Census conducted in 2001 together with the data compiled by Singh and Singh (2002) showed enormous growth of groundwater structures, about 18.5 million in 2001. Many people predicted (Shah, 2009) that by 2009, the number of groundwater structures might have gone up to 27 million. There is no reason to believe that the growth of groundwater structures and uses of groundwater in India are going to slow down in future, unless otherwise controlled by enforcing legislation, rather will continue to rise because of growing concern on water quality, socio-economic improvement and socio-cultural dimensions of the rural sector. With such huge number of groundwater abstraction structures and nearly 62% status of groundwater development (CGWB, 2014), India is placed now the largest groundwater user in the World (Shah, 2009). These intervening characteristics have put India's groundwater systems into a number of challenges, which include: (i) depletion of aquifer storage and groundwater levels, and their effects on availability, terrestrial and aquatic ecosystems, (ii) drying up of shallow wells, intensification of deep tube wells, and failure of tube wells in hard and fractured rock areas, (iii) deteriorating groundwater quality due to contaminants of geogenic origin (Arsenic, Fluoride, Iron, etc.) and intrinsic salinity, (iv) leaching of contaminants from anthropogenic activities (both organic and inorganic constituents),(v) groundwater salinization arising from various different processes of induced hydraulic disturbance and soil fractionation,(vi) changes of geochemical properties due to geological minerals mining and mineralization, (vi) threat of saline water ingress in coastal aquifers, etc.

Climate change impact on groundwater is an added complexity. Many areas in India are prone to hydro-meteorological drought. In the context of climate change, the severity of drought may increase. Groundwater planning and management in those areas would play a vital role for drought mitigation. Groundwater management in the hard and fractured rock areas possess a lot of uncertainty and has emerged as a big challenge to the stakeholders and policy makers.

2.1.3 Rainfall and groundwater resources of India

Alike varied hydrogeological provinces, India has wide variability of climatic conditions and hydrometeorology. The country has uneven spatial and temporal distribution of rainfall. The annual spatial variation of rainfall [based on data of 193 years (1813-2005)] showed variation ranged from less than 100 mm over parts of Ladakh (Jammu & Kashmir State) and Jaisalmer district (Rajasthan State) to less than 400 mm over central peninsula, between 1000 mm and 1788.4 mm over central highlands and eastern plateau, between 1000 mm and 11405.8 mm over northeast, and between 1000 mm and 7445.7 mm over Sahyadri range (Ranade et al., 2007). The temporal distribution has characteristics of both seasonal and annual variation. The annual variation of rainfall (1813-2005) ranged between 730.14 mm and 1487.05 mm with the mean annual for the whole country as 1165.9 mm, whose seasonality varied: 0.7% during winter, 9% during summer, 77.4% during monsoon, and 12.9% during post-monsoon (Guhathakurta and Rajeevan, 2006; Ranade et al., 2007).

India’s groundwater resources are primarily rainfall recharge driven. The annual dynamic (replenish annually) groundwater resources, as per the estimate of 2011 (CGWB, 2014), was 433 BCM (billion cubic meter or km^3), of which net available groundwater was 398 BCM, and annual draft for irrigation, domestic and industrial uses was 245 BCM that indicated an average stage of development as 62%. The availability and draft of groundwater are highly uneven; while availability is primarily characterized by rainfall, hydrology, hydrogeology, and surface and sub-surface interaction of water; on the other hand, groundwater draft is governed by availability and demands for various sectoral uses. Uses of groundwater conversely depend on usage and groundwater withdrawal infrastructural facilities available to the users.

2.1.4 Groundwater related issues in India

India is primarily an agro-economic based country and currently, 90.73% of groundwater usages are done for irrigation purposes (CGWB, 2014). Projection showed (Kumar et al., 2005) that by 2025 and 2050, groundwater based irrigation requirements may increase, respectively, by 11% and 38.5% over the withdrawal of 222 km^3 (BCM) in year 2010; while the total groundwater requirements for different sectoral uses may increase by 17% and 50%over the total withdrawal of 245 km^3 in year 2010. It means, there could be a possibility of equalizing groundwater demands with net availability, if no other impinging issues like climate change, impact the groundwater resources. The situation of groundwater resource prospects pronounces more challenging, when risk emerging from groundwater quality deterioration due to anthropogenic (leaching of both organic and inorganic contaminants from surface activities) and geogenic (Arsenic, Fluoride, Iron, Salinity, etc.) sources of contaminants is linked to the quantity of fresh water available. Over exploitation beyond the safe limit of withdrawal (70 % of annual replenishable quantity) together with the quality deterioration of groundwater is given/giving rise to a number of conflicting issues amongst the groundwater stakeholders, which include; increasing energy cost for withdrawal of groundwater, base flow reduction, abandoning of wells due to influence of contaminants, influences of multiple wells in close proximity of freshwater zones, livelihood problem of small farmers due to scarcity of groundwater, etc. On the other hand, in areas or a region likely to face hydro-meteorological drought, how groundwater particularly the static sources, can sustainably support demands of domestic and agricultural sector, is another issue that needs to be addressed by management strategy derived from mathematical modeling.

India has a long coastline of about 7500 km, of which about 5400 km belongs to peninsular India and the remaining to the Andaman, Nicobar and Lakshadweep Islands. The Country houses more than 63 million people living in low elevation coastal areas (land area 82,000 km^2 that constitutes about 3% of India's land area) and nearly 250 million people living within 50 km of the coastline (NIH, 2014). The coastal zones also provide sites for productive agriculture, export-processing zones, industries, harbours, airports, land ports, and tourism. Coastal aquifers are vital strategic resources that provide and supplement the demand for freshwater. Due to excessive groundwater withdrawals, a number of coastal stretches, viz. Minjur coast in Tamilnadu, a long stretch in Odisha, Saurashtra region in Gujarat, Sunderbans in West Bengal are under threat of ingress of sea water intrusion.

According to many experts (Tuinhof and Heederik, 2003; Zektser and Everett, 2004; Planning Commission, 2007; Siebertet al., 2010; Vijay Shankar et al., 2011; Gardunu et al., 2011) groundwater scarcity, depletion of water table and contamination of groundwater problems worldwide, including India, are not only because of limiting availability of groundwater resource but due to unscientific and haphazard extractions, lack of understanding of aquifer characteristics and management of groundwater, which got triggered by a number of unresolved cross-cutting issues.

As a step towards revival of depleted groundwater table, augmentation of groundwater resource in water scarce areas and dilution of contaminated aquifers, Government of India (CGWB, 2002; 2011b; 2013) together with State governments, as a countrywide program, is promoting artificial groundwater recharge by rainwater harvesting and conservation of monsoon surface runoffs. Artificial recharge basically addresses groundwater supply augmentation by recharge management. However, the groundwater problem resolving issue seems to remain unresolved, unless and until the demand-side (groundwater discharge) management is also taken up simultaneously.

Supply-side and demand-side management together with groundwater quality can effectively be managed when a sufficient understanding about groundwater systems, aquifers geometry and hydraulic properties are adequately known. The concept, based on which the groundwater availability and movement has been developed, is the 'Elementary Representative Volume (ERV)' (Bear, 1972). The application of idealized concept of groundwater theory to aquifers having heterogeneity and antistrophic properties/characteristics of materials, which a real-life groundwater system generally possesses, poses the primary challenges in defining a groundwater system. The tasks become further challenging when the aquifer databases are inadequate and a regional groundwater management plan is derived based on those scarce databases.

2.1.5 How modeling can help groundwater management?

To meet the goal of increasing demand of groundwater, modeling and management should go side by side. Groundwater Modeling is an efficient scientific tool, for management of resource that provides the framework to decide and predict the fate of decision variables, which are expected from a hydrogeological system (Ghosh and Sharma, 2006). Groundwater models are developed based on conceptual descriptions or approximations of physical systems or processes, which are translated into well-posed mathematical equations. The mathematical representation converts the physical system into the conceptual framework of computation through mathematical variables that helps perform the job of simulation and scenarios development for imposed stresses and/or strains without physically intervening into the system (Bear, 1972; 1979; Bear et al., 1992). In other words, a groundwater model is a simplified version of a groundwater system that approximately simulates the relevant excitation-response relations of a system. The simplification is introduced by a set of assumptions, which expresses the nature of the system, their features, and behaviors, which are relevant to the problem under investigation. Therefore, no model can be said to be unique for all hydrogeological setups and conditions.

2.1.6 Issues related to modeling

Numerous numerical groundwater models have been developed in the past and applied for groundwater modeling with different degrees of success. Some of those, viz. MODFLOW coupled with MT3D, or its various forms of development, have wide acceptability amongst groundwater professionals. In India, groundwater modeling, using either MODFLOW or its various forms or by using self developed source codes, has also gained popularity. However, a lot of uncertainty in model setups and predictions has been reported owing to scale effects in regionalization of hydraulic properties derived from scarce data. These uncertainties, many a times, have posed questions about efficacy of using available numerical models and modeling tools. Whether the existing widely accepted numerical models are adequate to apply in India’s complex hydrogeological setups with the available databases or there is a need to modify components of the existing models by integrating site-specific hydrological modules, or there is a necessity to develop altogether a separate model code to satisfy the hydrogeological conditions and requirements of India’s groundwater professionals. The subsequent sections bring out a critical appraisal on existing groundwater models, their capabilities, scope of using in India’s hydrogeological contexts, modification/improvement needed to reduce uncertainty in predictions, etc.

2.1.7 Modeling as the management tool

Use of groundwater models should not remain in the framework of model building, calibration and validation based on historical data; it should go beyond, as a tool for decision support system, for policy evaluation based on different management scenarios, and depicting the results in such a way that field professionals could interpret those as the decision variables. This is possible by coupling Simulation-Optimization models together with an interfaced platform based on demand driven decision support system for depicting results in different modes viz. graphs, thematic maps and tabular forms. These eventually call for development of a comprehensive integrated modeling tool, which is user friendly; process based and can navigate with advanced tools.

2.2 Subsurface Modeling

2.2.1 General

The sub-surface water system comprises two zones; the zone above the groundwater table called unsaturated zone or vadose zone, and the zone below the groundwater table called saturated zone (Fig. 2.2). In the vadose zone, the inter-granular space is partly filled with water; the remaining space is occupied by air. The zone of saturation is saturated by water. The unconfined aquifer represents the upper surface of the zone of saturation, which varies depending on recharge and discharge. The zone of aeration is further sub-divided into three categories from top to bottom; i.e., soil water zone, intermediate vadose zone and capillary zone (Fig. 2.2). There is no sharp boundary between these zones.

Unlike the saturated zone, the unsaturated zone is a source of readily available water for human consumption. It is of great importance in providing water, nutrients and contaminants to the saturated zone. Hydrologically, the unsaturated zone is often the main factor that controls water movement from land surface to aquifer. Thus, it strongly affects the rate of recharge and the transport of nutrients and contaminants to the saturated zone. It is often regarded as a filter that removes undesirable substances. To some extent this is true, but a more general fact is that flow rates and chemical reactions in the unsaturated zone control the fate of contaminants enter into the aquifer. Understanding of unsaturated-zone processes is crucial in determining the amount and quality of groundwater that is available for human use.

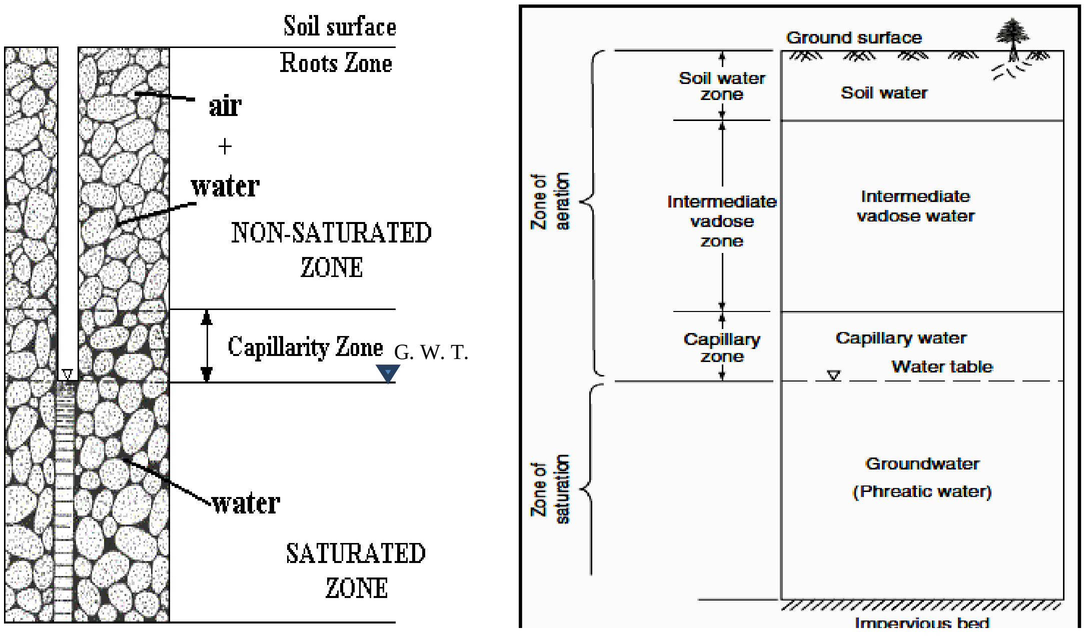


Figure 2.2: Classification of subsurface water

Groundwater may occur under confined, unconfined and semi-confined conditions.

The top aquifer that receives direct recharge from rainfall is the unconfined aquifer. In alluvial areas, confined and unconfined aquifers may be separated by clay or silty clay layers. Such clay layers may vary from few meters to several kilometres. Sometimes the confined and unconfined aquifers may be separated by clayey sand, silty sand or sandy loam that forms semi-confined conditions. The confined or semi-confined aquifers may be under unconfined conditions in some upper reaches. In hard rock areas, unconfined aquifers are formed from the weathering or deposition of rock materials. In these areas, groundwater occurs in fractures and fissured conditions, and under confined conditions depending on the type of formations.

2.2.2 Issues Related to sub-surface zone Modeling

The occurrence and movement of groundwater, both in terms of quantity and quality, in different aquifer systems (coastal, hard-rock, arid, semi-arid, etc.) are controlled by the local or regional physiographic, hydrology and subsurface geology and the forcing interventions onto the aquifers. Numerous spatiotemporal variables such as; aquifer parameters, recharge and discharge govern the flow and transport processes of sub-surface system.

The occurrence and movement of groundwater is not local. The localized or point scale estimation of groundwater system's response may cause erroneous results. A complete water balance approach, by following the governing laws of groundwater flow with initial and boundary conditions, is necessary to accurately estimate the responses of aquifer system. Analysis of groundwater systems is necessary to supplement the decision variables. Groundwater modeling provides a framework to decide and predict the fate of decision variables. Groundwater model tools help simulate current groundwater behaviour and predict future groundwater scenarios. Models analyze and predict the behaviour of aquifer systems representing varying hydro-geological settings on local and regional scale. Mathematical modeling tools provide a quantitative framework for visualization, analyzing data and quantitative assessment of system's response subjected to various internal and external forcing functions. The sub-surface water modeling is required to address the following main purposes:

- For evaluation of groundwater quantity and quality based on present and future developmental activities;
- Impact of proposed waste-disposal activities;
- Planning, design and evaluation of remediation strategies for both quantity and quality of groundwater;
- Assessment of transport of pollutants;
- Assessing and control of sea water intrusion in coastal aquifers;
- Reclaiming water logging and salinity problem by providing the subsurface drainage system;
- Optimization of existing and future groundwater monitoring system;
- Controlling groundwater level depletion and managed aquifer recharge;
- Studying river-aquifer interaction and enhancing base flow contribution to rivers and streams;

- Studying effect of channel on groundwater flow and chemical quality;
- For long-term risk assessment and management;
- Assessment of overall environmental impacts.

Water resource evaluation often involves an integrated analysis of groundwater and surface water conditions. Examples of questions generating a need for a modeling evaluation of surface water and groundwater interactions include (Varda et al., 2002):

- How will a transfer or new use of groundwater affect existing water uses on a stream system? (or, how will transfer of surface water uses impact present groundwater conditions?)
- How re-engineering of stream hydrograph impact groundwater elevations in the riparian zone?
- How will channel restoration activities change stream gains/losses and resulting shallow groundwater conditions?
- How will scheduling of groundwater use under a drought management plan impact base flows in a stream at present, and into future years, as lagged impacts?

The perfect analysis of an aquifer environment and its processes depend on one of the following four aspects and the method of modeling (Balasubramanian, 2001):

- Analysis pertaining to groundwater occurrence and flow, sources of recharge - discharge and their impacts (single phase or multi-phase; steady or transient groundwater flow models).
- Analysis of dispersal, mobility and distribution of solutes (contaminants) in groundwater systems (chemical mass or solute; steady or transient transport models).
- Analysis of the mechanisms of rock-water geochemical interactions controlling the distribution of solute species (aqueous geochemical models).
- Analysis of salinity intrusions in the complex coastal ecosystems (saltwater intrusion; steady or transient; sharp or dispersed interface models).

Each one of these, require careful application of unique numerical principles, typical databases and complicated solution strategies. Despite these challenges, attempts have been made so far by several eminent workers in using the mathematical models for various field problems and laboratory applications.

2.2.3 What Groundwater models can do?

A groundwater model can have two distinct components: (i) flow component, and (ii) contaminant transport and reactive reactions component. Groundwater flow and contaminant transport modeling together play an important role in characterization of groundwater bodies and management of groundwater. A groundwater flow modeling is a pre-requisite for developing a contaminant transport model of an area of interest, but *vice-versa* is not true. A groundwater flow model can provide a quantitative assessment of resources along with the following components: (i) estimating groundwater recharge, discharge, and storage at spatial scale; (ii) assessing the cumulative effects on existing and proposed water resources uses and developments; and (iii) evaluating the cumulative impacts on water resources due to various water management options. A groundwater contaminant transport model, however, assists in predicting the transportation or movement of dissolved constituents including their chemical reactions in groundwater and soil matrices.

For management of a groundwater system, a thorough understanding of the physical, chemical and biological processes in integrated environment is vital and modeling is a very effective tool to answer the system's response. Groundwater flow models provide valuable information on the occurrence, movement and flow of groundwater by integrating various inputs, outputs and storage parameters for a local or regional scale by solving specific problems like:

- Estimation of groundwater balance components, regional inflow and outflow patterns of groundwater, interaction with neighbouring water bodies;
- Changes in aquifer recharge pattern due to urbanization; changes resulting from irrigation return flow and canal seepage; long-term climatologically changes in piezometric levels and impacts of anthropogenic changes;
- Regional parameter estimation using inverse modeling;
- Estimation of groundwater withdrawal patterns and impacts on base flow contribution of rivers and streams;
- Prediction and movement of saline water interface;
- Estimation of seepage velocities for control of transport of pollutants;
- Management of groundwater resources and future development;
- Assessment of feasibility of conjunctive use.

Earlier models were concentrated on the analysis of flow behaviour in groundwater systems, whereas the recent attempts aim at addressing the water quality problems and simulate the transport contaminants in groundwater. Even though, there has been significant development in modeling tools and techniques, however, scientific challenges exist, as the credibility of field level application of the models have to be ascertained due to the existence of uncertainty in the conceptualization of boundary conditions, aquifer heterogeneity, natural recharge and others (Mohan, 2001).

2.3 Unsaturated/Vadose Zone Modeling

2.3.1 General

Various processes occurring within the unsaturated zone play a major role in determining the quality and quantity of water recharge to the groundwater. A quantitative analysis of water flow and contaminant transport in the unsaturated zone is a key factor in the improvement and protection of the quality of groundwater supplies.

2.3.2 Governing equations of water and transport in unsaturated soils

Analytical, semi-analytical, and numerical models are used for unsaturated zone modeling. These are usually based on the following three governing equations for water flow, solute transport, and heat movement, respectively:

$$\frac{\partial \theta(h)}{\partial t} = \frac{\partial}{\partial z}\left[K(h)\left(\frac{\partial h}{\partial z} + 1\right)\right] - S \quad \text{... (2.1)}$$

$$\frac{\partial \theta R c}{\partial t} = \frac{\partial}{\partial z}\left[\theta D\left(\frac{\partial c}{\partial z}\right) - qc\right] - \emptyset \quad \text{... (2.2)}$$

$$\frac{\partial C(\theta) T}{\partial t} = \frac{\partial}{\partial z}\left[\lambda(\theta)\left(\frac{\partial T}{\partial z}\right) - C_w q T\right] \quad \text{... (2.3)}$$

Suitable simplifications (mostly for analytical approaches) or extensions thereof (e.g. for two- and three-dimensional systems) are also employed. In equation (2.1), often referred to as the Richards equation, z is the vertical coordinate positive upwards, t is time, h is the pressure head, θ is the water content, S is a sink term representing root water uptake or some other sources or sinks, and $K(h)$ is the unsaturated hydraulic conductivity function, often given as the product of the relative hydraulic conductivity, K_r, and the saturated hydraulic conductivity, K_s. In equation (2.2), known as the *convection-dispersion equation* (CDE), c is the solution concentration, R is the retardation factor that accounts for adsorption, D is the dispersion coefficient accounting for both molecular diffusion and hydrodynamic dispersion, q is the volumetric fluid flux density, and Φ is a sink/source term that accounts for various zero- and first order or other reactions. In equation (2.3), T is temperature, λ is the apparent thermal conductivity, and C and C_w are the volumetric heat capacities of the soil and the liquid phase, respectively.

Solutions of the Richards equation (2.1) require knowledge of the unsaturated soil hydraulic functions, that is, the soil water retention curve, $\theta(h)$, describing the relationship between the water content θ and the pressure head h, and the unsaturated hydraulic conductivity function, $K(h)$, defining the hydraulic conductivity K as a function of h or θ. While under certain conditions (i.e. for linear sorption, a concentration-independent sink term Φ, and a steady flow field) equations (2.2) & (2.3) are linear equations; equation (2.1) is generally highly nonlinear because of the nonlinearity of the soil hydraulic properties. Consequently, many analytical solutions have been derived in the past for equations (2.2) and (2.3) and these analytical solutions are now widely used for analyzing solute and heat transport under steady-state conditions. Although a large number of analytical solutions of (2.1) exist, they can generally be applied only to drastically simplified problems. The majority of applications for water flow in the vadose zone require a numerical solution of the Richards equation.

2.3.3 Input data for unsaturated zone modeling

Simulation of water dynamics in the unsaturated zones requires input data concerning the model parameters, the geometry of the system, the boundary conditions and, when simulating transient flow, initial conditions. With geometry parameters, the dimensions of the problem domain are defined. With the physical parameters, the physical properties of the system under consideration are described. With respect to the unsaturated zone, it concerns the soil water characteristic, $h(\theta)$ and the hydraulic conductivity, $K(\theta)$.

To model the retention, movement of water and chemicals in the unsaturated zone, it is necessary to know the relationships between soil water pressure, water content and hydraulic conductivity. It is often convenient to represent these functions by means of relatively simple parametric expressions. The problem of characterizing the soil hydraulic properties then reduces to estimating parameters of the appropriate constitutive model. The measurements of $\theta(h)$ from soil cores (obtained through pressure plate apparatus) can be fitted to the desired soil water retention model. Once the retention function is estimated, the hydraulic conductivity relation, K(h), can be evaluated if the saturated hydraulic conductivity, K_s, is known. A number of models for water retention function and unsaturated hydraulic conductivity are well reported in literature, one of the most popular being van Genuchten model. For the van Genuchten (1980) model, the water retention function is given by

$$S_e = (\theta - \theta_r)/(\theta_s - \theta_r) = [\,1 + (\alpha_v |h|\,)^n\,]^{-m} \quad \text{for } h < 0$$

$$= 1 \qquad \text{for } h \geq 0 \qquad \ldots \qquad (2.4)$$

and the hydraulic conductivity function is described by

$$K = K_s\, S_e^{1/2}\, [1 - (1 - S_e^{1/m})^m]^2 \qquad \ldots \qquad (2.5)$$

where α_v and n are van Genuchten model parameters, m = 1 – 1/n, subscript s refers to saturation, i.e. the value of $\theta$for which h = 0, and the subscript r to residual water content.

The number and type of parameters required for modeling flow and transport processes in soils depend on the type of model chosen. These parameters can be categorized as control parameters (controlling the operation of the computer code), discretization data (grid and time stepping), and material parameters. The material parameters can be grouped in seven sets (Jury and Valentine, 1986) – static soil properties, water transport and retention functions, time-dependent parameters, basic chemical properties, contaminant source characteristics, soil adsorption parameters, and tortuosity functions. Table 2.1 lists many of the relevant material model parameters.

Table 2.1 Selected Material Parameters for Flow and Transport Modeling

Model Parameters		
Static Soil Properties **Porosity** Bulk Density Particle Size Specific Surface Area Organic Carbon Content Cation Exchange Capacity pH Soil Temperature	***Flow and Transport Variables and Properties*** Saturated Hydraulic Conductivity Saturated Water Content Moisture Retention Function Hydraulic Conductivity Function Dispersion Coefficient	***Basic Chemical Properties*** Molecular Weight Vapour Pressure Water Solubility Henry's Constant Vapour Diffusion Coeff.in air Liquid Diffusion Coeff.in water Half-life or decay Rate Hydrolysis Rate (s)
Time Dependent Parameters Water Content Water Flux Infiltration Rate Evaporation Rate Solute Concentration Solute Flux Solute velocity Air Entry Pressure Head Volatization Flux	***Contaminant Source Characteristics*** Solute Concentration of Source Solute Flux of Source Source Decay Rate ***Soil Adsorption Parameters*** Distribution Coefficient Isotherm Parameters Organic Carbon Partition Coefficient ***Tortuosity Functions*** Vapour Diffusion Tortuosity Liquid Diffusion Tortuosity	

2.3.4 Modeling of unsaturated Flow

Analytical solutions to the Richards equation for unsaturated flow under various boundary and initial conditions are difficult to obtain because of the nonlinearity in soil hydraulic parameters as well as governing equation. This difficulty is exaggerated when soil is heterogeneous. Generally, one has to rely on numerical approaches for predicting moisture movement in unsaturated soils, even for homogeneous soils. However, numerical approaches often suffer from convergence and mass balance problems. The nonlinearity of Richards equation is usually solved using an iterative procedure such as Newton or Picard methods. Perhaps the most important advantage of finite element techniques over standard finite difference methods is the ability to describe irregular system boundaries in simulations more accurately, as well as easily including non-homogeneous medium properties.

To numerically solve coupled systems of equations, the solution process requires some manipulation at each time step so that the dependence of one equation on the solution of the other is dealt with accurately. One way to overcome this is to use a fully implicit approach to solve the equations simultaneously. Any nonlinearity of the generated system can be handled by Newton’s method. The implicit nature of this scheme allows for larger time steps in simulation to find stable solutions compared to the time steps for explicit schemes. An alternative to the fully implicit scheme is to use the mixed implicit-explicit scheme. However, the explicit part of the scheme means that the algorithm is subject to a stability constraint which severely restricts the time step size and introduces numerical artefacts.

Initial and Boundary Conditions

Initial conditions must be defined when transient soil water flow is modeled. Usually values of matric head or soil water content at each nodal point within the soil profile are required. When these data are not available, water contents at field capacity or those in equilibrium with the ground water table might be considered as the initial ones.

While the potential evapotranspiration rate from a soil depends on crop and atmospheric conditions, the actual flux through the soil surface and the plants is limited by the ability of the soil matrix to transport water. Similarly, if the potential rate of infiltration exceeds the infiltration capacity of the soil, part of the water runs off, since the actual flux through the top layer is limited by moisture conditions in the soil. Consequently, the exact boundary conditions at the soil surface cannot be estimated a priori and solutions must be found by maximizing the absolute flux. The minimum allowed pressure head at the soil surface, h^{lim} (time dependent) can be determined from equilibrium conditions between soil water and atmospheric vapour. The possible effect of ponding has been neglected so far. In case of ponding, usually the height of the ponded water as a function of time is given. However, when the soil surface is at saturation then the problem is to define the depth in the soil profile where the transition from saturation to partial saturation occurs.

In most of the dynamic transient models, the surface nodal point is treated during the first iteration as a prescribed flux boundary and matric head h is computed. If $h^{lim} \leq h \leq 0$, the upper boundary condition remains a flux boundary during the whole iteration. If not, the surface nodal point is treated as a prescribed pressure head in the following iteration. Then in case of infiltration, h = 0 and in case of evaporation $h = h^{lim}$. The actual flux is then calculated explicitly and is subject to the condition that actual upward flux through the soil-air interface is less than or equal to potential evapotranspiration(time dependent).

At the lower boundary, one can define three different types of conditions: (a) Dirichlet condition, the pressure head is specified; (b) Neumann condition, the flux is specified; and (c) Cauchy condition, the flux is a function of a dependent variable. The phreatic surface (place, where matric head is atmospheric) is usually taken as lower boundary of the unsaturated zone in the case where recorded water table fluctuations are known a priori. Then the flux through the bottom of the system can be calculated. In regions with a very deep ground water table, a Neumann type of boundary condition is used.

Evapotranspiration (water extraction by roots)

In the field, steady-state conditions hardly exist. The living root system is dynamic (dying roots are constantly replaced by new ones), geometry is time dependent, water permeability varies with position along the root and with time. Root water uptake is most effective in young root material, but the length of young roots is not directly related to total root length. In addition, experimental evaluation of root properties is hardly practical, and often impossible. Thus, instead of considering water flow to single roots, a more suitable approach might be the macroscopic one, in which a sink term S representing water extraction by a homogeneous and isotropic element of the root system (volume of water per volume of soil per unit of time) is added to the conservation of mass equation. As it seems to be impossible and unpractical to look for a complete physical description of water extraction by roots, Feddes et al. (1988) described S semi-empirically by:

$$S(h_m) = \alpha(h_m)\, S_{max} \quad \text{... (2.6)}$$

where $\alpha(h_m)$ is a dimensionless prescribed function of pressure head and S_{max} is the maximal possible water extraction by roots. In the interest of practicality, a homogeneous root distribution can be assumed over the soil profile and define S_{max} according to

$$S_{max} = \frac{T_p}{|Z_r|} \quad \text{... (2.7)}$$

where T_p is the potential transpiration rate and $|Z_r|$ is the depth of the root zone.

Groundwater Recharge

There are two types of unsaturated zone (or soil-water) models which can be used for groundwater recharge estimation.

1. Water-balance models
2. Numerical models based on the Richards equation

The literature about practical applications of various types of models for assessing groundwater recharge is limited and does not contain straightforward recommendations about which type of model should be used under different conditions. It is commonly considered that Richards equation-based models are the most theoretically proven and allow to represent flow processes in the porous medium more realistically than water-balance models.

However, large-scale applications of Richards equation-based models to highly heterogeneous soils with variable hydraulic properties can be difficult and expensive.

A number of studies have used numerical models to solve Richards' equation for assessing groundwater recharge. A review of previous studies indicates that unit-gradient and fixed water table lower boundary conditions have been applied to models of both constant and variable vertical grid spacing (discretization). It is also reported that whenever the unsaturated flow modeling approach is used to estimate groundwater recharge, a fixed-head lower boundary condition should be selected because it also allows upward flux from the water table during dry periods, a situation that prevails on both sub-humid and semi-arid areas, where accurate groundwater recharge estimates are needed the most. The use of a fixed water table is a simple representation of the regional water table, which in reality interacts with the regional groundwater flow and surface water bodies (e.g., lakes and wetlands).

The use of a variable discretization at the points where both the wetting and drying fronts fluctuate (i.e., top and bottom of soil columns) improve simulation efficiency for the nonlinear unsaturated flow regime. The adequate selection of discretization and boundary conditions, which affect the simulation time, is of utmost importance when a large number of simulations is required (e.g., analysis of climate change scenarios).

2.3.5 Modeling of solute transport through unsaturated zone

Transport of dissolved solutes in soils is commonly described by the advection-dispersion equation. Prediction of solute migration under field conditions requires the simultaneous solution of the unsaturated flow and solute transport equations. First approximations involve or assume steady flow and constant water contents. Because of the natural complexity of unsaturated flow, methods of predicting solute transport have relied largely on finite difference or finite element approximations of the governing equations.

One of the distinctive features of the porous media on the field scale is the spatial heterogeneity of transport properties. These features have a distinct effect on the spatial distribution of contaminant concentration, as has been observed in field experiments and demonstrated by simulation of contaminant transport in unsaturated, heterogeneous soil. Description of the mixing process due to spatial variability of the unsaturated hydraulic conductivity has been advanced with the development of numerical solutions, which assume spatially variable soil properties; stochastic models; and stochastic stream tube models, which decompose the field into a set of independent vertical soil columns.

2.3.6 Unsaturated zone modeling software

Most of the early models developed for studying processes in the near-surface environment mainly focused on variably saturated water flow. They were used primarily in agricultural research for optimizing moisture conditions to increase crop production. This focus has gradually shifted to environmental research, with the primary concern now being the subsurface fate and transport of various agricultural and other contaminants. While the earlier models solved the governing equations (1) through (3) for relatively simplified system-independent boundary conditions (i.e. specified pressure heads or fluxes, and free drainage), models developed recently can cope with much more complex system-dependent boundary conditions evaluating surface flow and energy balances and accounting for the simultaneous movement of water, vapor, and heat. There are also composite models which simulate the processes both in unsaturated and saturated zones and other components of hydrological cycle. A few widely used unsaturated flow and composite models have been listed in Table 2.2.

Table 2.2 Numerical Models for Simulating Unsaturated Flow and Solute Transport

S.No.	Modeling Software	Salient Features
		Unsaturated Flow Models
1.	HYDRUS-1D	Public domain Modeling environment for analysis of water flow and solute transport; includes the one-dimensional finite element model HYDRUS for simulating the movement of water, heat, and multiple solutes in variably saturated media; supported by an interactive graphics-based interface for data-preprocessing, discretization of the soil profile, and graphic presentation of the results.
2.	HYDRUS 2D/3D	Software package for simulating water, heat, and solute movement in two- and three-dimensional variably saturated media; consists of a computational computer program and an interactive graphics-based user interface.
3.	R-UNSAT	USGS computer model for the simulation of reactive, multispecies transport in a heterogeneous, variably-saturated porous media; designed for simulating transport of volatile organic compounds in the unsaturated zone from point and nonpoint sources; can also be applied to other unsaturated-zone transport problems involving gas diffusion, such as radon migration and the deposition of compounds from the atmosphere to shallow groundwater.
4.	SWIM	A mechanistically-based model designed to address soil water and solute balance issues in unsaturated zone.
5.	UNSAT SUITE	Handle one-dimensional groundwater flow and contaminant transport in the unsaturated zone; simulates the downward vertical flow of groundwater and migration of dissolved contaminants in the groundwater through a thin column of soil.
6.	VS2DI	USGS graphical software package for simulating fluid flow and solute or energy transport in variably saturated porous media.
Composite Models		
7.	FEFLOW	Commercial software based on the finite element method for simulation of saturated and unsaturated flow, transport of mass (multiple solutes) and heat, with integrated GUI.
8.	HydroGeoSphere	Commercial three-dimensional control-volume finite element simulator designed to simulate the entire terrestrial portion of the hydrologic cycle; uses a globally-implicit approach to simultaneously solve the 2D diffusive-wave equation and the 3D form of Richards' equation.
9.	MIKE SHE	Commercial software for integrated catchment Modeling, with integrated GUI; uses the finite difference method for saturated groundwater flow, several representations of unsaturated flow, including the 1D Richards equation, MIKE 11 for flow in river and stream networks and the 2D diffusive-wave approach for overland flow.

S.No.	Modeling Software	Salient Features
10.	MODFLOW-SURFACT	Commercial software for simulation of saturated and unsaturated flow and solute transport: developed to overcome specific limitations in open source versions of MODFLOW and MT3D: also available in an extended form called MODHMS, which includes 2D diffusive wave simulation of overland flow and 1D simulation of flow in river and stream networks.
11.	SUTRA	Open source USGS software based on the finite element method for simulation of saturated and unsaturated flow, transport of mass and heat. It has been designed for density-coupled flow and transport.

2.3.7 Concluding remarks

Predicting water flow and contaminant transport on a field-scale based on the current monitoring and modeling techniques is a challenging task. There are large uncertainties in predictions mainly due to our inability to depict detailed spatial distributions of soil hydraulic properties on the field-scale. Due to the high costs of data acquisition, few field measurements are usually available for characterization of flow and contaminant transport, even though the spatial distribution of a contaminant plume may be highly irregular. Also, more research associated with water flow and contaminant transport in the unsaturated zone of aquifers containing fractures and karstic conduits is needed for future investigations.

2.4 Groundwater Modeling Process

2.4.1 General

Groundwater modeling is an integrative process. Therefore, the modeling team should possess a range of skills and broad knowledge of hydrogeology, groundwater flow processes, mathematical equations describing groundwater flow and solute movement, numerical and analytical methods for solving the governing equations, geo-statistics, and parameter estimation. For many modeling projects, expertise in bio- and geochemical reactions, subsidence, geologic modeling, and optimization may also be required.

2.4.2 Steps associated in modeling

Groundwater modeling studies (with the use of groundwater models) are very effective in understanding the nature and extent of groundwater regimes, and to arrive at feasible solutions to complex problems involving groundwater resource development, aquifer contamination, aquifer management as well as sustainability of aquifer systems. Here, we refer to groundwater models as mathematical models based on governing equations of groundwater flow (saturated / unsaturated flow as well as constant density / variable density), contaminant transport (non-reactive/ reactive and miscible/ immiscible), heat transport, as well as multiphase flows. Various advanced numerical techniques are being utilized to facilitate solving the model equations (which are differential equations that can be solved only by approximate methods using a numerical analysis) at various nodes in the domain. Since the computations in mathematical groundwater models are based on numerical techniques, these models are often called numerical or computational groundwater models.

Fig.2.3 presents the flow chart of any modeling endeavour. Here, the first stage is planning that involves identifying the intended use of the model, modeling objectives, and the type of model needed to meet the project objectives. The next stage focuses on conceptualization or formulation of the conceptual model that describes the known physical features and groundwater flow processes within the area of interest. Under the design stage, it is decided how to best represent the conceptual model using a mathematical model. Model construction is the implementation of model design by defining the inputs for the selected model including the boundary conditions. The calibration and sensitivity analysis of the model occurs through a process of matching model outputs to a historical record of observed data. In some cases, model calibration is not necessary, e.g. when using a model to test a conceptual model. Model validation is the process of testing the calibrated model by demonstrating that it can successfully predict a set of observations not used previously for model calibration. Field data collection that occurs during model development may require updates to both the conceptual and mathematical models. If significant effort has been expended on mathematical modeling, additional data may require re-calibration and re-validation. Model application or predictions comprise those model simulations that provide the outputs to address the questions defined in the modeling objectives. The predictive analysis is followed by an analysis of the implications of the uncertainty associated with the modeling outputs.

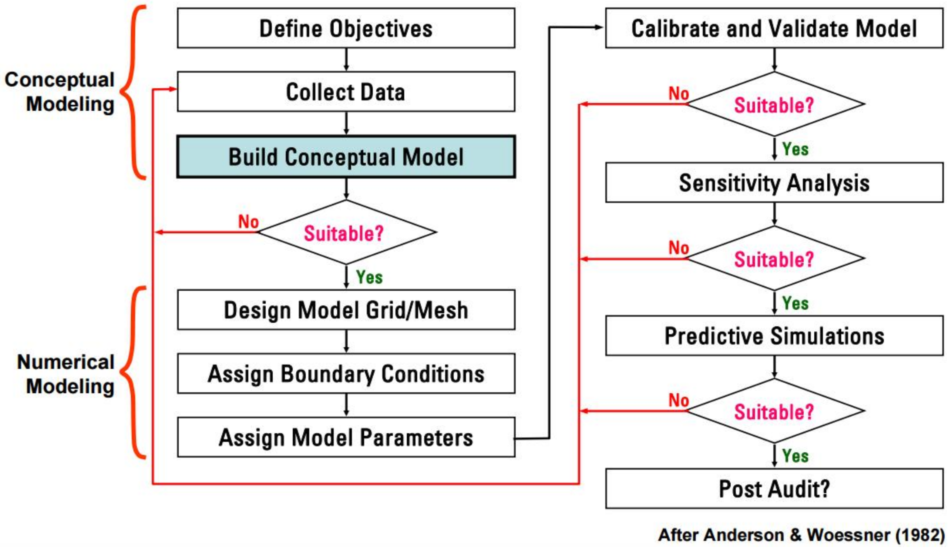


Figure 2.3: Flow chart of modeling endeavour

Most groundwater models in use today are deterministic mathematical models. Deterministic models are based on conservation of mass, momentum, and energy and describe cause and effect relations. Deterministic groundwater models generally require the solution of partial differential equations. Exact solutions can often be obtained analytically, but analytical models require that the parameters and boundaries be highly idealised. Some deterministic models treat the properties of porous media as lumped parameters, but this precludes the representation of heterogeneous hydraulic properties in the model.

Heterogeneity, or variability in aquifer properties, is characteristic of all geologic systems and is recognised as playing a key role in influencing groundwater flow and solute transport. It is, therefore, often preferable to apply distributed-parameter models, which allow the representation of more realistic distributions of system properties. Numerical methods yield approximate solutions to the governing equation (or equations) through discretization of space and time. The space and time are divided into discrete intervals where for each model grid cell, parameter values are defined including hydraulic conductivity, porosity, aquifer thickness, initial contaminant concentration, etc. Thus, within the discretized problem domain, the variable internal properties, boundaries, and stresses of the system are approximated. Instead of the rigid idealised conditions of analytical models or lumped-parameter models, usage of deterministic, distributed-parameter, numerical models permit a flexible approach for simulating field conditions and provides a more realistic solution for the field problem under consideration.

The number and types of equations to be solved are determined by the concepts of the dominant governing processes. The coefficients of the equations are the parameters that are measures of the properties, boundaries, and stresses of the system; the dependent variables of the equations are the measures of the state of the system and are mathematically determined by the solution of the equations. Groundwater models are broadly divided into two categories: groundwater flow models, which solve for the distribution of head in a domain, and solute transport models, which solve for the concentration of solute as affected by advection, dispersion, and chemical reactions.

2.4.3 Flow and transport processes

The process of groundwater flow is generally assumed to be governed by the relations expressed by Darcy's law and the conservation of mass. The purpose of a model that simulates solute transport in groundwater is to compute the concentration of dissolved chemical species in an aquifer at any specified time and place. Changes in chemical concentration occur within a dynamic groundwater system primarily due to four distinct processes (Bear, 1979; Domenico and Schwartz, 1998):

1. Advective transport, in which dissolved chemicals are moving with the flowing groundwater;
2. Hydrodynamic dispersion, in which molecular and ionic diffusion and small-scale variations in the flow velocity through the porous media cause the paths of dissolved molecules and ions to diverge or spread from the average groundwater flow direction;
3. Fluid sources, where water of one composition is introduced into and mixed with water of a different composition;
4. Reactions, in which some amount of a particular dissolved chemical species may be added to or removed from the groundwater as a result of chemical, biological, and physical reactions in the water or between the water and the solid aquifer materials or other separate liquid phases.

2.4.4 Governing equations

2.4.4.1 Groundwater flow equation

A general form of the equation describing the transient flow of a compressible fluid in a non-homogeneous anisotropic aquifer may be derived by combining Darcy's law with the continuity equation. A general groundwater flow equation may be written in Cartesian tensor notation as (Bear, 1979):

$$\frac{\partial}{\partial x_i}\left(K_{ij}\frac{\partial h}{\partial x_i}\right) = S_S\frac{\partial h}{\partial t} + W^* \qquad \text{... (2.8)}$$

where K_{ij} is the hydraulic conductivity of the porous media (a second-order tensor), $[LT^{-1}]$;h is the hydraulic head, [L]; S_S is the specific storage, $[L^{-1}]$; t is time, [T]; W* is the volumetric flux per unit volume (positive for outflow and negative for inflow), $[T^{-1}]$; and x_i are the Cartesian co-ordinates, [L].

Equation (2.8) can generally be applied if isothermal conditions prevail, the porous medium only deforms vertically, the volume of individual grains remains constant during deformation, Darcy's law applies (and gradients of hydraulic head are the only driving force), and fluid properties (density and viscosity) are homogeneous and constant. Aquifer properties can vary spatially, and fluid stresses (W*) can vary in space and time.

In some field situations (e.g. coastal aquifers), fluid properties such as density and viscosity may vary significantly in space or time. This may occur due to significant changes in water temperature or total dissolved solids concentration. In such cases, the flow equation is written and solved in terms of fluid pressures, fluid densities, and the intrinsic permeability of the porous media (Konikow and Grove, 1977; Bear, 1979).

2.4.4.2 Solute transport equation

A generalized form of the solute-transport equation in which terms are incorporated to represent chemical reactions and solute concentration both in the pore fluid and on the solid surface is (Grove, 1976; Bear, 1972):

$$\frac{\partial(\varepsilon C)}{\partial t} = \frac{\partial}{\partial x_i}\left(\varepsilon D_{ij}\frac{\partial C}{\partial x_j}\right) - \frac{\partial}{\partial x_i}(\varepsilon C V_i) - C' W^* + CHEM \qquad \dots (2.9)$$

where CHEM equals:

$-\rho_b \frac{\partial \bar{C}}{\partial t}$	for linear equilibrium controlled sorption or ion-exchange reactions,
$\sum_{k=1}^{s} R_k$	for 's' chemical rate-controlled reactions, and (or)
$-\lambda(\epsilon C + \rho_b \bar{C})$	for decay,

and, where D_{ij} is the coefficient of hydrodynamic dispersion (a second-order tensor), $[L^2T^1]$; C is the concentration of solute (single dissolved chemical species) in flowing groundwater $[ML^{-3}]$; C' is the concentration of the solute in the source or sink fluid, $[ML^{-3}]$; $\bar{C}$is the concentration of the species adsorbed on the solid (mass of solute/mass of solid); ρb is the bulk density of the solid, $[ML^{-3}]$; R_k is the rate of production of the solute in reaction k, $[ML^3T^{-1}]$; and λ is the decay constant, $[T^{-1}]$.

The first term on the right side of equation (2.9) represents the change in concentration due to hydrodynamic dispersion. This expression is analogous to Fick's Law describing diffusive flux. This Fickian model assumes that the driving force is the concentration gradient and that the dispersive flux occurs in a direction from higher concentrations towards lower concentrations. The second term represents advective transport and describes the movement of solutes at the average seepage velocity of the flowing groundwater. The third term represents the effects of mixing with a source fluid that has a different concentration than the groundwater at the location of the recharge or injection. The fourth term lumps all of the chemical, geochemical, and biological reactions that cause transfer of mass between the liquid and solid phases or conversion of dissolved chemical species from one form to another. The chemical attenuation of inorganic chemicals can occur by sorption/desorption, precipitation/dissolution, or oxidation/reduction; organic chemical can adsorb or degrade by microbiological processes.

2.4.5 Classification of groundwater models

Groundwater models can broadly be grouped into three categories: Analytical Models; Numerical Models; and Analytic Element Models.

2.4.5.1 Analytical models

Analytical models use exact solutions to the equations that describe groundwater flow or contaminant transport. In order to produce these exact solutions, the flow/transport equations have to be considerably simplified such that they are typically applicable only to simple flow and contaminant transport systems. Analytical models can be simple formulae, spreadsheets, or sequences of calculations packaged in a piece of software. The main advantage of analytical models is the ease of use and transparency of such models which will facilitate sensitivity analyses. Their main disadvantage is that they can only be applied to relatively simple flow (or transport) problems. The main uses of analytical models are to assist in conceptual modeling, simulate flow and/or transport in simple physical settings (or where there are only one or two simple objectives), and check results of the numerical model.

2.4.5.2 Numerical models

A numerical model uses numerical methods to solve the governing equations of groundwater flow and/or contaminant transport. In distributed numerical models, space and time are divided into discrete intervals where for each model grid cell, parameter values are defined including hydraulic conductivity, porosity, aquifer thickness, initial contaminant concentration, etc. Numerical models enable more complex systems to be represented than can be represented by analytical models. Furthermore, numerical models may allow for multiple modeling objectives to be addressed in parallel. Numerical models still require simplifications to be made about system behaviour.

The main advantage of numerical models is that different parameter values can be assigned to each cell, so that lateral and vertical variations in property values can be taken into account. The geometry of the model can be designed to reflect the geometry of the system. In addition, models can be constructed that include more than one layer; this enables multi-layered aquifers to be represented. For time variant models, model inflows (e.g. recharge and its contaminant concentration) and outflows (e.g. ground water abstractions) can be specified for each model time step. The main disadvantage of numerical models is that they can be costly and time-consuming. Another potential disadvantage is that the model complexity reduces the transparency of the model calculations and/or can mask the model uncertainty. Numerical models will generally be applicable where:

- Previous modeling studies using simple analytical models have shown that a more sophisticated approach, such as incorporating spatial variability, is required.
- Groundwater regime is too complex to be robustly represented by an analytical model.
- Required model accuracy (as defined by the model objectives) requires the use of a numerical model.
- Processes affecting contaminant transport cannot be adequately represented by simple transport equations.
- An analytical model is inadequate for the design of mitigation measures, e.g., in determining the optimal location and pumping rate for boreholes in a pump and treat scheme.

Numerical models should be considered where the scale and importance of the problem warrant the use of a more sophisticated approach. For such sites, the scale of the problem should demand detailed site investigations which should provide sufficient information to allow the construction of a numerical model.

2.4.5.3 Analytic element models

An analytic element model uses superposition of closed-form (analytical) solutions to the governing differential equation of groundwater flow to approximate both local and (near-field) and regional (far-field) flow. Hence, analytic element models do not require grid discretization or specifications of boundary conditions on the grid perimeter (Hunt et al., 1998). These characteristics allow for representation of large domains that include many hydrogeologic features outside the immediate area of interest (i.e., far-field) and easy modification of the regional flow field by adding analytic elements representing regional hydrologic features (Wels, 2012).

Analytic element models are well-suited for use as screening models (Hunt et al., 1998). Analytic element models can be used to develop conditions on the grid perimeter for a smaller numerical model, similar to the process of telescopic mesh refinement (TMR). The advantage over traditional TMR using finite difference models is that this method: (i) allows easy addition of far-field elements until the far field is correctly simulated; and (ii) avoids discretization problems that can occur in large-scale models with large cell/element sizes. A major limitation of analytic element models is that the method is computationally efficient only for steady-state flow in large aquifers where the vertical flow component can be ignored.

2.4.6 Numerical methods to solve flow and transport equations

Two major classes of numerical methods are well accepted for solving the governing flow equations, namely the finite-difference (FD) methods and the finite-element (FE) methods. Each of these two major classes of numerical methods includes a variety of subclasses and implementation alternatives. Although FD and FE models are commonly applied to flow and transport problems, other types of numerical methods applied to transport problems include method of characteristics (MOC), particle tracking, random walk, Eulerian-

Lagrangian methods, and adaptive grid methods. All of these have the ability to track sharp fronts accurately with a minimum of numerical dispersion.

The widely used MODFLOW is the USGS's open source three-dimensional (3D) FD based groundwater model. Originally developed and released solely as a groundwater-flow simulation code in 1984, MODFLOW's modular structure has provided a robust framework for integration of additional simulation capabilities that build on and enhance its original scope. The family of MODFLOW-related programs now includes capabilities to simulate coupled groundwater/surface-water systems, solute transport, variable-density flow (including saltwater), aquifer-system compaction and land subsidence, parameter estimation, and groundwater management.

FEFLOW (Finite Element subsurface FLOW system) is a computer program for simulating groundwater flow, solute and heat transfer in porous media and fractured media. The program uses FE based analysis to solve the groundwater flow equation of both saturated and unsaturated conditions as well as solute and heat transport, including fluid density effects and chemical kinetics for multi-component reaction systems.

In addition, many other simulation codes have been developed over the years for groundwater modeling applications. Appropriate model codes may be selected depending upon associated complexities in groundwater flows.

Flow through fractures and conduits. In case of uniformly distributed and well connected fracture system, an equivalent porous medium (EPM) approach may be adopted to simulate the system. The EPM approach may adequately represent the behavior of a system at regional scale, but local groundwater flows are poorly represented. Flow through discrete fractures within a porous matrix can be simulated using available codes such as FEFLOW, conduit flow processes in MODFLOW, and specialty codes such as Fracman (www.fracman.com). Presence of conduits and fractures in carbonate rocks offers additional challenges owing to changes in secondary permeability resulting from dissolution and precipitation.

Variable density flow: Examples of variable density flows (i.e., fluids that mix with groundwater) are seawater intrusion into coastal aquifers, mixing of highly concentrated dissolved contaminants in groundwater, freshwater storage in saline aquifers etc. Modeling variable density flow requires coupling of a density dependent flow model to a solute transport model. Codes such as SEAWAT (derived from MODFLOW and MT3DMS), SUTRA, FEFLOW can be used to simulate variable density flows.

Multiphase flow: Immiscible fluids move as separate phases within subsurface. Examples of multiphase flow include air and water in unsaturated zone; oil, gas and water in a petroleum reservoir; water and steam in a geothermal reservoir. The most common type of multiphase flow involves non-aqueous phase liquids or NAPLs that may be either lighter (LNAPL) or denser (DNAPL) than groundwater. Models simulating NAPLs movement in groundwater are complex and require a separate set of flow and transport equations for groundwater and each NAPL.

Linked and Coupled Models. On linking a flow model to a solute transport or rainfall-runoff model, the flow model is solved first and the results are input to the other model which is solved within the same time step as the flow model. However, when results from one model significantly affect parameters in another model within a time step, coupling of the models becomes necessary. Here, the models are solved iteratively within the time step and input to each model is updated to reflect output from the other.

2.4.7 Concluding remarks

Development of both simulation and management models for alluvial and hard rock regions (including coastal regions) supported by advanced numerical modeling and optimization tools as well as remote sensing technology is essentially needed. At the same time, usage of better field instrumentation, data acquisition and integration into models (as more data becomes available under the National Aquifer Mapping Program) will enormously help the modeling activities in developing reliable groundwater models for the water resources problems of the future.

2.5 An Overview of Groundwater Models

2.5.1General

Depending upon the flow domain, groundwater models can be one-dimensional, two-dimensional and three-dimensional. Two and three-dimensional models can account for the anisotropy of the aquifer system wherein the hydraulic properties may vary with respect to the principal directions. Again, based upon the objectives, groundwater models may be grouped into prediction/simulation models; identification or evaluation models; and management models.

The majority of models in common use are prediction models based on the numerical simulation technique. They predict the response of a groundwater system, in terms of variation of hydraulic heads, to natural and/or artificial hydraulic stresses, as well as hydrological responses.

A numerical simulation model may be developed to identify or evaluate the parameters and boundaries of a little known aquifer. This can be undertaken using the simulation model exclusively in calibration mode, adjusting the value of parameters and/or boundary conditions to reproduce the observed aquifer response to known stresses.

Three dimensional groundwater simulation models applied to complex, heterogeneous aquifer systems have often been utilized to explore groundwater management alternatives. For this purpose, the groundwater model may be executed repeatedly under various scenarios designed to achieve a particular objective, such as obtaining a sustainable water-supply, preventing saline water encroachment or controlling a contaminant plume. Further, groundwater management models are being developed by incorporating rigorous formulation of management objectives and/or policy constraints, through use of decision criteria or linear optimization programming, with numerical simulation of groundwater hydraulic or contaminant behaviour.

2.5.2 Groundwater simulation models

Depending upon the flow domain, different approaches are employed to simulate groundwater flow and solute transport in natural aquifer systems:

- Equivalent porous medium
- Discrete fracture network
- Dual porosity medium

The equivalent porous medium (EPM) approach assumes that the aquifer system can be represented by an equivalent porous medium, i.e. the aquifer system behaves like a porous medium and standard flow and transport equations apply. EPM approach is commonly used for unconsolidated materials such as overburden soils (colluviums), fluvial, alluvial and glacio-fluvial sediments, and highly weathered bedrock with high primary porosity.

EPM approach is commonly used to describe groundwater flow through fractured bedrock in which the primary porosity is very low and the effective permeability is controlled by fractures, fissures and bedding planes (i.e. secondary permeability). This approach is based on the assumption that at a sufficiently large scale (i.e. the representative elementary volume (REV)), the bedrock mass will behave like a porous medium and can be described by "effective" hydraulic properties. The majority of groundwater modeling codes uses the EPM approach to model groundwater flow.

In the discrete fracture network (DFN) approach, it is assumed that flow through the bedrock matrix is negligible and all groundwater flow occurs through an interconnected network of fractures. Such a discrete fracture network may either be described explicitly (with known geometry) or generated randomly using fracture network statistics (e.g. Dershowitz et al., 2004; Parker and Cherry, 2011). Sophisticated Modeling codes are available to generate DFNs and to simulate groundwater flow and solute transport in such a medium, including FracMan (available from http://www.fracman.com/) and Fractran.

Flow and transport in fractured bedrock and structured porous media (e.g. fractured sandstone) can be described using dual porosity models (DPM). This approach assumes that the medium consists of two regions, one associated with the macro pore or fracture network and the other with a less permeable pore system of soil aggregates or rock matrix blocks (Gerke and van Genuchten, 1993). Different models exist to describe the nature of flow and transport in these two domains and the extent of their interaction. In its simplest form, groundwater flow and advective transport is assumed to only occur in the highly permeable ("active") domain. Groundwater flow in the low-permeable ("inactive") domain is assumed to be negligible but this stagnant zone influences solute transport by diffusion.

At present, DFN and dual porosity models are predominantly used in research and/or in assessment of contaminated sites with very high risk and/or consequence (e.g., storage of radio-nuclides, large contaminated sites impacting drinking water supplies, etc.). The primary challenge with DFN and DPM models is model parameterization. A characterization of the fracture network and/or the dual porosity regime requires extensive field studies and/or detailed model calibration usually not available for natural resource projects.

In certain hydrogeological situations, fluid density variations occur because of changes in the solute or colloidal concentration, temperature, and pressure of the groundwater. These include seawater intrusion in coastal aquifers, high-level radioactive waste disposal, groundwater contamination, and geothermal energy production. When the density of the invading fluid is greater than that of the ambient one, density-driven free convection can lead to transport of heat and solutes over larger spatial scales and significantly shorter time scales than compared with diffusion alone. In such cases, variable density models are employed to simulate groundwater flow.

2.5.3 Groundwater management models

Distributed-parameter numerical models are important tools for assessment of groundwater flow systems and groundwater development strategies. Commonly, these models are used to test specific water resource management plans, or, in a trial-and-error approach, to select a single plan from a few alternative plans that best meets management goals and constraints. Because of the complex nature of groundwater systems, however, and the large number of engineering, legal, and economic factors that often affect groundwater development and management, the process of selecting a best operating procedure or policy can be quite difficult. To address this difficulty, groundwater simulation models have been linked with optimization-modeling techniques to determine best (or optimal) management strategies from among many possible strategies. Optimization models explicitly account for water resource management objectives and constraints, and have been referred to as management models (Ahlfeld and Mulligan, 2000).

Groundwater management models may be divided into three categories (Gorelick, 1990):

- Groundwater hydraulic management,
- Groundwater quality management, and
- Groundwater policy evaluation and allocation.

Simulation-optimization groundwater management models have been developed for a variety of applications, such as restoration of contaminated groundwater, control of aquifer hydraulics, allocation of groundwater and surface water resources, and evaluation of groundwater policies (Yeh, 1992).In some cases, however, the model may determine that none of the possible strategies are able to meet the specific set of management goals and constraints. Such outcomes, though often not desirable, can provide useful information for identifying the hydrologic, hydrogeologic, and management variables that limit water resource development and management options.

2.5.4Transport processes

While simulating solute transport in highly heterogeneous and fractured media, the advection-dispersion equation is a poor predictor of solute transport processes. The dual porosity approach is utilized to describe exchange of solute/heat between fractures or highly preferential flow paths and the surrounding porous medium. The dual porosity option is present in both MT3DMS (Zheng, 2009) and FEFLOW. To simulate reaction between two or more chemical species, geochemical reaction modules are interfaced with the transport code, such as MT3DMS interfaces with RT3D or PHT3D.

2.5.5 Surface water - groundwater interactions

Exchange of water from surface water bodies such as, rivers, lakes, wetlands and oceans are an integral component of groundwater modeling. In all groundwater models, simple surface water exchanges with groundwater system are adequately simulated via boundary conditions. Advanced options for representing surface water processes in groundwater models include stream flow routing in channels via Manning’s equation, representation of lakes etc. using suitable packages in MODFLOW. The simplified representations of surface water processes in groundwater models may be appropriate for many situations but in some cases coupling of rainfall-runoff model to a groundwater model is required.

2.5.6 Stochastic groundwater modeling

Using stochastic modeling, probabilities and multiple realizations can capture inherent uncertainties of the hidden subsurface. Multiple realizations may be generated using geostatistical methods, geologic process models and multiple-point geostatistics. In geostatistical methods, uncertain parameters are represented by random variables with assigned statistics. Stochastic modeling is computationally intensive, however, with advances in computer hardware and computational capabilities, the ability to evaluate multiple stochastic realizations in groundwater modeling will improve.

2.5.7 Optimization and decision making

Increasingly, groundwater applications are driven by regulatory requirements of water management planning. Optimization techniques can be used in conjunction with groundwater models to find an optimal solution for a given set of constraints (Ahlfeld and Mulligan, 2000; Anderson et al., 2015). With the perceived need for groundwater modelers to engage and include stakeholders, it is important that groundwater models are updated and maintained as ongoing management tools. Groundwater models are also being incorporated in Decision Support Systems (DSS). As part of DSS, the runtime of a groundwater model becomes important, because a DSS has to supply answers to ‘what if?’ queries quickly. If the runtime of a groundwater model is too long, then it will not prove to be useful in a DSS. However, simple groundwater models with short runtimes may not adequately simulate processes important for decision-making. Research is continuing for extracting fast-running simple models from long running complex models.

2.6 Data Requirements for Saturated Zone Modeling

2.6.1General

The first phase of any groundwater study consists of collecting all existing geological and hydrological data on the groundwater basin in question. This will include information on surface and subsurface geology, water tables, precipitation, evapotranspiration, pumped abstractions, stream flows, soils, land use, vegetation, irrigation, aquifer characteristics and boundaries, and groundwater quality. If such data do not exist or are very scanty, a program of field work must first be undertaken, for no model whatsoever makes any hydrological sense if it is not based on a rational hydrogeological conception of the basin. All the old and newly-found information is then used to develop a conceptual model of the basin, with its various inflow and outflow components.

A conceptual model is based on a number of assumptions that must be verified in a later phase of the study. In an early phase, however, it should provide an answer to the important question: does the groundwater basin consist of one single aquifer (or any lateral combination of aquifers) bounded below by an impermeable base? If the answer is yes, one can then proceed to the next phase: developing the numerical model. This model is first used to synthesize the various data and then to test the assumptions made in the conceptual model.

2.6.2 Data requirement

The data needed in general for a groundwater flow modeling study can be grouped into two categories: (a) Physical framework and (b) Hydrogeologic framework. The data required under physical framework are:

- Geologic map and cross section or fence diagram showing the areal and vertical extent and boundaries of the system.
- Topographic map at a suitable scale showing all surface water bodies and divides. Details of surface drainage system, springs, wetlands and swamps should also be available on map.
- Land use maps showing agricultural areas, recreational areas etc.
- Contour maps showing the elevation of the base of the aquifers and confining beds.
- Isopach maps showing the thickness of aquifers and confining beds.
- Maps showing the extent and thickness of stream and lake sediments.

These data are used for defining the geometry of the groundwater domain under investigation, including the thickness and areal extent of each hydrostratigraphic unit.

Under the hydrogeologic framework, the data requirements are:

- Water table and potentiometric maps for all aquifers.
- Hydrographs of groundwater head and surface water levels and discharge rates.
- Maps and cross sections showing the hydraulic conductivity and/or transmissivity distribution.
- Maps and cross sections showing the storage properties of the aquifers and confining beds.
- Hydraulic conductivity values and their distribution for stream and lake sediments.
- Spatial and temporal distribution of rates of evaporation, groundwater recharge, surface water - groundwater interaction, groundwater pumping, and natural groundwater discharge.

Some of the compiled information will be used not only during the conceptualisation, but also during the design and calibration of the model. This includes the data about the model layers and hydraulic parameters as well as observations of hydraulic head, watertable elevation, and fluxes. The conceptualisation stage may involve the development of maps that show the hydraulic heads in each of the aquifers within the study area. These maps help illustrate the direction of groundwater flow within the aquifers, and may infer the direction of vertical flow between aquifers.

The data used to produce maps of groundwater head is ideally obtained from water levels measured in dedicated observation wells that have their screens installed in the aquifers of interest. More often than not, however, such data is scarce or unavailable and the data is sourced from, or complemented by, water levels from production bores. These may have long well screens that intersect multiple aquifers, and be influenced by preceding or coincident pumping. The accuracy of this data is much less than that obtained from dedicated observation wells. The data can be further supplemented by information about surface expressions of groundwater such as springs, wetlands and groundwater-connected streams. It provides only an indication of the minimum elevation of the watertable (i.e. the land surface) in areas where a stream is gaining and local maximum elevation in areas where a stream is losing. As such, this data has a low accuracy, but can be very valuable nonetheless.

2.6.2.1 Hydrogeological domain

The hydrogeological domain involves:

- Describing the components of the system with regard to their relevance to the problem at hand, such as the hydrostratigraphy and the aquifer properties
- Describing the relationships between the components within the system, and between the system components and the broader environment outside of the hydrogeological domain
- Defining the specific processes that cause the water to move from recharge areas to discharge areas through the aquifer materials
- Defining the spatial scale (local or regional) and time scale (steady-state or transient on a daily, seasonal or annual basis) of the various processes that are thought to influence the water balance of the specificarea of interest
- In the specific case of solute transport models, defining the distribution of solute concentration in the hydrogeological materials (both permeable and less permeable) and the processes that control the presence and movement of that solute
- Making simplifying assumptions that reduce the complexity of the system to the appropriate level so that the system can be simulated quantitatively. These assumptions will need to be presented in a report of the conceptualisation process, with their justifications.

2.6.2.2 Hydrostratigraphy

A hydrostratigraphic description of a system consist of:

- Stratigraphy, structural and geomorphologic discontinuities (e.g. faults, fractures, karst areas)
- The lateral extent and thickness of hydrostratigraphic units
- Classification of the hydrostratigraphic units as aquifers (confined or unconfined) or as aquitards
- Maps of aquifer/aquitard extent and thickness (including structure contours of the elevation of the top and bottom of each layer)

2.6.2.3 Aquifer properties

The aquifer and aquitard properties control water flow, storage and the transport of solutes, including salt, through the hydrogeological domain. Quantified aquifer properties are critical to the success of the model calibration. It is also well understood that aquifer properties vary spatially and are almost unknowable at the detailed scale. As such, quantification of aquifer properties is one area where simplification is often applied, unless probabilistic parameterisation methods are applied for uncertainty assessment. Hydraulic properties that should be characterised include hydraulic conductivity (or transmissivity), specific storage (or storativity) and specific yield.

2.6.2.4 Conceptual boundaries

The conceptualisation process establishes where the boundaries to the groundwater flow system exist based on an understanding of groundwater flow processes. The conceptualisation should also consider the boundaries to the groundwater flow system in the light of future stresses being imposed (whether real or via simulations). These boundaries include the impermeable base to the model, which may be based on known or inferred geological contacts that define a thick aquitard or impermeable rock. Assumptions relative to the boundary conditions of the studied area should consider:

- Where groundwater and solutes enter and leave the groundwater system
- The geometry of the boundary; that is, its spatial extent
- What process(es) is(are) taking place at the boundary, that is, recharge or discharge
- The magnitude and temporal variability of the processes taking place at the boundary. Are the processes cyclic and, if so, what is the frequency of the cycle?

2.6.2.5 Stresses

The most obvious anthropogenic stress is groundwater extraction via pumping. Stresses can also be imposed by climate through changes in processes such as recharge and evapotranspiration. Description and quantification of the stresses applied to the groundwater system in the conceptual domain, whether already existing or future, should consider:

- If the stresses are constant or changing in time; are they cyclic across the hydrogeological domain?
- What are their volumetric flow rates and mass loadings?
- If they are localised or widespread (i.e., point-based or areally distributed).

2.6.2.6 Solute transport data

All available solute concentration data should be used during conceptualisation to determine the spatial distribution of solutes, identify source zones and migration pathways, and to determine appropriate boundary conditions. Solute transport models require input parameters that describe the combined effect of advection, dispersion and diffusion. This typically involves quantification of the following parameters:

- Effective porosity
- Longitudinal and transverse dispersivity
- Diffusion coefficient
- An equation(s) of state (for variable density problems).

An assessment of the relative importance of advection, diffusion and dispersion should be made during the conceptualisation stage, and a decision should be made on which processes are to be included in the solute transport model. The importance of variable-density flow should be assessed with a quantitative analysis using all available head and concentration data.

2.7 Applicability, Limitations and Future Trends of Groundwater Modeling

2.7.1 General

A good groundwater management strategy should aim at: (i) sustainable use of groundwater and preservation of its quality; (ii) incorporation of groundwater protection plans into environmental protection planning; and (iii) protection measures towards prevention of groundwater pollution and over-use. Thus, the sustainable management of groundwater resources implies equilibrium between groundwater development and groundwater protection, and should be based on scientific understanding of the processes involved, scientific assessment of present and prognostic scenarios, robust planning and judicious management strategies culminating in effective action.

Although groundwater is a renewable resource, few aquifers can withstand enormous extraction rates (exceeding that of the natural recharge rates) indefinitely. Similarly, all activities carried out on the land surface have a potential to pollute groundwater. There are point sources and dispersed sources of pollution contributing to groundwater contamination. Therefore, groundwater regimes can be stressed by contamination, over-exploitation, or a combination of these two. In order to formulate technically-sound, robust and environmentally sustainable groundwater resources management policies, one has to ponder over questions like:

- How long can an aquifer maintain the current rate of groundwater abstraction?
- What is the safety yield that the aquifer can sustain the continuous abstraction?
- What is the capture zone of a water supply well field?
- What is the most likely pathway of contaminants from domestic wastewater and leaches from solid waste disposal sites?
- What are the chances that the pollutants from those sources would arrive at water supply wells?
- How long a pollutant may take to reach the supply source?
- What should be the size of the protection zone to protect the well fields from pollution?

Providing answers to such questions necessitates good understanding of the groundwater systems and also the ability to predict system responses to various stresses as far as the aquifer system is concerned. Groundwater models are the best tools available to help groundwater hydrologists to meet these kinds of challenges and to come out with effective solutions as groundwater models are capable of simulating and predicting aquifer conditions.

2.7.2 Applicability of groundwater models

The development of groundwater simulation models provided groundwater managers with quantitative techniques for analyzing alternative management strategies. Mathematical modeling techniques have demonstrated their value in furthering the understanding of groundwater systems and, thereby improving evaluation, development, and management of groundwater resources. Groundwater modeling can be applied to issues like water supply management of regional aquifers, planning of groundwater development, optimisation of pumping rates, planning of cropping pattern for given groundwater withdrawals or given canal supplies supplemented by groundwater irrigation, optimal locations of wells, all kinds of groundwater quality/contamination problems including pollution source identification using contaminant transport models, aquifer depletion problems as wells as conjunctive use of groundwater and surface water for agriculture applications.

As per GEC norms, groundwater resources are estimated based on an assessment unit, i.e. block, taluka, etc. which is lumped within that assessment unit. However, distributed models have the beauty of resource estimation at the defined grid size; even further refinement of any grid is possible. Therefore, groundwater resource estimation based on distributed models (even in a very small grid) is more realistic as it is based on scientific principles.

There are situations, wherein it is not possible to monitor all aspects of groundwater flow and solute distribution just by investigations only. Information pertaining to the future and between monitoring locations is required for making meaningful and scientific decisions. Groundwater models can replicate the processes of interest at the respective sites and may be used to facilitate in evaluating and forecasting groundwater flow as well as transport.

Groundwater optimisation models can provide optimal groundwater planning or design alternatives in the context of each system's objectives and constraints. Such models aid decision-making in groundwater management by incorporating numerical groundwater flow and/or transport models into mathematical programming formulations. The advantage of this approach is that the methods allow expression of management goals explicitly in terms of objective functions that are to be optimised.

Conventionally, linked simulation-optimization models are employed to arrive at the optimal groundwater development plans. The plans may relate to well operation (Katsifarakis, 2007) or regional groundwater development (Kashyap and Chandra, 1982; Werner et al., 2006). The planning problem is posed as an optimization problem with the simulation model computing the state variables of the groundwater system appearing in the objective function and constraints. Optimization invariably involves sequential computation of the objective function and the constraints; therefore, the linked simulation-optimization approach restricts the scope of the planning because of the usually huge computational cost of repeatedly running a simulation model (Safavi et al., 2009). The problem of excessive computational cost may be overcome by replacing the traditional simulation models by approximate models such as regression (Alley, 1986) and Artificial Neural Networks (ANN) (Coppola et al., 2003). Other alternative strategies that do not compromise upon the rigor of the simulation are embedded technique (Gorelick and Remson, 1982; Gorelick, 1983) and the kernel function approach (Morel-Seytoux and Daly, 1975). Embedded technique treats the discrete heads as additional decision variables and embeds the simulator into the optimizer by treating the finite difference equations as additional constraints. The other strategy viz. the kernel function approach, is mostly applied to linear systems. It is based upon the concept of kernel function that describes the system response to a unit impulse/pulse of the input such as pumpage. Ghosh and Kashyap (2012a, b) have reported applications of computationally inexpensive simulators employing kernel model functions and ANN for planning of optimalgroundwater development for irrigation.

2.7.3 Uncertainty and limitations of groundwater models

Numerical groundwater flow models are physically founded mathematical models, based on certain simplifying assumptions, derived from Darcy's law and the law of conservation of mass. The simplifying assumptions typically involve the direction of flow, geometry of the aquifer, the heterogeneity or anisotropy of sediments or bedrock within the aquifer, the contaminant transport mechanisms and chemical reactions. By mathematically representing a simplified version of a hydrogeological system, reasonable alternative scenarios can be predicted, tested, and compared. The usefulness of a model depends on how closely the mathematical equations approximate the physical system being modeled. As such, accurate field data is a pre-requisite for model reliability. Thus, predictive results of groundwater simulations may vary from true values, which can be attributed to the uncertainty in model formulation, structure, processes, parameters, as well as data inputs. Besides, there can be scenario uncertainty, an uncertainty caused by boundary conditions. For this purpose, the modeler has to ensure and be careful about the selection of proper boundary condition types. The selected boundary conditions must be nearly true representative of the real field conditions. Similarly, the forcing functions like recharge, evapotranspiration, withdrawals as well as system parameters must be precisely estimated and verified alternatively before assigning into the model. Otherwise, inherent errors in these forcing functions and parameters will ultimately lead to model uncertainties. The uncertainty in regionalization of aquifer parameters and assigning parameters particularly in hard rock areas should be realistic enough, scientifically based and must be clearly defined. Therefore, in the application of groundwater models, especially of groundwater quality models, scientific judgement tempered with wide experience of field observation is desirable to produce sound interpretations.

It may be noted that solution procedures of all numerical groundwater models have certain inherent shortcomings. First of all, the solution is sought for the numerical values of state variables only at specified points in space and time domains defined for the problem, and not their continuous variations in the domain. Secondly, as analytical solutions of the partial differential equations that represent balances of the considered extensive quantities are not feasible, those are replaced by a set of algebraic equations written in terms of the sought, discrete values of the state variables at the discrete points in space and time. Further, the solution is obtained for a specified set of numerical values of the various model coefficients rather than as general relationships in terms of these coefficients. Lastly, computerized numerical solution techniques, which are employed to solve the set of simultaneous equations, have inherent instability issues. Thus, certain degree of inaccuracy may be expected in the state variables computed at discrete points (discontinuity).

Different levels of uncertainty are associated with modeling of aquifer systems. The degree of uncertainty varies with type of issues and complexity of the aquifer systems as well as the architecture of the model itself (e.g. inadequacies in mathematical representation of processes, numerical instabilities etc.). Uncertainties exist in the transport mechanisms; various sink/source phenomena for the considered extensive quantity; values of model coefficients, and their spatial/ sometimes temporal variation; initial conditions; domain boundaries and the conditions prevailing on them; data employed in model calibration; and the robustness of the model to cope with heterogeneity of varying scales. To estimate the uncertainty, methods are basically statistical and probabilistic. Some of the commonly used methods include Monte Carlo method, probabilistic method, joint aggregation method and method of moments.

When groundwater models are used as predictive tools, field monitoring must be incorporated to verify model predictions as predictive simulations are estimates that depend upon the quality and uncertainty of the input data. If the basic principles of groundwater flow/ contaminant transport and the underlying assumptions of Modeling are lost sight of, there is serious danger of gross mis-interpretation of model outputs. This is more likely to occur when models are automated, and commercially packed. Therefore, a groundwater model must be regarded as a tool to aid decision-making; but decision should not be based solely on the results generated by the model.

In an aquifer system, management decisions are to be taken with respect to flow/ pumping rates, location of pumping, artificial recharge, water quality, contamination chances, well-interferences, well head protection/ capture zone management etc. Often, management goals are linked with minimization of cost while maximizing benefits. The management objective function may depend on the decision variables, like pumping and the consequent response of the aquifer system. Constraints are expressed in terms of future values of state variables of the considered groundwater system. Only by comparing predicted values with specified constraints can decision makers conclude whether or not a specific constraint has been violated. In the management of a groundwater system in which decisions must be made with respect to both water quality and water quantity, a tool is needed to provide the decision maker with information about the future response of the system to the effects of management decisions.

Three-dimensional groundwater simulation models applied to complex, heterogeneous aquifer systems have often been utilized to explore groundwater management alternatives. For this purpose, the groundwater model may be executed repeatedly under various scenarios designed to achieve a particular objective, such as obtaining a sustainable water-supply, preventing saline water encroachment or controlling a contaminant plume. Use of such an approach, however, avoids rigorous formulation of groundwater management goals and may fail to consider important operational restrictions. In such cases, the groundwater model needs to be linked with an optimizer as discussed in section 7.2.

In the case of contaminant transport modeling, the concentration distribution associated with a given contaminant loading is also predicted. In view of the current limitations of such models, applications are commonly restricted to prediction of the distribution resulting from a simple, continuous point-source of pollution, with grossly-simplified representation of the processes of contaminant dispersion, sorption and degradation. The Modeling of this problem is usually limited to a local site scale. Prediction of contaminant transport at the regional scale, the migration of diffuse-source groundwater pollutants and behaviour of those pollutants involved in more complex chemistry cannot yet be predicted reliably.

In general, the underlying mathematical equations have been adequately verified, and the physical meaning of the parameters involved is clearly understood in the case of groundwater flow models. However, in the case of contaminant transport, more insight is needed on the mathematical characterisation and measurement of hydrodynamic dispersion, and about the best way to identify, measure, and model the chemical interactions and reactions that can occur in an aquifer. So, application of solute transport models and interpretation of the results thereof should be exercised with greater care.

2.7.4 Emerging issues and future trends in groundwater modeling

Groundwater Modeling is a key component in a wide variety of projects including water supply, agriculture, environmental, mining, chemical, and energy industries. Since it is difficult for a groundwater modeller to keep pace both with advances in groundwater Modeling as well as advances in these related fields, a team approach would be a more viable option in future where groundwater modellers work closely with computer professionals, atmospheric scientists, surface water hydrologists, and geochemists.

Need for efficient utilization of water resources will increase interaction of groundwater professionals with communities and stakeholders with different self-interests. With the fast pace of changes in the 21st century, interdisciplinary approaches would be required to address the complex flow mechanisms occurring within the hydrologic cycle as well as the water availability issues within the broader framework of societal, ecological, and environmental policy issues (Refsgaard et al., 2010; Langevin and Panday, 2012). For example, climate change and its impact on water availability through changes in precipitation patterns, air temperature, and sea level are complex issues wherein groundwater modeling would play a vital role as part of a larger inter disciplinary effort. With the ongoing aquifer mapping program in India, as the knowledgebase increases about various hydrogeologic units in alluvial and hard rock terrains in India, the groundwater quantity and quality issues present today will continue to be addressed with a more rigorous approach in future.

For groundwater models to be used effectively for the multidisciplinary problems of tomorrow, several technical components will require technological advances, i.e., multi-scale simulation, coupling with other processes, improvements in computational efficiency, and better data integration.

2.7.4.1 Multi-scale issues

Many groundwater problems are complicated due to scale related issues. Often, our interests lie in phenomenon occurring at a large scale, but the physical processes controlling the outcome operate at a much finer scale. To improve the accuracy of groundwater models, research in simultaneous solution of groundwater processes at multiple scales, using flexible gridding methods is needed. Efforts have been made to combine the strengths of numerical and analytic element methods to address scale issues (e.g., Haitjema et al. 2010), and to add the flexibility of unstructured, control volume finite difference (CVFD) methods to MODFLOW (Langevin et al. 2011).

2.7.4.2 Process coupling and alternative modeling frameworks

The best way to support multiple hydrologic processes in a modeling framework, either by linking/coupling using one-way sequential methods or by using a standard protocol is a debatable issue in the hydrologic Modeling community. Combining separate models, either directly as is done in GSFLOW (Markstrom et al., 2008), or through a coupling protocol, allows individual fields to develop and progress independently as has been done in the past. Conversely, a new modeling framework is a much larger endeavor, but it could be designed to use the latest advances in numerical methods, programming, and parallel computing. A common modeling framework would likely be easier to use than learning two or more separate codes. The trend now and in the near future is likely to be a need to couple MODFLOW with more complicated processes. More customized versions of MODFLOW (e.g., MODFLOW-FMP, MODFLOW-CFP, SEAWAT, MODFLOW-VSF) are expected if a process model does not fit cleanly into the MODFLOW structure.

It should be noted that scripting languages, such as Python, contain extensive library collections for linear and nonlinear systems of equations, performing spatial manipulations, and visualizing results in 3D. Usage of scripting languages, containing these libraries, frees the groundwater modeler from having to learn the details of these other fields and allows them to focus on applying the power of these tools to groundwater simulation.

Another new development in groundwater simulation is the emergence of general-purpose multi-physics computer programs that can be instructed, because of their flexibility, to solve one or more governing partial differential equations, such as saturated or unsaturated groundwater flow and solute or heat transport. As continental-scale models, including 3D hydrostratigraphic and geologic models, continue to advance and become more reliable, an increase in application of methods for rapidly developing in set models is expected using the best available hydrologic and geologic information.

2.7.4.3 Advances in computational efficiency

Advances in computer science and powerful new hardware technologies that offer much higher computational capabilities will be harnessed for future modeling problems. Recently, there seems to be a growing trend toward retail cloud computing, where computing resources appear almost endless. For tasks that require numerous independent forward simulations, it is relatively straightforward to use these computational resources, including the cloud-based resources. Splitting individual forward runs across multiple processors, however, has been a challenge for most modeling approaches. Parallelization methods for forward runs will continue to improve for shared memory systems, such as multiple-core processors, and for distributed memory systems, such as networks of desktop computers and cloud resources. These computational advances are also expected to be used to improve visualization and presentation of data and model results. These new and enhanced capabilities will help identify and correct deficiencies in models and more effectively communicate results to a wide variety of technical and non-technical audiences.

2.7.4.4 Uncertainty and optimization

In future, groundwater models will need to make more rigorous predictions and reveal the uncertainty of modeled estimates. Recent advances in sophisticated methods for quantifying uncertainty and increased availability of parallel computing will help such techniques to be incorporated into the pre- and post-processing toolkits, and create more reliable models, for assessing how estimated parameter values and distributions are affected by measurement and structural errors, and for evaluating the resulting uncertainty in predictions.

In many groundwater modeling contexts, the purpose of the modeling effort is to help identify effective management strategies, whether it be for optimizing a data collection network, maximizing effectiveness of a remediation system, or identifying groundwater extraction patterns that minimize harmful impacts to a wetland or stream. Application of formalized optimization techniques for these types of problems has been steadily increasing. The development and use of optimization techniques is expected to grow and become more widely used in practice. Usage of Artificial Intelligence (AI) techniques, such as artificial neural network, genetic algorithm and simulated annealing etc. has gained popularity over the years to deal with uncertainty and speed up optimization process in groundwater models.

2.7.4.5 Data acquisition and integration

Advanced modeling programs, faster computers, and better calibration strategies, would not be of much use without better quality data. Better future groundwater flow and transport models will require extensive real-time monitoring networks, remotely sensed data, progress in field instrumentation, and advances in related fields such as geochemistry and geophysics. Fast assimilation of new data as soon as they become available will be an important component of groundwater modeling. There are promising efforts toward improved data acquisition, storage, processing, and distribution tools. Work will be needed to address logistical problems inherent to groundwater models that require so many different types of data; each one typically in a different form, with different levels of uncertainty and availability.

The future of data for groundwater modeling will likely include a central repository, perhaps by state offices that store and provide raw data. Modern data encoding rules, such as the Extensible Markup Language (XML), are well suited for handling complex datasets. Having this type of information in an accessible and standardized database would lead to better and more reliable groundwater models. As detailed climatic data, using remote sensing technology, become available, better recharge estimates can be made at the local and regional scales using precipitation records, energy budget data, and soil characteristics.

2.7.5 Common errors in groundwater modeling

The accuracy of model predictions depends upon the degree of successful calibration and verification of the model and the applicability of groundwater flow and solute transport equations to the problem being simulated. Errors in the predictive model, even though small, can result in gross errors in solutions projected forward in time. The common errors in any groundwater modeling study may include the following.

Model Conceptualization Errors

- Inappropriate model selection
- Selection of inappropriate boundary conditions
- Excessive discretization
- Lack of far-field data
- Oversimplification of problem (2-D model when obviously 3-D flow)
- Placing model boundaries too close to area of interest, which may include pumping centre
- Lack of understanding of site hydrogeological processes

Data Input Errors

- Inconsistent parameter units
- Incorrect sign for pumping or recharge
- Well not specified correctly
- Aquifer stresses (pumping, recharge, evapotranspiration, etc.) not specified over entire transient simulation period
- Using interpolated input data
- Forcing questionable data to fit

Calibration Errors

- Forcing a fit either by using unrealistic data values or over-discretizing a aquifer or aquitard layer
- Target wells clustered in a small portion of the model - i.e. lack of far field calibration data
- Target wells too close to, or within, specified head boundaries
- Using interpolated data distribution rather than point data
- Misinterpreting mass balance information

Simulation Results Errors

- Omitting results inconsistent with preconceptions
- Not incorporating data variability or uncertainty into the analysis
- Blind acceptance of model output

One may refer to Kumar (2001) for further details about the above errors. Predictive simulations must be viewed as estimates, dependent upon the quality and uncertainty of the input data. Models may be used as predictive tools; however field monitoring must be incorporated to verify model predictions. The best method of eliminating or reducing modeling errors is to apply good hydrogeological judgement and to question the model simulation results. If the results do not make physical sense, find out why.

2.8 Groundwater Modeling Softwares

2.8.1 General

The development of (numerical) groundwater models in the seventies provided groundwater hydrologists with quantitative techniques for analyzing alternative planning/management strategies. It is well known that the equations describing groundwater flow in porous media are mathematically analogous to those governing the flow of electric current. Hence, electric analogue models were designed and used to study groundwater flow systems in 1950s. However, all analogue models have been superseded by numerical simulation models later, following the development of advanced digital computers.

Our interest here pertains only to numerical groundwater models that are physically founded mathematical models, based on certain simplifying assumptions, derived from equations of flow in porous media (like Darcy's law in saturated soil/ flow in unsaturated porous media etc.) and basic laws of conservation of mass/ solute transport / chemical laws etc. The simplifying assumptions typically involve the direction of flow, geometry of the aquifer, the heterogeneity or anisotropy of sediments or bedrock within the aquifer, the contaminant transport mechanisms, chemical properties and reactions. By mathematically representing a simplified version of a hydrogeological system, reasonable alternative scenarios can be predicted, tested, and compared.

Groundwater flow and contaminant transport models are being applied for arriving at solutions to many aquifer development/ management issues as well as environmentally related problems around the world. The applicability of these models in groundwater pollution investigations are of varying levels of success. These models are of use in all stages of site investigation and remediation processes. Nevertheless, the usefulness of a model depends on how closely the mathematical formulation approximates the physical system being modeled.

2.8.2 Categorization of groundwater modeling software

The evolution of groundwater models in the study of groundwater problems has been in perfect line with the advancement of technology. Therefore, groundwater modeling software may be classified in various manners depending upon their evolution, functionalities, dimensionalities, use of numerical techniques, and applicability.

On the basis of their formulation, we can classify them into Analytical Models, Porous Media Models, Viscous Fluid Models, Membrane Models, Electrical Analogue Models, Empirical Models, Mass Balance Models, and Numerical models. Further, according to their functionalities, one may classify them into aquifer parameter estimation models, flow models, contaminant transport models, and coupled models. Again a model may be classified depending upon the domain where it is applicable, like unsaturated flow model, saturated flow model, fractured aquifer model etc. It may be noted that even though fractured rocks and fractured porous media may behave like an equivalent porous media with regard to certain flow conditions and contaminant transport phenomena, they deserve separate treatment as they are governed by different processes. Likewise, flow and contaminant transport issues in unsaturated zones are also governed by nonlinear processes different from that of Darcy's law. Also, groundwater models may be subdivided according to their objectives, as: Prediction models; Identification or evaluation models; Management models. Flow domain (determined by the hydrogeological setup) also classifies models into one dimensional, two-dimensional or three-dimensional model.

Depending on the numerical technique employed in solving the mathematical model, there exist several types of numerical models: finite-difference models, finite-element models, boundary-element models, particle tracking models (method of characteristics, random walk models), and integrated finite-difference models.

2.8.2.1 Analytical modeling software

Analytical models offer straightforward answers towards evaluation of the physical characteristics of an aquifer system. These models enable one to carry out a preliminary analysis of the groundwater system/ flow aspects and contamination. Even though a number of simplifying assumptions with respect to flow/ transport are necessary to get an analytical solution in an analytical model, its utility in real life situations is valuable as an initiating tool, particularly where few data are available. Because of, complex numerical models are of limited use when there is scanty data. Nonetheless, application of analytical models to field situations demands good professional judgment and experience. Analytical models may be considered complementary to numerical models. Once sufficient data is available, numerical models can be used for evaluation/ simulation or decision making.

2.8.2.2 Numerical modeling software

In most of the practical cases, analytical solutions of the mathematical models are not feasible. Therefore, mathematical models are transformed into numerical models, which in turn are solved by specially designed computer codes. These codes account for physical aspects, Modeling aspects, and optimal management. As a first step towards numerical groundwater modeling, the natural system is to be conceptualized into an idealized system to be amenable to physical laws/ mathematical representations. Once the conceptual model is translated into a mathematical model in the form of governing equations, with associated boundary and initial conditions, a solution can be obtained by transforming it into a numerical model and writing a computer program for solving it using a digital computer.

Different numerical techniques may be employed in solving the set of algebraic equations representing the partial difference governing equations of the mathematical model. In a numerical model, the solution is sought for the numerical values of state variables only at specified points in space and time domains defined for the problem. The input data for a numerical groundwater model include natural and artificial stresses, parameters, dimensions, and physico-chemical properties of all aquifers considered in the model. A finer level of detail of the numerical approximation (solution) greatly increases the data requirements. Input data for aquifers are common values such as transmissivities, aquitard resistances, abstraction rates, groundwater recharges, surface water levels etc. The most common output data are groundwater levels, fluxes, velocities and changes in these parameters due to stresses put into the model.

2.8.3 Available groundwater models

Since 1970s, numerous groundwater models have been formulated in public domain as well as on commercial basis. The earlier attempts of development of groundwater software were towards analytical models with simplified assumptions and confined to one or two dimensional flow domains. With the advancement in digital computing technology, later part of twentieth century and recent years saw development of more sophisticated groundwater models that can be interfaced with GIS environment or coupled with other models for input and even to form decision support systems. It may be clearly discernible that in the evolution process of these models, the capabilities and precision have also been steadily improving with improved technology and more refined knowledge of governing aquifer processes.

The *groundwater modeling software* is generic name, and it includes models pertaining to groundwater flow, solute transport in groundwater flow, geochemical reactions in groundwater flow, groundwater/ surface water interaction, variably-saturated flow and solute transport, streamflow-based programs, and analysis of various aquifer tests.

Enlisting all relevant milestones in the history of groundwater model development may be beyond the scope of the article. Nonetheless, an application-wise listing of some of the popular/ important groundwater related software is given below (year of release of latest version is given in bracket) in Table 2.3.

Table 2.3 Groundwater models and their brief description

Model (Year of release)	**Description of the model**
Groundwater (Saturated) Flow	
GFLOW (2015) (License based)	Developed by Haitjema Software Group. It is an efficient stepwise groundwater flow modeling system based on the analytic element method. It models steady state flow in a single heterogeneous aquifer using the Dupuit-Forchheimer assumption. It is particularly suitable for modeling regional horizontal flow and also facilitates detailed local flow modeling. GFLOW supports a MODFLOW-extract option to automatically generate MODFLOW files in a user-defined area with aquifer properties and boundary conditions provided by the GFLOW analytic element model. GFLOW also supports conjunctive surface water and groundwater modeling using stream networks with calculated base flow.
GMS (2013) (License based)	GMS (Groundwater Modeling System) was developed by Environmental Modeling Research Laboratory or EMRL, USA.A comprehensive package which provides tools for every phase of a groundwater simulation including site characterization, model development, post-processing, calibration, and visualization. It features 2D and 3D geostatics, stratigraphic modeling and a conceptual modeling approach. It supports MODFLOW, MODPATH, MT3DMS, RT3D, FEMWATER, SEEP2D and UTEXAS.
HYDROTHERM (2008)	*Developed by the USGS for simulation of Two-Phase groundwater flow and heat transport in the temperature range of 0 to 1200 ^{o}C.It is*

Model (Year of release)	Description of the model
(Available in Public domain)	*a three-dimensional finite-difference model with graphical user interface to define simulation, running the HYDROTHERM simulator interactively, and display of results.*
MODFE (1998) (Available in Public domain)	Developed by the USGS. It is a modular finite-element model for areal and axi-symmetric groundwater flow problems and it is based on governing equations that describe two-dimensional and axisymmetric-radial flow in porous media. It is written in FORTRAN 77.
MODFLOW (MODFLOW-96, MODFLOW-2000, MODFLOW-2005) (Available in Public domain)	Developed by the USGS. It is a block-centered finite difference code for steady-state and transient simulation of two-dimensional, quasi-three-dimensional, and fully three-dimensional saturated, constant density flow problems in combinations of confined and unconfined aquifer-aquitard systems above an impermeable base. MODFLOW-2005 versionis the most stable version of MODFLOW series The family of MODFLOW-related programs now includes groundwater/surface water systems, solute transport, variable density flow (including saltwater), aquifer-system compaction and land subsidence, parameter estimation, and groundwater management. It is written in FORTRAN 77.
MODFLOW (MODFLOW-96, MODFLOW-2000, MODFLOW-2005): MODPATH (2012) (License based)	USGS particle-tracking post processing model for MODFLOW that was developed to compute three-dimensional flow paths using output from steady state or transient groundwater flow simulations by MODFLOW.
MODFLOW-NWT (2014)	The USGS MODFLOW-NWT is a Newton-Raphson formulation for MODFLOW-2005 to improve solution of unconfined groundwater-flow problems. MODFLOW-NWT is a standalone program that is intended for solving problems involving drying and rewetting nonlinearities of the unconfined groundwater-flow equation. The Surface-Water Routing (SWR1) and Seawater Intrusion (SWI2) Packages are also included in the MODFLOW-NWT.
MODFLOW-OWHM (2014) (Available on request)	MODFLOW-based integrated hydrologic flow model for the analysis of human and natural water movement within a supply-and-demand framework developed by USGS. It allows the simulation, analysis, and management of human and natural water movement within a physically-based supply-and-demand framework.
MODFLOW-USG (2015) (Available on request)	Unstructured grid version of MODFLOW for simulating groundwater flow and tightly coupled processes. Developed by USGS to support a wide variety of structured and unstructured grid types, including nested grids and grids based on prismatic triangles, rectangles, hexagons, and other cell shapes.
MODOPTIM (2005) (Available on request)	Developed by the USGS. A general optimization program for groundwater flow model calibration and groundwater management in MODFLOW tool that simulates flow with MODFLOW-96 as a subroutine. Water levels, discharges, water quality, subsidence, and pumping-lift costs are the five direct observation types that can be compared in MODOPTIM.

Model (Year of release)	Description of the model
Visual MODFLOW Flex.(License based)	It is promoted by Waterloo Hydrogeologic. The Visual MODFLOW Flex is a graphical user interface for MODFLOW groundwater simulations. It brings together industry-standard codes for groundwater flow and contaminant transport, essential analysis and calibration tools, and stunning 3D visualization capabilities in a single. With Visual MODFLOW Flex, groundwater modelers have all the tools required for addressing local to regional-scale water quality, groundwater supply, and source water protection issues.
FEFLOW (2013) (License based)	Developed by DHI with user interface supports. It is a 2D/3D finite element subsurface flow system - model for density dependent groundwater flow, heat flow and contaminant transport with GIS interface. The program uses finite element analysis to solve groundwater flow equation of both saturated and unsaturated conditions as well as mass and heat transport, including fluid density effects and chemical kinetics for multi-component reaction systems.
Solute Transport (Saturated Flow)	
SUTRA (2014) (Available in Public domain)	Developed by the USGS. SUTRA is a finite-element simulation model for 2D or 3D saturated-unsaturated, fluid-density-dependent ground-water flow with energy transport or chemically-reactive single-species solute transport model. The model employs a two-dimensional hybrid finite-element and integrated-finite-difference method to approximate the governing equations that describe the two interdependent processes that are simulated:(1) fluid density-dependent saturated or unsaturated ground-water flow, and either (2) transport of a solute in the ground water, and (3) transport of thermal energy in the ground water and solid matrix of the aquifer.
HST3D (2005) (Available in Public domain)	Developed by the USGS. It simulates groundwater flow and associated heat and solute transport in three dimensions. The HST3D program may be used for analysis of problems such as those related to sub-surface-waste injection, landfill leaching, saltwater intrusion, freshwater recharge and recovery, radioactive-waste disposal, hot-water geothermal systems, and subsurface-energy storage. The three governing equations are coupled through the interstitial pore velocity, the dependence of the fluid density on pressure, temperature, and solute-mass fraction, and the dependence of the fluid viscosity on temperature and solute-mass fraction. The solute-transport equation is for only a single, solute species with possible linear-equilibrium sorption and linear decay. Finite-difference techniques are used to discretize the governing equations using a point-distributed grid.
MT3D (2010) (Available in Public domain)	Developed by the USGS. It is a modular 3-D multi-species transport model for simulation of advection, dispersion, and chemical reactions of contaminants in groundwater systems coupled with MODFLOW.
HYDRUS (2014) (License based)	A software package developed by PC-Progress Engineering Software Developer of Czech Republic for simulating water, heat, and solute movement in two- and three-dimensional variably saturated media. The software package consists of a computational

Model (Year of release)	Description of the model
	computer program and an interactive graphics-based user interface.
MOC3D (2004) (Available in Public domain)	USGS three-dimensional method-of-characteristics groundwater flow and transport model. The model computes changes in concentration of a single dissolved chemical constituent over time that are caused by advective transport, hydrodynamic dispersion including both mechanical dispersion and diffusion), mixing (or dilution) from fluid sources, and mathematically simple chemical reactions (including linear sorption, which is represented by a retardation factor, and decay).The model can also simulate ground-water age transport and the effects of double porosity and zero-order growth/loss.
SEAWAT (2012) (Available in Public domain)	SEAWAT developed by the USGS is a generic MODFLOW/MT3DMS-based computer program designed to simulate three-dimensional variable-density groundwater flow coupled with multi-species solute and heat transport. SEAWAT uses the familiar structure of MODFLOW and MT3DMS. It also allows to work with many of the MODFLOW-related software programs, such as MODPATH, ZONEBUDGET, and parameter estimation programs.
SHARP (2004) (Available in Public domain)	It was developed by the USGS. It is a quasi-three-dimensional finite-difference model to simulate freshwater and saltwater flow in layered coastal aquifer systems.
Unsaturated Flow and Transport	
MF2K-VSF (2006) (Available in Public domain)	USGS developed a three-dimensional finite-difference groundwater model (MODFLOW) 2000 version with variably saturated flow.
R-UNSAT (2006) (Available in Public domain)	Reactive, multispecies transport in a heterogeneous, variably-saturated porous media.
SUTRA (2014) (Available in Public domain)	2D and 3D, variable-density, variably-saturated flow, solute or energy transport.
VS2DH (2004) (Available in Public domain)	A graphical software package for simulating for simulation of water and energy transport developed by USGS.
VS2DI (2004) (Available in Public domain)	A graphical software package for simulating fluid flow and solute or energy transport in variably saturated porous media. It allows gravity driven vertical flow out of the domain assuming a unit vertical hydraulic gradient but does not allow flow into the domain. The VS2DI software package includes three applications: VS2DTIfor simulation of water and solute transport, VS2DHI for simulation of water and energy transport, and VS2POST a standalone postprocessor for viewing results saved from previous simulation runs.
VLEACH (2007) (Available in Public	Developed by the US -EPA. It is a one-dimensional, finite difference model for making preliminary assessments of the effects on

Model (Year of release)	Description of the model
domain)	groundwater from the leaching of volatile, sorbed contaminants through the vadose zone. The program models four main processes: liquid-phase advection, solid-phase sorption, vapor-phase diffusion, and three-phase equilibrium.
HELP (1994) (Available in Public domain)	HELP (Hydrologic Evaluation of Landfill Performance) is a hydrologic numerical model developed by the US-EPA for landfill. The model uses a water-balance approach to model evapotranspiration and drainage through soil layers. It is a quasi-two-dimensional, deterministic, water-routing model for determining water balances.
Groundwater Flow & Transport with Geochemical Reactions	
PHAST (2014) (Available in Public domain)	Developed by the USGS. It simulates groundwater flow, solute transport, and multi-component geochemical reactions.
PHREEQC (2012) (Available in Public domain)	Developed by the USGS. It is a computer program for speciation, batch-reaction, one-dimensional transport, and inverse geochemical calculations. It is a 1-D advective reaction-transport model.
Groundwater/ Surface-Water Interactions	
GSFLOW (2015) (Available in Public domain)	Developed by the USGS. It is a coupled groundwater and surface water flow model based on the USGS Precipitation-Runoff Modeling System (PRMS) and modular groundwater flow model (MODFLOW-2005). It simulates groundwater/surface-water flow in one or more watersheds by simultaneously simulating flow across the land surface, within subsurface saturated and unsaturated materials, and within streams and lakes. It considers climate data consisting of measured or estimated precipitation, air temperature, and solar radiation, as well as groundwater stresses and boundary conditions.
Groundwater Management	
GWM (2015) (Available in Public domain)	Developed by the USGS. Groundwater Management process for MODFLOW using optimization. Current Versions include GWM-2005 and GWM-VI. It uses a response-matrix approach to solve several types of linear, nonlinear, and mixed-binary linear groundwater management formulations. Each management formulation consists of a set of decision variables, an objective function, and a set of constraints.
Stream flow Based Groundwater Models	
PART (2012) (Available in Public domain)	Developed by the USGS. A computer program for base-flow-record estimation.
PULSE (2007) (Available in Public domain)	Developed by the USGS. Model-estimated groundwater recharge and hydrograph of groundwater discharge to a stream. It also allows for a gradual hydrologic gain or loss term in addition to the instantaneous pulse, to simulate the effects of gradual recharge to water table, groundwater evapotranspiration, or downward leakage to a deeper aquifer.
RECESS (2012) (License based)	Developed by the Scientific Software Group. RECESS comprises a group of six programs (RECESS, RORA, PART, TRANS, CURV

Model (Year of release)	Description of the model
	and STREAM) for describing the recession of groundwater discharge and for estimating mean groundwater recharge and discharge from streamflow records.
RORA (2012) (Available in Public domain)	The recession-curve-displacement method for estimating recharge is used for the analysis of streamflow records using data in a particular format developed by the USGS
Aquifer Test Analysis Models	
AIRSLUG (1996) (Available in Public domain)	Developed by the USGS. It is a Fortran program to generate type curves to interpret the recovery data from prematurely terminated air-pressurized slug tests. Air-pressurized slug tests offer an efficient means of estimating the transmissivity (T) and storativity (S) of aquifers.
Analyze HOLE (2009) (Available in Public domain)	An integrated well bore flow analysis tool developed by the USGS.
AQTESTSS (2004) (Available in Public domain)	Developed by the USGS. Several spreadsheets for the analysis of aquifer-test and slug-test data. Each spreadsheet incorporates analytical solution(s) of the partial differential equation for ground-water flow to a well for a specific type of condition or aquifer.
BAT3 Analyzer (2008) (Available in Public domain)	Developed by the USGS. It provides real-time display and interpretation of fluid pressure responses and flow rates measured during geochemical sampling, hydraulic testing, or tracer testing conducted with the Multifunction Bedrock-Aquifer Transportable Testing Tool (BAT3).
FLASH (2011) (Available in Public domain)	Developed by the USGS. FLASH (Flow-Log Analysis of Single Holes) is a computer program for the analysis of borehole vertical flow logs. It is based on an analytical solution for steady-state multi-layer radial flow to a borehole. The code includes options for (1) discrete fractures and (2) multi-layer aquifers. Given vertical flow profiles collected under both ambient and stressed (pumping or injection) conditions, the user can estimate fracture (or layer) transmissivities and far-field hydraulic heads.
WTAQ (2012) (Available in Public domain)	Developed by the USGS for calculating drawdowns and estimating hydraulic properties for confined and water-table aquifers. It is based on an analytical model of axial-symmetric ground-water flow in a homogeneous and anisotropic aquifer. The program allows for well-bore storage and well-bore skin at the pumped well and for delayed drawdown response at an observation well.
AQTESOLV (2014) (License based)	Developed by HydroSOLVE Inc. It is a software for slug test analysis including methods for single and multi-well tests, over-damped and under-damped conditions, wells screened across the water table, and for all type of aquifers.
Groundwater Flow and Transport Models in Fractured Mediat	
BIOF&T (1995) (License based)	Developed by Scientific Software Group. It simulates biodegradation and bioremediation, flow and transport in the saturated/unsaturated zones in 2 or 3 dimensions in heterogeneous, anisotropic porous

Model (Year of release)	Description of the model
	media or fractured media. It considers convection, dispersion, diffusion, adsorption and microbial processes based on oxygen limited anaerobic first order or Monod-type biodegradation kineticsas well as anaerobic or first-order sequential degradation involving multiple daughter species.
HYDRO-GEO-SPHERE (2013) (Licensebased)	HydroGeoSphere(HGS) developed by Aquanty Inc., Canadais a 3D control-volume finite element groundwater model based on a rigorous conceptualization of the hydrologic system consisting of surface and subsurface flow regimes in fractured or unfractured porous media. For each time step, the model solves surface and subsurface flow, solute and energy transport equations simultaneously, and provides a complete water and solute balance. Originally, it was known as FRAC3DVS. It uses a globally-implicit approach to simultaneously solve 2D diffusive-wave equation and 3D form of Richards' equation.
SWIFT (1998) (License based)	Developed by Integrated Groundwater Modeling Centre, Colorado. It is athree-dimensional transient flow in fractured or unfractured, anisotropic, heterogeneous porous media. Viscosity dependency as a function of temperature and brine concentrations.
Analytical Groundwater Models	
MPNE1D (Available in Public domain)	Developed by S.S. Papadopulos & Associates, Inc. It is a general analytical solution for one-dimensional solute transport is based on FORTRAN90 code that implements the general analytical solution for one-dimensional solute transport.
3DADE (Available in Public domain)	Developed by the USDA. It is a Fortran computer program for evaluating a series of analytical solutions of the 3-dimensional advection-dispersion equation. The analytical solutions pertain to three-dimensional solute transport during steady unidirectional water flow in porous media with uniform transport and flow properties. The transport equation contains terms accounting for solute movement by advection and dispersion, as well as for solute retardation, first-order decay, and zero-order production.
AGU-10 (Available in Public domain)	A collection of screening level analytical flow and transport programs for homogeneous, isotropic flow fields, based on the American Geophysical Union's Water Resources Monograph 10. Developed by Integrated Groundwater Modeling Center (IGWMC). It consists of five simulation programs in FORTRAN and two pre-/postprocessors in Microsoft BASIC.
AT123D (License based)	Developed by Scientific Software Group. It is based on an analytical solution for transient one-, two-, or three-dimensional transport of a dissolved chemical or radionuclide or heat in a homogeneous aquifer with uniform, stationary regional flow. It models for long-term pollutant fate and migration in groundwater -advection, dispersion, adsorption and decay.
CAPZONE (Available in Public domain)	Developed by Integrated Groundwater Modeling Centre, Colorado. An analytical flow model that can be used to construct groundwater flow models of two-dimensional flow systems characterized by isotropic and homogeneous confined, leaky-confined, or unconfined

Model (Year of release)	Description of the model
	flow conditions.
ONE-D (Available in Public domain)	Developed by the USDA. It is a package of five analytical models of the one-dimensional convective-dispersive transport equation with linear adsorption, zero-order production, and first-order decay.

2.8.4 Selection of modeling software

Some of the frequently used groundwater models (software packages), under various categories and applications, have been listed in Table 3. Many of those models are multi-functional (like simulation of flow/ surface water-groundwater interaction/ solute transport etc.). As such, it may not be possible to confine these groundwater models to a particular category, and then to enlist strictly under that category. Their functionality spreads over a few different categories.

The important aspects to be reckoned with in a groundwater model study are, therefore, model applicability to specific problem, ease of its use, transparency, accuracy of results, closeness in emulating natural aquifer processes in the model, portability, adaptability as well as input data requirements. In recent years, groundwater models as software packages have been developed for almost all classes of problems encountered in the management of groundwater. Some models are very comprehensive and can handle a variety of specific problems as special cases, while others are tailor-made for particular problems. Therefore, in order to make a wise choice of the right model for a given investigation, a modeler need to have prior knowledge of the factors mentioned earlier.

Another significant issue is with regard to freedom in the assignment of input parameters and data. Coping up with the technological advancements, the groundwater models are also under continuous refinement or modifications. Considering the large variability and quick development of groundwater models, a new and more sophisticated model may often replace a previously applied model. Additionally, the reconsideration of the conceptual model and regeneration of the mesh may need a new allocation of the parameters. Therefore, it is important that model data (information) are stored independently from a given model, with a preference for GIS based databases. This makes the set-up and modification of models easier and time effective (e.g. Visual MODFLOW/ FEFLOW). Such popular groundwater models, with modular structure, incorporate mathematical modeling with GIS based data exchange interfaces.

2.8.5 Review of popular groundwater models

Management of groundwater involves determining the quantity and quality of groundwater movement over time and space as influenced by natural processes and human activities. Unlike surface water conditions, groundwater observations are limited to boreholes and pumping test, and thus understanding the hydrogeological system as well as predicting changes is more difficult due to management activities. Therefore, the ability to characterize groundwater systems and to develop and evaluate resource management strategies for sustainable water allocation is greatly dependent on groundwater model predictions. In India, groundwater models are used by water resources managers for:

- Characterizing aquifer properties
- Evaluating groundwater pumping impacts on groundwater levels
- Quantifying sustainable yield
- Identifying groundwater recharge zones and determining the placement and design of groundwater recharge structures (e.g. check dams, tanks, recharge wells),
- Evaluating proposed policies and projects
- Developing conjunctive management strategies
- Developing aquifer storage systems
- Determining the fate and transport of chemical solutes in groundwater
- Computing the saline intrusion in coastal zones
- Evaluating the economic impact of groundwater conditions
- Communicating groundwater quality and quantity conditions to policy makers and stakeholders.

Often, groundwater models are developed to satisfy multiple uses. Distributed hydrogeological models (DHgMs) are physically-based distributed models that represent groundwater movement using 2-D or 3-D gridded finite difference and finite volume solutions based on Darcy's equations. Simulations include both steady-state and transient simulations. The data requirements for DHgMs include the aquifer thickness, hydrogeological parameters (e.g. hydraulic conductivity, transmissivity), boundary conditions (e.g. constant flow, fixed head, non-flow), groundwater recharge, and pumping rates. Typical output includes groundwater heads, drawdown, flow magnitude and direction, and water budgets throughout the Modeling domain. If simulating water quality is required, capabilities include the fate and transport of chemicals and, for some packages, the temperature and multi-density flow (saline intrusion). DHgMs are applicable for the uses listed above and have been successfully applied to aquifers in India.

Borden (2015) has evaluated six DHgM including GMS, Groundwater Vistas, MODFLOW, iMOD, MIKE SHE, and Visual MODFLOW. General descriptions of each package are listed below:

- **GMS** (Aquveo) is a groundwater modeling system, based on MODFLOW code, which provides tools for every phase of a groundwater simulation including site characterization, model development, post-processing, calibration, and visualization.GMS supports TINs, solids, borehole data, 2-D and 3-D geostatistics, finite element, and finite difference model. Currently supported models include MODFLOW, MODPATH, MT3D, RT3D, FEMWATER, SEEP2-D, SEAM3D, PEST, UCODE and UTCHEM. Due to the modular nature of GMS, a custom version of GMS with desired modules and interfaces can be configured. Detailed information regarding GMS is available at:

  http://www.aquaveo.com/software/gms-groundwater-modeling-system-introduction.

- **Groundwater Vistas** (Rockware) is a Windows Modeling environment for the MODFLOW family of model that allows for the quantification of uncertainty. Groundwater Vistas includes a series of tools for assessing risk using more complex and real-world groundwater model. Detailed information regarding Groundwater Vistas is available at: https://www.rockware.com/product/overview.php?id=147.

- **iMOD** (Deltares) is an open source, easy to use Graphical User Interface + an accelerated Deltares-version of MODFLOW with fast, flexible and consistent sub-domain Modeling techniques. iMOD facilitates very large, high resolution MODFLOW groundwater Modeling and also geo-editing of the subsurface. iMOD also facilitates interaction with SEAWAT (for density-dependent groundwater flow) and MT3D (groundwater quality).See detailed information regarding iMOD at: http://oss.deltares.nl/web/imod/about-imod.
- **MODFLOW** (USGS) is 3-D finite-difference groundwater model first published in 1984.Although originally conceived solely as a groundwater-flow simulation code, MODFLOW's modular structure has provided a robust framework for integration of additional simulation capabilities that build on and enhance its original scope. The family of MODFLOW-related programs now includes capabilities to simulate coupled groundwater/surface-water systems, solute transport, variable-density flow (including saltwater), aquifer-system compaction and land subsidence, parameter estimation, and groundwater management. The MODFLOW program is free, open-source software. The software can be used, copied, modified, and distributed without any fee or cost. For information regarding MODFLOW visit: http://water.usgs.gov/ogw/modflow/.
- **MIKE SHE** (DHI) is an integrated hydrological Modeling system for simulating surface water flow and groundwater flow. MIKE SHE simulates the entire hydrologic cycle and allows components to be used independently and customized to local needs. MIKE SHE can be used for the analysis, planning, and management of a wide range of water resources and environmental problems related to surface water and groundwater, especially surface water impact from groundwater withdrawal; conjunctive use of groundwater and surface water; wetland management and restoration; river basin management and planning; and impact studies for changes in land use and climate. MIKE SHE can be used at multiple scales (local to basin wide) and simulates detailed water management operations. Information regarding MIKE SHE can be found at: http://www.mikepoweredbydhi.com/products/mike-she.
- **Visual MODFLOW** (Waterloo Hydrogeologic Software) simplifies model development by providing a workflow driven GUI to guide construction and use of groundwater flow and contaminant transport model. Model development is broken into model development, simulation, and output modules guiding the modeller through the development. It comes with pre-processing and post-processing tools; MODFLOW-88, MODFLOW-96, MODFLOW 2000, and MODFLOW-2005; MT3D, MT3DMS, RT3D and MOC3D; PMPATH 99; and UCODE and PEST-ASP. For detailed information, visit:http://www.novametrixgm.com/groundwater-modeling-software/visual-modflow-flex.

2.8.5.1 Computational capabilities

All packages support a 3-D gridded finite difference model, allowing for construction of multilayer models with varying hydrogeological parameters throughout the domain that are able to simulate flows in confined and unconfined aquifers. The MODFLOW engine based software enables modellers to vary grid cell sizes within the domain for greater grid resolution in regions of interest (e.g. proposed groundwater pumping area or chemical spill). MODFLOW-USG simulates groundwater flow with finite volume solutions, allowing for unstructured grids. iMOD uses an accelerated version of the MODFLOW engine. MIKE SHE uses a 3-D gridded finite difference model based on the Darcy's equations to simulate groundwater movement. The grid in MIKE SHE is fixed throughout the model domain.

MODFLOW system consists of a core program that couples with a series of highly independent subroutines called packages. Each package simulates a specific feature of the hydrologic system (e.g. unsaturated zone flow, river flow), water quality (e.g. solute transport), or a specific method of solving equations that simulate the flow system. Packages supporting calibration routines in PEST (model-independent parameter estimation and uncertainty analysis) and Monte Carlo analysis for quantifying uncertainty are available. MODFLOW's use of packages allows users the ability to examine specific hydrologic features of the model independently, as well as the facilitation for new packages that can be added without modifying existing programs. A list of the MOFLOW packages can be found at http://water.usgs.gov/ogw/modflow/MODFLOW.html. The foundation code for GMS, Visual MODFLOW, and Groundwater Vistas use the MODFLOW engine.

MIKE SHE's structure includes dynamically linked modules to compute saturated zone flow, evapotranspiration, overland flow, river and lake flow, unsaturated zone flow, and anthropogenic use (e.g. irrigation, groundwater pumping, irrigation drains) to allow for the examination of the full hydrologic cycle. For each module, several numerical methods are available, granting flexibility to adjust given the question being addressed and the data available. MIKE SHE can be coupled with the Auto-calibration module to assist in calibration of groundwater model. Within the Auto-calibration module is the ability to perform uncertainty analysis through several methods.

Water quality applications in India include salinity in irrigation, fate and transport of chemical spills, and the prediction of saline intrusion along coastal zones. MODFLOW, iMOD, and MIKE SHE offer multiple means to compute this water quality. Transport packages associated with MODFLOW includeMT3DMS, MT3D99, SEAWAT, RT3D and PHT3Detc. GMS, Visual MODFLOW, and Groundwater Vistas support the use of many of these packages.

iMOD uses the D-Water Quality module that simulates almost any water quality variable and its related water quality processes. A full description is supplied in the Delft 3D Suite water quality description of flooding models. MIKE SHE addresses water quality with ECO LAB, an open-ended ecological and water quality modeling framework that allows user-defined equations and water quality model to be defined. Templates are available for standard constituents to expedite water quality modeling. In India, MIKE SHE with ECO

LAB was used to evaluate the effects of rainwater harvesting on the leakage from an ash-pond on the site of the Himavat Thermal Power Plant.

2.8.5.2 Overview of GUI

ModelMuse (USGS's GUI for MODFLOW), iMOD, GMS, Visual MODFLOW, and Groundwater Vistas use the MODFLOW engine and modules as the simulation base, but have built-in tools for expediting and enhancing the Modeling process. These include site characterization, model development, post-processing, calibration, and visualization. All applications are developed for operation with Windows, though MODFLOW works on Windows, OSX, Linux, and Unix platforms.

All packages evaluated are well supported with sophisticated GUI interfaces for inputting data and viewing results. USGS has developed ModelMuse to support MODFLOW, an interface that provides the basics in editing and viewing function. Third party software including GMS, Visual MODFLOW, and Groundwater Vistas offer more sophisticated visualization and post-processing wrappers around the MODFLOW engine and modules, providing a workflow driven GUI to guide construction, use, and resulting presentation from the groundwater flow and contaminant transport model. Model development is broken into model development, simulation, and output modules, thus guiding the modeller through the development. A 3-D visualization and animation package, 3-D groundwater explorer, is also included.

2.8.5.3 Licensing and support

ModelMuse and iMOD are open source software packages for use in developing groundwater models. Both are supported with manuals, online tutorials, and user forums. Additional support from Deltares and training courses can be purchased and offered for using iMOD. The USGS does not provide training courses, but third party organizations offer MODFLOW courses for a fee.

GMS, Visual MODFLOW, and Groundwater Vistas require licenses. License fees begin from around Rupees 1 lakh per seat for basic model and increases with added interface functionality (pre-processing, post-processing, visualization) and access to additional MODFLOW packages. All packages have online tutorials and courses to promote faster learning. Vendors provide training courses for a fee.

MIKE SHE requires a license that allows access to the core mode functionality listed above, pre- processing and post-processing tools, and limited support during the year. Service maintenance agreements can be purchased annually for additional support, and consulting services are also available. Additional modules for water quality simulations, control structures, and auto-calibration routines are additional cost. The model is supported with manuals, tutorials, training courses, and online materials. Starting at 5.5 lakh INR/seat, MIKE SHE is the most expensive option of the DHgM packages evaluated.

2.8.5.4 Choice of groundwater model

The evaluation matrix for the distributed hydrogeological models has been presented in Table2.4. It provides the evaluation by Borden (2015) for the modeling software packages

- GMS, iMod, MIKE SHE, Groundwater Vistas, MODFLOW, MODFLOW-OWHM and Visual MODFLOW. It presents the evaluation (Best, Good, Fair, Poor) under the categories GUI Overview, Licensing/Software Support, and other Modeling issues (3D Mesh, Multicore Processing, Groundwater Pumping, Surface Water, Overland Flow, Unsaturated Zone, Groundwater, Groundwater Recharge, Water Quality).

Table 2.4 Evaluation Matrix for the Distributed Hydrogeological Models (Borden, 2015)

	GUI Overview (General)						Licensing/Software Support													
Software Package	Operating Systems	Workflow Guidance	Pre-Processing Tools	Post-Processing Tools	GIS Interface	Animations	Cost Government Agency	Service Maintenance Agreement	Support	Indian Applications	Worldwide Licenses	3D Mesh	Multicore Processing	Ground water Pumping	Surface Water	Overland Flow	Unsatruated Zone	Groundwater	Groundwater Recharge	Water Quality
GMS	Good	Best	Best	Best	Best	Poor	Fair	Best	Best	?	Good	Best	Best	Good	Fair	Fair	Fair	Best	Good	Best
iMod	Good	Best	Best	Best	Best	Best	Best	Best	Best	?	Good	Best	Best	Good	Fair	Fair	Fair	Best	Good	Best
MIKE SHE	Good	Best	Best	Best	Good	Best	Poor	Best	Best	Fair	Good	Fair	Best	Best	Best	Best	Best	Best	Best	Best
Groundwater Vistas	Good	Best	Best	Best	Best	Poor	Fair	Best	Best	?	Good	Best	Good	Good	Fair	Fair	Fair	Best	Good	Best
MODFLOW	Best	Fair	Fair	Fair	Good	Poor	Best	Poor	Poor	?	Best	Best	Best	Good	Fair	Fair	Fair	Best	Good	Best
MODFLOW-OWHM	Best	Fair	Fair	Fair	Good	Poor	Best	Poor	Poor	?	Fair	Best	Best	Good	Good	Good	Good	Best	Good	Best
Visual MODFLOW Flex	Good	Best	Best	Best	Best	Poor	Fair	Best	Best	?	Good	Best	Best	Good	Fair	Fair	Fair	Best	Good	Best

● Best ◑ Good ○ Fair ● (grey) Poor

All packages simulate groundwater quantity and quality using similar algorithms and offer support for users of their software packages. The difference between the evaluated software packages lies in the GUI interface and price of the software. Experienced groundwater modelers familiar with developing MODFLOW model natively or with using GMS, Visual MODFLOW, and Groundwater Vistas will likely want to remain with the software with which they are familiar and can use efficiently.

GMS provides a platform to support the modular nature of MODFLOW while Visual MODFLOW provides GUI that guides groundwater model development through a straightforward workflow. iMOD, with the pre-processing and post-processing, strong visualization abilities, strong support, and open source availability, may also be the strong candidate of the groundwater models evaluated and can be preferred for groundwater Modeling. While MIKE SHE simulates groundwater, its fixed grid system and licensing fee limits adoption for strictly groundwater simulations. MIKE SHE shines in situations where it is important to simulate the interaction between surface water and groundwater.

2.9 Way Forward

Groundwater, one of the India's most important natural resources, is under constant threat of exploitation with increasing population and economic development. Proper understanding and modeling of subsurface water movement has been an enduring challenge for hydrologists and practitioners. Current modeling efforts are plagued by the complex heterogeneity within the subsurface, reconciliation with spatial and temporal scales, and lack of supporting data. Long-term consequences of droughts in aquifers and efficient management of the available resources in arid and semi-arid regions of the country deserve special attention. Assessing the potential impacts of climate change on groundwater is yet another long-term challenge that confounds both researchers and managers. Developing new models that account for uncertainties and provide more realistic assessment of predictive capabilities is needed for devising effective management practices. Current data acquisition techniques need to be improved for reliable modeling and impact studies. Some of the long standing challenges in groundwater are identified as follows:

1. Estimation of recharge is crucial for assessing sustainability of groundwater systems as it is the major replenishing mechanism for most aquifers. However, recharge rates to aquifer are among the most difficult to measure directly. Although these rates are key to conducting water balance studies, they are often treated as calibration quantities. Methods for estimating recharge rates and understanding how they are affected by Climate Changes are needed to assess the fate of groundwater storages and fluxes in the future.
2. Data challenges continue to plague modeling efforts. Complex models have too many parameters that need to be estimated accurately and independently for the models to be used at their full potential. Most efforts rely on calibration and corroboration exercises that are fraught with uncertainty in their own right. Field-scale experiments are time-consuming and costly. There is a need to devise non-expensive and rapid ways to accurately determine hydrogeologic parameters.
3. Heterogeneity is still perhaps the greatest challenge posed to hydrologists, both in terms of characterization and in terms of techniques needed to resolve sub-grid processes. Although some progress has been made in terms of assimilating large remotely-sensed data sets, appropriate algorithms and up-scaling techniques need to be developed.
4. Uncertainties in modeling and in defining climate change scenarios make it difficult to assess the state of future groundwater resources. Future climate scenarios are based on GCMs that do not have a strong groundwater component. Besides, models do not adequately represent the interactions with surface water storage and human intervention. Methods for quantifying and reducing these uncertainties need to be derived using advanced mathematical techniques, and modeling strategies.
5. With increasing threats from competing demands and mounting hydrologic stresses on the groundwater system, there is a pressing need to develop effective management strategies. Aquifer recharge and recovery operations are often met with constraints related to water quality and aquifer integrity. A major task ahead is bridging the gap between researchers and policy makers for successful implementation of conjunctive groundwater management decisions.
6. Fractured and hard rock flow and transport modeling in India have been less explored although the country has more than 70% hard rock areas; some of the reasons are: inadequate and unstructured databases, insufficient understanding of the hardrock

aquifer systems, etc. While the hard rock aquifers in India are under severe groundwater stresses, and failure of wells are very common.

7. India has initiated the task of "Aquifer Mapping" upto a depth of about 400 m and trying to develop groundwater management plan as policy matter.
8. Uptil now, the main focus of groundwater modeling activities in India was towards developing simulation models for groundwater development and formative aquifer responses from various recharge strategies. Discharge (demand) management has got limited attention in the groundwater modeling activities. Managed Aquifer Recharge (MAR) together with demand management in conjunction with surface and ground water under the framework of Integrated Water Resources Development and Management (IWRD&M) can be the most promising way forward towards the futuristic Optimization-Simulation Model.
9. MODFLOW-2005 and its related modules and other software, which are available in public domain and popularly accepted worldwide and have been found formed parts of most commercial software presently used world over, can be an excellent choice to explore further for fitting to Indian conditions. GSFLOW or coupling of SWAT with MODFLOW, both available in public domain, can also be thought as an alternative for IWRD&M. Further, Indian researchers, both in academia and R & D sectors, have developed a number of surface water, groundwater and hydrological models (published in reputed journals) based on knowledgebase and data of Indian conditions, rope in those research models and amalgamation of suitable models to the appropriate components of the MODFLOW framework can also been alternative.
10. Developing/customizing an Indian groundwater model – In view of the above considerations, it would be highly desirable to develop a groundwater model suitable for Indian meteorological, hydrological and hydrogeological conditions commensurate with corresponding availability of relevant data.

References

1. Al-Barwani, H.H., Al-Lawatia, M., Balakrishnan, E. and Purnama, A. (2000), Modeling Flow and Transport in Unsaturated Porous Media: A Review. Science and Technology, pp. 265-280.
2. Alley, W. M. (1986) Regression approximation for transport model constraints sets in combined aquifer simulation-optimization studies. Water Resour. Res., 22(4), 581–586.
3. Alley, William M,James W La Baugh, andThomas E Reilly, (2005). Groundwater as an element in the hydrologic cycle. Encyclopaedia of Hydrological Sciences. John Wiley & Sons, Ltd. DOI: 10.1002/0470848944.hsa153.
4. Anderson, M.P. and Woessner, W.W., (1992) Applied Groundwater Modeling: Simulation of Flow and Advective Transport, Academic Press, Inc., San Diego, CA., 381 p.
5. Anderson, M.P., W.W., Woessner, and R.J. Hunt (2015), Applied Groundwater Modeling: Simulation of Flow and Advective Transport, 2nd Edition, Elsevier, New York
6. Appel, C.A. and Reilly, T.E. (1988) Selected Reports That Include Computer Programs Produced by the U.S. Geological Survey for Simulation of Ground-Water Flow and Quality. WRI 87-4271. U.S.G.S., Reston, Virginia.
7. Balasubramanian, A. (2001), Overview of groundwater models. In: Modeling in Hydrogeology, Eds: L. Elango and R. Jayakumar, UNESCO-IHP, Allied Publishers, 2001, 17-24.
8. Bear, J. and A. Verruijt. 1987. Modeling Groundwater Flow and Pollution. Kluwer Academic

Publishers, Hingham, Massachusetts.
9. Bear, J. and Verruijt, A., 1987. Modeling Groundwater Flow and Pollution, D. Reidel Publishing Company, 414 p.
10. Bear, Jacob, (1972). Dynamics of fluids in porous media. American Elsevier, New York. 764p.
11. Bear, Jacob, (1979). Hydraulics of Groundwater. McGraw-Hill, New York. 567 p.
12. Bear, Jacob, Milovan S. Beljin, and Randall R. Ross, (1992). Fundamentals of groundwater modeling, EPA-Groundwater Issue, US-EPA, Solid Waste and Emergency Response.Report No. EPA/540/S-92/005, 1992.
13. Beck, M.B. (1985) Water Quality Management: A Review of the Development and Application of Mathematical Models. IIASA 11, Springer-Verlag, Berlin, West Germany.
14. Beljin, M.S. and P.K.M. van der Heijde (1989) Testing, Verification, and Validation of Two-Dimensional Solute Transport Models. In (G. Jousma et al., eds.) Groundwater Contamination: Use of Models in DecisionMaking. Kluwer Academic Publishers, Hingham, Massachusetts.
15. Borden, Carter (2015), "Water Resource Software - Overview and Review", Draft Report created for The World Bank, Centered Consulting International, LLC
16. Boutwell, S.H., Brown, S.M., Roberts, B.R., & Atwood, D.F. (1985) Modeling Remedial Actions of Uncontrolled Hazardous Waste Sites, EPA-540/2-85/001, US EPA, Cincinnati, Ohio.
17. CGWB(a), (2011). Dynamic Groundwater Resources of India (as on March, 2009). Ministry of Water Resources, Government of India, New Dehli: Central Ground Water Board. 225p.
18. CGWB(b), (2011). Selected Case Studies, Rainwater Harvesting and Artificial Recharge, Ministry of Water Resources, Government of India, New Dehli: Central Ground Water Board.
19. CGWB, (2002). Master Plan for Artificial Recharge to Ground Water in India. Ministry of Water Resources, Govt. of India: Central Ground Water Board.
20. CGWB, (2006). Dynamic Groundwater Resources of India (as on March, 2004). Ministry of Water Resources, Government of India, New Dehli: Central Ground Water Board. 120p.
21. CGWB, (2013). Master Plan for Artificial Recharge to Groundwater in India. Ministry of Water Resources, Government of India. 208p.
22. CGWB, (2014). Dynamic groundwater resources of India (As on 31st March, 2011). Ministry of Water Resources, Government of India. 279p.
23. Coppola, E. Jr., Poulton, M., Charles, E., Dustman, J., and Szidarovszky, F. (2003)Application of artificial neural networks to complex groundwater management problems. Nat. Resour. Res., 12(4), 303–320.
24. De Marsily, G (1986) Quantitative Hydrogeology. Academic Press, Inc., Orlando, Florida.
25. Dershowitz, W.S., La Pointe, P. R., & Doe, T.W. (2004). Advances in discrete fracture network Modeling. Procedings of 2004 US EPA/NGWA Fractured Rock Conference: State of the Science and Measuring Success in Remediation. Portland, Maine.
26. Domenico, P.A. (1972) Concepts and Models in Groundwater Hydrology. McGraw-Hill, New York, New York.
27. Domenico, P.A., Schwartz, F.W. (1998), Physical and Chemical Hydrogeology. John Wiley & Sons, New York [2nd Ed.]: 506 pp.
28. Feddes, R.A., Kabat, P., Van Bakel, P.J.T.,Bronswijk, J.J.B and Halbertsma, J. (1988), Modeling Soil Water Dynamics in the Unsaturated Zone - State of the Art. Journal of Hydrology, Vol. 100, pp. 69-111.
29. Garduno, Hector, Saleem Romani, B. Sengupta, Albert Tuinhof, and Richard Davis, (2011). India Groundwater Governance – Case Study. Water Partnership Program. 63p.
30. Gelhar, L.W. (1986) Stochastic Subsurface Hydrology from Theory to Applications. Water Resources Research, v. 22, no. 9, pp. 135S-145S.
31. Gerke, H.H., & van Genuchten, M.T. (1993). A dual-porosity model for simulating the preferential movement of water and solutes in structured porous media. Water Resources Research, 29(2), 305-319.
32. Ghosh, N.C., and K. D. Sharma (Eds.), (2006). Groundwater Modeling and Management.Capital Publishing Company, New Delhi, 634p.

33. Ghosh, S. and Kashyap, D. (2012a) Kernel Function Model for Planning of Agricultural Groundwater Development, J. Water Resour. Plann. Manage.138(3): 277–286.
34. Ghosh, S. and Kashyap, D. (2012b) ANN based model for planning of groundwater development for agricultural usage, Irrigation and Drainage (Wiley) DOI: 10.1002/ird.686.
35. Gorelick, S. M., and Remson, I. (1982)Optimal dynamic management of groundwater pollutant resources. Water Resour. Res., 18(1), 71–76.
36. Gorelick, S.M. (1983) A Review of Distributed Parameter Groundwater Management Modeling Methods. Water Resources Research, v. 19, no. 2, pp. 305-319.
37. Gorelick, S.M. (1990) Large scale nonlinear deterministic and stochastic optimization: Formulations involving simulation of subsurface contamination, Mathematical Programming, 48, 19-39, 1990.
38. Grove, D.B. (1976), Ion Exchange Reactions Important in Groundwater Quality Models, in Advances in Groundwater Hydrology, Am. Water Res. Assoc. (1976) 409-436.Harbaugh, A.W. (2005) MODFLOW-2005, The U.S. Geological Survey Modular Ground-Water Model—the Ground-Water Flow Process. U.S. Geological Survey Techniques and Methods 6-A16.
39. Grove, D.B. and K.G. Stollenwerk (1987) Chemical Reactions Simulated by Ground-Water Quality Models. Water Resources Bulletin, v. 23, no. 4, pp. 601-615.
40. Guhathakurta, P and M. Rajeevan, (2006). Trends in the rainfall patter over India. National Climate Centre, Research Report No. 2/2006. India Meteorological Department, Pune, 23p.
41. Haitjema, H., D. Feinstein, R. Hunt, and M. Gusyev. 2010. A hybrid finite-difference and analytic element groundwater model. Ground Water 48: 538–548. DOI: 10.1111/j.1745-6584.2009.00672. x.
42. Harbaugh A.W., Banta E.R., Hill M.C. and McDonald M.G. (2000)MODFLOW-2000, the U.S. Geological Survey Modular Ground-water Model – User Guide to Modularization Concepts and the Ground-Water Flow Process, U.S. Geological Survey: Open-File Report 00-92.
43. Herrling, B. and A. Heckele (1986) Coupling of Finite Element and Optimization Methods for the Management of Groundwater Systems, Adv.Wat. Resour., Vol. 9(4), pp 190-195.
44. Hunt, R.J., Kelson, V.A., and Anderson, M.P., 1998, Linking an analytic element flow code to MODFLOW – Implementation and benefits. p. 497-504 in MODFLOW '98: Proceedings of the 3rd International Conference of the International Ground Water Modeling Center. Golden, CO: Colorado School of Mines.
45. Huyakorn, P.S., B.H. Lester, and C.R. Faust (1983) Finite Element Techniques for Modeling Ground Water Flow in Fractured Aquifers, Wat. Resour. Res., Vol19 (4), pp 1019-1035.
46. Jury W. A. and Valentine R. L. (1986), Transport Mechanisms and Loss Pathways for Chemicals in Soil. In: S.C. Hern and S.M. Melancon (eds.), Vadose Zone Modeling of Organic Pollutants, Lewis Publishers, Inc., MI, pp. 37-60.
47. Kashyap, D. (1989) Mathematical Modeling for Groundwater Management- Status in India, Indo-French Seminar on Management of Water Resources, Festival of France:Jaipur.
48. Kashyap, D., and Chandra, S. (1982)A Distributed Conjunctive Use Model for Optimal Cropping Pattern. Proc., Exeter Symp., IAHS Publ. No. 135, International Association of Hydrological Sciences (IAHS), Wallingford, UK, 377–384.
49. Katsifarakis, L. K. (2007) Groundwater pumping cost minimization-an analytical approach. Water Resour. Manage., 22(8), 1089–1099.
50. Konikow, L.F., Bredehoeft, J.D. (1978) Computer Model of Two-Dimensional Solute Transport and Dispersion. In: Ground Water Techniques of Water-Res. Invests. of the U.S. Geol. Survey, Book 7, Ch. C2: 90 pp.
51. Konikow, L.F., Grove, D.B., 1977. Derivation of Equations Describing Solute Transport in Ground Water. U.S. Geol. Survey Water-Res. Inv. 77-19: 30 pp.
52. Konikow, L.F., Reilly, T.E., (1998) Groundwater Modeling. In: The Handbook of Groundwater Engineering [J.W. Delleur, ed.], CRC Press, Boca Raton 20:1-20.40
53. Kumar, C. P. (2001) Common Ground Water Modeling Errors and Remediation, J. of Indian Water Resources Society,Vol. 21 (4), pp 149-156.
54. Kumar, C. P. (2012) Groundwater Modeling Software: Capabilities and Limitations, IOSR

Journal of Environmental Science, Toxicology and Food Technology, Vol.1(2), p46-57.

55. Kumar, Rakesh, R. D. Singh, and K. D. Sharma, (2005). Water Resources of India. Current Science, 89(5):794-811.
56. Langevin, C.D. and Panday, S. (2012) Future of Groundwater Modeling, Groundwater, Vol. 50, No. 3, May-June, pp. 333-339.
57. Langevin, C.D., S. Panday, R.G. Niswonger, J.D. Hughes, and M. Ibaraki. 2011. Local grid refinement with an unstructured grid version of MODFLOW. In MODFLOW and More 2011: Integrated Hydrologic Modeling—Conference Proceedings, June 5–8, 2011, International Groundwater Modeling Center, Colorado School of Mines.
58. Markstrom, S.L., R.G. Niswonger, R.S. Regan, D.E. Prudic, and P.M. Barlow. 2008. GSFLOW—Coupled ground-water and surface-water flow model based on the integration of the Precipitation-Runoff Modeling System (PRMS) and the Modular Ground-Water Flow Model (MODFLOW-2005): U.S. Geological Survey Techniques and Methods 6-D1, 240. Reston, Virginia: USGS.
59. Mathew K Jose and Sastry R G S (2006). Analytical computation of aquifer potentials in a layered porous medium, J. Ind. Geophys. Union, 8(4), pp- 243-252.
60. McDonald M.G. and Harbaugh A.W. (2003) The history of MODFLOW, Groundwater, 41(2), p280-283.
61. McDonald, M.G. and A.W. Harbaugh, (1988) A Modular Three-Dimensional Finite-Difference Ground-Water Flow Model, Techniques of Water-Resources Investigations, USGS Manual, Book 6, 586 p.
62. Mercer, J.W. (1991) Common Mistakes in Model Applications. Proc. ASCE Symposium on Ground Water, Nashville, Tennessee, July 29 - August 2, 1991.
63. Mohan, S. (2001), Ground water Modeling: Issues and requirements. In: Modeling in Hydrogeology, Eds: L. Elango and R. Jayakumar, UNESCO-IHP, Allied Publishers, 2001, 3-16.
64. Moore, J.E. (1979) Contribution of Groundwater Modeling to Planning. Journal of Hydrology. v. 43 (October), pp.121- 128.
65. Morel-Seytoux, H. J., and Daly, C. J. (1975)A discrete kernel generator for stream-aquifer studies. Water Resour. Res., 11(2), 253–260.
66. Mualem, Y. (1976), A New Model for Predicting the Hydraulic Conductivity of Unsaturated Porous Media. Water Resources Research, Volume 12, pp. 513-522.
67. Narasimhan, T.N. and P.A. Witherspoon (1976) An Integrated Finite-Difference Method for Analyzing Fluid Flow in Porous Media. Water Resources Research v. 12, no. 1, pp. 57-64.
68. NIH (National Institute of Hydrology), (2014). Research Study Report on “Coastal Groundwater Dynamics and Management in the Saurashtra Region, Gujarat”. Under Hydrology Project-II of Ministry of Water Resources, Government of India. 121p.
69. Ogden, F. L., W. Lai, R. C. Steinke, J. Zhu, C. A. Talbot, and J. L. Wilson (2015), A new general 1-D vadose zone solution method, Water Resour. Res., vol. 51.
70. Parker, B. & Cherry, J.A. (2011). The discrete fracture network (DFN) for contaminated bedrock site characterization, University of Guelph, April 2011.
71. Parkhurst D.L. (1995) PHREEQC: A Computer Program for Speciation, Reaction-Path, Advective Transport, and Inverse Geochemical Calculations, Water-Resources Investigation Report 95-4227, U.S. Geological Survey, Lakewood.
72. Paul K.M. van der Heijde (1994), Identification and Compilation of Unsaturated/Vadose Zone Models. USEPA, May 1994.
73. Planning Commission, Government of India, (2007). Report of the Expert Group on “Groundwater Management and Ownership”. 61p.
74. Planning Commission, Government of India, (2011). Report of the Working Group on Sustainable Groundwater Management- An input to 12th Plan. 68p.
75. Prommer H., Barry D.A. and Zheng C. (2003) MODFLOW/ MT3DMS-based reactive multicomponent transport Modeling. Groundwater, 41(2), 247 – 257.
76. Ranade, Ashwani A., Nityananda Singh, H. N. Singh, and N. A. Sontakke, (2007). Characteristics of hydrological wet season over different river basins of India. IITM, ISSN 0252-1075. Research Report No RR-119, 155p.

77. Refsgaard, J.C., A.L. Højberg, I. Møller, M. Hansen, and V. Søndergaard (2010) Groundwater modeling in integrated water resources management—Visions for 2020. Ground Water 48: 633–648. DOI: 10.1111/j.1745-6584.2009.00634. x.
78. Reilly T E (2001) System and boundary conceptualization in groundwater flow simulation, USGS paper, pp29.
79. Rushton, K.R., (2003) Groundwater Hydrology: Conceptual and Computational Models. John Wiley and Sons Ltd.
80. Saaltink M.W., Ayora C. and Carrera J. (1998) A mathematical formulation for reactive transport that eliminates mineral concentrations. Water Resources Research, 34(7), 1649 – 1656.
81. Safavi, H. R., Darzi, F., and Marino, M. A. (2009) Simulation optimization modeling of conjunctive use of surface and groundwater. Water Resour. Manage., 24(10), 1965–1988.
82. Saifadeen, Alan and Gladnyeva, Ruslana, Modeling of Solute Transport in the Unsaturated Zone using HYDRUS-1D - Effects of Hysteresis and Temporal Variabilty in Meteorological Input Data. Division of Water Resources Engineering, Avdelningen för Teknisk Vattenresurslära
83. Schmelling, S.G. and R.R. Ross (1989) Contaminant Transport in Fractured Media: Models for Decision Makers. USEPA Superfund Ground Water Issue Paper. EPA/540/4-89/004.
84. Shah, Tushar, (2009). Taming the anarchy: Groundwater governance in south Asia. Resources for the future. Washington D.C., International Water Management Institute, Colombo.
85. Siebert, S., J. Burke, J. M. Faures, K. Krenken, J. Hoogeveen, P. Doll, and F. T. Partmann, (2010). Groundwater use for irrigation- a Global Inventory. Hydrol. Earth Syst. Sci., 14:1863-1880. Doi:10.5194/hess-14-1863-2010.
86. Simunek, Jirka (2005), Models of Water Flow and Solute Transport in the Unsaturated Zone. In: Encyclopedia of Hydrological Sciences, Edited by M. G. Anderson, John Wiley & Sons, Ltd., pp. 1171-1180.
87. Singh Dhirendra K, and Singh Anil K, (2002). Groundwater situation in India: Problems & perspectives. Water Resour. Dev., 18(4):563-580.
88. Source: http://groundwater.ucdavis.edu/materials/groundwater_modeling_web-links/
89. Source: http://igwmc.mines.edu/software/review_software.html
90. Source: http://www.ehsfreeware.com/gwqclean.htm
91. Source: https://en.wikipedia.org/wiki/MODFLOW
92. Source: https://www.hzdr.de/fwr/vb/modeling.html
93. Source: USGS website - http://water.usgs.gov/software/lists/groundwater
94. Strack, O.D.L. (1989) Groundwater Mechanics. Prentice Hall, Englewood Cliffs, New Jersey
95. Task Force, (2009). Report of the Task Force on Irrigation. Planning Commission. Government of India.
96. Tuinhof, Albert, and Jan Piet Heederik, (2003). Management of Aquifer Recharge and Subsurface Storage – Making better use of our largest reservoir. Netherlands National Committee for IAH. The Netherlands. 85p.
97. United Nations Economic Commission for Europe - Charter on Groundwater Management (1989)
98. vanGenuchten,M.Th. (1980). A Closed-form Equation for Predicting the Hydraulic Conductivity of Unsaturated Soils", Soil Sci. Soc. Am. J., Volume 44, pp. 892-898.
99. Varda, S. B., Deborah,L. H., Kaylea, M. W. (2002). Modeling flow at the stream-aquifer interface: A review of this feature in tools of the trade. http://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.128.1712&rank=1
100. Vijay Shankar, P.S., Himanshu Kulkarni, and S. Krishnan, (2011). India's Groundwater Challenge and the Way Forward. Economic and Political Weekly. XLVI (2):37-45.
101. Walton, W. (1989) Analytical Ground Water Modeling. Lewis Publishers, Chelsea, Michigan.
102. Wang, H.F. and M.P. Anderson, (1982) Introduction to Groundwater Modeling: Finite Difference and Finite Element Methods, Academic Press, San Diego, Boston, 237 p.
103. Wels, C. (2012), Guidelines for Groundwater Modeling to Assess Impacts of Proposed Natural Resource Development Activities. British Columbia, Ministry of Environment.
104. Werner, A. D., Gallagher, M. R., andWeeks, S.W. (2006)Regional scale, fully coupled

modeling of stream interaction in a tropical catchment. J. Hydrol.,328(3-4), 497-510.
105. Winter, T.C.,J.W. Harvey, O.L. Franke, and W.M. Alley, (2013). Groundwater and Surface water A Single Resource. U. S. Geological Survey Circular 1139. http://pubs.usgs.gov/circ/circ1139/htdocs/title.htm
106. Yeh, W (1986) Review of Parameter Identification Procedures in Groundwater Hydrology: The Inverse Problem. Water Resources Research, v. 22, no. 2, pp. 95-108.
107. Yeh, W.W-G., (1992) Systems analysis in groundwater planning and management, ASCE J. Water Resour. Plan. and Manag., 118(3), 224-237.
108. Zektser, Igor S., and Lorne G. Everett, (2004). Groundwater Resources of the World and their Use. UNESCO, IHP Series on Groundwater NO. 6, ISBN 92-9020-007-0, 346p.
109. Zheng, C. (1990) MT3D, A modular three-dimensional transport model for simulation of advection, dispersion, and chemical reactions of contaminants in groundwater systems, Report to the Kerr Environmental Research Laboratory, US Environmental Protection Agency, Ada, OK.
110. Zheng, C. (2009) Recent developments and future directions for MT3DMS and related transport codes, Ground Water, 47(5), doi: 10.1111/j.1745-6584.2009.00602.x.
111. Zheng, C. and G.D. Bennett, (1995) Applied Contaminant Transport Modeling, Theory and Practice, Van Nostrand Reinhold, New York.

CHAPTER 3

SNOW/GLACIER MELT RUNOFF MODELING

3.1 General

Snow is of great importance as a key environmental parameter. It not only influences earth's radiation balance but also plays a significant role in river discharge. A major source of river discharge in middle and higher latitudes are contributed through snowmelt from seasonal snow covered areas of the Earth's mountain region. The Himalayan mountain system is the source of one of the world's largest suppliers of freshwater. From west to east the Himalayan glaciers can be divided into three segments according to their latitudes and topographic features: those on the Western Himalayas, the Central Himalayas and the Eastern Himalayas. Broadly rivers originating from the Himalayan region can be grouped in three main river systems; the Indus, the Ganges and the Brahmaputra. In India, 35% of the geographical area is mountainous and out of which 58% is covered under Himalaya. This area covers about 16% of India's total geographical area. The water flowing in the Himalayan Rivers is the combined drainage from rainfall, snowmelt and glacier-melt runoff. In Himalayan region, several water resources projects are under operation and many more are coming up to harness these resources. These projects are of considerable national and local importance in terms of hydropower generation, irrigation, flood control and subsequent socio-economic development of the region. Proper planning and management of these projects depends on correct assessment of stream flow generated from snow and glacier melt.

The Himalayan region, including the Tibetan Plateau, has shown consistent trends in overall warming during the past 100 years (Yao et al. 2007). Various studies suggest that warming in the Himalayas has been much greater than the global average of 0.74°C over the last 100 years (IPCC, 2007). Long-term trends in the maximum, minimum and mean temperatures over the north western Himalaya during the 20^{th} century (Bhutiyani and others, 2007) suggest a significant rise in air temperature in the north western Himalaya, with winter warming occurring at a faster rate. Global warming has remitted in large-scale retreat of glaciers throughout the world. This has led to most glaciers in the mountainous regions such as the Himalayas to recede substantially during the last century and influence stream run-off of Himalayan Rivers. The widespread glacial retreat in the Himalayas has resulted in the formation of many glacial lakes. Glacier retreat and shrinking could form dangerous moraine lakes, which can produce sudden glacier lake outburst floods (GLOFs) damaging life and property downstream over a long distance. For water resources planning and management, it is therefore essential to study and monitor the Himalayan glaciers and glacial lakes including GLOF. There are very limited studies on the impact of climate change on the Himalayan River basins. However, NIH has conducted sensitivity analysis using the SNOWMOD on some of the Himalayan basins i.e. Sutlej, Spiti, Chenab, Beas and Dokriani basins.

3.2 Snow and Glacier Melt Runoff

Snow and glacier runoff play a vital role in making all these rivers perennial, whereas the rainfall contribution during the monsoon period is critical for storages in various reservoirs. Estimation of the snow and glacier contribution in the annual runoff of various

Himalayan rivers is necessary for the development and efficient management of water resources, which include flood forecasting, reservoir operation, design of hydraulic structures, etc. The planning of new multi-purpose projects on the Himalayan Rivers further emphasizes the need for reliable estimates of snow and glacier runoff. Despite their well-recognized importance and potential, not many attempts have been made to assess the snow and glacier contributions in these rivers, although a few hydrological studies have been carried out for glacierized river basins in the western Himalayan region (Singh *et al*., 1994, 2005; Singh & Kumar, 1997; Singh & Jain, 2002). Singh *et al.* (1994) estimated about 28% as the average contribution of snow- and glacier-melt in the annual flow of the Ganga River at Devprayag. Singh *et al.* (1997) estimated about 49% as the snow and glacier contribution for the Chenab River at Akhnoor. In a similar study of the Satluj River at Bhakra Dam site, the snow- and glacier-melt contribution was estimated to be 60% (Singh & Jain, 2002) and 39% for Beas basin up to Pandoh dam (Jain et al., 2010).

The snowmelt model is designed to simulate daily streamflow in mountainous basin where snowmelt is major runoff component. The process of generation of streamflow from snow covered areas involves primarily the determination of the amount of basin input derived from snowmelt along with some contribution from glacier melt and rain. Most of the Himalayan basins experience runoff from the snowmelt as well as rain. The contribution of rain comes from the lower part of the basin having elevation less than 2000m, the middle part between 2000m to 4000m contributes runoff from the combination of rain and snowmelt while in the high altitude region having elevation more than 4000m, runoff computation comes from the glacier melt. The contribution from snow and glacier is controlled by the climatic conditions and therefore, varies from year to year. For the Himalayan basins, most important factor influencing the development of model and the approach to be adopted is the limited availability of data. There is very sparse network of measurement stations in the high altitude region of the Himalayas. Data collected at most of the measurement stations consist of mostly temperature and precipitation data. Most of the meteorological data required for the application of energy balance approach is hardly available. Therefore, development of a conceptual model with an index approach for calculating the snow and glacier melt runoff is the suitable choice for snowmelt runoff in the Himalayan basins. Keeping in view the limited data availability, the structure of the present model has been kept simple so that all suitable/available data is properly utilised.

3.3 Modeling Approach

Modeling of streamflow from a basin is based on transformation of incoming precipitation to outgoing streamflow by considering losses to the atmosphere, temporary storage, lag and attenuation. Hydrological models use for simulation or forecasting of streamflow are generally categorized as simple regression models, black-box models, conceptual models and physically based models. Black-box models are generally lumped in nature by treating a basin as a single spatial unit. Physically based models use appropriate physical equations contain equations for all the processes involved. These models are invariably distributed and involve desegregation of basin into zones or grid cells. Conceptual models may be either lumped or distributed with one or more storage represented by conceptual units and connected by incoming and outgoing fluxes representing different hydrological pathways.

The conversion of snow and ice into water is called snowmelt, which needs input of energy (heat). Hence snowmelt is linked with the flow and storage of energy into and through the snowpack (USACE, 1998). Snowmelt models have two basic approaches towards calculating the amount of snowmelt occurring from a snowpack: energy budget method and temperature index method. The energy budget approach attempts to make the process as physically based as possible. The goal is to simulate all energy fluxes occurring within the snowpack to give an accurate account of total snowmelt in response to each of these energy fluxes over time and space. This approach is extremely data intensive, requiring vast amounts of input data either to force an initial run of a model, or to calibrate it based on historical data before running a forecast. Too often, this approach suffers from inadequate data supply or simply that the level of data is unwarranted for the purpose at hand. In light of the intensive data requirements necessary for the energy budget approach, an alternative method known as the temperature index or degree day approach allows for snowmelt calculation with much less data input. The basis of the temperature index approach is that there is a high correlation between snowmelt and air temperature due to the high correlation of air temperature with the energy balance components which make up the energy budget equation.

When precipitation falls as snow it accumulates in the basin and snowpack is developed. The solid precipitation results in temporary storage and the melt water reach the river in the melt season. The snow accumulation in Himalayas is generally from November to March, while snowmelt is from April to June. During April to June, snowmelt is the predominant source of runoff and during July to September it forms a significant constituent of melt. The snowmelt runoff modeling is of vital importance in forecasting water yield. Snow and glacier melt runoff is very important particularly in the lean season and it plays a vital role in making perennial nearly all the rivers originating in Himalayas perennial. Conceptually snowmelt runoff models are rainfall-runoff models with additional component or routines added to store and subsequently melt precipitation that falls as snow. Some snowmelt runoff models are purpose built and are not intended for use in non snowy environments, though they have to make some allowance for precipitation which falls as rain during the melt season. In general, the part of the model which deals with snowmelt has to achieve three operations at each time step.

- Extrapolate available meteorological data to the snowpack at different altitude zones calculate rates of snowmelt at different points, and
- Integrate snowmelt over the concerned effective area of the basin and estimate the total volume of new melt water.

The energy balance or heat budget of a snowpack governs the production of meltwater. This method involves accounting of the incoming energy, outgoing energy, and the change in energy storage for a snowpack for a given period of time. The net energy is then expressed as equivalent of snowmelt. The energy balance equation can be written in the form (Anderson, 1973):

$$\Delta Q = Q_n + Q_e + Q_h + Q_g + Q_m \qquad (3.1)$$

where:Q_n=net radiation (long and short wave), Q_e = latent heat transfer, Q_h = sensible heat transfer, Q_g = ground snow interface heat transfer, Q_m = heat transfer by mass changes (advected heat), ΔQ = change in heat storage.

In the above equation, different components of energy are considered in the form of energy flux, which is defined as the amount of energy received on a horizontal snow surface of unit area over unit time. The positive value of Q_m will result in the melting of snow.

The relative importance of the various heat transfer processes involved in melting of a snowpack depends on time and local conditions. For example, radiation melting dominates the weather conditions when wind is calm. Melting due to sensible heat flux dominates under warm weather conditions. When all the components of energy balance equation are known, the melt rate due to energy flux can be expressed as,

$$M = Q_m/[\rho_w.L.\beta] \qquad (3.2)$$

where

M = depth of meltwater (m/day)

L= latent heat of fusion (333.5 kJ/kg)

ρ_w = density of water (1000 kg/m^3)

β = thermal quality of snow

The thermal quality of snow depends on the amount of free water content (generally 3 – 5 %) and temperature of the snowpack. For a snow that is thermally ripened for melting and contains about 3% of free water content, the value of β is 0.97. For such cases equation (3.2) reduces to,

$$M = Q_m/[1000*333.5*0.97] \qquad (3.3)$$

which leads to a simple relationship,

$$M = 0.0031 * Q_m \quad \text{(mm/day)} \qquad (3.4)$$

Data required to evaluate Equation (3.1) are measurements of air temperature, albedo, wind speed, vapour pressure and incoming solar radiation (Anderson, 1973).These data are difficult to obtain on a basin scale and extrapolation to areal values from point data is another problem, especially the spatial detail is required for distributed models. This becomes further difficult when such data is required for a highly rugged terrain, such as Himalayan terrain. As such application of the energy balance equation is usually limited to small, well-instrumented or experimental watersheds.

3.3.1 Degree-day approach or temperature index approach

The specific type of data required for the energy budget method is rarely available for carrying out the snowmelt studies. This is particularly true for the Himalayan basins where the network for data collection is poor. The commonly available data in the Himalayan basins are daily maximum and minimum temperatures, humidity measurements and surface wind speed. This is why the temperature indices are widely used in the snowmelt estimation. It is generally considered to be the best index of the heat transfer processes associated with the snowmelt. Air temperature expressed in degree-days is used in snowmelt computations as an index of the complex energy balance tending to snowmelt. A ‘degree-day’ in a broad sense is a unit expressing the amount of heat in terms of persistence of a temperature for 24-hour period of one-degree centigrade departure from a reference temperature. The simplest and the most common expression relating daily snowmelt to the temperature index is,

$$M = D\,(T_i - T_b) \qquad (3.5)$$

where

M= melt produced in mm of water in a unit time
D= degree-day factor (mm $^{o}C^{-1}day^{-1}$)
T_i = index air temperature (^{o}C)
T_b = base temperature (usually 0 ^{o}C)

Daily mean temperature is the most commonly used index temperature for snowmelt. The mean temperature is computed by,

$$T_i = T_{mean} = (T_{max} + T_{min}) / 2 \qquad (3.6)$$

There are several methods of dealing with the index temperatures used in calculating the degree-day value. When using the maximum-minimum approach, the most common way is to use the temperature as they are recorded and calculate the average daily temperature. The inclusion of minimum temperature at an equal weight with the maximum temperature gives undue emphasis to this effect. On the other hand, the use of maximum temperature only excludes this effect entirely. In order to counteract such problems, alternatives have been suggested in which unequal weight to the maximum and minimum temperatures are given. U.S. Army Corps of Engineers (1956), used the following index temperatures,

$$T_i = (2T_{max} + T_{min}) / 3 \qquad (3.7)$$

Another approach is given by,

$$T_i = T_{max} + (T_{min} - T_{max})/b \qquad (3.8)$$

where b is a coefficient less than 2.

When the basin is subdivided based on elevation zones, the degree-days are extrapolated to an elevation zone by using a suitable lapse rate i.e.,

$$T_{i,j} = \delta\,(h_{st} - h) \qquad (3.9)$$

where

$T_{i,j}$= degree-day of the elevation zone
δ= temperature lapse rate in ^{o}C per 100 m
h =zonal hypsometricmean elevation in m.
h_{st}= altitude of the temperature station in m.

In a basin with little seasonal variation, a lapse rate of 0.65 ^{o}C /100 m has been found to be suitable.

3.4 Forecasting of Snowmelt Runoff

Streamflow forecasting is the process of estimating future stages of flow and their time sequence at selected places along a river. The best possible forecast is the one which completely and identically describes the process that is supposed to occur in the future. If the forecast is not available sufficiently before the event occurs, its value is nil. The entire forecasting has to be planned around a time factor. The lead time of a forecast often determines the value of the forecast. Since very precise forecasts are not possible, the forecast should be used with minimum variance forecast errors. In real-time forecasting, the time needed for data to reach from upstream catchment to the place of analysis is very important and it involves checking inconsistent and incomplete data and its validation before it is used for computing an accurate forecast.

Reliable long-term or seasonal forecasts are essential to various aspects of water resources planning and management. The short-term forecast, a few days in advance, is very helpful in operation of reservoirs or other flow controls. For short-term forecasting, only the present state of the watershed and streamflow are needed, while for long-term forecasts it is necessary to have a reliable prediction of various meteorological parameters in addition to the knowledge of initial conditions of the basin. When the temperature index method is used for snowmelt computation, the success of forecasting depends especially on the accuracy of forecasting temperature, precipitation, and snow covered area. In general, temperature can be forecasted with higher accuracy than precipitation. Known historic meteorological records can be used to forecast the input parameters of a model.

Depending on the snow cover and temperature conditions in the basin, the entire basin or a part thereof can contribute to melting. Therefore, forecasting of the snowline elevation is also very important. Snowline also decides the snow covered area and snow free or bare area of the catchment. If rainfall occurs during a snow-cover period, the contributions of rainfall from bare area and snow covered area will be different. The complete melting of seasonal snow cover occurs generally within a known period of time, but uncertainty in the upper position of snowline in glacier regions limits the accuracy of long-range forecasting. Therefore, seasonal forecasting is not much successful in the areas where glaciers exist. Reliable climatic forecasts may help improve the accuracy of short-range or long-range snowmelt runoff forecasts. The reliability of a method used for forecasting depends on the adequacy of available hydrological data used for calibration and capability of forecasting of input variables. As temperature can be predicted more accurately than other parameters used in the energy balance equation, the temperature index methods are mostly used in operational forecasting.

3.5 Data and Parameters

3.5.1 Snow Cover Area (SCA)

Conventional snow cover data, such as snow surveys, provide detailed information on such snow pack properties but their site specific nature and infrequent occurrence limit their potential for use in distributed models. In order to provide distributed information characterizing the snow cover of a watershed, snow survey measurements must be extended to regions where no snow survey data are available. Remote sensing offers a significant potential for collecting this data in cost effective manner. Because of difficult access and expensive operation of hydrological stations, radar or satellite data are particularly appropriate. However, ground truth data are indispensable in the calibration and verification of remotely sensed data. Aerial and satellite surveys are useful in mapping snow lines. The wealth of observational material obtained by remote sensing can be integrated into models, such as snowmelt runoff models, considerably improving the forecast accuracy. Snow was first observed by satellite in eastern Canada from the TIROS-1 satellite in April 1960. Since then, the potential for operational satellite based snow cover mapping has been improved by the development of higher temporal frequency satellites such as GOES (Geostationary

Operational Environmental Satellite), Landsat, SPOT and IRS series, and NOAA-AVHRR, NIMBUS-SMMR and DMSP SSM/I satellites.

Another possible source for snow cover information is microwave satellite imagery. The regular and frequent mapping of snow cover is possible using a sensor independent of time and weather. Depending on wavelength, microwave radiation will penetrate clouds and most precipitation, thus providing an all-weather observational capability, which is very significant in snow regions where clouds frequently obscure the surface (Schanda et al. 1983).There are two types of microwave sensors: active and passive. Passive radiometers include NIMBUS-7 Scanning Multi-channel Microwave Radiometer (SMMR) and the DMSP SS/I satellites and measure surface brightness temperatures. Active satellite sensors contain synthetic aperture radar (SAR) and emit microwave radiation at a specific frequency and polarization and measure the return backscatter in the form of the backscatter coefficient.

Microwaves have unique capabilities for snow cover modeling:

1. They can penetrate cloud cover (Chang, 1986), providing reliable data;
2. They can penetrate through various snow depths depending on wavelength therefore potentially capable of determining internal snowpack properties such as snow depth and water equivalent (Rott, 1986);

Active microwave sensor on the First European Remote Sensing Satellite (ERS-1) and Canadian RADARSAT offer the possibility to observe seasonal snow cover characteristics in detail over the entire snow-cover season. In one simulation of RADARSAT data, snow-cover classification accuracy was 80%, comparable to aircraft Synthetic Aperture Radar (SAR). Comparing a classification of snow-covered area based on SAR with that done using TM suggests that a SAR-based classification is sufficiently accurate to substitute for visible-and-near-IR based estimates when such data are not available, e.g., due to cloudiness.

Passive microwave signals are also sensitive to the liquid-water content of snow, thus offering the potential to develop snow wetness estimates. The sensitivity of passive microwave signals to snow wetness aids in determining the onset of spring melt and the occurrence of multiple melt events during the winter.

3.5.2 Division of catchment into elevation bands

There are two approaches for defining a computer model of a watershed; a lumped model, which does not take into account spatial variability of processes, and a distributed model, which consider these. Lumped model is a simple approach and can be applied for basins that have a wide variety of physical features. However, the major limitation with this model is that it does not run beyond a single event (USACE, 1998). Distributed model on the other hand can be run for continuous simulation. In such models, the watershed is divided into subunits with variables being computed separately for each. This method of subdividing the basin is logical one, since in mountainous areas hydrological and meteorological conditions are typically related to elevation.

Distributed models attempt to account for the spatial variability by dividing the basin or catchment into sub-areas and computing snowmelt runoff for each sub area independently with a set of parameters corresponding to each of the sub-areas. Generally distributed models use one of the following general approaches to sub-divide a basin: (i) Elevation zone or band (ii) basin characteristics such as slope, aspect, soil, vegetation etc. and (iii) a fixed or variable length, two or three-dimensional grid. Lumped and distributed models are classified further by their use of energy balance approach or temperature index approach to simulate the snowmelt process.

3.5.3 Degree days

Degree-days are the departures of temperature above or below a particular threshold value. Generally, a threshold temperature of 0ºC is used, with snowmelt considered to have occurred if the daily mean temperature is above 0ºC. This follows from the idea that most snowmelt results directly from the transfer of heat from the air in excess of 0°C. The difference between the daily mean temperature and this threshold value is calculated as the degree-day. Snowmelt-runoff models, which incorporate a degree-day or temperature index, routine are the most commonly used in operational hydrology and have been successfully, verified world-wide over a range of catchment sizes, physical characteristics and climates. The basic form of the degree-day approach is:

$$M = D(T_{air} - T_{melt}) \tag{3.10}$$

Where M = daily snowmelt (mm/day); D = degree-day factor (mm ° C^{-1} day^{-1}); T_{air} = index air temperature (°C); and T_{melt} = threshold melt temperature (usually, 0°C).

Although air temperature and other hydrological variables vary continuously throughout the day, the daily mean air temperature is the most commonly used index temperature. When daily maximum (T_{max}) and minimum (T_{min}) air temperature is available, daily mean air temperature is calculated as

$$T_{air} = T_{mean} = \frac{(T_{\max} + T_{\min})}{2} \tag{3.11}$$

3.5.4 Degree day factor

The degree-day method is popular because temperature is a reasonably good measure of energy flux, and, at the same time, it is a reasonably easy variable to measure, extrapolate, and forecast (Martinec and Rango, 1986). The degree-day factor, D, is an important parameter for snowmelt computation and converts the degree-days to snow melt expressed in depth of water. D is influenced by the physical properties of snowpack and because these properties change with time, therefore, this factor also changes with time. The seasonal variation in melt factor is well illustrated by the results obtained from the study reported by Anderson (1973); the lower value being in the beginning of melt season and higher towards the end melt season. A wide range of a values has been reported in the literature with a generally increase as the snowpack ripens.

3.5.5 Rain on snow

Rain-on-snow event is hydrologically an important phenomenon as most of the floods in British Columbia, Washington, Oregon and California were reported to have occurred due to this event (Colbeck, 1975; Kattelmann 1987; Brunengo, 1990; Berg et al., 1991; Archer et al., 1994). Further, this event is one of the prime causes of avalanches as rain falling over snow weakens the bond between the snow packs thereby reducing the mechanical strength of the snowpack (Conway et. al, 1988; Heywood, 1988; Conway and Raymond, 1993).

3.6 Processes of Snow/Glacier Melt Runoff Modeling

3.6.1 Snow accumulation processes

A detailed understanding of the seasonal and spatial variations of snow accumulation within a basin is critical for the winter water budget and is a key issue to reduce uncertainties in modeling snowcover ablation and snowmelt runoff. Snow accumulation is what remains after falling snow has been modified by interception in vegetation canopies, sublimation, redistribution as a result of wind transport, and melt. Consequently, it is incorrect to assume that an increase of the snow on the ground is equivalent to snowfall (Pomeroy and Gray, 1995). Estimation of snowfall is particularly challenging. The properties and characteristics of fallen snow change as a function of energy fluxes, temperature, wind, moisture, water vapour, and pressure (Gray and Male, 1981). Sublimation reduces the snow available for accumulation. Compared with snow on the ground, snow sublimates more quickly in forest canopies because of greater absorption of short-wave radiation by the canopy and a higher exposure to turbulent-exchange forces (Lundberg et al., 2004). Forest canopy is important in controlling the interception-sublimation process (Pomeroy et al., 2002).

3.6.2 Snow ablation process

Snowmelt is the most significant hydrological event in arctic and subarctic environments, since the spring snowmelt freshet is usually the largest runoff event of the year. The snowmelt period is characterised by complex and dynamic processes resulting in rapid changes in albedo, turbulent fluxes, internal snow energy, and surface temperature as the snow cover is depleted. These changes have drastic effects on the surface-atmosphere exchanges (Pomeroy et al., 1998b).

3.6.3 Precipitation data and distribution

The most challenging object of hydrological simulation of a mountain basin is the measurement of meteorological variables. The major problems posed in high mountain areas are the accessibility to the mountains on a continuous basis, the accuracy of measured meteorological variables, and the areal representativeness of measurements (Panagoulia, 1992). It has been observed that the most important factor in accurate estimation of snowmelt runoff is the assumptions of the spatial distribution and form of precipitation. In a distributed model, it is very essential to distinguish between rain and snow in each elevation band because these two form of precipitation behaves very differently in terms of contribution to the streamflow. Rainfall is contributed faster to the streamflow whereas snowfall is stored in the basin until it melts. The form of precipitation is influenced by two factors; meteorological and topographical. Meteorological factor includes air temperature, lapse rate, wind etc and topographical factors include elevation, slope, aspect, vegetation cover etc. Snow falling through warmer atmosphere or melting level air temperature melts and falls as rain. Similarly, snow falls at elevation above melting level and rain falls at elevation below melting level. Fig. 3.1 shows schematically how topographic and meteorological factors influence the form of precipitation. Similarly, the figure explains the mechanism adopted by the distributed hydrological model to determine the form of precipitation, considering topographic and meteorological factors, as below:

If $T_m \geq T_c$, all precipitation is considered as rain;

If $T_m \leq 0°C$, all precipitation is considered as snow

where T_m is mean air temperature.

In the cases, if $T_m \geq 0°C$ and $T_m \leq T_c$, the precipitation is considered as a mixture of rain and snow and their proportion is determined as follows:

$$Rain = \frac{T_m}{T_c} \times P \tag{3.12}$$

$$Snow = P - Rain \tag{3.13}$$

Where P is the total observed precipitation

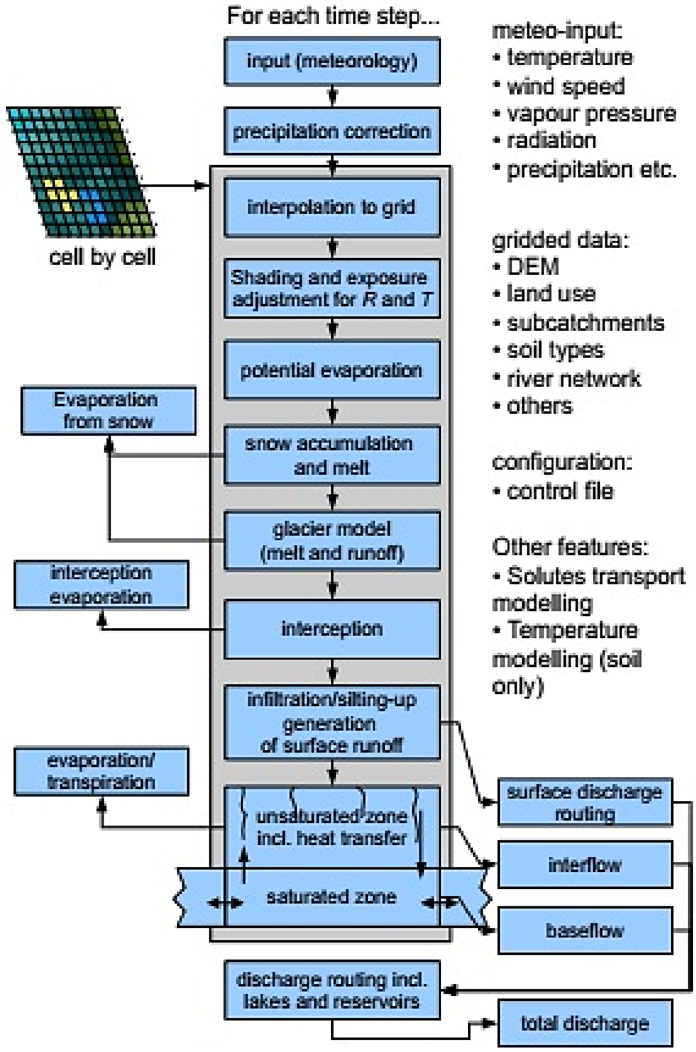


Figure 3.1: Schematic flow chart of model input parameters in a distributed hydrological model

3.6.4 Temperature data – Space and time distribution and Lapse Rate

Air temperature has a logical connection with many of the energy exchanges involved in snowmelt. Also it is the meteorological variable which is readily available to hydrologists in historical and near real time. Hence air temperature is the most widely used index in snowmelt (Sorman, 2005). Daily mean temperature is the most commonly used parameter in snowmelt computation. For the present study daily mean air temperature was calculated by using the equation given below:

$$T_{air} = T_{mean} = \frac{(T_{\max} + T_{\min})}{2} \qquad (3.14)$$

Temperature shows an inverse relation with elevation. The rate with which the temperature changes with increase in elevation is called as lapse rate. Lapse rate is not a constant value but changes with season and region. Lapse rates are known to be quite variable, ranging from high values of about the dry adiabatic lapse rate to low values representing inversion conditions. For example, during continuous rainstorm conditions the lapse rate will approximate the saturated adiabatic rate, whereas under clear sky, dry weather conditions, the lapse rate during the warm part of the day will tend to the dry adiabatic rate. During the night, under clear sky conditions, radiation cooling will cause the temperature to fall to the dew point temperature, and this is particularly true for a moist air mass.As a result, night-time lapse rates under clear skies will tend to be quite low, and at times even zero lapse rates will occur (Jain, 2001). Hence to define the spatial coverage of air temperature by extrapolation in a more representative manner, we need to input seasonally varying lapse rate value in the model (Jain et al., 2007c).

The daily temperature in the various elevation bands can be calculated by using the temperature lapse rate approach by extending data from the base station using the equation,

$$T_{i,j} = T_{i,base} - \delta(\mathrm{h_j} - \mathrm{h_{base}}) \qquad (3.15)$$

Where $T_{i,j}$ = daily mean temperature on i^{th} day in j^{th} zone (^oC), $T_{i,base}$= daily mean temperature (^oC) on i^{th} day at the base station, h_j= zonal hypsometric mean elevation (m), h_{base}= elevation of base station (m), and δ= Temperature lapse rate in ^oC per 100 m.

3.7 Snowmelt Runoff Models

3.7.1 Snowmelt runoff model (SRM)

The snowmelt runoff model (SRM) of is widely used. The Snowmelt-Runoff Model is designed to simulate and forecast daily streamflow in mountain basins where snowmelt is a major runoff factor. Most recently, it has also been applied to evaluate the effect of climate change simulation. It can be written as:

$$Q_{n+1} = [C_{Sn} \, . a_n (T_n + \Delta T_n) \, S_n + C_{Rn} P_n] \frac{A.10000}{86400} (1 - K_{n+1}) + Q_n K_{n+1} \quad (3.16)$$

where

Q = average daily discharge [m^3s^{-1}];

c = runoff coefficient expressing the losses as a ratio (runoff/precipitation), with cS referring to snowmelt and c_R to rain;

a = degree-day factor [cm $^oC^{-1}d^{-1}$] indicating the snowmelt depth resulting from 1 degree-day;

T = number of degree-days [^oC d];

Δ T = the adjustment by temperature lapse rate when extrapolating the temperature from the station to the average hypsometric elevation of the basin or zone [^oC d];

S = ratio of the snow covered area to the total area; and

P = precipitation contributing to runoff [cm].

A preselected threshold temperature, T_{CRIT}, determines whether this contribution is rainfall and immediate. If precipitation is determined by T_{CRIT} to be new snow, it is kept on storage over the hitherto snow free area until melting conditions occur.

A = area of the basin or zone [km^2];
k = recession coefficient indicating the decline of discharge in a period without snowmelt or rainfall;
k = Q_{m+1}/Q_m (where m and m + 1 are the sequence of days during a true recession flow period).
n = sequence of days during the discharge computation period. Equation (3.16) is written for a time lag between the daily temperature cycle and the resulting discharge cycle of 18 hours. In this case, the number of degree-days measured on the nth day corresponds to the discharge on the n + 1 day. Various lag times can be introduced by a subroutine. 10000/86400 = conversion from $cm^{-1}km^2d^{-1}$ to $m^3\ s^{-1}$

It is clear from equation (3.16) that the application of the SRM requires both the area of snow cover, which can be obtained from remotely sensed imagery and ancillary data such as temperature, precipitation, and runoff, which cannot be obtained in this way. The SRM is essentially a form of geographic information system in which data from different sources are fused. The ability to distinguish between frozen and melting snow cover can enhance the performance of the model.

3.7.2 Snowmelt Model (SNOWMOD)

The snowmelt model (SNOWMOD) is a temperature index model, which is designed to simulate daily streamflow for mountainous basins having contribution from both snowmelt and rainfall. The generation of streamflow from such basins involves with the determination of the input derived from snowmelt and rain, and its transformation into runoff. It is a distributed model and for simulating the streamflow, the basin is divided into a number of elevation zones and various hydrological processes relevant to snowmelt and rainfall runoff are evaluated for each zone. The model achieves three operations at each time steps. At first the available meteorological data are extrapolated at different altitude zones. Than the rates of snowmelt are calculated at each time step. Finally, the snowmelt runoff from SCA and rainfall runoff from SFA (snow-free area) are integrated, and these components are routed separately with proper accounting of baseflow to the outlet of the basin. The model optimizes the parameters used in routing of the snowmelt runoff and rainfall runoff. Fig.3.1 schematically shows the different steps involved with in the model. Details of computation of melt runoff and generation of streamflow.

3.7.2.1 Model structure

The flow chart of the model structure is shown in Fig.3.1. Specific major considerations in the design of the model components are as follows:

(a) The model computes or simulates the snow melting and runoff processes on a daily basis. The basin is divided into snow covered and snow free part and modeling of runoff is carried out separately from these two parts.

(b) Use of practical yet theoretically sound methods for subdividing the basin in evaluating the various physical and hydrologic processes relevant to snow melt and its appearance as streamflow at the outlet.

(c) The model has ability to perform simulation computations over any specified time interval according to the availability of input data

(d) Capability of the model to adjust itself to specified or observed conditions of streamflow from the previously computed amounts, and maintaining continuity of functions in further processing.

(e) Optimisation of parameters used in routing of the rainfall-runoff and snowmelt runoff.

To execute this model, the following input data are required:

1. Physical features of the basin which include snow covered area, elevation bands and their areas, altitude of meteorological stations, and other watershed characteristics affecting runoff.
2. Time variable data include precipitation, air temperatures, snow-covered area, streamflow data and other parameters determining the distribution of temperature and precipitation.
3. Information on the initial soil moisture status of the basin
4. Miscellaneous job controls and time control data which specify such items as total computation period, routing intervals etc.

3.7.3 Water flow and balance simulation model (WaSiM)

Water Flow and Balance **Si**mulation **M**odel (WaSiM) is a grid-basedtool for investigating the spatial and temporal variability of hydrological processes in complex river basins. It is a distributed, deterministic, physically based hydrologic model. The model can be used in various spatial and temporal scales ranging from the sizes of <1 km^{2}up to more than 100,000 km^2 with temporal resolution ranges from minutes to several days. WaSiM also equipped tobe used for both short-term (floods) and long-term simulations (long-term water balance simulations). For each time step, the sub models are processed one by one for the entire model grid thus taking most advantage of parallelized algorithms as offered by the OpenMP standard. Depending on the general availability of data and the hydrological problem to be solved, WaSiM allows a selection from several algorithms for the simulation of a specific process. The minimum data requirements for the model are time series of precipitation and temperature, as well as raster data for topography, land use and soil properties.

3.7.4 GEOtop hydrological model

GEOtop is a distributed model of the mass and energy balance of the hydrological cycle. GEOtop is applicable to simulations in continuum in small or relatively large mountain catchments. GEOtop deals with the effects of topography on the interaction between energy balance (evapotranspiration, heat transfer) and hydrological cycle (water, glacier and snow).

3.7.4.1 Availability

The source code of GEOtop 2.0 with detailed documentation is available at the following link: https://github.com/geotopmodel
Stefano Endrizzi, is maintaining his own source code at: https://github.com/se27xx/GEOtop/

3.7.4.2 Use and license of GEOtop

GEOtop 2.0 is provided with a GNU General Public License, version 3 (GPL-3.0). The source code, a first version of the manual (Dall'Amico et al., 2011b), and some template simulations are available through GitHub at the address: https: //github.com/se27xx/GEOtop/. Gubler et al. (2013) provide a good starting point for the selection of many parameter values; however, optimal choices and sensitivities may differ from application to application.

3.7.4.3 Brief Description

The GEOtop 2.0, an improved version of the open-source software GEOtop, which simulates the energy and water balance at and below the land surface, soil freezing, snow cover dynamics, and terrain effects are included. It is a research tool for studying, for example, the hydrological and thermal phenomena at locations that differ in soil types and topography to specific climatic forcings. Output consists of variables such as temperature, water and ice contents, or of integrated variables such as stream discharge. The software operates in point-wise and distributed modes and can be flexibly controlled, because all relevant parameters that govern e.g. discretisation, input/output or numerics can be set via keywords.

GEOtop describes the evolution in time of temperature and water content in the soil and snow cover and is driven by meteorological forcings. This is accomplished by solving the heat and water flow equations with boundary conditions accounting for the interactions with the atmosphere at the surface in terms of energy and water fluxes. The solution of the equations is obtained numerically in the soil domain and snow cover.

GEOtop 2.0 is significantly different from GEOtop 0.75. It includes a fully three-dimensional description of the Richards equation, whereas in the previous version the equation was only solved in the vertical direction and the lateral flow was parameterised, in a similar way as in large-scale land surface models. In the new version, a multilayer snow cover and the surface energy balance are fully integrated in the heat equation for the soil, which is solved with a rigorous numerical method based on Kelley (2003), while in the previous version, snow cover was described with a bulk method (Zanotti et al., 2004) and the surface energy balance, though complete in its components and accommodating complex terrain, was not numerically coupled to the soil heat equation.

In GEOtop 2.0 (hereafter GEOtop), soil freezing and thawing are represented, meteorological forcings are distributed, and channel routing is described as overland flow with the shallow water equation neglecting the inertia. The description of vegetation with a double-layer surface scheme in order to more accurately represent the heat and vapour exchanges of vegetation with the soil surface and the atmosphere has also been included in GEOtop and is described in Endrizzi and Marsh (2010).

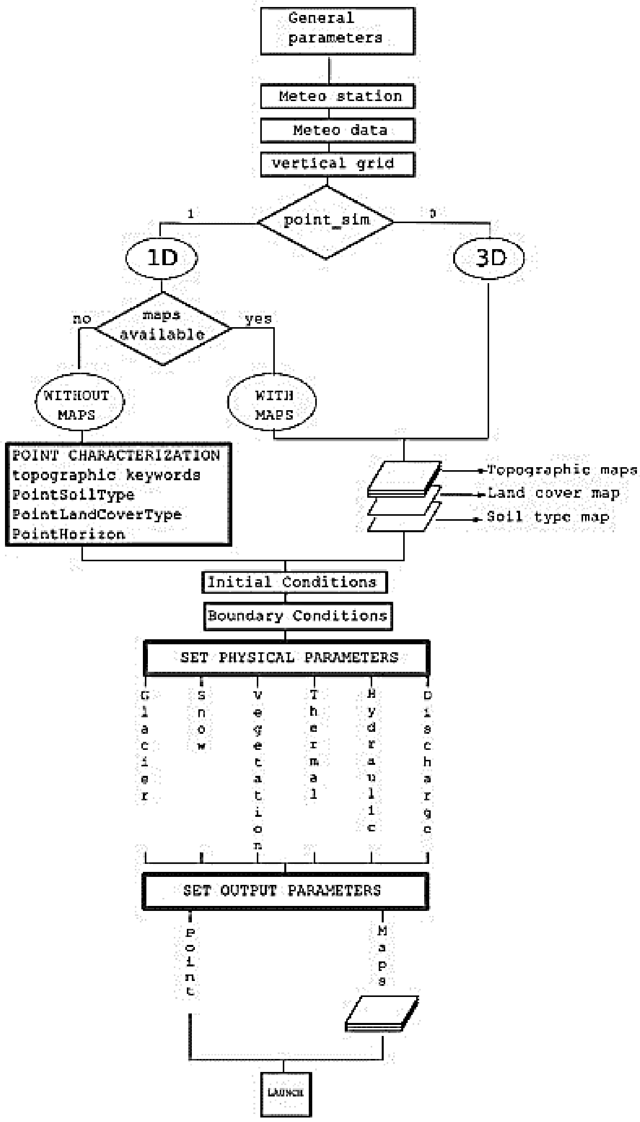


Figure 3.2: GEOtop flow chart: user point of view for preparing a simulation

GEOtop is known to run under the following Operating Systems:

- Mac OS X 10.8 or later
- Cent OS 6.5 or later
- Debian 7

GEOtop has NOT been tested on Microsoft Windows either with Cygwin or MinGW compiler. This configuration therefore is NOT supported

3.7.5 HBV Light

HBV light is a model that simulates daily discharge using daily rainfall, temperature and potential evaporation as input. Precipitation is simulated to be either snow or rain depending on whether the temperature is above or below a threshold temperature. In the snow routine snow accumulation and snowmelt are computed by a degree-day method. In the soil routine groundwater recharge and actual evaporation are simulated as functions of actual water storage. In the response (or groundwater) routine, runoff is computed as a function of water storage. Finally, in the routing routine a triangular weighting function is used to simulate the routing of the runoff to the catchment outlet.

3.7.5.1 Advantage & Shortcomings

This model is a good compromise between black-box models, which do not allow processes to be readily transparent, and physically-based models, which are usually too complex to be easily applied. The model is freely available to download. HBV-ETH does not distinguish the different glacier surface conditions for melt water simulation as TAC D does.

3.7.6 TAC D

The model TAC D (Tracer Aided Catchment Model, Distributed) is a fully distributed, modular catchment model, which at its core has a process-based runoff generation routine based on dominant process conceptualizations. A temperature-index method is used for the calculation of snow and ice melt as in TAC D, whereas the computation of melt of debris-covered glaciers is treated the same way as of debris-free glaciers.

3.7.6.1 Advantages & Shortcomings

Certain periods, e.g. short-term runoff fluctuations during snow melt periods, could not be simulated well even when different model modifications were executed. This indicates model shortcomings because of incomplete process understanding and the necessity for further experimental research as well as for new concepts of model structure.

3.7.7 SWAT model

The Soil and Water Assessment Tool or SWAT is a river basin or watershed scale model developed by the USDA Agricultural Research Service (Arnold et al., 1998). SWAT is a semi-distributed, continuous watershed modeling system, which simulates different hydrologic responses using process- based equations. Spatial variabilities of the various types in a catchment are represented by dividing the catchment area into sub-watersheds which are further subdivided into hydrologic response units (HRUs). This subdivision is based on soil, land cover and slope characteristics. The model computes the water balance from a range of hydrologic processes such as evapotranspiration, snow accumulation, snowmelt, infiltration and generation of surface and subsurface flow components.

To estimate snow accumulation and melt, SWAT uses a temperature-index approach. Snowmelt is calculated as a linear function of the difference between average snowpack maximum temperature and threshold temperature for snowmelt. Snowmelt is included with rainfall in the calculation of infiltration and runoff. Although the SWAT model does not include an explicit module to handle snow melt processes in the frozen soil, it has a provision for adjusting infiltration and estimating runoff when the soil is frozen (Neitsch et al., 2005). However, this is not considered a major limitation and SWAT is one of the most appropriate integrated models currently available for application in cold regions environment.

3.7.8 University of british columbia watershed model (UBC)

The UBC watershed model has been developed by Quick and Pipes (1977) at the University of British Columbia, Canada. The model has been designed primarily for mountainous watersheds and calculates the total contribution from both snowmelt and rainfall runoff. A separate calculation can also be made for runoff occurring from glacier covered areas. The model has been designed to use sparse data networks which are, generally, found in mountainous regions. The basic structure of the model depends on a division of the watershed into a number of elevation bands. The elevation increment for each band is the same and an area for each band is specified. The UBC watershed model was also included in the WMO project on intercomparison of snow melt models (WMO, 1986).This model was revisited by Quick et.al. (1995).

3.8 Way Forward

The mountain snow and glaciers are huge storage and very important source of fresh water. In mid and high latitude mountain ranges, for example, seasonal snow cover exerts a strong influence on runoff variability, where as glaciers are the dominant source of water during the dry season at low latitudes. During summer period, substantial runoff is generated from the glaciers in all the Mountain River. Snow and glacier melt runoff studies will improve management of available water resources in the region.

Snowmelt runoff models developed so far have been categorised in two categories i.e. temperature index or degree day model and energy balance model. As per the literature survey most of the models falls under degree day approach. Some modeling studies have been carried out using energy balance approach. The degree approach involves computing the daily snowmelt depth by multiplying the number of degree days by the degree day factor. This approach can be used over large areas with limited data input requirements. However, the degree day method can be easily predicted by the temperature. Although degree day approach is simple for runoff estimation but there is problem in determination of melt rate. It is possible to estimate melt rate with the help of components of energy balance equation, therefore Energy balance approach is more physically based, enabling it to account directly for many of the physical processes that effect snowmelt. Incorporating the physical process involved in snowmelt increases the data input requirements needed to run these models. Due to scarcity of input data to run energy balance models, which has prevented them from gaining dominance over the Degree day approach. The intensive input data for energy balance approach include incoming thermal radiation, net radiation, cloudiness, wind speed and humidity etc. And process involved in data preparation is not only time consuming but also subject to errors due to the extensive manual editing and manipulation that may be difficult to automate. In other words, theoretical superiority of energy balance model is outweighed by its excessive data requirements. Therefore, degree day approach retains its prominence for snowmelt runoff.

In the Himalayan region long term series of temperature and precipitation are available at low altitude ranges. Also stream flow data and snowfall distribution availability is very limited. The lack of data availability in Himalayan region is one of the major constraints in projecting changes in runoff due to melt water and making a viable management programme for Himalayan rivers. A number of advances in snowmelt runoff simulation have been made during the past few decades. These advances resulted from an improved understanding of the physical processes of snowmelt and basin runoff, and the development of new technologies in the areas of data collection and computer technology.

Research needs can be categorized into five general areas of emphasis. These are: (a) Improvement of data measurement and extrapolation techniques. Use of new technologies and the combined application of point and areal measurement technologies need to be investigated. Procedures to expedite the processing and distribution of remotely sensed data for near real time applications need to be developed. (b) Development of a more physically based understanding of the hydrological processes and process interactions involved in snow accumulation and melt, and in basin runoff response. (c) Development of parameter measurement and estimation techniques those are applicable over a range of space and time scales. In conjunction with the development of physically based parameters, the variability and applicability of these parameters at different spatial and temporal scales needs to be determined. (d) Improvement of forecasting techniques to include objective procedures for updating components of the modeled system and the forecast itself. Improvements in data quality and availability and in hydrological process simulations will improve forecast capabilities. However, there always will be uncertainty in these forecast elements, and techniques to minimize this uncertainty need to be developed. (e) Development of modular modeling system and data management shells for developing, analysing, testing, and applying model components and for facilitating the incorporation of advances made in (a), (b), (c) and (d) above.

Maximum use of current and future advances in the fields of expert systems, geographical information systems, remote sensing, information management, and computer science needs to be done. Presently due to lack of data available Temperature Index models are popularly used. The indigenous model SNOWMOD can be transformed into operational environment and towards an ensemble approach. The other development could be propagating uncertainty through model inputs and parameterization.

References

1. Anderson, E. A., 1973, National Weather Service River Forecast System—Snow Accumulation and Ablation Model, NOAA Technical Memorandum NWS HYDRO-17, U.S. Dept. Commerce, Silver Spring, MD.
2. Archer, D.R., Bailey, J.O., Barret, E.C., and Greenhill, D., 1994, The potential of satellite remote sensing of snow cover Great Britain in relation to snow cover, Nordic Hydrology, Vol. 25, pp. 39-52.
3. Arnold, J.G., Srinivasan, R., Muttiah, R.S., Williams, J.R., 1998. Large area hydrologic modeling and assessment Part I: Model development. J. American Water Resour. Assoc. 34(1), 73-89.
4. Berg, N., Osterhuber, R. and Bergman, J., 1991, Rain-induced outflow from deep snowpacks in the central Sierra Nevada, California. Hydrologic Sciences Journal, Vol. 36, pp. 611-629.
5. Bhutiyani, M.R., V.S. Kale and N.J. Pawar. 2007. Long-term trends in maximum, minimum and mean annual air temperatures across the Northwestern Himalaya during the twentieth century. *Climatic Change*, **85**(1–2), 159–177.
6. Brunengo, M.J., 1990, A method of modeling the frequency characteristics of daily snow amount for stochastic simulation of rain-on-snowmelt events, Proceeding of Western Snow Conference, Vol. 58, pp. 110-121.
7. Chang A T C 1986 Nimbus-7 SMMR snow cover data. Glaciological Data. Report GD-18: 181-187

8. Colbeck, S.C., 1975, A theory of water flow through a layered snowpack, Water Resources Research, Vol. 11, pp. 261-266.
9. Conway, H., Breyfogle, S., and Wilbour, C.R., 1988, Observations relating to wet snow stability, International Snow Science Workshop, ISSW'88 Comm. Whitler, B.C., Canada.
10. Conway, H. and Raymond, C.F., 1993, Snow stability during rain, Journal of Glaciology, Vol. 39, pp. 635-642.
11. Dall'Amico, M., Endrizzi, S., Gruber, S., and Rigon, R.: GEOtop Users Manual. Version 1.0, Technichal report, Mountaineering Srl, Siemensstr. 19 Bolzano, Italy, 2011b.
12. Endrizzi S, Marsh P. 2010. Observations and modeling of turbulent fluxes during melt at the shrub-tundra transition zone 1: point scale variations. Hydrology Research 41: 471–491.
13. Gubler, S., Endrizzi, S., Gruber, S., and Purves, R. S.: Sensitivities and uncertainties of modeled ground temperatures in mountain environments, Geosci. Model Dev., 6, 1319–1336, doi:10.5194/gmd-6-1319-2013, 2013.
14. Heywood, L., 1988, Rain on snow avalanche events-some observations, Proceeding of International Snow Science Workshop, ISSW'88 Comm. Whistler, B.C. Canada.
15. Kattelmann, R., 1987, Uncertainty in Assessing Himalayan Water Resources, Mountain Research and Development, Vol. 7, No. 3,pp. 279-286.
16. IPCC, 2007, Climate Change 2007, The Physical Science Basis, Contribution of Working Group 1 to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (eds. S. Solomon, D. Qin, M. Manning, Z. Chen, M.C. Marquis, K. Averyt, M. Tignor and H.L. Miller), Intergovernmental Panel on Climate Change, Cambridge and New York.
17. Jain, SanjayK., 2001, Snowmelt runoff modeling and sedimentation studies in Satluj basin usingremote sensing and GIS, PhD Thesis unpublished, University of Roorkee.
18. Jain, Sanjay K., L N Thakural and Anju Chaudhary, 2010, Snow and glacier melt contribution in a Himalayan basin, Proc. Water availability and management in Punjab, National Institute of Hydrology, Roorkee, December 2010.
19. Kelley, C. T.: Solving Nonlinear Equations with Newton's method, Society for Industrial and Applied Mathematics, SIAM, Philadelphia, USA, 2003.
20. Martinec J, Rango A. 1986. Parameter values for snowmelt runoff modeling. Journal of Hydrology 84: 197–219.
21. Neitsch, S.L., Arnold, J.G., Kiniry, J.R., Williams, J.R., 2005. Soil and Water Assessment Tool: Theoretical Documentation. Blackland Research Center, Grassland, Soil and Water Research Laboratory, Agricultural Research Service: Temple, TX, USA. 476 pp.
22. Panagoulia, D., 1992, Hydrological modeling of a medium size mountainous catchment from incomplete meteorological data, Journal of Hydrology, Vol. 137, pp. 279-310.
23. Pomeroy JW, Gray DM, Shook KR, Toth B, Essery RLH, Pietroniro A, Hedstrom N. 1998b. An evaluation of snow ccumulation and ablation processes for land surface modeling. Selected Papers from the 55th Eastern Snow Conference held in Jackson, New Hampshire,USA, Taylor S, Hardy JP (eds). Hydrological Processes 12: 2339–2367.
24. Pomeroy JW, Gray DM, Hedstrom NR, Janowicz JR. 2002. Prediction of seasonal snow accumulation in cold climate forests. Hydrological Processes 16: 3543–3558.
25. Pomeroy, J.W., and Gray, D.M. 1995. Snow Accumulation, Relocation and Management. NHRI Science Report No. 7. National Hydrology Research Institute, Saskatoon.
26. Quick, M. C., and A. Pipes, 1977: UBC Watershed Model. Hydrol. Sci. Bull., 306, 215–233.
27. Quick, M. C. & Pipes, A., 1995, UBC Watershed Model Manual (Version 4.0). Univ. of British Columbia, Vancouver, Canada.
28. Schanda E., M¨atzler C. and K¨unzi K. (1983) Microwave remote sensing of snow cover. International Journal of Remote Sensing, 4(1), 149–158.
29. Singh, P., and Kumar, N. (1997) Effect of Orography on Precipitation in the Western Himalayan Region, Journal of Hydrology 199, 183–206.
30. Singh, P., and Jain, S. K., 2002, Snow and glacier melt in the Satluj River at Bhakra dam in the western Himalayan region, hydrological sciences journal, Vol. 47, No. 1, pp-93-109.
31. Singh J, Knapp HV, Arnold JG, Demissie M. (2005). Hydrological modeling of the Iroquois River watershed using HSPF and SWAT. J. American Water Resour. Assoc. 41(2): 343-360.

32. Singh, P., Jain, S. K. & Kumar, N. (1997) Snow and glacier melt runoff contribution in the Chenab River at Akhnoor. Mountain Res. and Develop. 17(1), 49–56.
33. Singh, P., Jain, S. K., Kumar, N. & Singh, U. K. (1994) Snow and glacier contribution in the Ganga River at Devprayag, Report no. CS (AR)-132, National Institute of Hydrology, Roorkee, India.
34. World Meteorological Organization (WMO), 1986, Intercomparison of models of snowmelt runoff. Operation Hydrological Report No. 23, (WMO No. 646), World Meteorological Organization, Geneva.
35. U.S. Army Corps of Engineers. 1956. Snow Hydrology: Summary Report of the Snow Investigation. North Pacific Division: Portland; 462.
36. USACE (US Army Corps of Engineers), 1998. HEC-5: Simulation of flood control and conservation systems. Hydrologic Engineering Center, Davis, CA, USA.
37. Yao, T., Pu, J., Lu, A., Wang, Y. and Yu, W. 2007: Recent glacial retreat and its impact on the hydrological processes on the Tibetan Plateau, China, and surrounding regions. *Arctic Antarctic and Alpine Research* 39, 642–50.

CHAPTER 4

SOIL EROSION AND SEDIMENT TRANSPORT MODELING

4.1 Introduction

Natural processes of soil erosion and sediment transport are highly complex. Computational modeling of these processes has been a very challenging but important task for hydro-scientists and engineers, and thus many numerical models have been developed since 1950s. Merritt et al. (2003) noted that most of the erosion and transport models can suffer from a range of problems including over-parameterisation, unrealistic input requirements, unsuitability of model assumptions or parameter values to local conditions and inadequate documentation of model testing and resultant performance. Therefore, a clear understanding of a model is important for its appropriate use. The present report is an effort in achieving a greater understanding of soil erosion and sediment transport modeling.

In the present work, an effort has been made to review various aspects of erosion and sediment transport modeling, available approaches for modeling these processes, existing models and the concepts behind these models. The review is expected to be of interest to researchers, watershed managers and decision-makers while searching for models to study erosion and sediment transport phenomena and related processes such as pollutant and nutrient transport.

4.2 Brief Review of Soil Erosion and Sediment Transport Modeling Approaches

The processes, controlling sediment detachment, transport, and deposition on the hill slope scale, lumped under the term erosion processes, are complex and interactive (Lane et al., 1988). This complexity leads to the need for upland erosion models as tools in resource management. Since runoff is the main carrier of sediment, the erosion models are used in combination with a hydrologic model to estimate the sediment yield at the outlet of the watershed. A wide range of models exists for use in simulating sediment erosion, transport and associated pollutant transport. Bryan (2000) carried out a review on the water erosion modeling on hillslopes while Zhang et al. (1996a) reviewed modeling approaches used for the prediction of soil erosion in catchments. Merritt et al. (2003) provided a comprehensive review of specific models based on model input–output, model structure, runoff, erosion/transport and water quality modeling, and accuracy and limitation of the model. Borah and Bera (2003a) reviewed mathematical basis of eleven watershed scale hydrologic and nonpoint-source pollution models. Most recently, Aksoy and Kavvas (2005) carried out a review of hillslope and watershed scale erosion and sediment transport models.

Available models can be classified according to different criteria that may encompass process description, scale, and technique of solution (Singh, 1995). Some models may be similar because they are based on the same assumptions and some may be distinctly different.

4.3 Classification of Models

In general, models may be classified into three main categories, depending on the physical processes simulated by the model, the model algorithms describing these processes, and data dependence of the model: (i) empirical (ii) conceptual, and (iii) Physically-based. The models may also contain a mix of modules (Merritt, et al, 2003). For example, while the rainfall-runoff component of a water quality model may be physics-based or conceptual, empirical relationships may be used to model erosion or sediment transport.

4.3.1 Empirical models

Empirical models are generally the simplest of all three model types. The computational and data requirements for such models are usually less than for conceptual and physics-based models, often being capable of being supported by coarse measurements.

Wischmeier and Smith (1965), based on over 10,000 plot years of natural and simulated runoff data, presented Universal Soil Loss Equation (USLE), expressed as,

$$A = R\ K\ LS\ C\ P \qquad (4.1)$$

where A is the annual potential soil erosion (t ha^{-1} $year^{-1}$); R is the rainfall erosivity factor (MJ mm ha^{-1} hr^{-1} $year^{-1}$) taken as the long term average of the summation of the product of total rainfall energy (E) and maximum 30 minute rainfall intensity (I_{30}), i.e. EI_{30}; K is the soil erodibility factor (t ha hr ha^{-1} MJ^{-1} mm^{-1}); LS is the slope length and steepness factor (dimensionless); C is the cover management factor (dimensionless); and P is the supporting practice factor (dimensionless). The dimensions used here are consistent with the work of Renard et al. (1991).

Three major limitations of the USLE restricted its application in many modeling analysis. First, it was not intended for estimating soil loss from single storm events (Haan et al., 1994); second, it was an erosion equation, and consequently did not estimate the deposition (Wischmeier, 1976); and third, it did not estimate gully or channel erosion.

Since 1965, efforts have been to improve the USLE and it has been expanded for additional types of land use, climatic conditions and management practices. Williams (1975) presented a Modified Universal Soil Loss Equation (MUSLE) for predicting sediment yield from individual storm events. Renard et al. (1991) proposed revised USLE (RUSLE) incorporating a method for computing kinetic energy of rainfall for individual storm events using the equation proposed by Brown and Foster (1987).

4.3.2 Remarks on empirical models

The major weakness of the empirical models is that they only provide a limited insight in the relative importance of the various variables and their sensitivity in different environments. The major weaknesses of empirical modeling include: (i) the spatial and temporal resolution and extent are limited by the data available; (ii) their lack of process explicit process representation can limit predictive ability outside the study area or measured range of environmental characteristics; (iii) the heterogeneity of catchment characteristics such as rainfall, topography, lithology and land use is not usually represented in spatially lumped models; this reduces predictive ability, given the significant spatial correlations, and nonlinear dependencies, between slope gradient, runoff and other driving variables of erosion (iv) the absence of source and sink process representations in empirical sediment yield models can limit the number of different types of data which can be meaningfully assembled. The advantage with empirical models, however, is that they can be implemented in situations with limited data and parameter inputs and are particularly useful as a first step in identifying sources of sediment and nutrient generation.

USLE so far remains the well accepted and most widely used empirical approach for estimation of upland erosion despite the development of a number of conceptual and physically process based models (Lane et al., 1988; Narula et al., 2002). Researches and investigators have applied USLE with suitable modifications for estimation of annual soil loss and sediment yield as well as its temporal variation on single storm event basis, and to study the effect of various parameters that affect the soil loss.

4.4Conceptual Models

Conceptual models are based on spatially lumped forms of continuity equations for water and sediment and some other empirical relationships. These models include a general description of catchment processes, without including the specific details of process interactions, which would require detailed catchment information (Sorooshian, 1991). They consist of a number of interconnected reservoirs which represents the physical elements in a catchment in which they are recharged by rainfall, infiltration and percolation and are emptied by evaporation, runoff, drainage etc. Semi empirical equations are used in this method and the model parameters are assessed not only from field data but also through calibration. Large number of meteorological and hydrological records is required for calibration. The calibration involves curve fitting which makes the interpretation difficult and hence the effect of land use change cannot be predicted with much confidence. Many conceptual models have been developed with varying degree of complexity. To summarize, conceptual models of sediment are analogous in approach to those of surface runoff, and hence, embody the concepts of the unit hydrograph theory.

Johnson (1943) was perhaps the first to derive a distribution graph for suspended sediment concentration employing the hypothesis analogous to that embodied in the unit hydrograph. Rendon-Herrero (1978) extended the unit hydrograph method to directly derive a unit sediment graph (USG) for a small watershed. Williams (1978) extended the concept of an instantaneous unit hydrograph (IUH) to instantaneous unit sediment graph (IUSG) to determine the sediment discharge from an agricultural catchment. The concept of USG has been also employed by Singh et al. (1982), Chen and Kuo (1986), Kumar and Rastogi (1987), Raghuwanshi et al. (1994), Banasik and Walling (1996), among others, for the purpose of estimating the temporal variation of sediment yield. Kalin et al. (2004) developed a modified unit sedimentograph approach for identification of sediment source areas within a watershed.

4.4.1 Concluding remarks on conceptual models

Spatial lumping of model domains into morphological units or sub-catchments, and application of lumped parameter values across units and time scales is common in conceptual models. Therefore, the main limitations of the conceptual models lie in the poor physical description of the processes which, among other things, results in distortion of parameter values determined by calibration (Elliot et al., 1994). Because the parameter values are determined through calibration against observed data, conceptual models tend to suffer from problems associated with the identifiability of their parameter values (Jakeman and Hornberger, 1993).

4.5Physically-Based Models

Significant research and understanding of basic processes of erosion and sediment transport led to the development of more complicated, physically-based sediment models. These models have been developed in a coupled structure such that the algorithms for computing runoff are combined with the algorithms for computing sediment detachment, deposition and their transport. The physically-based sediment models involve solutions to the simultaneous partial differential equations of mass, momentum and energy conservation for simulation of hydrological and erosion processes which are non-linear in nature.

The fundamental relationship normally used in overland flow erosion model is given as follows (Bennett, 1974; Foster and Meyer, 1975).

$$\frac{\partial\ q_s}{\partial\ x} + \rho_s \frac{\partial\ (C_s\ h)}{\partial\ t} = D_i + D_r \qquad (4.2)$$

Where q_s = sediment discharge [$ML^{-1}T^{-1}$], ρ_s = mass density of the sediment particles [ML^{-3}], C_s = concentration of the sediment being transported [L^3L^{-3}], h is the depth of flow [L], D_i = detachment by raindrop impact [$ML^{-2}T^{-1}$] and D_r = detachment by flow [$ML^{-2}T^{-1}$]. The term $\partial q_s / \partial x$ is build-up or loss of sediment load with distance and $\rho_s\, \partial (C_s h) / \partial t$ is storage rate of sediment within the flow depth and D_r and D_i are the contributions from lateral flow.

When quasi-steady sediment transport is assumed, the mass continuity equation (Equation4.1) for down slope sediment transport is expressed as follows (Curtis, 1976; Thomas, 1976; Foster and Huggins, 1977).

$$\frac{dq_s}{dx} = D_r + D_i \qquad (4.3)$$

where, q_s is sediment load per unit width per unit time (sediment flux); x is down slope distance; D_r is the net rate of rill flow detachment or deposition, i.e., rill erosion; and D_i is the rate of soil particles detached by inter-rill erosion. Rill detachment (or deposition), D_r, may be assumed to be as given by Equation (4.3) (Foster and Meyer, 1975).

$$D_r = \alpha \cdot (T_c - q_s) \qquad (4.4)$$

where, α is the first order reaction coefficient for deposition [L^{-1}], and T_c is the transport capacity [$ML^{-1}T^{-1}$]. The Equation (4.2) may be rewritten as (Foster and Meyer, 1972):

$$\frac{D_r}{D_{rc}} + \frac{q_s}{T_c} = 1 \qquad (4.5)$$

where $D_{rc} (= \alpha\ T_c)$ is the rill erosion detachment capacity rate [$ML^{-1}T^{-1}$]. The first order reaction coefficient for overland deposition can be computed using Equation (4.5).

$$\alpha = \varepsilon \cdot V_s / q \qquad (4.6)$$

where V_s is the fall velocity [LT^{-1}] and q is the discharge per unit width [L^2T^{-1}]. The value of ε for overland flow can be taken as 0.5 and 1.0 for channel flow (Foster, 1982).

The physically-based erosion models generally separate the ground surface into inter-rill and rill erosion areas (Wu et al., 1993; Meyer et al., 1975; Kothyari and Jain, 1997). As such, these models consist of three major component processes viz. inter-rill erosion, rill erosion and transport process as discussed below.

4.5.1 Inter-rill erosion process

Raindrop impact on soil surface, and velocity and depth of flow over the surface are the factors that affect the amount and rate of inter-rill and rill erosion in a catchment. Both detachment and transport of sediment particles occur on inter-rill and rill areas. Since Ellison (1947), many researchers have investigated this process and related it with the physiographic, land use, soil characteristics, management practices such as contouring etc. and proposed the relationships for modeling in the watershed. The important relationships proposed by various researchers for computation of inter-rill erosion are summarized by Tyagi (2007).

4.5.2 Rill erosion process

Erosion in rills has been attributed to component processes including scour, head-cutting, sidewall sloughing, and slaking (incipient failure, or mass erosion). Equations that describe rill erosion have generally been limited to describing the scouring process through relation of flow, shear, and slope. Almost all natural soil surfaces where flow occurs are irregular causing shear stress concentrations. If stress at these concentrations is greater than the soil's critical shear stress, soil erosion occurs. Total rill erosion on an area can be modelled by describing soil erosion in each individual rill (Foster and Meyer, 1975). To date, physically-based rill erosion models have been based almost exclusively on shear stress excess concept (Haan et al., 1994). The relationships developed for the rill erosion process in the watersheds are summarised by Tyagi (2007).

4.5.3 Transport process

Once sediment particles are detached, they become part of the overland flow and are transported downstream to distances varying from a few millimetres to hundreds of kilometres. The distances so traversed are dependent on the sediment transport capacity of the flow, which in-turn depends on sediment characteristics and hydraulic parameters associated with flow path (Haan et al., 1994). No single sediment transport equation is said to be superior to others as all these equations require calibration for representing sediment transport by overland flow (ASCE, 1975). A summary of the important relationships for overland flow transport capacity are given in Tyagi (2007).

4.5.4 Concluding remarks on physically-based models

Physically-based models are expected to provide reliable estimates of sediment transport. In theory, the parameters used in physically-based models are measurable and so are 'known'. However, in practice, the large number of parameters involved and the heterogeneity of important catchment characteristics require that these parameters must often be calibrated against observed data (Beck et al., 1995; Wheater et al., 1993). This creates uncertainty in parameter values. Given the large number of parameter values needed to be estimated using such a process, problems with a lack of identifiability of model parameters and non-uniqueness of 'best fit' solutions can be expected (Beck, 1987; Wheater et al., 1993).

The physics behind the model structure are generally based on laboratory or small-scale in-situ field experiments, and hence are affected by the nature of the experiments themselves. Extrapolation to larger (e.g. catchment) scales often involves the assumption that the physical processes and properties are independent of scale, raising uncertainty about their applicability (Beven, 2004). To reduce computational burden and data requirements, simplified physics are sometimes used to represent the physics (e.g. simplified St. Venant equations, the Green-Ampt equation [Green and Ampt, 1911; Mein and Larson, 1973)], leading to deviation from the physical basis and additional questionability.

The practical applications of physically-based models are still limited in developing countries because of large number of input parameters, uncertainty in specifying model parameter values and also due to the difference between the scales of application i.e. a catchment versus a field (Wu, et al., 1993).

4.6 Selecting an Appropriate Model

All types of mathematical models are useful but in somewhat different circumstances. Each has its own effectiveness, depending upon the objective of study, the degree of complexity of the problem, and the degree of accuracy desired. There is no conflict between these models; they represent different levels of approximation of reality. In their review of erosion and sediment transport models, Merritt, et al. (2003) have presented important aspects that need to be considered in selecting an appropriate model and some of them are produced below for the benefit of model users.

4.7 Model Structure

Choice of a suitable model structure relies heavily on the purpose that the model needs to serve. Within the literature, the preferences of researchers for certain model types over others largely reflect two main viewpoints: emphasis on the processes at work or emphasis on the output (Merritt et al., 2003). For example, Thorsen et al. (2001) considered that 'the predictive capability of empirical and conceptual models with regards to assessing the impacts of alternative agricultural practices is questionable, due to the semi-empirical nature of the process description'. Yet, other authors argue that simple conceptual models, or empirical models, when used within the developed framework, can be more accurate than models with more complicated structures (e.g. Ferro and Minacapilli, 1995; Letcher et al., 1999). Perrin et al. (2001) noted that models with a larger number of parameters generally yield a better fit to observed data during the calibration period than more simple models, although in the verification phase this trend of improved performance is not apparent. Simpler models tend to be more robust, thus providing more stable performances than more complicated models. Overly complicated models with large numbers of processes considered, and associated parameters, run the risk of having a high degree of uncertainty associated with the model inputs which are translated through to the model outputs. The ultimate factor determining a model's value is its simplicity relative to its explanatory power (Steefel and Van Cappellan, 1998).

4.8 Spatial Representation

Traditionally, models have treated input parameters as lumped over the area of analysis. In the last two decades, however, lumped models have been challenged by distributed hydrologic models. Distributed hydrologic models, with the capability to incorporate a variety of spatially-varying land characteristics and precipitation forcing data, are thought to have great potential for improving hydrologic forecasting. However, uncertainty in the high resolution estimates of precipitation and model parameters may diminish potential gains in prediction accuracy achieved by accounting for the inherent spatial variability. In distributed models, parameters need to be defined for every spatial element and for each process representing equation. In principle, parameter adjustment should not be necessary for this type of model because parameters should be related to the physical characteristics of the surface, soil and land use. However, in practical applications, calibration procedures are required for both lumped and distributed models; consequently, the models require effective or equivalent values for some parameters. Despite these difficulties, there has been a strong surge in the use of distributed modeling specially for soil erosion and sediment transport modeling over the last decade. Ferro and Minacapilli (1995) argue that the dependence of the sediment delivery process on local factors, such as sediment detachment and flow transport travel time, emphasises the need to use a spatially distributed approach for modeling this phenomenon. However, in most practical applications, little geographical and spatial information is available.

A compromise between fully distributed methodologies and lumped models are the semi-distributed models that break a catchment down into a group of sub-catchments or other biophysical regions over which the model is applied. Ultimately the choice between lumped or distributed models depends on the desired output of the model. Increasingly, resource managers are requiring knowledge of the origin of the major sources of pollutants or sediments. Distributed models have the potential to assist management in this situation if the data requirements do not inhibit model application.

4.9 Temporal Resolution

A key consideration in determining an appropriate model for application is the timing of the events or processes that the model user wants to predict. Sediment-associated water quality or erosion models tend to have been developed from two opposed viewpoints. Event-based models were developed to look at the response of the modelled area to single storm events. For each event, the model time-step is of the order of minutes to hours. The model algorithms that describe these processes were often developed for application to small plots or grid cells in a catchment. Alternatively, a larger temporal resolution was used and models were applied to explore broad trends over time to changes in rainfall, vegetation or land management. A third approach was to use a continuous time step, usually daily, that is responsive to, for example, the development and recession of saturated zones or other processes that can be captured at this time step, yet does not capture responses to high intensity and short duration events.

4.10 Review of Popular Erosion and Sediment Yield Models

A multitude of erosion and sediment transport models are available now a day that differ in complexity, the processes modelled, the treatment of the sediment generation, transport and deposition processes, the scale to which they are applied, and assumptions on which they are based. Some of the commonly used models are reviewed in this Section.

4.10.1 Universal Soil Loss Equation (USLE) and Modifications

The USLE (Wischmeier and Smith, 1965) is the most widely used and accepted empirical soil erosion model Equation (4.1). It predicts the long-term average annual rate of erosion on a field slope based on rainfall pattern, soil type, topography, crop system and management practices. USLE only predicts the amount of soil loss that results from sheet or rill erosion on a single slope and does not account for additional soil losses that might occur from gully, wind or tillage erosion. Model outputs are both spatially and temporally lumped. This erosion model was created for use in selected cropping and management systems, but is also applicable to non-agricultural conditions such as construction sites. The USLE can be used to compare soil losses from a particular field with a specific crop and management system to "tolerable soil loss" rates. Alternative management and crop systems may also be evaluated to determine the adequacy of conservation measures in farm planning.

Five major factors are used to calculate the soil loss for a given site as explained in sub-section 3.1.1. Each factor is the numerical estimate of a specific condition that affects the severity of soil erosion at a particular location. The erosion values reflected by these factors can vary considerably due to varying weather conditions. Therefore, the values obtained from the USLE more accurately represent long-term averages.

Although developed for application to small hill-slopes, the USLE and its derivatives have been incorporated into many catchment scale erosion and sediment transport modeling applications. Due to the identified limitations of the USLE, a number of modifications and revisions to the basic format have been proposed in the literature. These include the modified USLE (Williams, 1975), the revised USLE (Renard and Ferreira, 1993; Renard et al., 1994), and the USLE-M (Kinnell and Risse, 1998). These continue to improve components of the model making it more process-based.

4.10.2 AGNPS

The Agricultural Non-Point Source (AGNPS) model (Young et al., 1987) is a single-storm event model. It simulates surface runoff, soil erosion, and transport of sediment, nitrogen (N), phosphorous (P), chemical oxygen demand (COD), and pesticides from non-point and point sources resulting from a single rainfall event. The model generates total or average responses for a storm event considering the storm duration as one time step. The watershed is divided into uniform square areas (cells).

AGNPS computes runoff volume using the SCS runoff curve number method. Peak runoff rate for each cell is computed using an empirical function of drainage area, channel slope, runoff volume, and watershed length-width ratio. Computation of soil erosion due to rainfall is based on the USLE. Detached sediment is routed using sediment transport and depositional relations based on a steady-state sediment continuity equation, effective sediment transport capacity, particle fall velocity, and Manning's equation. A modification to Bagnold's stream power equation is used for the effective sediment transport capacity.

AGNPS simulates chemical transport in soluble and sediment-adsorbed phases. Nutrient yield in the sediment adsorbed phase is empirically calculated using sediment yield, nutrient (N or P) content of the soil, and an enrichment ratio. Soluble N or P contained in runoff is computed simply by multiplying an extraction coefficient of N and P, the mean concentration of soluble N or P at the soil surface during runoff, and total runoff. AGNPS uses an N decay factor when simulating N movement through stream channels. COD is calculated based on runoff volume, with average concentration in that volume as the background concentration obtained from the literature.

AGNPS accounts for nutrient and COD contributions from point sources, such as feedlots, springs, and wastewater treatment plants, and estimated sediment contributions from stream bank, stream bed, and gully erosion as user input values. AGNPS simulates impoundments and their impacts on reducing peak discharges, sediment yield, and yield of sediment-attached chemicals.

AGNPS contains a mix of empirical and physically-based components. It is spatially distributed but temporally lumped, and is relatively robust with runtime estimates in minutes; it is suitable for both sediment and nutrient Total Maximum Daily Loads (Borah et al. 2006).

4.10.3 AnnAGNPS

The Annualized Agricultural Non-Point Source (AnnAGNPS) model (Bingner and Theurer, 2003) is a batch-process, continuous simulation watershed model developed from the single event Agricultural Nonpoint Source (AGNPS) model. AnnAGNPS was designed by the USDA Agriculture Research Service (USDA-ARS) and the USDA Natural Resources Conservation Service (USDA-NRCS) to evaluate nonpoint source (NPS) pollution from agriculturally dominated watersheds. The model simulates the same processes as AGNPS (surface runoff, soil erosion, and transport of sediment, nutrients, and pesticides) plus snowmelt, irrigation, subsurface flow, tile drain flow, feedlots, and gullies at continuous daily or sub-daily time steps.

AnnAGNPS allows the user to select either a grid (or cell) spatial representation or a hydrologic response unit spatial representation, with the selected unit being characterized by homogeneous land and soil properties. AnnAGNPS hydrologic simulations are based on a simple water balance approach. The runoff volume is computed using the SCS runoff curve number method, and the sediment yield routine is upgraded to the Revised Universal Soil Loss Equation (RUSLE) (Renard et al., 1997) for erosion computations. Refereed AnnAGNPS applications are predominantly for sites in the U.S. (e.g., Yuan et al., 2001; Yuan et al., 2002; Polyakov et al., 2007); however, applications in other countries have also been published, e.g., Australia (Baginska et al., 2003), Canada (Das et al., 2006), and China (Hong et al., 2005).

4.10.4 ANSWERS

The ANSWERS (Areal Nonpoint Source Watershed Response Simulation) model (Beasley et al., 1980) includes a conceptual hydrological process and a physically based erosion process. The erosion process assumes that sediment can be detached by both rainfall and runoff but can only be transported by runoff. ANSWERS model divides a watershed into small, independent elements. Within each element the runoff and erosion processes are treated as independent functions of the hydrological and erosion parameters of that element. In the model, surface conditions and overland flow depth in each element are considered uniform. No rilling is considered (Aksoy and Kavvas, 2005). The effect of rills is assumed to be described by the roughness coefficient of the Manning equation used in the model. According to ANSWERS subsurface return flow and tile drainage are assumed to produce no sediment. A detached sediment particle is reattached to the soil, if it deposits. Detachment of such a particle requires the same amount of energy as required for the original detachment. Channel erosion is negligible. In the erosion part, the differential equation given by Foster and Meyer (1972) is used. Preparing input data file for ANSWERS is rather complex (Norman, 1989) as it is the case for many physically based hydrology and erosion and sediment transport models. The model can be considered a tool for comparative results for various treatment and management strategies (Beasley et al., 1980).

The applicability of ANSWERS is limited in many catchments by the large spatial and temporal input data requirements of the model. Given the lack of such data in most catchments, parameters may need to be calibrated, raising problems with model identifiability and the physical interpretability of model parameters. There are also other potential problems with the model. Fisher et al. (1997) concluded from a spatial sensitivity analysis on the model that many outputs were insensitive to changes in the spatial distribution of input variables to the model. The authors proposed three possible explanations: lack of variability of important parameters in the study catchment; key model components were unaccounted for; or variables not subjected to spatial mixing in any run may swamp the effect of mixing. These findings indicate the possible shortcomings of the model in effectively modeling the processes addressed by the model (Fisher et al., 1997).

4.10.5 CREAMS

The CREAMS (Chemical, Runoff and Erosion from Agricultural Management Systems) model (Knisel, 1980) model was developed as a tool to evaluate the relative effects of agricultural practices on pollutants in surface runoff and in soil water below the root zone. The model consists of three major components namely, hydrology, erosion-sedimentation, and chemistry and target non-point source pollution. The hydrology component estimates runoff either by SCS curve number method or by the Green-Ampt infiltration equation depending upon the availability of data. The erosion component considers the processes of detachment, transportation and deposition. Detachment is described by a modification of USLE for a single storm event. Transport capacity of overland and channel flow is derived from Yalin’s sediment transport equation. It assumes that sediment load is controlled either by the losses at transport capacity or by the amount of sediment available for transport. In simulating the nutrients, nitrogen and phosphorous attached to the soil particles are lost with the sediment; soluble nitrogen and phosphorous are lost with the surface runoff, and; soil nitrate is lost by leaching with percolating water or by plant uptake. The pesticide component estimates pesticide concentration in runoff, and the total mass of pesticide carried from the field for each storm during the period of interest.

The major drawbacks of CREAMS are its complexity, intensive data requirements, and its reliance on modified USLE relationships and parameters. This degree of empiricism employed in the CREAMS model makes it useful for planning purposes and immediate application to field conditions, but limits its use for research in the physical processes causing erosion.

The CREAMS model has been used in many parts of the world with varying degree of success. Algorithms in CREAMS have been used in numerous other models of erosion and water quality (e.g. PERFECT model, WEPP model). Model outputs are computed temporally on a daily or event basis for a field sized catchment assumed uniform in soil, topography and land use.

4.10.6 HSPF

The Hydrologic Simulation Program - Fortran (HSPF) was developed based on the 1960s Stanford Watershed Model, for the simulation of watershed hydrology and water quality (nitrogen, phosphorus, suspended sediment and other toxic organic or inorganic pollutants) (Walton and Hunter, 1996). The model is a catchment scale, conceptual model and performs typically at an hourly time step and produces a time history of water quantity and quality at any point in a watershed. The watershed is divided into sub-watersheds, each conceptualized as a group of pervious and impervious land uses all routed to a representative stream segment or a mixed reservoir. Routing is performed by assuming that the sub-watersheds, streams, and the reservoirs (impoundments) are a series of one-dimensional reservoirs.

HSPF uses a comprehensive, physically based water budgeting procedure with interaction among the various storages and processes. It accounts for interception, infiltration, evapotranspiration, snowmelt, surface runoff, interflow, groundwater loss and recharge, and base flow; these are mostly represented by empirical equations. HSPF allows routing of in-stream flows and can simulate reservoir behavior as well.

Pervious land surface erosion and transport are modelled using exponential relationships for soil detachment, detached sediment washoff, and gully erosion. Sediment from impervious areas is also modeled with buildup/washoff routines. In-stream sediment transport, deposition, and scour of sediment are simulated for each of three particle-size classes (sand, silt, and clay) based on physical properties and using published equations.

HSPF includes very detailed subroutines of nutrient dynamics and calculates individual nutrient balances at a user-specified time step, representing a series of storages and phases with transport either by runoff in the dissolved phase or attached to sediment in the particulate phase. HSPF allows for detailed inputs of field operations and fertilization rates (management activities) through its special actions module. It simulates in-stream fate and transport of a wide variety of pollutants, such as nutrients, sediment, tracers, DO, biochemical oxygen demand, temperature, bacteria, and user-defined constituents, including pesticides.

BMPs can be simulated either through land use changes, a variety of special action functions that include direct reductions of input source loads and distributions, or through the Best Management Practice (BMPRAC) module. The BMPRAC module simulates simple removal fractions for a wide variety of constituents, including sediment and many forms of nutrients. These removal fractions can vary monthly or be constant.

Primary strengths of HSPF include: flexibility, ability to simulate a wide range of user-configurable inputs, modular structure that allows use of only those components needed for a specific application, and USEPA and USGS support (Borah et al. 2006). HSPF's limitations include large input data requirements and the need of monitored data for calibration for parameterisation (Walton and Hunter, 1996).With the relatively large number of parameters required to be calibrated this raises problems associated with parameter identifiability, and the physical meaningfulness of model parameters.

4.10.7 IHACRES-WQ

The IHACRES-WQ model contains the rainfall runoff model of the IHACRES (Jakeman et al., 1990) and the STARS model (Green et al., 1999; Dietrich et al., 1999). The input data include time series data for stream flow, rainfall and, depending on the version of IHACRES, also include temperature or evapotranspiration. The STARS model requires upstream and downstream concentration for calibration purposes. Based on the instantaneous unit hydrograph, the IHACRES model is a hybrid metric-conceptual model using the simplicity of the metric model to reduce the parameter uncertainty inherent in hydrological models.

The IHACRES model is a lumped model providing outputs at the catchment outlet on daily basis. However, when linked with a model such as STARS, it can be applied in a distributed manner with IHACRES applied to individual sub-catchments and the runoff generated from each sub-catchment routed through to the catchment outlet by STARS. The STARS model, while it is distinguished from empirical models by explicitly considering the processes of particle settling, deposition and re-suspension of sediments, describes these processes with conceptual algorithms.

The main objective of the IHACRES model is to characterise catchment-scale hydrological behaviour using as few parameters as possible. The model has been applied for catchments with a wide range of climates and sizes (Croke and Jakeman, 2004). It has been used to predict stream flow in un-gauged catchments to study land cover effects on hydrologic processes and to investigate dynamic response characteristics and physical catchment descriptors. The small number of model parameters in both IHACRES and STARS suggests that the models are less likely to suffer from problems of identifiability than more complex models. However, parameters values must be calibrated against observed data. By linking the IHACRES and STARS models, the runoff and in-stream components of catchment scale sediment transport and deposition are accounted for. However, there is no land surface erosion component to the model that predicts the sediment generation due to overland erosion and the contribution of this sediment into the stream network. Likewise, contribution from gully erosion is not considered.

4.10.8 MIKE-11

MIKE 11, developed by the Danish Hydrologic Institute (DHI), is a software that simulates flow and water level, water quality and sediment transport in rivers, flood plains, irrigation canals, reservoirs and other inland water bodies. It is a 1-dimensional river model. The basic modules are a rainfall-runoff module, a hydrodynamic module, a water quality module, and a sediment transport module. MIKE-11 contains a mix of conceptual and physics-based modules.

The rainfall-runoff module includes (i) the unit hydrograph method (UHM) to simulate the runoff from single storm events, (ii) a lumped conceptual continuous hydrological model (NAM) that simulates overland flow, interflow and base flow as a function of the moisture content in each of four storages namely, the snow, surface, root zone and groundwater storages, and (iii) a monthly soil moisture accounting model. It includes an auto-calibration tool to estimate model parameter based on statistic data of comparison of simulated water levels/discharges and observations.

The hydrodynamic module provides fully dynamic solution to the complete nonlinear1-D Saint Venant equations, diffusive wave approximation and kinematic wave approximation,Muskingum method and Muskingum-Cunge method for simplified channel routing.

The erosion and transport module includes a description of the erosion and deposition of both cohesive and non-cohesive sediments (http://www.dhisoftware.com/mike11). Erosion and deposition are modelled as source or sink terms in an advection–dispersion equation. The advection–dispersion module is based on the one-dimensional equation of conservation of mass of dissolved or suspended materials. It is also possible to simulate non-cohesive sediments with the A-D module. For non-cohesive sediments, the erosion and deposition terms are described by conventional sediment transport formulations.

The water quality module simulates the reaction processes including the degradation of organic matter, photosynthesis and respiration of plants, nitrification and the exchange of oxygen with the atmosphere.

The model requires large data for its application which means that the model is likely to suffer from problems caused by error accumulation and from a lack of identifiability of model parameters in situations where model parameters must be calibrated.

4.10.9 SWAT

SWAT, Soil and Water Assessment Tool (Arnold et al., 1998) emerged mainly from SWRRB (Arnold et al., 1990), and contains features from CREAMS (Knisel, 1980), GLEAMS (Leonard et al., 1987), EPIC (Williams et al., 1984), and ROTO (Arnold et al., 1995). It was developed to assist water resources managers in predicting and assessing the impact of management on water, sediment and agricultural chemical yields in large un-gauged watersheds or river basins. It is a continuous model and operates on a daily time step. Model components include weather, hydrology, erosion/sedimentation, plant growth, soil temperature, nutrients, pesticides, agricultural management, channel routing, and pond/reservoir routing. The model is intended for long term yield predictions and is not capable of detailed single-event flood routing.

SWAT contains a mix of empirical and physically-based components. It is a watershed scale model that uses spatially distributed data on topography, land use, soil, and weather. SWAT subdivides a watershed into a number of sub-basins for modeling purposes. Each sub-basin delineated within the model is simulated as a homogeneous area in terms of climatic conditions, but additional subdivisions are used within each sub-basin to represent different soils and land use types. Each of these individual areas is referred to as a hydrologic response unit (HRU) and is assumed to be spatially uniform in terms of soils, land use, and topography.

SWAT requires a significant amount of data and empirical parameters for development and calibration (Benaman et al., 2001). It requires specific input on weather, soil properties, topography, vegetation, and land management practices to model hydrology and water quality in a watershed. Model output include all water balance components (surface runoff, evaporation, lateral flow, recharge, percolation, sediment yield, nutrients and pesticides) at the level of each sub-basin at daily, monthly or annual time steps.

The daily water budget in each HRU is computed based on daily precipitation, runoff, evapotranspiration, percolation, and return flow from the subsurface and ground water flow. Runoff volume in each HRU is computed using the SCS runoff curve number approach. A recent addition to the model is the Green and Ampt (1911) infiltration equation to compute runoff volume. Peak runoff rate is computed using a modification to the Rational formula. Lateral subsurface flow is computed using the Sloan et al. (1983) kinematic storage model and ground-water flow using empirical relations.

The sediment from sheet erosion for each HRU is calculated using the Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975). The transport of sediment in the channel is controlled by simultaneous operation of two processes: deposition and degradation. Whether channel deposition or channel degradation occurs depends on the sediment loads from the upland areas and the transport capacity of the channel network.

The transformation and movement of nitrogen and phosphorus within an HRU are simulated in SWAT as a function of nutrient cycles consisting of several inorganic and organic pools. Losses of both N and P from the soil system in SWAT occur by crop uptake and in surface runoff in both the solution phase and on eroded sediment. Simulated losses of N and P can also occur in percolation below the root zone, in lateral subsurface flow including tile drains, and by volatilization to the atmosphere.

Pesticides are simulated as per the GLEAMS model (Leonard et al., 1987), which is based on plant leaf-area-index, application efficiency, wash-off fraction, organic carbon adsorption coefficient, and exponential decay according to half lives. The in-stream kinetics used in SWAT for nutrient routing are adapted from QUAL2E (Brown and Barnwell, 1987).

Borah and Bera (2003b) reviewed seventeen SWAT applications found in the literature. They noted that the model requires a significant amount of data and empirical parameters for development and calibration. The model was found suitable for predicting yearly flow volumes, sediment and nutrient loads. Monthly predictions were generally good, except for months having extreme storm events and hydrologic conditions. Daily predictions were generally not good.

Gassman et al. (2007) reviewed a large number of peer-reviewed published applications of SWAT. The ability of SWAT to replicate hydrologic and/or pollutant loads at a variety of spatial scales on an annual or monthly basis was confirmed in numerous studies. However, the model performance was found inadequate in some studies, especially when comparisons of predicted output were made with time series of measured daily flow and/or pollutant loss data. These weaker results underscore the need for continued testing of the model, including more thorough uncertainty analyses, and ongoing improvement of model routines. Some users have addressed weaknesses in SWAT by component modifications, which support more accurate simulation of specific processes or regions, or by interfacing SWAT with other models.

4.10.10 SWRRB/SWRRB-WQ

The Simulator for Water Resources in Rural Basins (SWRRB, Arnold et al., 1990) was developed by the Grassland, Soil, and Water Research Laboratory of the Agricultural Research Service (ARS) of the USDA. SWRRB is designed to predict the effect of various types of watershed management practices on water and sediment yield in un-gauged agricultural watersheds. The major processes reflected in the model include precipitation, surface runoff, percolation, lateral sub-surface flow, evapotranspiration, pond and reservoir evaporation, erosion and sedimentation, soil temperature, crop growth, and irrigation. Precipitation may be either inputted or developed by the model as a Markov process using inputted probabilities. SWRRB is conceptual in framework although its components utilise both physically-based and empirical algorithms to describe the major processes. SWRRB operates on a continuous basis. A watershed, based on soil, land use, and climatic characteristics, may be divided in to as many as ten sub-watersheds. The soil profile can also be divided in to as many as ten layers. The hydrologic computations are based on the water balance equation. The SCS Curve Number method is used to compute runoff volume. Sediment yield is determined using the modified universal soil loss equation and a sediment routing model.

The Simulator for Water Resources in Rural Basins – Water Quality (SWRRB-WQ) was developed by adding water quality modeling capabilities to SRRB. SWRRB-WQ simulates weather, hydrology, erosion, sediment yield, nitrogen and phosphorous cycling and movement, pesticide fate and movement, crop growth and management, pond and reservoir management and other processes (Arnold et al., 1991).

SWRRB-WQ has been used by the Agricultural Research Service, Soil Conservation Service, Environmental Protection Agency and other agencies to assess the effects of land management on off-site water quantity and quality, pollution of coastal bays and estuaries, reservoir sedimentation, and registration of pesticides.

4.10.11 WEPP

WEPP (Water Erosion Prediction Project) (Nearing et al., 1989) was developed to be used by the USDA Soil Conservation Service, USDA Forest Service, and USDI Bureau of Land Management, and other organizations involved in soil and water conservation and environmental planning and assessment. WEPP is a physically-based, continuous simulation model to predict soil erosion and sediment delivery from fields, farms, forests, rangelands, construction sites and urban areas. Although WEPP was original developed to simulate hill slopes, WEPP now includes the abilities to simulate small watersheds (500 ha or less). The WEPP model includes the following components: climate generation, winter processes, irrigation, hydrology, soils, plant growth, residue decomposition, hydraulics of overland flow, and erosion. Spatial differences in land characteristics are designated in WEPP using "strips" or overland flow elements (OFEs). Each OFE represents a region of homogeneous soils, cropping, and management.

Rainfall excess is predicted using the Green-Ampt Mein-Larson (GAML) infiltration equation. The soil water status is updated on a daily basis and is required to obtain infiltration and surface runoff volumes, the driving force in the detachment by flowing water in rills and channels. The water balance component uses information about climate, plant growth and infiltration to estimate daily potential evapotranspiration and soil and plant evaporation. WEPP divides runoff between rills and inter-rill areas. Consequently, it calculates erosion in the rills and inter-rill areas separately. The steady-state sediment continuity equation is used to predict rill and inter-rill processes (Nearing et al., 1989). Rill erosion occurs if the shear stress exerted by flow exceeds the critical shear stress while sediment load in the flow is smaller than the transport capacity of flow. Inter-rill erosion is considered to be proportional to the square of the rainfall intensity. Inter-rill area delivers sediment to rills. The model solves the non-dimensional (normalized) detachment and deposition equations. The normalized load is calculated and then is converted to the actual load.

It was found by Zhang et al. (1996b) that the model was reliable in predicting long term averages of soil loss under cropped conditions. Refereed articles of the catchment form of the WEPP model are not as numerous as applications of the hillslope WEPP model. However, some catchment applications include Cochrane and Flanagan (1999) and Covert et al. (2005) in the U.S., Ampofo et al. (2002) and Saenyi and Chemelil (2002) in Africa, and Raclot and Albergel (2006) in the Mediterranean.

4.10.12 LASCAM

A continuous (daily time interval), conceptual sediment generation and transport algorithm was coupled to an existing water and salt balance model, LASCAM (Viney and Sivapalan, 1999). LASCAM was originally developed to predict the effect of land use and climate change on the daily trends of water yield and quality in forested catchments in Western Australia. The model uses gridded topographic information to define a stream network and to disaggregate the catchment into a series of interconnected sub-catchments of area 1-5 km^2. The sub-catchments are the basic building blocks of the model. It is at the sub-catchment scale that the hydrological processes are modelled, before being aggregated to yield the response of the entire catchment.

Sediment generation in the sub-catchments is assumed to occur by erosion processes associated with surface runoff. The model is a conceptualization of the universal soil loss equation (USLE), giving daily hillslope sediment generation. Sediment transport involves the processes of channel deposition and re-entrainment, and bed degradation. The model assumes that these processes are governed by a stream sediment capacity that is a function of stream power. The developed sediment transport algorithm does not discriminate between sediment size classes. Viney et al. (2000) later coupled a conceptual model of nutrient mobilisation and transport to the LASCAM.

The inputs to the model are daily rainfall (distributed), pan evaporation and land use information (e.g. leaf area index, which is allowed to vary with time), while topographic data are needed to define the sub-catchments and the stream network. The outputs from the model, for each sub-catchment and for the total catchment, are surface and subsurface runooff, actual evaporation, recharge to the permanent groundwater table, base flow and measures of soil moisture. The model has shown considerable potential as a sediment yield model (Viney and Sivapalan, 1999) and has been used to predict water yield, salinity, sediments, nitrogen and phosphorus for the entire Swan-Avon River Basin in Western Australia.

4.10.13 KINEROS

KINEROS (KINematic EROsion Simulation) (Smith, 1981; Woolhiser et al., 1990) is composed of elements of a network, such as planes, channels or conduits, and ponds or detention storages, connected to each other. KINEROS is an extension of KINGEN, a model developed by Rovey et al. (1977), with incorporation of erosion and sediment transport components. The kinematic wave theory was initially used for estimation of runoff, and then some correction was done on infiltration section, regarding basin element, erosion and sediment transportation estimation and finally the model was named as KINEROS. KNEROS is a physically-based distributed model.

The KINEROS model components include infiltration, infiltration at the end of rain, surface flow of Hortan, flow in channels, flow in the storage, erosion and sediment transportation, channel erosion, and sedimentation in the basin. The sediment component of the model is based upon the one dimensional unsteady state continuity equation. Erosion/deposition rate is the combination of raindrop splash erosion and hydraulic erosion/deposition rates. Splash erosion rate is given by an empirical equation in which the rate is proportional to the second power of the rainfall. Hydraulic (runoff) erosion rate is estimated to be proportional to the transport capacity deficit, which is the difference between the current sediment concentration in the flow and steady state maximum concentration. Hydraulic erosion may be positive or negative depending upon the local transport capacity. A modified form of the equation of Engelund and Hansen (1967) was used for determining the steady state flow concentration. A single-mean sediment particle size was used in the formulation. KINEROS does not explicitly separate rill and inter-rill erosion. Channel erosion is taken the same as the upland erosion except for the omission of the splash erosion as it is no longer effective on erosion in the channel phase. Soil and sediment are characterised by a distribution of up to five size class intervals in the new version of the model, KINEROS2 (Smith et al., 1995). Smith et al. (1999) applied the model to a catchment in the Netherlands. It was also applied to a catchment in Northern Thailand to see its applicability for unpaved mountain roads (Ziegler et al., 2001).

4.10.14 SHESED

SHESED (Wicks, 1988) is the sediment transport component of the SHE hydrological model (Abbott et al., 1986 a, b). SHESED considers erosion as the sum of erosion by raindrop and leaf drip impacts and that by overland flow. Erosion takes place in the channel bed too. The eroded sediment is transported by overland flow to channels. Once the eroded sediment gets to the channel, it is further transported downstream. Soil erosion by raindrop and leaf drip impacts is given by an equation based on the theoretical work of Storm et al. (1987). The overland flow soil detachment is given by an equation accounting for inter-rill areas and rills together. Therefore, rills are not accounted for explicitly in the model. Ground cover, given in the raindrop detachment equation, is low-lying cover, which shields the soil from raindrop impact erosion. Canopy cover refers to taller vegetation, which shields the soil from the direct impact of the raindrops but allows the rainwater to coalesce on its surface and fall to the ground as large leaf drips (Wicks and Bathurst, 1996).

In SHESED, overland flow and sediment transport are based upon the two-dimensional mass conservation equations. Either the Ackers and White (1973) equation or the Engelund and Hansen (1967) equation is used in determining the transport capacity of flow. Selection of the transport capacity equation in SHESED is based upon a trial and error technique, and is chosen in the calibration stage of the model. Also the raindrop and overland flow erodibility coefficients are calibrated. The sediment yield simulations showed sensitivity to the erodibility coefficient. Therefore, accurate calibration is needed (Wicks et al., 1992). Particle size distribution is not considered. The equation is solved by an explicit finite difference method (Bathurst et al., 1995). Channel erosion in SHESED includes local bed erosion (bed load plus suspended load) in the channel, sediment inflow from upstream, and sediment flow from overland flow. A one-dimensional transport equation is used. Inputs of the channel component are overland flow and rainfall conditions, supplied by either SHE or taken directly from measurements. Gullying, mass movement, channel bank erosion, or erosion of frozen soil are not considered in the SHESED (Aksoy and Kavvas, 2005). It does not feedback to SHE, meaning that change at the channel bed elevation due to erosion is not given as input to SHE, as the change is very small.

4.10.15 EUROSEM

The European Soil Erosion Model (EUROSEM) is a single event process-based model with modular structure for predicting water erosion from fields and small catchments. The model is the result of 25 scientists ‘attempts from 10 European countries. The catchment is split into elements for which uniform properties are assumed, these are then linked together to form a network of planes and channels. Each element requires 37 parameters that describe its soil, vegetation, micro-topography, size and slope. Rainfall is entered as break point data and different rain gauges can be assigned to different elements within the catchment.

The model simulates erosion, sediment transport and deposition over the land surface by rill and interrill processes. Runoff is routed over the soil using the kinematic wave equation. Continuous exchange of particles between water flow and soil surface is balanced within the model. Soil loss is computed as sediment discharge by a dynamic mass balance equation. Model output includes total runoff, total soil loss, the storm hydrograph and storm sediment graph. Compared with other erosion models, EUROSEM has explicit simulation of interrill and rill flow; plant cover effects on interception and rainfall energy; rock fragment (stoniness) effects on infiltration, flow velocity and splash erosion; and changes in the shape and sizes of rill channels as a result of erosion and deposition. The transport capacity of runoff is modelled using relationships based on over 500 experimental observations of shallow surface flows. Most of the work to date on evaluating EUROSEM has been concentrated in Europe.

4.10.16 Summary of Models

The foregoing review reveals that the erosion and sediment transport models are extensions of hydrological models. Therefore, erosion and sediment transport equations are coupled to existing hydrological algorithms. In such a coupling, output of the hydrological model becomes input for the erosion part of the model. A multitude of erosion and sediment prediction models have been developed by various researchers that vary significantly in the processes they represent, the manner in which these processes are represented and the temporal and spatial scales of application for which they were developed. Some models represent sediment erosion only while others include sediment deposition as well as their transport. Some models also have explicit representation of the processes to estimates soil loss from permanent gullies. Table 4.1 provides a summary of some of the models and the processes they explicitly represent.

4.11 Way Forward

Erosion is a very important natural phenomenon ending with soil loss. As a result, modeling of soil erosion and sediment transport has advanced tremendously. As is clear from the foregoing sections, a large number of models that range from simple to complex in nature are available for use in soil erosion and sediment transport modeling. Each model has got its own unique characteristics and respective applications. Some of them are comprehensive and uses the physics of underlying hydrological processes and are distributed in space and time. Determining the appropriate model for an application requires consideration of the suitability of the model to local catchment conditions, data requirements, model complexity, the accuracy and validity of the model, model assumptions, spatial and temporal variation, components of the model, and the objectives of the model user(s).Therefore, a model user must fully understand the background, potentials, and limitations of a model before using it.

The catchment managers require spatial aspects of soil erosion and sediment transport. Therefore, research efforts are required for the development of a distributed model of relatively low complexity and plausible physical basis. Alternatively, the existing models, for example SWAT and MIKE-11, which have physical basis and also incorporate land surface and in-stream processes including water quality, offer premise for application to small to very large basins for addressing a wide range of sediment and water quality associated problems. SWAT has been widely used in various regions and climatic conditions on daily, monthly and annual basis and for the watershed of various sizes and scales. SWAT has also been successfully used for simulating runoff, sediment yield and water quality of small watersheds for Indian catchments. These two models proposed here can be taken up for further assessment in Indian catchments.

Table 4.1 Summary of processes represented in erosion and sediment models (source: Merritt et al., 2003)

Model	Type*	Scale	Rainfall-runoff	Land surface sediment			Gully	In-stream sediment			Sediment associated water quality	
				G	T	D		G	T	D	Land	In-stream
USLE	Empirical	Hillslope	no	yes	no	no[a]	no	no	no	no	no	no
AGNPS	Conceptual	Small catchment	yes	yes	no	no	yes	yes	yes	yes	yes	yes
ANSWERS	Physically-based	Small catchment	yes	yes	yes	yes	no	no	no	no	no	no
CREAMS	Physically-based	field 40–400 ha	yes	yes	yes	yes	yes	no	no	no	yes	no
EMSS	Conceptual	Catchment	yes	no[b]	no	no	no	yes	yes	yes	no	no
GUEST	Physically-based	Plot	yes	yes	yes	yes	no	no	no	no	no	no
HSPF	Conceptual	Catchment	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes
IHACRES-WQ	Empirical/ Conceptual	Catchment	yes	no	no	no	no	yes	yes	yes	yes	yes
LASCAM	Conceptual	Catchment	yes	yes	no	no	no	yes	yes	yes	yes	yes
LISEM	Physically-based	Small catchment	yes	yes	no	no	no	yes	yes	yes	no	no
MIKE-11	Physically-based	Catchment	yes	yes	yes	yes	no	yes	yes	yes	yes	yes
PERFECT	Physically-based	Field	yes	yes	no	no	no	no	no	no	yes	no
SEDNET	Empirical/ Conceptual	Catchment	yes	yes	no	no[a]	yes	yes	yes	yes	yes	yes
SWAT	Empirical/ Physically-based	Catchment	yes	yes	yes	yes	no	yes	yes	yes	yes	yes
SWRRB	Conceptual	Catchment	yes	no	no	no	no	yes	yes	yes	yes	yes
TOPOG	Physically-based	Hillslope	yes	yes	yes	yes	no	no	no	no	no	no
WEPP	Physically-based	Hillslope/ Catchment	yes	yes	yes	yes	no	yes	yes	yes	no	no

*Model classification refers to the over-arching process representation of the model. Model components generally contain a mix of empirical, conceptual and physics-based algorithms.
G: sediment generation; T: sediment transport; D: deposition.
[a] Requires a sediment delivery ratio (SDR) to compute sediment yield from gross erosion.
[b] Uses prescribed loads for a land use type.

References

1. Abbott, M.B., Bathurst, J.C., Cunge, J.A., O'Connell, P.E., Rasmussen, J., 1986a. An introduction to the European hydrological system—systeme hydrologique Europeen, (SHE): 1. History and philosophy of a physically-based, distributed modeling system. J. of Hydrology 87, 45– 59.
2. Abbott, M.B., Bathurst, J.C., Cunge, J.A., O'Connell, P.E., Rasmussen, J., 1986b. An introduction to the European hydrological system—systeme hydrologique Europeen, (SHE): 2. Structure of a physically-based, distributed modeling system. J. 87, 61–77.
3. Ackers, P., White, W.R., 1973. Sediment transport: new approach and analysis. ASCE Journal of the Hydraulics Division 99 (HY11), 2041– 2060.
4. Aksoy, H. and M.L. Kavvas 2005. A review of hillslope and watershed scale erosion and sediment transport models, CATENA, 64 (2005) 247-271.
5. American Society of Civil Engineers (ASCE), 1975. Sedimentation Engineering. American Society of Civil Engineering, New York, NY, 745 pp.
6. Ampofo, E.A., Muni, R.K., Bonsu, M. 2002. Estimation of soil losses within plots as affected by different agricultural management. Hydrol. Sci. J. 47(6):957-967.
7. Arnold, J.G., Williams, J.R., Griggs, R.H., Sammons, N.B., 1990. SWRRB—a basin scale simulation model for soil and water resources management. A&M Press, Texas.
8. Arnold, J.G., Williams, J.R., Griggs, R.H., Sammons, N.B., 1991. SWRRBWQ - a basin model for assessing management impacts on water quality. USDA, ARS, Grassland, Soil, and Water Research Laboratory, Temple, TX.
9. Arnold, J.G., Williams, J.R. Maidment, D.R., 1995. Continuous-time and sediment- routing model for large basins. ASCE Journal of Hydraulic Engg. 121(2), 171-183.
10. Baginska, B., W. Milne-Home, and P. S. Cornish. 2003. Modeling nutrient transport in Currency Creek, NSW, with AnnAGNPS and PEST. *Environ. Modeling and Software* 18(8): 801-808.
11. Banasik, K., and Walling, D.E., 1996. Predicting sedimentographs for a small catchment. Nordic Hydrology, 27(4):275-294.
12. Bathurst, J.C., Wicks, J.M., O'Connell, P.E., 1995. The SHE/SHESED basin scale water flow and sediment transport modeling system. In: Singh, V.P. (Ed.), Computer Models ofWatershed Hydrology.Water Resources Publications, Littleton, CO, pp. 563– 594.
13. Beasley, D.B., Huggins, L.F., Monke, E.J., 1980. ANSWERS - model for watershed planning. Trans Am Soc Agric Eng 23, 938–944.
14. Beck, M.B., 1987. Water quality modeling: a review of uncertainty. Water Resources Research 23 (8), 1393–1442.
15. Beck, M.B., Jakeman, A.J., McAleer, M.J., 1995. Construction and evaluation of models of environmental systems. In: Beck, M.B., McAleer, M.J. (Eds.), Modeling Change in Environmental Systems. John Wiley and Sons, pp. 3–35.
16. Bennett, J.P., 1974. Concepts of mathematical modeling of sediment yield. Water Resources Research 10 (3), 485–492.
17. Beven K. 2004, Robert E. Horton's perceptual model of infiltration processes, *Hydrological processes*, 18, 3447-3460.
18. Bingner, R. L. and F. D. Theurer. 2003. AnnAGNPS technical processes documentation, Version 3.2. Available at: www.wsi.nrcs.usda.gov/products/w2q/h&h/tools_models/agnps/model.html.
19. Borah D. K., and M. Bera. 2003a. Watershed−scale hydrologic and nonpoint−source pollution models: Review of mathematical bases. *Trans. ASAE* 46(6): 1553−1566.
20. Borah, D. K., Bera, M., 2003b. SWAT model background and application reviews. ASAE Paper No. 032054. Presented at the 2003 ASAE Annual Int. Meeting. St. Joseph, Mich.
21. Borah, D. K., Yagow, G., Saleh, A., Barns, P. L., Rosenthal, W., Krug, E. C., and Hauck, L. M. 2006. Sediment and nutrient modeling for TMDL development and implementation. Trans. ASABE, 49(4), 967–986.
22. Brown, L.C., Foster, G.R., 1987. Storm erosivity using idealized intensity distributions. Trans. ASAE, 30(2): 379-386.

23. Brown, L. C., and T. O. Barnwell, Jr. 1987. The enhanced water quality models QUAL2E and QUAL2E-UNCAS documentation and user manual. EPA document EOA/600/3-87/007. Athens, Ga.: USEPA.
24. Bryan, R.B., 2000. Soil erodibility and processes of water erosion on hillslope. Geomorphology 32, 385–415.
25. Chen, V.J. and Kuo, C.Y., 1986. A study of synthetic sediment graphs for ungauged watersheds. J. Hydrology, 84:35-54.
26. Cochrane, T.A. and Flanagan, D.C. 1999. Assessing water erosion in small watersheds using WEPP with GIS and digital elevation models. Journal of Soil and Water Conservation 54(4), 678-685.
27. Covert, S.A., Robichaud, P.R., Elliot, W.J., Link, T.E. 2005. Evaluation of runoff prediction from WEPP-based erosion models for harvested and burned forest watersheds. Trans. ASAE 48, 1091–1100.
28. Croke, B.F.W. and A.J. Jakeman. 2004. A catchment moisture deficit module for the IHACRES rainfall-runoff model. *Environmental Modeling & Software* 19:1-5.
29. Curtis, D.C., 1976. A deterministic urban storm water and sediment discharge model. In: Proceedings of National Symposium on Urban Hydrology, Hydraulics and Sediment Control, University of Kentucky, Lexington, KY: 151-162.
30. Das, S., R. P. Rudra, P. K. Goel, B. Gharabaghi, and N. Gupta. 2006. Evaluation of AnnAGNPS in cold and temperate regions. *Water Sci. Tech.* 53(2): 263-270.
31. Dietrich, C., Green, T.R., Jakeman, A.J., 1999. An analytical model for stream sediment transport: application to Murray and Murrumbidgee reaches, Australia. Hydrological Processes 13 (5), 763–776.
32. Ellison, W.D., 1947. Soil erosion studies. Agricultural Engineering, 28: 145-156, 197-201, 245-248, 297-300, 349-351, 402-405, 442-444.
33. Engelund, F., Hansen, E., 1967. A Monograph on Sediment Transport in Alluvial Streams. Teknish Vorlag, Copenhagen.
34. Ferro, V., Minacapilli, M., 1995. Sediment delivery processes at basin scale. Hydrological Sciences Journal 40 (6), 703–717.
35. Fisher, P., Abrahart, R., Herbinger, W., 1997. The sensitivity of two distributed non-point source pollution models to the spatial arrangement of the landscape. Hydrological Processes 11, 241–252.
36. Foster, G.R., Huggins, L.F., 1977. Deposition of sediment by overland flow on concave slopes. In: Soil Erosion Prediction and Control. Special Publication No. 21, Soil Cons. Soc. of Am., Ankeny, IA, pp. 167-182.
37. Foster, G.R., and Meyer, L.D., 1972. A closed form soil erosion equation for upland areas. In: Shen, H.W. (ed.), Sedimentation (Einstein), Chapter 12, Colorado State University, Fort Collins, CO.
38. Foster, G.R., Meyer, L.D., 1975. Mathematical simulation of upland erosion by fundamental erosion mechanics. In: Present and Prospect Technology for Predicting Sediment Yields and Sources. US Department of Agriculture, Agricultural Research Service, Southern Region, New Orleans, Louisiana, pp. 190–207 ARS-S-40.
39. Gassman, P. W., Reyes, M. R., Green, C. H., Arnold, J. G., 2007.The soil and water assessment tool: historical development, applications, and future research directions. American Society of Agricultural and Biological Engineers, 50(4): 1211-1250.
40. Green, T.R., Beavis, S.G., Dietrich, C.R., Jakeman, A.J., 1999. Relating stream-bank erosion to in-stream transport of suspended sediment. Hydrological Processes 13 (5), 777–787.
41. Green, W.H., and Ampt, C.A., 1911. Studies of soil physics, I. Flow of air and water through soils. J. Agric.Science, 4: 1-24.
42. Haan, C.T., Barfield, B.J., Hayes, J.C., 1994. Design Hydrology and Sedimentology for Small Catchments. Academic Press 588 pp.
43. Hong, H. S., J. L. Huang, L. P. Zhang, and P. F. Du. 2005. Modeling pollutant loads and management alternatives in Jiulong River watershed with AnnAGNPS. *Huan Jing Ke Xue* 26(4): 63-69.

44. Jakeman, A., Littlewood, I., Whitehead, P., 1990. Computation of the instantaneous unit hydrograph and identifiable component flows with application to two small upland catchments. Journal of Hydrology 117, 275–300.
45. Jakeman, A.J., Hornberger, G.M., 1993. How much complexity is warranted in a rainfall-runoff model? Water Resources Research 29 (8), 2637–2649.
46. Johnson, J.W., 1943. Distribution graph of suspended matter concentration. Trans. ASAE, 108:941-964.
47. Kalin, L., Govidaraju, R. S., and Hantush, M.M., 2004. Development and application of a methodology for sediment source identification. I: Modified unit sedimentograph approach. J. Hydrol. Engg., ASCE, 9(3): 184-193.
48. Kinnell, P., Risse, L., 1998. USLE-M: Empirical modeling rainfall erosion through runoff and sediment concentration. Soil Sci Soc Am J 62 (6), 1667–1672.
49. Knisel, W.G. (ed.), 1980. CREAMS: A field scale model for chemicals, runoff and erosion from agricultural management system. Cons. Res. Report, No. 26, USDA-SEA, Washington, D.C., 643p.
50. Kothyari, U.C., Jain, S.K., 1997. Sediment yield estimation using GIS. J. Hydrol. Sciences, 42(6), 833-843.
51. Kumar, S., and Rastogi, R.A., 1987. A conceptual catchment model for estimating suspended sediment flow. J. Hydrology, 95: 155-163.
52. Lane, L.J., Shirley, E.D., and Singh, V.P., 1988. Modeling erosion on hillslopes. In: Anderson, M.G. (ed.), Modeling Geomorphological Systems, John Wiley and Sons Ltd.: 287-308.
53. Leonard, R.A., Knisel, W.G., and Still, D.A., 1987. GLEAMS: Groundwater loading effects on agricultural management systems. Trans. ASAE, 30(5):1403-1428.
54. Letcher, R.A., Jakeman, A.J., Merritt, W.S., McKee, L.J., Eyre, B.D., Baginska, B., 1999. Review of Techniques to Estimate Catchment Exports. EPA Technical Report 99/73. Environmental Protection Authority, Sydney http://www.environment.gov.au/epg/npi/pubs/pubs/nswreport.pdf.
55. Merritt, W.S., Letcher, R.A., Jakeman, A.J., 2003. A review of erosion and sediment transport models. Environmental Modeling & Software 18, 761–799.
56. Meyer, L.D., Foster, G.R., and Romkens, M.J.M., 1975. Source of soil eroded by water from upland slopes. In: Present and Prospective Technology for Predicting Sediment Yields and Sources. ARS-S 40. USDA-Agricultural Research Service, 177-189.
57. Nearing, M.A., Foster, G.R., Lane, L.J., Finkner, S.C. 1989. A process based soil erosion model for USDA-Water Erosion Prediction Project Technology. Trans. ASAE. 32(5), 1587–1593.
58. Norman, S.E. 1989. An evaluation of ANSWERS, a distributed parameter watershed model. Thesis submitted in partial satisfaction of the requirements for the degree of MS in Water Science in the Graduate Division of the University of California, Davis, California.
59. Perrin, C., Michel, C., Andreassian, V., 2001. Does a large number of parameters enhance model performance? Comparative assessment of common catchment model structures on 429 catchments. Journal of Hydrology 242, 275–301.
60. Polyakov, V., A. Fares, D. Kubo, J. Jacobi, and C. Smith. 2007. Evaluation of a nonpoint-source pollution model, AnnAGNPS, in a tropical watershed. *Environ. Modeling and Software* 22(11): 1617-1627.
61. Raclot, D., and J. Albergel. 2006. Runoff and water erosion modeling using WEPP on a Mediterranean cultivated catchment. *Physics and Chem. of the Earth* 31(17): 1038-1047.
62. Raghuwanshi, N.S., Rastogi, R.A., and Kumar S., 1994. Instantaneous-unit sediment graph. J. Hydr. Engg., ASCE, 120(4): 495-503.
63. Renard, K.G., Foster, G.R., Weesies, G.A., and Porter, J.P., 1991. RUSLE: Revised Universal Soil Loss Equation, J. Soil and Water Cons., 46(1): 30-33.
64. Renard, K.G., Ferreira, V.A., 1993. RUSLE model description and database sensitivity. Journal of Environmental Quality 22, 458–466.
65. Renard, K.G., Laflen, J.M., Foster, G.R., McCool, D.K., 1994. The revised universal soil loss equation. In: Lad, R. (Ed.), Soil Erosion: Research Methods, pp. 105–126.

66. Renard, K. G., G. R. Foster, G. A. Weesies, D. K. McCool, and D.C. Yoder, coordinators. 1997. Predicting soil erosion by water: A guide to conservation planning with the Revised Universal Soil Loss Equation (RUSLE). Agriculture Handbook No. 703. Washington, D.C.: USDA Agricultural Research Service.
67. Rendon-Herrero, O., 1978. Unit sediment graph. Water Resources Research, 14: 889-901.
68. Rovey, E.W., Woolhiser, D.A., Smith, R.E., 1977. A distributed kinematic model of upland watersheds. Hydrology Papers, vol. 93. Colorado State University, Fort Collins, CO.
69. Saenyi, W. W., and M. C. Chemelil. 2002. Modeling of suspended sediment discharge for Masinga catchment reservoir in Kenya. *J. Civil Eng.*, *JKUAT* 8: 89-98.
70. Singh, V.P., Banicekiewiez, A., and Chen, V.J., 1982. An instantaneous unit sediment graph study for small upland watersheds. In: Singh, V.P. (ed.), Modeling Components of Hydrologic cycle, Littleton, Colo., Water Resources Publications:539-554.
71. Singh, V.P. 1995. Watershed modeling. In: Singh, V.P. (Ed.), Computer Models of Watershed Hydrology. Water Resources Publ., Highlands Ranch, CO, pp. 1– 22.
72. Sloan, P.G., I.D. Moore, G.B. Coltharp, and J.D. Eigel., 1983. Modeling Surface and Subsurface Stormflow on Steeply-Sloping Forested Watersheds. Water Resources Institute Report 142, University of Kentucky, Lexington, KY.
73. Smith, R.E., 1981. A kinematic model for surface mine sediment yield. Transactions of the ASAE, 1508– 1514.
74. Smith, R.E., Goodrich, D.C., Quinton, J.N., 1995. Dynamic, distributed simulation of watershed erosion: the KINEROS2 and EUROSEM models. Journal of Soil and Water Conservation 50 (5), 517–520.
75. Smith, R.E., Goodrich, D.C., Unkrich, C.L., 1999. Simulation of selected events on the Catsop catchment by KINEROS2, a report for the GCTE conference on catchment scale erosion models. Catena 37, 457– 475.
76. Sorooshian, S., 1991. and model validation: conceptual type models. In: Bowles, D.S., O'Connell, P.E. (Eds.), Recent Advances in the Modeling of Hydrological Systems. Kluwer Academic, pp. 443-467.
77. Steefel, C.I., Van Cappellan, P., 1998. Reactive transport modeling of natural systems. Journal of Hydrology 209, 1–7.
78. Storm, B., Jorgensen, G.H., Styczen, M., 1987. Simulation of water flow and soil erosion processes with a distributed physically-based modeling system. IAHS Publications 167, 595–608.
79. Thomas, W.A., 1976. Scour and deposition in rivers and reservoirs. HEC-6, Hydrologic Engineering Center, US Army Corps of Engineers.
80. Thorsen, M., Refsgaard, J.C., Hansen, S., Pebesma, E., Jensen, J.B., Kleeschulte, S., 2001. Assessment of uncertainty in simulation of nitrate leaching to aquifers at catchment scale. Journal of Hydrology 242, 210–227.
81. Tyagi, J.V., 2007. Modeling sediment yield from natural watersheds. Unpub. Ph.D. thesis, Indian Institute of Technology, Roorkee, Roorkee, India.
82. Viney, N.R., Sivapalan, M., 1999. A conceptual model of sediment transport: application to the Avon River Basin in Western Australia. Hydrological Processes 13, 727–743.
83. Viney, N.R., Sivapalan, M., Deeley, D., 2000. A conceptual model of nutrient mobilisation and transport applicable at large catchment scales. Journal of Hydrology 240, 23– 44.
84. Walton, R., Hunter, H., 1996. Modeling water quality and nutrient fluxes in the Johnstone River Catchment, North Queensland. In: 23rd Hydrology and Resources Symposium, Sydney, Wasson, R., Banens, B., Davies, P., Maher, W., Robinson, S., Volker, R., Tait, D., Watson-Brown, S., 1996. Inland Waters. State of the Environment, Australia.
85. Wheater, H.S., Jakeman, A.J., Beven, K.J., 1993. Progress and directions in rainfall-runoff modeling. In: Jakeman, A.J., Beck, M.B., McAleer, M.J. (Eds.), Modeling Change in Environmental Systems. John Wiley and Sons, Chichester, pp. 101–132.
86. Wicks, J.M., 1988. Physically-based mathematical modeling of catchment sediment yield. Thesis submitted for the degree of doctor of philosophy, Department of Civil Engineering, University of Newcastle Upon Tyne.

87. Wicks, J.M., Bathurst, J.C., 1996. SHESED: a physically based, distributed erosion and sediment yield component for the SHE hydrological modeling system. Journal of Hydrology 175, 213– 238.
88. Wicks, J.M., Bathurst, J.C., Johnson, C.W., 1992. Calibrating SHE soil-erosion model for different land covers. ASCE, J. of Irrigation and Drainage Engineering 118 (5), 708– 723.
89. Williams, J.R., 1975. Sediment yield prediction with Universal equation using runoff energy factor, In: Present and Prospective Technology for Predicting Sediment Yields and Sources, USDA-ARS, S-40, USDA: 244–252.
90. Williams, J.R., 1978. A sediment graph model based on an instantaneous unit sediment graph. Water Resources Research, 14: 659-664.
91. Williams, J.R., Jones, C.A., Dyke, P.T., 1984. A modeling approach to determining the relationship between erosion and soil productivity. Transactions of the ASAE 27, 129–144.
92. Wischmeier, W.H., and Smith, D.D., 1965. Predicting rainfall-erosion losses from cropland east of Rocky Mountains, USDA Agricultural Handbook No. 282, Washington, DC.
93. Woolhiser, D.A., Smith, R.E., Goodrich, D.C., 1990. KINEROS, a kinematic runoff and erosion model. Documentation and User Manual, USDA, Agricultural Research Service, ARS-77. 130 pp.
94. Wu, T.H., Hall, J.A., and Bonta, J.V., 1993. Evaluation of runoff and erosion models. J. Irrig. and Drain. Engg., ASCE, 119(4): 364-382.
95. Young, R.A., Onstad, C.A., Bosch, C.D. and Anderson, W.P. (1987). AGNPS, Agricultural - Non-Point-Source pollution model; A large watershed analysis tool. Conservation Research Report 35, USDA-ARS, Washington, DC.
96. Yuan, Y., R. L. Bingner, and R. A. Rebich. 2001. Evaluation of AnnAGNPS on Mississippi Delta MSEA watersheds. *Trans. ASAE* 44(3): 1183-1190.
97. Yuan, Y., S. Dabney, and R. L. Bingner. 2002. Cost/benefit analysis of agricultural BMPs for sediment reduction in the Mississippi Delta. *J. Soil and Water Cons.* 57(5): 259-267.
98. Zhang, L., O'Neill, A.L., Lacey, S., 1996a. Modeling approaches to the prediction of soil erosion in catchments. Environmental Software 11 (1–3), 123– 133.
99. Zhang, X.C., Nearing, M.A., Risse, L.M., McGregor, K.C., 1996b. Evaluation of WEPP runoff and soil loss predictions using natural runoff plot data. Transactions of the ASAE 39 (3), 855– 863.
100. Ziegler, A.D., Giambelluca, T.W., Sutherland, R.A., 2001. Erosion prediction on unpaved mountain roads in northern Thailand: validation of dynamic erodibility modeling using KINEROS2. Hydrological Processes 15, 337–358.

CHAPTER 5
SURFACE WATER QUALITY MODELING

5.1 Introduction

5.1.1 General

Both natural processes and human activities influence the quality of surface waters. The natural processes and their sources of pollution in surface water bodies are relatively inconsequential, except pollution from natural disaster. Surface water pollution and contamination from humans and human activities, comprising both organic and inorganic constituents, known as anthropogenic pollutants, originate from domestic and municipal source, agricultural production, mining, industrial production, power generation, forestry practices, and other factors, which alter the physical, chemical and biological characteristics of water, are of main concern for surface water bodies. Amongst these sources, the major pollution is from human settlements, industrial and agricultural activities. Pollution and contamination from such sources manifest itself in the form of higher concentration of nutrients, sediments, salts, trace metals, chemicals and other toxins, as well as pathogenic organisms that may thrive in warmer and contaminated waters. In addition, a growing number of new contaminants are being detected in the world's waterways (UN-Water, 2011). These include contaminants from pharmaceutical products, steroids and hormones, industrial additives and agents, as well as gasoline additives (WHO, 2011; UL, 2015; Eslamian, 2016). These contaminants present a new challenge to water quality management (UN-Water, 2011). The synergistic interactions of these contaminants and pollutants may result in complex concoctions that are difficult to treat.

Degraded surface water quality affects the aquatic environment. The degradation of ecosystem affects people most who live near the contaminated waterways and those who have no alternate access to safe water or improved sanitation. Although the "water crisis" tends to be viewed as a water quantity problem, water quality is increasingly recognized in many countries as a major factor in the water crisis (UN-Water, 2011). Historically, poor water quality has been principally associated with public health concerns through transmission of water-borne diseases.

Declining water quality is a global issue of concern as human populations grow, industrial and agricultural activities expand, and climate change threatens to cause major alterations to the hydrological cycle (UN-Water, 2011). Globally, the most prevalent water quality problem is eutrophication particularly in lentic water bodies, a result of high-nutrient loads (mainly phosphorus and nitrogen), which substantially impairs beneficial uses of water. Major nutrient sources include agricultural runoff, domestic sewage (also a source of microbial pollution), industrial effluents and atmospheric inputs from fossil fuel burning and bush fires. Lakes and reservoirs are particularly susceptible to the negative impacts of eutrophication because of their complex dynamics, relatively longer water residence times and their role as an integrating sink for pollutants from drainage basins (Zhen-Gang, 2008).

5.1.2 India's status of river water quality

India has a large network of rivers across its length and breadth. It has also huge numbers of surface water bodies, viz. lakes, reservoirs, tanks, ponds, etc, of varying sizes spread over the country. Those surface water bodies in many parts of the country act as the sources of drinking and agricultural water in addition to the eco-system services of the area. Unfortunately, the nation is unable to retain these rich natural resources of surface water bodies including rivers, because of deteriorating water quality. Water pollution is a major environmental issue in India and its concern is mainly because of discharge of untreated sewage in water bodies. The reports of Central Pollution Control Board (CPCB, 2011; 2013) estimate that 75-80% of water pollution by volume is due to organic pollution measured in terms of bio-chemical oxygen demand (BOD) and coliform bacterial count. As reported, it was mainly due to discharge of untreated domestic wastewater from the urban centres of the country. The municipal bodies at large are not able to treat increasing load of municipal sewage flowing into water bodies. On the other hand, the receiving water bodies also do not have adequate water for dilution because of abstraction structures and diversion of water from the river. Further, there is a large gap between generation and treatment of domestic wastewater in India (CPCB, 2011; 2013). The problem is not only that India lacks sufficient treatment capacity but also that the sewage treatment plants that exist do not operate and maintain properly. The report (CPCB, 2009) showed that out of estimated 38,354 million litres per day (MLD) of sewage generation from major cities of India; only 30.8% is treated and remaining untreated sewages flow on/in to overland, rivers/streams and other surface water bodies. The situation of treatment of industrial wastewater is somewhat better, out of 13,468 MLD generates from about 57,000 major polluting industries, 60% is treated. Water pollution from diffuse sources viz. agricultural activities, due to application of pesticides and herbicides to control pests, and runoffs of nitrogen (N) and phosphorus (P) applied to agricultural land move with rainfall may cause eutrophication to surface water bodies. Municipal sewages along with agricultural run-offs and industrial effluents are main concern of India's surface water pollution causing deteriorated water quality including eutrophication.

5.1.3 Issues related to lakes and estuaries

The word "Lake" is used loosely in India to describe different types of surface water bodies, except rivers/streams. These water bodies are natural, manmade, ephemeral and wetlands. The manmade (artificial) water bodies are generally called reservoirs, ponds and tanks. Ponds and tanks are small in size compared to lakes and reservoirs. Numerous natural lakes of varying sizes are present in India either at high altitude Himalayan region or in low altitude region. Many of the lakes in Himalaya have fresh water with or without inflow and outflow. These lakes have varying chemistry in terms of solutes, bio-geochemistry, mineralogy vis-a-vis eco-hydrology of the water body, which are primarily related to enormous altitude variation governing climate, vegetation, agriculture, lithology, tectonics and intensity of erosion/weathering at source. The high altitude lakes are mostly oligotrophic and are fed from snow-melt, precipitation and spring, whereas lakes of low altitudes receive water from local rains, through streams, *nalas* and spring and some of them have approached a higher level trophic state (eutrophic or hyper-eutrophic) due to strong impact of anthropogenic influence such as tourist influx, unplanned settlements, landuse, development activities in the catchment area, and disposal of municipal and domestic wastes. In general, the Indian lakes have either fresh water or salt water. Some of them are sacred lakes.

Due to alteration of landscapes by denuding forests, urbanization and discharge of wastes, sedimentation and eutrophication have increased in most of Indian lakes. Many high altitude lakes, particularly in Kashmir and Garhwal Himalayans, which remained clean and non-eutrophied for centuries, are showing signs of deterioration. The famous Dal Lake of Kashmir, which was about 40 km^2 of area in the beginning of nineteenth century, has presently about 20 km^2.Almost half of the lake Renuka (Water spread area of 670 ha), the biggest lake of Himachal Pradesh in the lesser altitude of Siwaliks of Himalayan region, is filled up by sediment. The situation is much worst in the plains or in peninsular India. Osmansagar in Hyderabad, Upper Lake in Bhopal and Poondi, Red Hills in Chennai, which are sources of drinking water in the respective area, have shrunk considerably in the recent past causing great hardship to the city dwellers. Due to mismanagement and various other reasons, most of the lakes of smaller sizes located in the urban areas are used as dumping spot of wastes, both solid and liquid. These have resulted in problem of eutrophication. Very precisely, occurrence of inorganic nutrients in water and the resulting increase in plant productivity has led to a serious water quality problem for many lakes in India.

Along the coast line of India, numerous bays and gulfs are formed where big or small rivers meet, thereby forming estuarine zone. Along coastal line numerous brackish water lakes are in existence, which join with sea during floods. A typical Indian estuary is highly productive, as waters receive abundant qualities of nutrients from the connected fresh water systems and surrounding land areas. Most of the Indian estuaries are monsoon dominated. The abundant fresh water influx received by these estuaries is more or less limited to the monsoon season extending from July to October. In the summer months of March to June very little fresh waters are added and the severity of pollution hazards comes into prominence during this period.

The major estuarine systems in India are: Hooghly-Metlah estuarine system, Mahanadi estuarine system, Krishna estuary, Pulicat Lake, Cauvery estuary, Vembanad Lake and Narmada-Tapti estuary. In Mahanadi estuary, the tidal effect is felt only up to about 35 kms upstream of the mouth. In the Gautami, which is the main component of the Godavari estuarine system, the tidal inflow extends up to about 50 km from the mouth. Increase in salinity has been observed in the rivers in recent years.

5.1.4 Water quality challenges in India

Indian rivers and other surface water bodies are primarily monsoon driven except the rivers of Himalayan origin, which carry snow and glacier melt waters during non-monsoon months. India's climate is dominated by temperate and tropical condition. The physicochemical and biological characteristics of domestic and municipal uses of water do not contain any hard lining chemical constituents. Surface water quality problems face by the country have the constituents' characteristics comprising suspended solids, BOD, low DO, Total and Fecal coliform, nutrient loads, etc., which represent contaminants of pathogenic in nature, originate mainly from municipal, agricultural and industrial sources. India has characteristic religious notions of disposal of worships refusals into water bodies. Although, India has a Water Prevention and Control of Pollution Act (1974), its effective enforcement would require a number of political and administrative pursuits. On the other hand, the water quality problems in India are emerging as a major hurdle to attain water security.

Pathogenic (organic) wastes/pollutants discharged into natural water bodies such as; rivers, lakes and the seas disappear slowly with time by the processes called self purification of natural water systems (White and Lack, 1982). The self purification is a complex process that often involves physical, chemical and biological processes working simultaneously. The amount of Dissolved Oxygen (DO) in water is one of the most commonly used indicators of river health. The major physical processes involved in self-purification of a river are dilution, sedimentation and re-suspension, filtration, gas transfer and heat transfer. Lakes and reservoirs are typically standing waters, the former naturally occur and the latter man-made. They exhibit a vast range of surface areas, volumes, depths and water retention times. Self-purification processes in lakes and reservoirs are controlled by the hydraulic behaviour of the water mass and by a series of other important factors, namely: dissolved oxygen supply, pH changes, water column stability and stratification residence time in the littoral region, particulate suspended and dissolved solids, including organic matter, temperature profiles, atmospheric loadings, nutrient and productivity controls depth and concentration gradients in aquatic eco-community. Thus, the physical processes of water quality hydrodynamics and transport mechanism associated with river are different than a lake or reservoir.

5.1.5 Challenges in surface water quality modeling

Water quality management is a critical component of overall integrated water resources management (Murty and Surender Kumar, 2011). Water quality can effectively be managed, if spatial and temporal variations of assimilative capacity of constituents and their transport mechanisms in a water body are known. Modeling as a management tool can give answer to assimilative capacity of constituents and waste load allocation as means of water-quality management along a water body wherein the amount of pollutant removal require at a number of discharge points can be determined. This can help achieve or maintain an acceptable level of water quality in an optimal manner. The other situation that may arise from the capacity expansion problem wherein one or more point sources has to increase in influent loading and the appropriate increase in the size of treatment facilities need to be determined. Another example may be the problem that occurs when an additional discharger wishes to locate on a water body that would necessitate a reallocation of the assimilative capacity of the water body among the existing dischargers (Burn, 1989) and so on.

Waste load allocation for water quality management can be accomplished by simulation and optimization modeling of hydrodynamic and transport behaviour of the water system through which contaminants move (McCutcheon, 1989). The prediction of water motion and the transport of materials impacting the water quality are carried out using some mathematical principles developed based on underlying mechanisms that cause change. The mathematical principles are to establish *cause-and-effect* relationships between sources of impurities, and the effects on water quality (Martin and McCutcheon, 1999). These relationships help us test hypotheses about a particular aquatic system, or process, aids in the diagnosis of factors contributing to particular water quality problems and help forecast the impacts of various environmental controls. The underlying *cause-and-effect* relationships are expressed mathematically by mechanistic models. In addition, empirical models such as; many statistical models allow description of the relationships with a minimum understanding about how the system works. However, the present-day models and modeling works encourage use of mechanistic models than empirical models; because empirical models are case specific and subjected to a lot of uncertainty although have a potential to associate with mechanistic models by their integration. Mechanistic models have three chief advantages (Martin and McCutcheon, 1999):

- Modeling allows researchers and scientists to gain insight and increased understanding of the water quality of a particular stream, lake and estuary;
- The process of calibrating mechanistic model not only provides information on cause-and-effect relationships, but also indicates what is not understood. Understanding the limits of knowledge about a particular water body is also important in making decisions about water resources,
- Most important is that mechanistic models provide a predictive capability that is not available in purely empirical models.

Water quality modeling deals with development and application of models by integrating the present understanding of transport and transformation of materials to predict the fate of those materials in the natural environment (Martin and McCutcheon, 1999). Water quality modellers construct and apply models that incorporate the present knowledge to test hypotheses, predict the effect of some action or solve a practical problem.

5.1.6 Status of surface water quality modeling in India

Ironically, surface water quality management issue in India is still to gear up for policy level planning, evaluation, and conservation measures. What has been emphasized in the past is water quality monitoring and quality assessment based on one-time monitored data of 2500 stations located in different rivers, lakes and groundwater wells. Water quality simulation modeling and management in India is a subject mostly dealt in academia and R & D organizations for specific research interest and knowledge gathering. Limited efforts are in place for strategic management of water quality problems. This could be due to the facts that; (i) there is inadequate spatio-temporal water quality data, which are not enough to conceive, calibrate and validate a model, (ii) lack of information/data on source of pollution and their magnitude and characteristics, (iii) lack of data on water quality hydrodynamics and kinetics, and (iv) lack of understanding of physical behaviour of the water system. Over the years, research investigations by different Indian researchers have generated considerable databases and knowledge understanding on water quality modeling of surface water systems. Further, Government of India has also launched “Ganga Rejuvenation” program with the vision to restore the wholesomeness of the river defined in terms of ensuring “Aviral Dhara” (Continuous Flow”), “Nirmal Dhara” (“Unpolluted Flow”), Geologic and ecological integrity. To achieve such goals, decisions are to be taken based on different water quality management scenario analyses. To a great extent, it is possible by pursuing/adopting suitable simulation-optimization models for water quality management as a scientific tool. The models should be such that they are appropriate for hydrodynamics and kinetics of Indian surface water systems, and can reasonably be used as decision support system for water quality management. This eventually advocates the need of evaluating the capability, performance, and effectiveness of existing widely used surface water quality models and strengthens the fitting model(s) by testing with Indian conditions.

5.2 Surface Water Quality Modeling: Importance

Increasing national and international interest in finding rational and economical approaches to water-quality management is one of the major issues in implementation of Water Framework Directive (WFD), particularly in terms of pollution control and management of water resources quality. Insightful application of mathematical models, attention to their underlying assumptions, and practical sampling and statistical tools can help maximize a successful approach to water-quality modeling. Mathematical modeling of water quality facilitates prediction of quantitative reaction and status of aquatic environments and impacts for defined pressures on aquatic environments, that is, human and natural activities in its surrounding. When correctly selected and used under strictly defined conditions and limitation, the mathematical model can play a very powerful tool in planning and management of water quality. Primarily, water quality models can serve for a quality interpretation of water resources status, and the causes of the status change can be detected. Further, the evaluation methods can be optimized. Secondly, these models can facilitate an analysis of the effects of future actions on the aquatic ecosystem and can support to the selection of the most sustainable options. Third, these models can assist in filling the gaps in our knowledge and defining a cost-effective monitoring program (Vanrolleghem *et al.*, 1999). Models help us gain insights into hydrological, ecological, biological, environmental, hydrogeochemical, and socioeconomic aspects of watersheds (Singh and Woolhiser, 2002), and thus contribute to systematized understanding of how ecosystems function (Lund and Palmer, 1997), which is essential to integrated water resources management and decision making (Madani and Marino, 2009).

Surface water pollution comprising rivers, lakes, reservoirs, ponds, etc is a major environmental problem in India that has negative consequences for humans and wildlife. To prevent its consequences, the sources and severity of pollution must be determined by monitoring water quality, followed by the measures necessary to control the contamination. Models are important tools for predicting adverse effects of pollution along a stream or in a water body, and they can help guide practical investments in stream health and management of surface water bodies.

While framing a mathematical model for surface water quality management, the purpose of modeling should be clear and well defined to achieve maximum simplicity consistent with the required degree of accuracy and detail in the process of description of the natural system. In general, the purpose of modeling falls into one of the following categories (Zheng and Bennett, 1995):

- In a scientific sense - to develop a clear conceptual model based on all available information as well as to understand more fully the transport regime of the pollutant:

to test hypotheses, to ensure that they are consistent with governing principals and observations, and to quantify the dominant controlling processes. Without this understanding, a simulation code can be used only as a black-box, and this clearly limits intelligent application of the model;

- Often in connection with efforts to assign responsibility or assess exposures, to reconstruct the history of pollutant transport, to establish time ranges within which an event could have begun, or within which contaminants could have reached specified level in certain areas;
- Future contaminant distributions, either under existing conditions or with engineering intervention to control the source or alter the flow regime, can be calculated. These include the choice of computer code, the way of discretization, the level of effort required in model calibration, and the analysis of the appropriated assumptions.

By definition of model, it is a simplified approximation to the real system. A simple model is always preferred than a complex model, as long as it captures the essence of the problem. An overly complex model not only increases computational time and costs, but also introduces additional uncertainties if detailed data are not available.

5.3 Modeling for Sustainable Water Quality Management

Water (and its deteriorating quality) is under the most severe stress due to the exponentially growing human population. Problems are becoming increasingly complex and diverse and require more and more specific knowledge and efficient integration across various disciplines, sectors, countries, and societies. The major challenge before us is to realize the desired integration and to resolve the large amount of existing gaps and barriers.

Challenges of water quality and quantity management adhering to the principle of sustainable development have been of significant concerns to many researchers and decision makers. These issues involve a large number of social, economic, environmental, technical, and political factors, coupled with complex spatial variability and cascading effect (Li et al., 2014). Climate change and human interference could affect the related management systems at a regional scale and lead to more significant spatial and temporal variations of water quantity and availability as well as the associated environmental and ecological conditions. Such complexities force researchers to develop more robust mathematical methods and tools to analyze the relevant information, simulate the related processes, implement mitigation strategies, assess the potential impacts/risks, and generate sound decision alternatives. Mathematical techniques can aid decision makers in formulating and adopting cost-effective and environment-benign water management plans and policies (Li et al., 2014).

In summary, the effective mathematical methods for modeling water quantity and quality are becoming one of the most important goals pursued by governments, industries, communities, and researchers. The contribution of degraded water to the water crisis, if measured in terms of loss of beneficial could be; water that is lost for beneficial human, agricultural, and ecological uses through excessive pollution by pathogens, nutrients, heavy metals and acid mine drainage, trace organic contaminants such as agricultural pesticides and pesticides associated with wood treatment, and localized high levels of oil and related pollutants, including salt, hydrocarbons, metals and other toxic wastes, and high levels of turbidity and sedimentation from excessive loadings of sediments. Therefore, to achieve the goal of sustainable water quality management, a number of issues involving identification, occurrence, and perception of various problems (e.g. eutrophication, acidification, global warming), pollution control types, wastewater treatment, modeling and monitoring, planning and environmental impact assessment, legislation and institutions, the notion of sustainable development, and the role of science and engineering, are to be addressed (UN-Water Analytical Brief).

5.4 Basic concept, Governing equations, Rate constants and Coefficients

5.4.1 Basic concepts

The fundamental principles for water quantity and quality modeling are (Chapra, 1997):

- Conservation of energy states (first law of thermodynamic);
- Conservation of mass states (mass balance models); and
- Conservation of momentum states (Newton's second law of motion).

These laws form the underlying principles of flow and water quality modeling. Conservation of energy is the basis of all mechanistic temperature modeling. Conservation of mass is the basis for transport modeling. When the mass balance is expanded to include kinetic changes of non-conservative parameters, these transport models are referred to as water quality models. Conservation of momentum is the basis for all flow models.

The basic principle underlying water quality modeling is that of mass balance. Modeling involves performing a mass balance for defined control volumes for a specified period of time. Typically, material balances involve dissolved and suspended materials such as dissolved oxygen, organic carbon, nitrogen, phosphorus, and suspended sediments and this principle is also applied to any substance whose transformation kinetics is known. The mass balance is performed by accounting for all material that enters and leaves a defined volume of water plus accounting for all changes in mass of a constituent caused by physical, chemical and biological processes. The conservation or balance equations in terms of mathematical statement can be stated as (Martin and McCutcheon, 1999):

$$\text{Accumulation} = \pm \text{Transport} \pm \text{Sources/Sinks} \qquad (5.1)$$

where accumulation is equal to the difference in transport into or out of a system, plus and gains or losses that resulted from sources and sinks. Accumulation is therefore the time rate of change by which a conservative property builds up or accumulates inside a system.

5.4.2 Governing equations

The mass conservation in a one-dimensional control volume where all processes act on it is depicted in Fig.5.1.

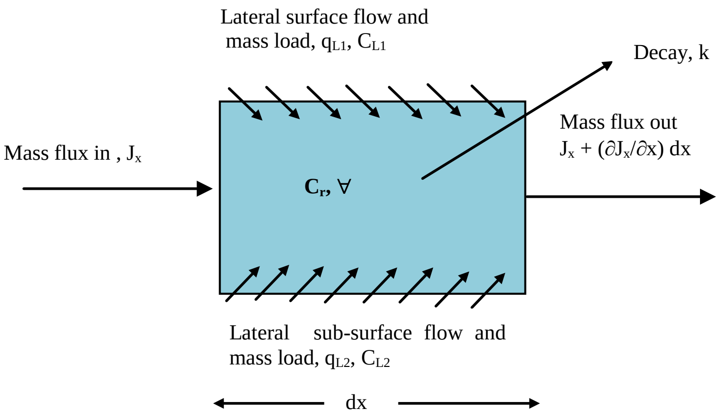


Figure 5.1: Mass conservation in a one-dimensional control volume.

Based on the basic principle of conservation of mass and the accumulation equation (eq. 5.1), the governing one-dimensional contaminant transport representing advective and dispersive mass fluxes, biochemical transformations, water column-sediment interactions, adsorption, external loadings, and change of mass of substance with time and space for a Newtonian fluid with constant density shown in Fig.5.1 is given by:

Rate of change of mass in control volume | Advective mass loading from surface lateral inflow | Advective mass loading from sub-surface lateral inflow | Dispersive mass loading from sub-surface lateral inflow | Mass influx

$$\frac{\partial (C_r \forall)}{\partial t} = q_{L1} C_{L1}\,dx + q_{L2} C_{L2}\,dx - n_{sed} D_{sed} \frac{C_{L2}-C_r}{\Delta z} w_r\,dx + \left(V\,A\,C_r - A\,D_x \frac{\partial C_r}{\partial x}\right) - \left[\left(V\,A\,C_r - A\,D_x \frac{\partial C_r}{\partial x}\right) + \frac{\partial}{\partial x}\left(V\,A\,C_r - A\,D_x \frac{\partial C_r}{\partial x}\right) dx\right] - k\,C_r \forall \qquad (5.2)$$

Mass outflux | Biochemical decay

where, C_r is the mass density of a constituent (ML^{-3}); $\forall$ is the control volume (L^3); q_{L1} is the lateral surface discharge per unit length , ($L^3L^{-1}T^{-1}$); C_{L1} is the constituent concentration of lateral surface flow, (ML^{-3}); q_{L2} is the lateral subsurface discharge per unit length, ($L^3L^{-1}T^{-1}$); C_{L2} is the constituent concentration of lateral subsurface flow, (ML^{-3}); n_{sed} is the sediment porosity, (dimensionless); w_r is the width of the sediment layer at which the lateral subsurface flow takes place, (L); Δz is the thickness of the sediment layer, (L); D_{sed} is the dispersive properties of sediment, (L^2T^{-1}); V is the advective velocity of water along x direction, (LT^{-1}); A is the flow area, (L^2); D_x is the longitudinal dispersion coefficient, (L^2T^{-1}); k is the decay rate coefficient, (T^{-1}); dx is the length of the elementary stretch, (L); and $\partial C_r/\partial x$ derivative of C_r with respect to x.

Simplification and rearrangement of Equation (5.2), gives:

$$\frac{\partial (C_r \forall)}{\partial t} = q_{L1} C_{L1}\, dx + q_{L2} C_{L2}\, dx - n_{sed} D_{sed} \frac{C_{L2} - C_r}{\Delta z} w_r\, dx - \frac{\partial}{\partial x}\left(V\, A\, C_r - A\, D_x \frac{\partial C_r}{\partial x}\right) dx - k\, C_r A\, dx \tag{5.3}$$

In terms of mass transport, considering $M = C_r \forall$, Equation (5.2) can be written as:

$$\frac{\partial M}{\partial t} + \frac{\partial}{\partial x}(VAC_r)\, dx = \frac{\partial}{\partial x}\left(A\, D_x \frac{\partial C_r}{\partial x}\right) dx - k\, C_r A\, dx + q_{L1} C_{L1}\, dx + q_{L2} C_{L2}\, dx - n_{sed} D_{sed} \frac{C_{L2} - C_r}{\Delta z} w_r\, dx \tag{5.4}$$

When there is no contribution from lateral inflows, Equation. (5.4) represents well known contaminant transport equation in one-dimension that is used for river contaminant transport modeling:

$$\frac{\partial M}{\partial t} + \frac{\partial}{\partial x}(VAC_r)\, dx = \frac{\partial}{\partial x}\left(A\, D_x \frac{\partial C_r}{\partial x}\right) dx - k\, C_r A\, dx \tag{5.5}$$

The three dimensional governing equation representing advective and dispersive mass fluxes, biochemical transformations, sources and sinks, and change of mass of the substance with time and space, based on Equation. (5.5) is given by:

$$\frac{\partial M}{\partial t} + \frac{\partial (V_x A_x C_r)}{\partial x} dx + \frac{\partial (V_y A_y C_r)}{\partial y} dy + \frac{\partial (V_z A_z C_r)}{\partial z} dz = \frac{\partial}{\partial x}\left(A_x\, D_x \frac{\partial C_r}{\partial x}\right) dx + \frac{\partial}{\partial y}\left(A_y\, D_y \frac{\partial C_r}{\partial y}\right) dy + \frac{\partial}{\partial z}\left(A_z\, D_z \frac{\partial C_r}{\partial z}\right) dz \pm k(x, y, z, t)\, C_r\, dx\, dy\, dz \pm S \tag{5.6}$$

In which, M is the mass of constituents, (M); D_x, D_y, and D_z are the dispersive mass fluxes in the spatial directions x, y, and z ($L^{-2}\ T^{-1}$);V_x, V_y, and V_z are the components of the flow velocity in spatial directions x, y, and z ($L\ T^{-1}$); A_x, A_y, and A_z are the cross-sectional area of the control volume in directions x, y, and z, (L^{-2});t is time (T); *dx, dy,* and *dz* are the dimension of the control volume in direction x, y, and z, (L); ∂x, ∂y, and ∂z are the derivative in direction x, y, and z;*k(x,y,z,t)* is the growth and decay coefficients of the constituent, (T^{-1}); andS is the external sources and sinks of the constituent, ($M\ L^{-3}\ T^{-1}$).

Organic matters undergo changes because of air-water interface and nutrients interactions into the water body. The air-water interface and nutrients interactions affect the water temperature, dissolved oxygen, Nitrogen, and Phosphorous cycle, which in turn, change the fate of water quality constituents and also the ecology of water system. Fig. 5.2 depicts the interactions of constituents of organic matters in a surface water body. For management of water quality and ecology of a surface water system, one has to know the fate of the organic constituents' concentration on spatial and temporal scale.

Lake water quality modeling deals with two components: hydrodynamic and pollutant transport. The governing system of equations for the flow and transport in a lake include the conservation equations of mass, momentum and energy. The contaminant transport equation is based on the conservation of mass and Equation. 5.6 holds good for lake water quality modeling. For hydrodynamic modeling, conservation of momentum, mass and energy provide the fundamental principles.

The major difference between rivers and lakes is in the speed of water flow. Water speeds are generally much smaller in lakes than in rivers. Thus, in Equation 5.6, the advection term is generally much larger than the mixing term in rivers, while the advection term may be comparable to or even smaller than the mixing term in lakes. Lakes are also distinguished from estuaries that have interchanges with the ocean and are subject to tide.

Due to its relatively large velocity, a river, especially a shallow and narrow river, can often be represented by one-dimension. By contrast, a lake generally has much more complicated circulation patterns and mixing processes, which are largely affected by lake geometry, vertical stratification, hydrological and meteorological conditions. Lakes and reservoirs tend to store water over seasons and years. Such a long retention time often makes internal chemical and biological processes significant in the lake water column and the sediment bed. Thus, the hydrodynamic modeling of a lake is much complicated than the transport modeling, however, without hydrodynamic modeling, a transport modeling cannot be addressed.A variety of factors control the in-lake hydrodynamic condition, they include: (i) depth, length, width, volume, and surface area; (ii) inflows and outflows; (iii) hydraulic residence time; and (iv) lake stratification.

Lakes and reservoirs are sensible to pollutants from point and non-point sources. Lake eutrophication by the excessive algal growth and low DO levels are common symptoms originate from excessive nutrient loadings, namely Nitrogen and Phosphorous.The interactions of organic constituents depicted in Fig. 5.2 also hold good for Lake eutrophication modeling.

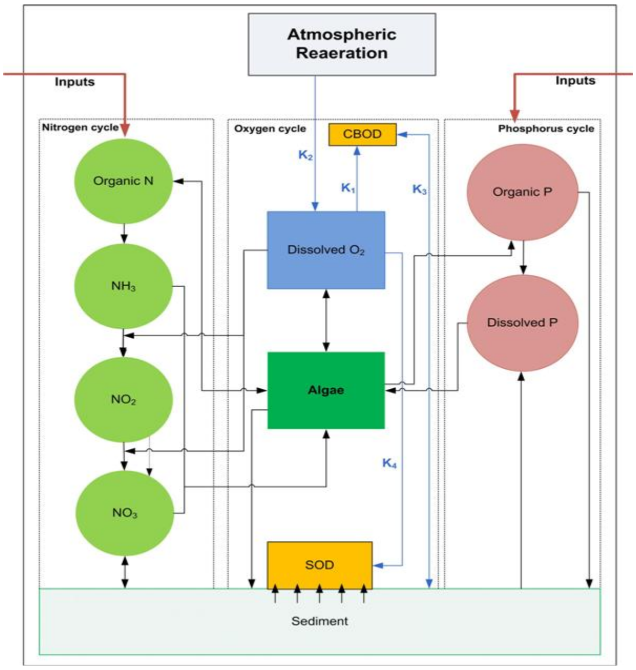


Figure 5.2: Interactions of organic constituents in a water body.

The chemical and biological processes and their reaction kinetics are temperature dependant. These processes can be modeled by first-order kinetic equations.

5.4.3 Temperature

Temperature impacts almost all water quality processes that take place in a water body. Temperature is modelled by performing a heat balance on each computational element in the system. The simplified model for temperature prediction is:

$$\frac{dT}{dt} = \frac{K_H(Te - T)}{\rho C_P h} \qquad (5.7)$$

where K_H (cal/cm^2/day/°C) is the overall heat exchange coefficient; *Te* (°C) is the equilibrium temperature; T (°C) is actual temperature; ρ (g/cm^3) is the water density; *Cp* (cal/g/°C) is the heat capacity of water; and *h* (cm) is the water depth.

The temperature computed by Equation 5.7 is used to correct the rate coefficients of the source/sink terms of the water quality variables. Generally, these coefficients are determined at controlled temperature of 20ºC. The correction to the rate coefficient for temperature is:

$$X_T = X_{20}\theta^{T-20°} \qquad (5.8)$$

Where X_T is the value of the coefficient at the desired temperature [T]; X_{20} is the value of the coefficient at the standard temperature (20ºC); and θ is an empirical constant for each reaction coefficient.

5.4.4 De-oxygenation model

De-oxygenation is the process that involves the removal of oxygen from water. In water quality modeling, it describes how dissolved oxygen (DO) in water decreases by degradation of biochemical oxygen demand (BOD). Mathematically, the deoxygenating equation is described by first order kinetics, as follows:

$$\frac{dL}{dt} = -K_1 L \qquad (5.9)$$

in which, L is the BOD concentration, [ML^{-3}]; K_1 is the de-oxygenation rate coefficient and is temperature dependent, [T^{-1}].

5.4.5 Re-aeration model

Re-aeration is the process of oxygen exchange between the atmosphere and water body in contact with the atmosphere. The re-aeration process is modelled as the product of a mass transfer coefficient multiplied by the difference between dissolved oxygen saturation and the actual dissolved oxygen concentration, that is:

$$\frac{dC}{dt} = K_2(C_s - C) \qquad (5.10)$$

where C is the concentration of oxygen in water volume, [ML^{-3}]; C_S is the saturated concentration of oxygen in water volume, [ML^{-3}]; K_2 is the re-aeration coefficient, and is temperature dependent, [T^{-1}].

5.4.6 BOD and DO model

Streeter and Phelps (1925) established the relationship between the decay of organic waste measured in terms of BOD and dissolved oxygen (DO). The relation between the DO and BOD concentration over time is modelled by the linear first order differential equation, as follows:

$$\frac{dD}{dt} = -K_1 L - K_2 D \qquad (5.11)$$

where D is the dissolved oxygen (DO) deficit, [ML^{-3}]; K_1 and K_2 represent the de-oxygenation and re-aeration rate coefficient, respectively and they are temperature dependent [T^{-1}]

The solution of Equation 5.11 gives the well known DO sag model:

$$D = \frac{K_1 L_0}{K_2 - K_1}\left(e^{-K_1 t} - e^{-K_2 t}\right) + D_0 e^{-K_2 t} \qquad (5.12)$$

where, $L_0$is the initial oxygen demand of organic matter in the water, also called the ultimate BOD, [ML^{-3}]; D_0 is the initial DO deficit, [ML^{-3}]; and $D = DO_{sat} - DO$.

The DO processes which involve consumption and release of oxygen in receiving water are described by Equation 5.13 (Palmer, 2001). Equation 5.13 expresses DO as sum of the sources i.e, re-aeration & algal production and sinks i.e, BOD, sediment oxygen demand (SOD) and nitrogen oxidation.

$$\frac{dDO}{dt} = K_2\left(DO_{sat} - DO\right) + (\alpha_3 \mu - \alpha_4 \rho)A - K_1 L - \frac{K_4}{H} - \alpha_5 \beta_1 N_1 - \alpha_6 \beta_2 N_2 \qquad (5.13)$$

where, K_2 is the re-aeration rate coefficient [T^{-1}]; α_3 is the rate of oxygen production per unit of algal photosynthesis;α_4 is the rate of oxygen uptake per unit of algal respired; α_5 is the rate of oxygen uptake per unit of ammonia nitrogen;$\alpha_6$is the rate of oxygen uptake per unit of nitrite nitrogen; μ is the growth rate of algae, [T^{-1}]; ρ is the algal respiration rate, T^{-1}; A is the algal biomass concentration, [ML^{-3}]; H is depth(m);K_4 is sediment oxygen demand [$ML^{-2}T^{1}$]; β_1 is the rate constant for biological oxidation of ammonia nitrogen, temperature dependent, [T^{-1}]; N_1 is the concentration of ammonia nitrogen, [ML^{-3}]; β_2 is the rate constant for oxidation of nitrite nitrogen, temperature dependent, [T^{-1}]; N_2 is the concentration of nitrite nitrogen, [ML^{-3}].

5.4.7 Nutrients model

In water quality modeling, nitrogenous and phosphorous compounds play important roles as they consume oxygen during oxidation processes in conversion of different forms i.e., nitrogen and phosphorous cycle (USEPA, 1987). Fig. 5.2 describes the constituents' interactions in the nitrogen and phosphorous cycle.

5.4.8 Nitrogen cycle

In natural aerobic waters, there is a stepwise transformation from organic nitrogen to ammonia, to nitrite, and finally to nitrate. The differential equations governing transformations of nitrogen from one form to another are given by (USEPA, 1987).

5.4.8.1 Organic Nitrogen Model

Referring to Fig. 5.2, the organic Nitrogen model is described as:

$$\frac{dN_4}{dt} = \alpha_1 \rho A - \beta_3 N_4 - \sigma_4 N_4 \quad (5.14)$$

where N_4 is the concentration of organic nitrogen, [M-N L^{-3}] ; β_3 is the rate constant for hydrolysis of organic nitrogen to ammonia nitrogen, temperature dependent, [T^{-1}]; α_1 is the fraction of algal biomass that is nitrogen, (M-N/M-A); ρ is the algal respiration rate, day^{-1}; A is the algal biomass concentration, (M-AL^{-3}); and σ_4 is therate coefficient for organic nitrogen settling, temperature dependent, [T^{-1}].

5.4.8.2 Ammonia Nitrogen Model

Referring to Fig.5.2, the Ammonia Nitrogen model is described as:

$$\frac{dN_1}{dt} = \beta_3 N_4 - \beta_1 N_1 + \frac{\sigma_3}{d} - F_1 \alpha_1 \mu A \quad (5.15)$$

where $F_1 = \frac{P_N N_1}{(P_N N_1 + (1-P_N) N_3)}$; N_1 is the concentration of ammonia nitrogen, (M-NL^{-3});N_3 is the concentration of nitrate nitrogen, (M-NL^{-3}); N_4 is the concentration of organic nitrogen, (M-NL^{-3}); β_1 is the rate constant for biological oxidation of ammonia nitrogen, temperature dependent, [T^{-1}]; β_3 is the organic nitrogen hydrolysis rate, [T^{-1}]; α_1 is the fraction of algal biomass that is nitrogen, (M-N/M-A); σ_3 is the benthos source rate for ammonia nitrogen, M-N/L^2-day; d = mean depth of flow, [L]; μ is the local specific growth rate of algae, [T^{-1}]; F_1 is the fraction of algal biomass that is nitrogen, mg-N/mg-A; A is the algal biomass concentration, M-A/L^3; and P_N is the preference factor for ammonia nitrogen (0 to 1.0). The ammonia preference factor is equivalent to the fraction of algal nitrogen uptake from the ammonia pool when the concentration of ammonia and nitrate nitrogen is equal.

5.4.8.3Nitrite Nitrogen Model

Referring to Figure 2, the Nitrite Nitrogen model is described as:

$$\frac{dN_2}{dt} = \beta_1 N_1 - \beta_2 N_2 \quad (5.16)$$

where N_1 is the concentration of ammonia nitrogen, M-N/L^3; N_2 is the concentration of nitrite nitrogen, M-N/L^3; β_1 is therate constant for oxidation of ammonia nitrogen, temperature dependent, (T^{-1}); β_2 is the rate constant for oxidation of nitrite nitrogen, temperature dependent, (T^{-1}).

5.4.8.4 Nitrate Nitrogen Model

Referring to Fig.5.2, the Nitrate Nitrogen model is described as:

$$\frac{dN_3}{dt} = \beta_2 N_2 - (1 - F) \alpha_1 \mu A \quad (5.17)$$

where F is the fraction of algal biomass that is nitrogen, M-N/M-A; α_1 is the fraction of algal biomass that is nitrogen, M-N/M-A; and μ is the local specific growth rate of algae, (T^{-1}).

5.4.8.5 Phosphorous Cycle

Organic forms of phosphorous are generated by the death of algae, which then convert to the dissolved inorganic state, where it is available to algae for primary production. Fig. 5.2 refers the constituents' interactions in the Phosphorous cycle.

5.4.8.6 Organic Phosphorous Model

The differential equation representing the organic Phosphorous model is given by:

$$\frac{dP_1}{dt} = \alpha_2 \rho A - \beta_4 P_1 - \sigma_5 P_1 \quad (5.18)$$

where P_1 is the concentration of organic phosphorous, M-P/L; $\alpha_2$is the phosphorous content of algae, M-P/M-A; ρ is the algal respiration rate, [T^{-1}]; A is the algal biomass concentration, M-A/L; β_4 is the organic phosphorous decay rate, temperature dependent, [T^{-1}]; σ_5 is the organic phosphorous settling rate, temperature dependent, [T^{-1}].

5.4.8.7 Dissolved Phosphorous

The differential equation for modeling dissolved Phosphorous is given by:

$$\frac{dP_2}{dt} = \beta_4 P_1 - \sigma_2/d - \alpha_2 \mu A \quad (5.19)$$

where $P_2$is the concentration of inorganic or dissolved phosphorous, M-P/L; σ_2 is the benthos source rate for dissolved phosphorous, temperature dependent, M-P/L-T; d is the mean stream depth, [L]; µis the algal growth rate, [T^{-1}]; and A is the algal biomass concentration, M-A/L.

5.4.9 Coliform

Coliforms are used as an indicator of pathogen contamination in surface waters. Expressions for estimating coliform concentrations are usually first order decay functions, which only take into account coliform die-off (Bowie et al., 1985) and can be expressed as:

$$\frac{dE}{dt} = K_5 E \quad (5.20)$$

where E is the concentration of coliforms, colonies/100 ml; and K_5 is the coliform die-off rate, temperature dependent, (T^{-1}).

5.4.10 Algae formulation

Chlorophyll_a is considered to be directly proportional to the concentration of phytoplanktonic algal biomass. In modeling, algal biomass is converted to Chlorophyll a by the simple relationship:

$$Chl\_a = \propto_0 A \quad (5.21)$$

where Chl_a is the Chlorophyll_a concentration , M-Chl_a/L; A is the algal biomass concentration, M-A/L;$\propto_0$ is a conversion factor (M-Chl_a/M- A).

The differential equation that governs the growth and production of algae (Chlorophyll_a) is formulated according to the following relationship:

$$\frac{dA}{dt} = \mu A - \rho A - \frac{\sigma_1}{d} A \quad (5.22)$$

where t is the time, [T]; µ is the local specific growth rate of algae, which is temperature dependent, [T^{-1}]; ρ is the local algal respiration rate, which is temperature dependent, [T^{-1}]; σ_1 is the local settling rate for algae, which is temperature dependent, [LT^{-1}]; and d is the mean stream depth, [L].

5.5 Approaches to Surface Water Quality Modeling

5.5.1 Rivers/Stream water quality modeling

Except the initial mixing length from the entry of point source pollution, contaminant transport in a river/stream is normally one-dimensional. In the initial period of mixing, contaminant transport is governed by 3-dimension. River/stream contaminant transport equation in one-dimension governed by advection-dispersion-decay/growth-sorption and sources/sinks can be modelled by Equation 5.6 neglecting y and z directional components, i.e., by considering $Vy = V_z = 0; D_y = D_z = 0$, and $y = z = 0$.

For one-dimensional transport modeling, the data requirements are: (i) river/stream geometry (width, depth and slope); (ii) river/stream hydraulic data (cross-sectional average velocity, and flow rate); (iii) transport properties (longitudinal dispersion coefficient, reaction kinetics, water temperature, and initial concentration of contaminants of interest; sources and sinks of contaminant in the system); (iv) ambient temperature; (v) concentration of organic constituents; and (vi) input stresses of contaminant.

These data are case specific and vary from one river to another and can be obtained from field and laboratory investigations. The estimation of longitudinal dispersion coefficient, D_x or D_L, that depends on river/stream hydraulic properties and mixing phenomena of contaminant, and may vary from location to location, is not a straight forward approach. Methods suggested by different investigators for estimation of D_L are listed in Table 5.1.

Table 5.1 Methods suggested by investigators for estimation of D_x (Source: Ghosh, 2000; and Muthu Krishnavellaisamy, 2007)

Sl. No.	Investigators	Equation	Method
1.	Taylor (1921)	$\frac{d\sigma^2}{dt} = 2D$; where, σ^2 is the variance of solute distribution and D is the diffusion co-efficient.	Experimental
2.	Chatwin (1971), and Valentine and Wood (1979)	$D_L = \frac{\bar{u}^3}{2} \frac{d\sigma_t^2}{dx}$ where, $\bar{u}$ is the average flow velocity, σ_x is the spatial variances of concentration distribution.	Experimental
3.	Elder (1959)	$D_L = \left[\frac{0.404}{\kappa^3} + \frac{\kappa}{6}\right] yU_*$ where κ is the Von Karman's coefficient, and U_* is the shear velocity, and y is the vertical distance.	Theoretical
4.	Fischer *et al.*, (1979)	$D_L = -\frac{1}{A}\int_0^B u' y \int_0^y \frac{1}{\varepsilon_t y} \int_0^B u' ydydydy$ where u' is the deviation of velocity from the cross sectional mean velocity, y is the depth of flow, and ε_t is the transverse mixing coefficient.	Theoretical
5.	Taylor (1954)	$D_L = 10.1\ U_* r$ where U_* is the shear flow velocity , and r is the radius of the pipe.	Empirical
6.	Elder (1959)	$D_L = 6.3\ U_* H$ where H is the depth of flow	Empirical
7.	Yotsukura and Fiering (1964)	$D_L = 9.0 \text{ to } 13.0\ U_* H$	Empirical
8.	Fischer (1966)	$D_L = 0.011\ u^2\ W^2 / U_* H$ where W is the width of he stream, and u is the mean flow velocity.	Empirical
9.	Thackston and Krenkal (1967)	$D_L = 7.25\ U_* H \{u / U_*\}^{1/4}$	Empirical
10.	Sumer (1969)	$D_L = 6.23\ U_* H$	Empirical
11	Fukuoka and Sayre	$D_L / RU_* = 0.8\{r_c^2 / L_B H\}^{1.4}$	Empirical

Sl. No.	Investigators	Equation	Method
	(1973)	where R is the hydraulic depth, r_c is the	
12.	McQuivey and Keefer(1974)	$D_L = 0.058\ Q/SW$	Empirical
11.	Jain (1976)	$D_L = u^2\ W^2\ /k\ AU_*$	Empirical
12.	Beltaos (1978)	$D_L/RU_* = \alpha\ \{W/R\}^2$	Empirical
13.	Liu (1977)	$D_L = Q^2/2U_* R^3\ \{U_*\ /u\}^2$	
14.	Magazine (1983)	$D_L/R_bU_* = D_L/R_wU_* = 75.86\ (Pr)^{1.632}$ Where $Pr = C_w/\sqrt{g}\ \{x/h\}^{0.3}\{x_1'/b\}^{0.3}\{1.5+e/h\}$	Empirical
15.	Marivoet and Craenenbroec (1986)	$D_L = 0.0021\ u^2\ W^2/U_* H$	Empirical
16.	Asai *et al.* (1991)	$D_L/\ U_* H = 2.0\ \{W/R\}^{1.5}$	Empirical
17.	Ranga Raju *et al.* (1997)	$D_L/qS = 0.4\ Pt$ Where $Pt = \{W/R\}^{2.16}\{u\ /\ U_*\}^{-0.82}\{S\}^{-0.2}$	Empirical
18.	Koussis and Mirasol (1998)	$D_L = \Phi\ \sqrt{}\ (gRS)/H\ \{W\}^2$	Empirical
19.	Seo and Cheong (1998)	$D_L/U_* H = 5.915\{W/H\}^{0.628}\{u/\ U_*\}^{1.428}$	Empirical
20.	Kezhong and Yu (2000)	$D_L/U_* H = 3.5\{W/H\}^{1.125}\{u/\ U_*\}^{0.25}$	Empirical

Empirical formulae indicate that D_L is a function of stream flow characteristic and stream geometry. By analyzing empirical formulae, Seo and Cheong (1998) suggested a generalized functional relationship of D_L with flow characteristic and geometry of a stream of the following form:

$$\frac{D_L}{U_* H} = a\left(\frac{W}{H}\right)^b\left(\frac{u}{U_*}\right)^c \qquad (5.23)$$

where W is the river width, H is the depth of the flow, u is the mean longitudinal velocity, U_* is the shear velocity, $(=\sqrt{gRS}$;where g is the gravitational acceleration constant; R hydraulic radius (flow area/wetted perimeter); and S is the friction slope ($S \approx \partial h/\partial x \approx$bed slope) (Bashitialshaaer *et al.*, 2011), and *a, b, c* are constants.

The parameters of reactive kinetics viz., decay rate coefficient, sorption kinetic coefficients, benthic kinetic coefficient; kinetic coefficients related to Nitrogen and Phosphorous cycle, algal and coliform cycle can be determined from the field and laboratory experiments.

5.5.2 Lake and estuary water quality modeling

Lake and estuary water quality modeling is a complicated and tedious job. It involves numerical approach towards hydrodynamic and pollutant transport modeling in 3-dimension. Hydrodynamic and pollutant transport processes are mathematically modelled using field observations and laboratory experimental data, as illustrated in Fig.5.3.

5.6 A Review of different modeling approaches

Surface water quality models have undergone a long period of development since Streeter and Phelps built the first water quality model (S-P model) to control river pollution in Ohio State of the US (Streeter and Phelps, 1925). More than 100 surface water quality models have been developed up to now (Wang *et al.*, 2013). The models developed, to deal with real life issues, field complexity, research interest, and water quality management, forriver/stream water quality modeling include: Empirical or Mechanistic models, Conceptual models, Processes based models, Stochastic models, Analytical models, Numerical models, Black-box models and Stream tube models.

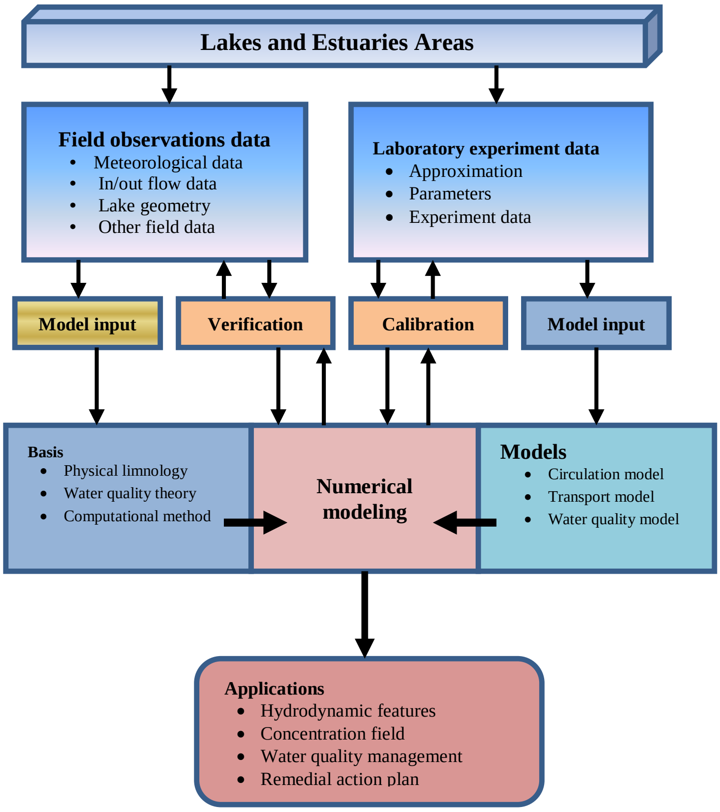


Figure 5.3: Schematic diagram of approaches for lake/estuary numerical hydrodynamic and transport modeling (source: modified from Tsanis and Wu, 1994)

5.6.1 Empirical and mechanistic models

The models are often divided into two broad categories as empirical and mechanistic depending on the way in which they influence the determinants, but the distinction is not clear-cut and mechanistic descriptions will often contain empirically derived components (Cox, 2003). The empirical models make no attempt to explicitly model hydrochemical processes; instead the model inputs are related directly to its outputs by one or more relationships obtained experimentally. Empirical models are derived by curve fitting or statistical analysis of stream/river data defining a process of interest, while a mechanistic model is formulated on a hypothesis of controlling mechanism. By contract, a mechanistic model is different from empirical model by statistical analysis without regard to controlling mechanisms. In mechanistic models, the transfer of water and solutes between stores is governed by mass-balance budgeting. As a result, mechanistic models are evidently equivalent to theoretical and phenomenological models.Any good model has both empirical and mechanistic features.

Examples: (i) Empirical models for estimating the concentration and exports of metals in rural rivers and streams developed by Cuthbert and Kalff (1993); (ii) Empirical regression models for prediction of nutrient export specific to the Muskoka-Haliburton area of Central Ontario; (iii) Streeter and Phelps oxygen sag model (1925) is a mechanistic model; (iv) Biofilm consumption model is a mechanistic model (Lau, 1990).

5.6.2 Conceptual models

A conceptual model describes essential features of a phenomenon and identifies the principal processes taking place in it. Thus, the conceptual models represent physical processes and also statistical and empirical relationships to process-based and physically-based models derived from physical and physicochemical laws including some equations based on empirical knowledge. Simplified conceptual models sometime suffer from a lack of description of physical processes.

Example: Almost all numerical river water quality models are conceptual models, viz. QUAL series, WASP series, SWAT, MIKE series models, etc. Cells-in-series (Stefan and Demetracopoulos, 1981), Hybrid-cells-in-series (Ghosh *et al.*, 2004), Aggregated Dead Zone (ADZ) model (Beer and Young, 1984), etc are conceptual models for solute transport in one-dimensional stream/river.

5.6.3 Process based models

Process-based models (sometimes known as deterministic or comprehensive models) are those, which are derived based on the mathematical representation of one or several processes characterizing the functioning of the natural system using mainly on mathematical representation of physical laws on the flow of mass, momentum and energy. As a rule, a physically based model has to be fully distributed, and has to account for spatial variation of all variables.

Examples: SWAT and SWIN model,

5.6.4 Stochastic models

Stochastic models incorporate the inherent uncertainty of models by describing the central tendency and some measures of variability of parameters. This results in a probability density function for the prediction. Stochastic models sometimes use empirical description of parameter variability. Monte Carlo simulation, Markov chain, Kalman filter, Fokker-Planck equation, etc are used for stochastic water quality modeling.

Examples: SORM-Stochastic River Water Quality Model.

5.6.5 Analytical models

Analytical models are those that are based on analytical solution of the governing equations. Analytical models are based on exact solutions of the equations of mathematical physics. The plug-flow solution of the dissolved oxygen balance equation, known as the Streeter –Phelps equation, is perhaps the best known analytical model in stream modeling. In analytical modeling, the model parameters in a reach remain constant. The Ogata and Banks solution for the one-dimensional advection-dispersion equation is well known analytical model for solute transport in stream modeling. Analytical solutions are quite limited use and are very useful to verify numerical solution techniques.

Examples: Streeter and Phelps model, Ogata and Banks solution (1963) of 1-D ADE, etc.

5.6.6 Numerical models

The numerical models are those that require finite difference, finite element, and other approximate methods for solving water quality equations. Numerical models use approximate solutions. They are used in most general purpose stream water quality models. Almost all commercial and public domain water quality models are based on numerical solutions.

Examples: QUAL2E, WASP, MIKE, etc.

5.6.7 Black-box models

Lumped models are also referred as the Back-box models. Lumped-parameter models refer to the absence of space-dependency, therefore, they are zero-dimensional in space; they are based on an assumption of uniform conditions throughout the system modelled.

5.6.8 Stream tube models

The fundamental concept of stream tube model was given by Yotsukura and Cobb in the year 1972 considering the cumulative partial discharge at a given cross-section instead of lateral distance as independent variable by dividing the cross-section into a number of vertical strips termed as “stream tubes”. In the traditional approach, the strips are equal to width. Later on, Gowda (1980) extended it for water quality prediction in mixing zones of shallow rivers. In the stream tube model, analytical solutions of the steady state, 2-D convection-diffusion equation are modified to account for the longitudinal variability of decay and dispersion parameters. Stream tube models have not gained popularity like other modeling approaches.

5.7 An Appraisal of WaterQuality Models

The water quality models have come a long way and a wide variety of models are available today for assessment and management of water quality of rivers, reservoirs, lakes, estuaries, and watersheds worldwide. The assessment of water quality, understanding of its transport mechanism, simulation & prediction of transport processes and optimization of engineering interventions to control pollution, involve good databases for developing and/or selecting a suitable model. Mathematical modeling has become the standard procedure especially in characterizing and investigating water quality management problems in water bodies (Bath *et al.*, 1997; Chapra, 1997; Fitzpatrick *et al.*, 2001; Imhoff, 2003). Cox (2003) states that a great deal of work and time would be saved if an existing model suitable for the purposes of the study is chosen based on the data requirements and the appropriateness to deal with the water quality management problem at hand. Tsakiris and Alexakis (2012) suggested criteria for classification of water quality models as: (i) type of approach: physically based, conceptual, and empirical; (ii) pollutant item: nutrients, sediments, salts etc.; (iii) area of application: catchment, groundwater, river system, coastal waters, integrated; (iv) nature: Deterministic or Stochastic; (v) state analysed :steady state or dynamic simulation; (vi) spatial analysis: lumped, distributed; (vii) dimensions: 1-D or 2-D models; and (viii) data requirements: extensive databases, minimum requirements models (MIR).

Based on the approaches of modeling, numerous professional water quality models developed in the past have been complied and discussed in length by a number of researchers (Palmer, 2001; Riecken, 1995; Wang, 2013; Zieminska-Stolarska, 2012). Table 1 provides a list of some professional "*Water Quality Models*" with their special characteristics. These models are listed in three categories: (i) models applicable to assist transport of contaminants exclusively for catchment/watershed, (ii) models applicable for simulation of contaminants' transport in rivers/streams, and (iii) models applicable for contaminants transport modeling in rivers, lakes, estuaries and wetlands. A critical appraisal of each of these models based on the environment modelled, basic principle and process description, assumptions, data inputs and requirements, modeling capability, level of complexity, scale of their use, availability, degree of uncertainty, and their strengths and weaknesses, is presented here to help identify the "*most suitable water quality models*" for developing countries like India for sustaining the ever deteriorating water quality in the arena of urbanisation, industrialization, climate change, and to secure "Clean and Continuous Water Supplies" for ever-growing population.

According to Whitehead (1980), while critically appraising the water quality models, stated that an ideal model should qualify the following criteria:

(a) It should be a truly dynamic model capable of accepting time-varying inputs of the upstream water quality, which are used to compute time varying output responses downstream;
(b) It should provide a reasonable mathematical approximation of the physical, chemical and biological changes occurring in the river system and should be compared with real data collected from the river at a sufficiently high frequency and for a sufficiently long period of time;
(c) The model should be as simple as possible whilst retaining the ability to adequately characterize the important aspects of the system behaviour;
(d) It should be able to account for the inevitable errors associated with laboratory analysis and sampling, and account for the uncertainty associated with imprecise knowledge of the pertinent physical, chemical and biological mechanisms.

Table 5.2 summarizes a total of 27 water quality models, out of which 16 have been grouped into rivers, lakes, reservoirs, watershed and estuaries, wetlands category and 11 models specifically for river water quality modeling. If we critically examine Table 1 on the basis of modeling capability, processes involved and data requirement, then AQUATOX, DYRESM 1D, and MINLAKE models can be specifically used for lakes and reservoirs, and TSM, for lakes only. The AQUATOX is the simplest model and is available in free domain, and can simulate nutrients and organic chemicals, and their effects on the ecosystem, including fish, invertebrates, and aquatic plants, while DYRESEM 1D and MINLAKE are license based and hydro-dynamic in nature and could be classified as complex and intermediate complex models. Based on modeling capabilities, the AQUATOX can be preferred over MINLAKE and DYRESEM 1D models.

The models, such as BASINS, ECM, EUTROMOD and HSPF, are used for water quality modeling of watersheds, lakes and streams. In these models, the BASINS and HSPF models can be specifically used for NPS water quality modeling of watersheds and in-streams and lakes, respectively. The HSPF model is very data intensive, and can be explored for detailed water quality analysis of watersheds, lakes and streams.

The model simulates detailed watershed temperatures and concentrations of various water quality constituents in river (Gao and Li, 2014).The ECM and EUTROMOD models, though have comparatively lower data requirements, but have very limited applicability. The ECM model has been used in predicting the total amount of phosphorus and nitrogen (Bowes *et al.* 2008, European Commission 2003 a-c). The EUTROMOD model has limited applications in lake water quality modeling.

The models such as, CE-QUAL-W2, EFDC, COASTOX, and WASP7 can simulate simultaneously the water quality of rivers, lakes, reservoirs, wetlands, estuaries, and coastal ocean regions. The models like CE-QUAL-W2, EFDC and WASP has been widely used in water quality modeling worldwide (Gao and Li, 2014). WASP is one of the most widely used water quality models in the United States and throughout the world. Because of the models capabilities of handling multiple pollutant types, it has been widely applied in the development of Total Maximum Daily Loads (TMDL). However, the use of COASTOX model has been found limited in water quality modeling. MIKE 11 has been wildly used by researchers mainly for rivers and lakes. It operates on a number of timescales from single storm events to monthly water balance. A common problem with complex process models like MIKE 11 is the need of large amounts of data that may not be available in many situations, like in Indian conditions.

The WASP model can be combined with EUTRO and TOXI to simulate eutrophication, nutrient, metals, toxics, and sediment transport. The model has a user-friendly windows-based interface with a pre-processor; sub-model processors and a graphical postprocessor. WASP has capabilities of linking with hydrodynamic and watershed models, which allow for multi-year analysis under varying meteorological and environmental conditions. The outputs of WASP can be transferred to programs used for Geographical Information System (GIS) and water quality statistics. MIKE 11 model is an advanced model of flow and water-quality in stream and can simulate solute transport and transformation in complex river systems. Although a promising model, but its large data requirement, complex computational processes, long computational times and licensing put a limiting condition to MIKE11 for large scale uptakes

Table 5.2 A list of some Surface Water Quality Models with their special characteristics

Sl. No.	Model	Dimensions and State of Hydraulics	Pollutant type it can handle	Description	Year of Development & by whom	Open /license	Applicability	Reference
RIVERS, LAKES, RESERVOIRS, WATERSHED AND ESTUARIES WATER QUALITY SIMULATION MODELS								
1	**AQUATOX**	2-Dimensional, dynamic model	It predicts the fate of various pollutants, such as nutrients and organic chemicals, and their effects on the ecosystem, including fish, invertebrates, and aquatic plants.	AQUATOX is a PC based ecosystem model that predicts the fate of nutrients, sediments, and organic chemicals in water bodies, as well as their direct and indirect effects on the resident organisms.	Developed in year 2003 and latest release 3.1 was in year 2014 by the US-EPA	Open	Lakes and reservoirs.	Center for Exposure Assessment Models (CEAM), US-EPA.
2	**CE-QUAL-W2**	2-Dimensional(longitudinal-vertical)hydrodynamic	It can simulate eutrophication processes such as temperature-nutrient-algae-dissolved oxygen-organic matter and sediment relationships.	It considers longitudinal-vertical hydrodynamics and water quality in stratified and non-stratified systems, nutrients-dissolved oxygen-organic matter interactions, fish habitat, selective withdrawal from stratified reservoir outlets, hypolimneticaeration, multiple algae, epiphyton/ periphyton, zooplankton, macrophyte, CBOD, sediment diagenesis model and generic water quality groups.	Based on the algorithms developed by US Army Engineer Waterways Experiment Station (WES)in year 1975.	Open	Rivers, estuaries, lakes, reservoirs and river basin systems.	Water Quality Research Group of Portland State University, USA (http://www.ce.pdx.edu/w2/).
3	**EFDC** *(Environmental Fluid Dynamics Code)*	1D/2D/3D hydro-dynamic model for water and water quality constituent transport modeling	Salinity, temperature, suspended cohesive and non-cohesive sediment, dissolved and adsorbed contaminants, and a dye tracer.	It is a multifunctional surface water modeling system, which includes hydrodynamic, sediment-contaminant, and eutrophication components.	Developed by Dr. John M. Hamrick in year 1990 and subsequent support by the US-EPA.	Open	Rivers, lakes, reservoirs, wetlands, estuaries, and coastal ocean regions	Center for Exposure Assessment Models (CEAM), US-EPA
4	**HSCTM2D** *(Hydrodynamic, Sediment, and Contaminant Transport Model)*	2-D vertically-integrated, surface water flow sediment transport and contaminant transport.	Advection-dispersion of concentrations of suspended sediment dissolved and sorbed contaminants.	A finite element model. The modeling system consists of two modules, one for hydrodynamic modeling (HYDRO2D) and the other for sediment and contaminant transport modeling (CS2D). HYDRO2D solves the equations of motion and continuity for nodal depth-averaged horizontal velocity components and flow depths.CS2D solves the advection-dispersion equation for nodal vertically-integrated concentrations of suspended sediment, dissolved and sorbed contaminants, and bed surface elevations.	Developed by National Exposure Research Laboratory of the US-EPA in 1995.	Open	Riverine or estuarine hydrodynamics	Center for Exposure Assessment Models (CEAM), US-EPA

Sl. No.	Model	Dimensions and State of Hydraulics	Pollutant type it can handle	Description	Year of Development & by whom	Open /license	Applicability	Reference
5	**HSPF** (*Hydrological Simulation Program-Fortran)*	1-D stream channels and on watershed & basin scale.	It allows the integrated simulation of land and soil contaminant runoff processes with In-stream hydraulic and sediment-chemical interactions. It simulates water quality for both conventional and toxic organic pollutants.	HSPF incorporates watershed-scale ARM and NPS models into a basin-scale analysis framework that includes fate and transport in one dimensional stream channels.It simulates three sediment types (sand, silt, and clay) in addition to a single organic chemical and transformation products of that chemical.	Developed by the US EPA in year 1997	Open	Watersheds, Streams, and Lakes.	Center for Exposure Assessment Models (CEAM), US-EPA
6	**COASTOX**	2-D simulation of radionuclides in solute, suspended sediments and in bottom depositions of reservoirs, floodplains and coastal areas.	sediment transport, radionuclidetransports in shallow reservoir, ,lakes and coastal water	The model is used to analyze radionuclide dispersion in water bodies. It also calculates the dynamics of the bottom deposition contamination and describes the rate of sedimentation and resuspension.	Cybernetics Center, Kiev	-	Lakes, Reservoir & River	IAEA, Vienna
7	**WASP models** *(Water Quality Analysis Simulation Program)*	1D/2D/3D water quality simulation in rivers, lakes, estuaries, coastal wetland, and reservoirs.	Capable of handling multiple pollutant types including Total Maximum Daily Loads (TMDL).	WASP is a dynamic compartment-model for aquatic systems, including both water column and the underlying benthos. The time varying processes of advection, dispersion, point and diffuse mass loading and boundary exchange are represented in the model. It also can be linked with hydrodynamic and sediment transport models to provide flows, depths velocities, temperature, salinity and sediment fluxes. The latest release of WASP contains the inclusion of the sediment diagenesis model linked to the advanced Eutro-phication sub model to predict SOD and nutrient fluxes from the underlying sediments.	Developed originally by Di Toro *et al.*, in year 1983 and subsequently enhanced by Connolly and Winfield (1984); Ambrose, R.B. *et al.*, (1988)	Open	Rivers, Lakes, Estuaries, Coastal wetlands, and Reservoirs.	Center for Exposure Assessment Models (CEAM), US-EPA
8	**MIKE models** • MIKE 11 • MIKE 21 • MIKE31	1D/2D/3D unsteady	**MIKE 11 (1D):** DO, BOD, NO3, NH4, P, Coliform. MIKE 21 (2D): physical, chemical or biological processes in coastal or marine areas	**MIKE 11** simulates hydrology, hydraulics, water quality and sediment transport in estuaries, rivers, irrigation systems and other inland waters. **MIKE 21** simulates surface flow, waves, sediment transport and environmental processes and can be used for estuarine and coastal modeling. MIKE 31 for estuaries, coastal areas, and seas. It covers a wide range of	First developed in year 1995 and subsequently promoted by Denmark Hydrology Institute.	License	Rivers, Estuaries, and Tidal wetlands	DHI (https://www.dhigroup.com/)

Sl. No.	Model	Dimensions and State of Hydraulics	Pollutant type it can handle	Description	Year of Development & by whom	Open /license	Applicability	Reference
			MIKE 31 (3D): hydrodynamics, sediment dynamics, water quality and ecology.	hydrodynamic, environmental and sediment transport processes				
9	**DELFT3D**	3 D hydrodynamic Model	investigate hydrodynamics, sediment transport, morphology and water quality for fluvial, estuarine and coastal environments	The package consists of several modules coupled together to provide a complete picture of three-dimensional flow, surface waves, water quality, ecology, sediment transport and bottom morphology and is capable of handling the interaction between these processes.	Deltares	Open	Coastal waters, estuaries, rivers, lakes	Deltares (https://www.deltares.nl/en/)
10	**EUTROMOD** *(Eutrophication model)*	-	Nutrient loading, various trophic state concentration, and trihalomethane concentrations.	Watershed and lake modeling procedure for eutrophication management with emphasis on uncertainty.	Developed by Kenneth H. Reckhow in year 1992	License	Watershed& Lake.	North American Lake Management, Florida
11	**TSM** *(Lake Trophic Status Model)*	-	Mean Phosphorous concentration or values of other trophic status indicators, viz., chlorophyll a and Secchi depth.	It is based on empirical and semi-empirical equations. The model can include upto 15 tributary streams for study of a lake and upto 3 lakes upstream in each tributary.	Developed by Dillon and Rigler (1975)	Open	Lakes	Ontario Ministry of Environment, (1991).
12	**MINLAKE**	Dynamic 1 D model	Temperature, dissolved oxygen, phosphorus, Chlorophyl- a nitrogen and dissolved substances	Minlake model was developed to serve as a tool for evaluating lake management strategies. It include advective and diffusive transport, settling, chemical and biological kinetics.	Developed by Riley and Stefen (1987)	-	Lakes & Reservoirs	Riley and Stefen (1988)
13	**DYRESM 1D** *(Dynamic Reservoir simulation model)*	1D lagrangian hydro-dyamic model	Temperature, salinity and density in lakes and reservoirs	It provides a means of predicting seasonal and inter-annual variability of lakes and reservoirs as well as sensitivity testing to long-term changes in environmental factors or watershed properties	Center for Water Research, CWR, at the University of Western Australia	License	Lakes & Reservoir	Stolarska and Skrzypski (2012)
14	**ECM** *(Export Coefficient Model)*	-	Nutrient loading, Total N, Total-P	The ECM approach aims to predict the nutrient loading at any surface water sampling site as a function of export of nutrients from each contamination source in the catchment above that site. It relies on data from readily available databases. It is less data demanding model.	Developed in 1976 by J. M. Omernik of University of Reading, USA	Open	Watershed & River	Omernik, (1976)
15	**Dynamic River**		Simulates CBOD, DO,	Analyzes the impact of point source	Developed by US-	Computer		Yearsley, J.

Sl. No.	Model	Dimensions and State of Hydraulics	Pollutant type it can handle	Description	Year of Development & by whom	Open /license	Applicability	Reference
	Basin Water Quality Model	-	algal biomass, organic-N, NH_4-N, NO_2, NO_3, organic-P, orthophosphate, temperature, coliform bacteria, and two conservative constituents.	wastes from industries and municipalities, non-point sources and water diversion upon the aquatic ecosystems of freely-flowing rivers, river-run-reservoirs and stratified reservoirs.	Environmental Protection Agency (EPA) in year 1991.	Program is freely available.	Rivers & Reservoirs	(1991).
	CATCHMENT/WATERSHED WATER QUALITY MODEL							
16	**BASINS** *(Better Assessment Science Integrating point & Non-point Sources)*		BASINS assist in watershed management and TMDL estimation. It is a useful tool for watershed management, development of total maximum daily loads (TMDLs), coastal zone management, nonpoint source programs, water quality modeling,	BASINS is a multipurpose environmental analysis system model developed to help regional, state, and local agencies perform watershed- and water quality-based studies.	Developed by US-EPA	Open	Watershed	Center for Exposure Assessment Models (CEAM), US-EPA.
RIVER WATER QUALITY MODELS								
1	**CE-QUAL-RIV1**	1-D(longitudinal) Dynamic model	Temperature, DO, CBOD, Organic-N,NH_4-N, NO_3-N, Orthophosphate-P,Coliform bacteria, Dissolved Iron, Dissolved Mn, Algae and Macrophytes	Consists of two parts: a hydrodynamic (RIV1H) part, and water quality (RIV1Q) part. Model allows simulation in branched river systems with multiple hydraulic control structures and can simulate transient water quality conditions under unsteady state.	In year 1990 by US-Army Engineers Waterways Experiment Station.	Open	Rivers and Streams	Environmental Laboratory (1990)
2	**CHARIMA**	1-D fully mixed simulation model for unsteady mobile-bed hydrodynamics and contaminant transport modeling.	Mobile-bed sediment (bed load and/or suspended load) transport. Contaminant transport includes any number of conservative contaminants and heat.	CHARIMA model can simulate steady or unsteady water, sediment and contaminant transport in simple or complex systems of channels.	Iowa Institute of Hydraulic Research, University of Iowa, USA	Not available to outside users.	Rivers	Holly*et al.*, (1990)
3	**DSSAMT** *(Dynamic Stream and Simulation Model with Temperature)*	1-D Steady state river flow and 14 water quality constituents' model.	Water temperature, organic and inorganic fractions of nitrogen and phosphorous, BOD, DO, pH, alkalinity, CO_2, TDS, Chloride, blue green and non-blue-	The river processes the model considers include: equilibrium temperature and heat exchanges; advection, biochemical and physical kinetics of all 14 constituents including variation over 24-day; nutrient, spatial, and light limitation of benthic primary production; algal removal	Developed by Craig L. Caupp, James T. Brock, and Henry M. Runke from USA in year 1991.	The programme isavailable from Rapid Creek Research, Inc. Idaho, USA	Rivers	Rapid Creek Research, Inc. P.O. Box 2616;, Boise,Idaho, 83701-2616, USA.

Sl. No.	Model	Dimensions and State of Hydraulics	Pollutant type it can handle	Description	Year of Development & by whom	Open /license	Applicability	Reference
			green benthic algae, and coliform bacteria.	processes.				
4	**DRAINMOD**	-	Total N, salt	Developed to assist in the simulation of the transport of water and the transport and transformation of nitrogen in a stream. The most recent version of DRAINMOD PC version (released 6.1) has been extended to predict the movement of nitrogen (DRAINMOD-N) and salt (DRAINMOD-S) in shallow water table soils.	First developed in year 1980 and latest PC version in year 2012 by Soil & Water Management Group, North Carolina State University, USA	Open	Drain, Stream and Soil.	Skaggs, (1981)
5	**DUFLOW 1D**	1D unsteady flow for open watercourses.		A micro-computer package for the simulation of one-dimensional unsteady flow and water quality in open channel systems	International Institute for Hydraulic and Environmental Engineering (IHE) The Netherland,	A free student's version is available, which includes all options, but is restricted in the nurnber of channel sections and structures.	Open Channel, Rivers	IHE, TU Delft, Wageningen University and Stowa
6	**SIMCAT** *(Simulation of Catchments)*	1-Dimensional, deterministic, steady state.	Determines fate and transport of solutes in rivers from point sources, particularly DO, BOD, NO_3 and conservative substances.	It is a stochastic model and makes use of Monte Carlo analysis technique. The model helps in the process of planning the measures needed to improve water quality in a catchment. The model can account for 600 reaches and 1400 features such as discharges and abstractions. SIMCAT ver. 6.0 can be used for Integrated water quality modeling.	Developed by Scottish Environmental Protection Agency.	Open	River	Warn, A. E. (1987)
7	**STREAMDO-IV** *(Stream Dissolved Oxygen Model)*	1-Dimensional steady state model	DO and Unionized NH_4.	It is a spreadsheet based model for analyses of waste load in river reaches. It requires flow, velocity, slope, depth, temperature, DO, CBOD, organic nitrogen, ammonia, nitrite, nitrate, pH, and SOD as inputs.	Developed by US-EPA in 1990.	Open	River	Zander and Love, (1990)
8	**Streeter-Phelps (S-P) models**	1-Dimensionalsteady-state& Mechanistic	BOD and DO	S-P models focus on oxygen balance and 1st order decay of BOD.	First established by Streeter-Phelpsin year 1925, thereafter modified by O'Connor, Dobbins-Camp	Open	River	Streeter and Phelps (1925)
9	**TOMCAT**	1-Dimensional	DO, NH_4, BOD	The model uses Monte Carlo analysis technique to review the effluent quality	Developed in year 1984	-	River	Bowden and

Sl. No.	Model	Dimensions and State of Hydraulics	Pollutant type it can handle	Description	Year of Development & by whom	Open /license	Applicability	Reference
	(Temporal/Overall Model for Catchment)	steady state (time invariant)		standards at sampling sites to meet the objectives of surface water quality preservation. The model allows complex temporal correlations taking into account the seasonal and diurnal effects in the flow data and the recorded water quality and reproduces these effects in the simulated data. TOMCAT calculates quality and flow in each reach by solving the process equations.	by Bowden and Brown,			Brown, (1984)
10	**QUAL models** • **QUAL I** • **QUAL II** • **QUAL2E** • **QUAL2E-UNCAS** • **QUAL 2K** • **QUAL2Kw**	1-Dimensional steady-state or dynamic model	It can simulate 15 water quality constituents in a branching stream system, viz. Total-N, Total-P, BOD, DO,NH_4 –N, NO_2-N, NO_3-N, SOD, algae, pH, periphyton pathogen.	The model uses finite difference solution of the advective-dispersive mass transport and reaction equations. The model simulates changes in flow conditions along the stream by computing a series of steady-state water surface profiles and the calculated stream-flow rate, velocity, cross-sectional area, and water depth serve as a basis for determining the heat and mass fluxes into and out of each computational element due to flow. QUAL2E uses chlorophyll a as the indicator of planktonic algae biomass. QUAL2E-UNCAS includes uncertainty analysis of using Monte Carlo simulation (MCS) of constituents.	QUAL I was developed by the Texas Water Development Board in year 1960.Thereafter, several improved versions of the model were developed by US-EPA. Last release was Jan., 2009.	Open	River	CEAM of US-EPA
11	**QUASAR model**	1-Dimensional dynamic model.	Simulates 8 variables in additional to flow; NO_3, ionized and unionized NH_4, DO, BOD, pH, temperature and any conservative or inert material in solution.	The river system is modelled by a series of reaches. The model performs a mass balance of flow and quality of each reach taking into account inputs from previous reach, tributaries, effluent discharges and abstractions.	Developed by the Institute of Hydrology, UK in year 1997.	Open	Large river	Center for Ecology and Hydrology,UK (http://www.ceh.ac.uk/services/pc-quasar)

The models like, HSCTM2D, DELFT3D and Dynamic River Basin have found their limited applications in water quality modeling. The Dynamic River Basin water quality model is available free of cost from their developers and can further be explored as it has capability to simulate a number of water quality parameters.

The listed 11 water quality models (Table 5.2) developed specifically for river water quality modeling also showed a mixed acceptability. The CHARIMA model, which is license based, has not been widely used outside USA. Similarly, the DSSAMT model, though capable of simulating most of the water quality conditions in a river system where polluting substances enter the modelled reach from a variety of sources, including tributaries, point effluent discharges, surface water point and non-point runoff, groundwater, leaching and scouring from the bottom sediments, however has find limited applications. The DRAINMOD, DUFLOW 1D and STREAMDO-IV models have their limited applicability with limiting modeling capabilities. The models like CE-QUAL-RIV1, SIMCAT, TOMCAT, Streeter-Phelps (S-P) models, QUAL series models (i.e., QUAL I, QUAL II, QUAL2E, QUAL2E- UNCAS, QUAL 2K) and QUASAR model have been widely used for water quality modeling. Cox (2003), Jha et al. (2007), Gao and Li (2014), Kannel et al. (2011) discussed the modeling capabilities and limitations of some of these models. The most used models by the UK Environment Agency are SIMCAT and TOMCAT, however, they rarely appeared in the literature (Jamieson and Fedra, 1996), because they are not generally used for regulation outside of the UK and this is probably due to their stochastic component as well as a lack of commercial exposure.

Majority of water quality professionals refer to the United States Environmental Protection Agency (USEPA) model QUAL2E, with reported applications in the Americas, Europe, Asia and Australasia (Cox, 2003). The QUAL2E model is probably the most widely-used water-quality model in the world and although it is unable to handle temporal variability in a river system. The QUAL2E was first released in 1985 and the USEPA has used and improved this model extensively since then. More recently, the model has been integrated with other USEPA models such as, HSPF and WASP in a GIS (Geographical Information System) environment in software called BASINS. Thus, QUAL series of the models is more comprehensive and has worldwide acceptability and applicability than the other models. The QUAL2E is a much more complex model than SIMCAT and TOMCAT models. QUAL2E is the latest version of QUAL-II and has been wildly used in water quality prediction and pollution management (Gao and Li, 2014). Zhang et al. (2012) showed that QUAL2K is an effective tool for the comparative evaluation of potential water quality improvement programs through simulating the effects of a range of water quality improvement scenarios. The main advantage of QUAL2K is the capability of simulation of algae (Chlorophyll-a), an extensive documentation of its code and theoretical background. An extension of the QUAL2E model called QUAL2E–UNCAS allows the user to perform uncertainty analyses by investigating model sensitivity to changes in one variable at a time (sensitivity analysis) or all of the variables at once (first-order error analysis) or by using Monte Carlo techniques. The QUASAR is well suited to investigating lowland river systems. Sharma and Kansal (2013) found that the models namely, QUAL2Kw, WASP and AQUATOX are capable of simulating maximum number of parameters. AQUATOX, QUAL2Kw and WASP include the sediment diagnosis model for re-mineralization. QUAL2Kw can also simulate SOD and hyporheic metabolism, which are vital for predicting river water quality and for planning the management options. As observed, WASP model has an advantage of simulating toxicants as well. Therefore, looking into the overall applicability and simplicity of the models, and their availability, the following models are finally short-listed (Table 5.3) for direct applications or their inter-coupling and interfacing to provide most sustainable solution to water quality assessment and management problems.

5.8 Ways Forward

Surface water quality management is a critical component of overall integrated water resources management. Water quality modeling as a powerful tool can give answers to a large number of management questions related to prospective social, economic, environmental, technical and political issues of future scenarios based on past and present conditions. Decisive use of water quality modeling in India as a tool for policy evaluation & decision, water quality management, risk assessment, and water quality conservation is yet to pick up momentum in India. Some of the reasons behind this are; (i) inadequate spatio-temporal water quality data to conceive, calibrate and validate a model, (ii) lack of information/data on source of pollution and their magnitude and characteristics, (iii) inadequate data and understanding on water quality hydrodynamics and kinetics to describe the physical behaviour of the water systems, etc. Growing concern on drinking water security, emerging threat to ecosystem and environmental imbalances, and climate change impacts on water quality together with population pressure for safe and sustainable water quality, pose major challenges to maintaining sustainability in water quality management. Organized surface water quality monitoring networks together with increased frequency of monitoring can help build good databases for adoption of large-scale water quality modeling approach in policy planning, evaluation and decision, management of river and other surface water quality conservation and management, etc. of India. Generation of good water quality databases including contaminant kinetics is one of the primary requirements; on the other hand, systematic and continual capacity building on water quality modeling is another important pursuit the nation should adopt for resolving water crisis emerging from water quality threat. The report has brought out a comprehensive list of surface water quality models developed and successfully adopted for solving different environmental and water quality problems world over. Some of those models are generic, process based, less data driven and have proven effective and capable to simulate conditions prevalent in India. It is, therefore, desirable that the potential of adopting some of those models, which have open access, be studied in detailed with the understanding of India's water system's hydro-physicochemical & biological conditions, instead of developing per se new version of surface water quality models. The pursuit should also be focused towards integrating the modules developed based on the study of India's hydro-physicochemical & biological conditions, with the existing models. Amongst the potential water quality models, HSPF for watershed, streams, and lakes; WASP 7 for rivers, lakes, estuaries, coastal wetlands, and reservoirs; and QUAL series for rivers and streams, developed and promoted by US-EPA (all have open access) are found most promising for detailed study, and recommended for inclusion as an integral part of the comprehensive hydrologic model that the Institute is focusing under the National Hydrology Project.

Table 5.3 Selected Water Quality Models based on their Applicability, Modeling Capability, Availability and Processes Involved

Models		**AQUATOX**	**HSPF**	**CE-QUAL-W2**	**WASP7**	**EFDC**	**QUAL Series**		**MIKE Series**
							QUAL2E-UNCAS	**QUAL 2KW**	
Types (Dimension and State of Hydraulics)	1D	**N**	**Y**	**N**	**Y**	**Y**	**1D**	**Y**	**Y**
	2D	**Y**	**N**	**Y**	**Y**	**Y**	**N**	**N**	**Y**
	3D	**N**	**N**	**N**	**Y**	**Y**	**N**	**N**	**Y**
	Steady state	**Y**	**N**	**N**	**N**	**N**	**Y**	**Y**	**N**
	Dynamic	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**
	Stochastic	**Y**	**N**	**N**	**N**	**N**	**N**	**N**	**N**
Modeling Approach	ADE	**N**	**N**	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**
	CSTRS	**Y**	**Y**	**N**	**N**	**N**	**N**	**N**	**N**
Modeling capability	Temp., Bacteria, DO-BOD, Nitrogen Phosphorous Silicon Phytoplankton Zooplankton Benthic algae SOD, COD CBOD Sediment, etc)	pH, DO nutrients, NH4 toxicity, detritus, Phytoplanton, Periphyton, Zooplankton, sediment digenesis, fish, invertebrates, and aquatic plants	pH, NH4, DO, BOD, temp., pesticides,conservatives, fecal coliforms,sediment detachment and transport, nitrite-nitrate, organic nitrogen, orthophosphate, organic Phosphorous, phytoplankton, and zooplankton.	Nutrients, DO, organic matter interactions, fish habitat, multiple algae, epiphyton/periphyton, zooplankton, macrophyte, CBOD, TOC, sediment diagenesis, and generic water quality groups	DO, temp, N (ON, NO2, NO3 NH3), P (OP, PO4), coliform, salinity, SOD, CBOD, bottom algae, silica, pesticides, OCHEM	Salinity, temp.,suspended cohesive and non-cohesive sediment, dissolved and adsorbed contaminants, and dye tracer	Temp., Chlorophyll-*a* Bacteria, DO-BOD, N, P, Silicon, Phytoplankton Zooplankton Benthic algae, uncertainity analysis	Temp, pH, N (ON, NO2, NO3 NH3), P (OP, PO4), DO, CBOD, TIC, alkalinity, phytoplankton, bottom-algae, SOD, detritus, pathogen	Temp. Bacteria DO-BOD Nitrogen Phosphorus Silicon Phytoplankton Zooplankton Benthic algae
Availability (Open /license)		Open	Open	Open	Open	Open	Open	Open	License
Applicability		Lakes and reservoirs	Watersheds, Streams, and Lakes	rivers, estuaries, lakes, reservoirs and river basin system	Rivers, Lakes, Estuaries, Coastal wetlands, and Reservoirs	Rivers, lakes, reservoirs, wetlands, estuaries, coastal ocean regions	Rivers and streams	Rivers and streams	Rivers, Estuaries, and Tidal wetlands
Source/Reference		Center for Exposure Assessment Models (CEAM), US-EPA.		Water Quality Research Group of Portland State University, USA.	Center for Exposure Assessment Models (CEAM), US-EPA.		Center for Exposure Assessment Models (CEAM), US-EPA		DHI

References

1. Asai, K., Fujisaki, K., and Awaya, Y. (1991). Effect of aspect ratio on longitudinal dispersion coefficient. In Environmental Hydraulics, Lee and Cheung (Ed.), Vol. 2, Balkema, Rotterdam, The Netherlands, pp. 493-498.
2. Bashitialshaaer, R., Bengtsson, L., Larson, M., Persson, K.M., Aljaradin, M., and Hossam, I. A. (2011). Sinuosity effects on Longitudinal Dispersion Coefficient, Int. J. of Sustainable Water and Environmental Systems, 2(2), pp. 77-84
3. Bath, A. J., Gorgens, A. H. M., Smidt, K. O. D., and Larsen, E. J. (1997). The applicability of hydrodynamic reservoir models for water quality management of stratified water bodies in South Africa: application of dyresm and ce-qual-w2. Water Research Commission. http://www.wrc.org.za/lists/knowledge%20hub%20items/attachments/7269/304-2-97. Accessed 17 Sep 2012.
4. Beer, T., and P.C.Young, (1983). Longitudinal dispersion in natural streams. Jour. Environ. Eng. Div., Am. Soc. Civil Engrs., 109(5), 1049-67.
5. Beltaos, S. (1978). An interpretation of longitudinal dispersion data in rivers. Report no. SER 78-3, Transportation and surface water div., Alberta Research Council, Edmonton, Canada.
6. Bowden, K, and Brown, S.R. (1984). Relating effluent control parameters to river quality objectives using a generalised catchment simulation model. Water Sci Technol., Vol. 16, pp. 197 – 205.
7. Bowes, M.J., Smith, J.T., Jarvie, H.P., Neal, C. (2008). Modeling of phosphorus inputs to rivers from diffuse and point sources. Sci Total Environ 395:125-138.
8. Burn, Donald H. (1989). Water Quality Management through Combined Simulation-Optimization Approach. J. Environ. Eng., ASCE, 115(5):1011-1024.
9. Chapra, S. C. (1997). Surface water quality modeling. Waveland Press Inc., USA.
10. Chatwin, P.C. (1971). On the interpretation of some longitudinal dispersion experiments. Jour. Fluid Mech., 48, 689-702.
11. Cox, B. A. (2003). A review of currently available in-stream water-quality models and their applicability for simulating dissolved oxygen in lowland rivers. The Science of the Total Environment 314 –316, pp. 335–377.
12. CPCB (Central Pollution Control Board), (2009). Status of Water Supply, Wastewater Generation and Treatment in Class-I Cities & Class-II Towns of India. Control of Urban Pollution, Series: CUPS/70/2009-10. 88p.
13. CPCB, (2011). Status of Water Quality in India-2010. Monitoring of Indian National Aquatic Resources, Series: MINARS/2010-11, 26p.
14. CPCB, (2013a). Status of Water Quality in India-2011. Monitoring of Indian National Aquatic Resources, Series: MINARS/2013-14, 191p.
15. CPCB, (2013b). Status of Water Quality in India-2012. Monitoring of Indian National Aquatic Resources, Series: MINARS/36/2013-14, 237p.
16. Cuthbert, J. D., and J. Kalff, (1993). Empirical models for estimating the concentrations and exports of models in rural rivers and streams. Water, Air, and Soil Pollution, 71:205-230.
17. Elder, J.W., (1959). The dispersion of marked fluid in turbulent shear flow.Jour. Fluid Mech., 5(4), 544-60.
18. European Commission (2003a). Common Implementation Strategy for the Water Framework Directive. Guidance Document No. 2, Identification of Water Bodies. The Directorate General Environment of the European Commission, Brussels.
19. European Commission (2003b). Common Implementation Strategy for the Water Framework Directive. Guidance Document No. 3, Analysis of Pressures and Impacts. The Directorate General Environment of the European Commission, Brussels.
20. European Commission (2003c). Common Implementation Strategy for the Water Framework Directive. Guidance Document No. 7, Monitoring under the Water Framework Directive. The Directorate General Environment of the European Commission, Brussels.

21. Fischer, H. B., Imberger, J., List, E. J., Koh, R.C.Y. and Brooks, N.H. (1979). Mixing in inland and coastal waters.483 p., Academic press, New York.
22. Fischer, H. B., (1966). A note on the one-dimensional dispersion model. Int. Jour. Air. wat.pollut., 10, 443-52.
23. Imhoff,J.C. (2003). Recent comparison studies to assist in selection of advanced modeling tools for TMDL development. http://www.hspf.com/pdf/chicagowef-jci.pdf Accessed 24 Jan 2013.
24. Fitzpatrick J, Imhoff J, Burgess E, Brashear R (2001). Final report water quality models: a survey and assessment (No. Project 99-wsm-5). Water Environment Research Foundation.
25. Fukuoka, S., and Sayre, W. W. (1973). ‘‘Longitudinal dispersion in sinuous channels.’’ J. Hydr. Div., ASCE, 99(1), 195–217.
26. Gao, L., and Li, D. (2014).A review of hydrological/water-quality models. Front. Agr. Sci. Eng., Vol. 1(4), pp. 267–276, DOI: 10.15302/J-FASE-2014041
27. Ghosh, N. C., (2001). Study of solute transport in a river. Ph. D. Thesis. Civil Engineering Department, I.I.T. Roorkee, Roorkee
28. Ghosh, N.C., G.C. Mishra, and C.S.P. Ojha, (2004). A hybrid-cells-in-series model for solute transport in river,Jour. Env.Engg.,ASCE, Vol. 124 (10), pp. 1198-1209.
29. Gowda, T. P. H., (1980). Stream tume model for water prediction in mixing zones of shallow river. Water Resources paper no. 14. Toronto: Water Resources Branch, Ontario Ministry of the Environment.
30. Holly, F. M., Jr., Yang, J. C., Schwarz, P., Schaefer, J., Hsu, S. H., and Einhellig, R., (1990). CHARIMA: Numerical simulation of unsteady water and sediment movement in multiply connected networks of mobile-bed channels. Iowa Institute of Hydraulic Research Report No. 343, The University of Iowa.
31. Jain, S. C., (1976), Longitudinal dispersion coefficients for streams. Jour. Envron. Engg. Div., Proc. Am. Soc. Civil Engrs., 102(2), 465-74.
32. Jha, R., Ojha, C. S. P., & Bhatia, K.K.S. (2007). Critical appraisal of BOD and DO models applied to a highly polluted river in India. Hydrological Sciences–Journal–des Sciences Hydrologiques, 52(2), pp. 362-375.
33. Jamieson, D. G., Fedra, K. (1996). The WaterWare decision-support system for river-basin planning. 2: Planning capability. J. Hydrol., Vol. 177, pp. 177:177.
34. Kannel, P. R., Kanel, S. R., Lee, S., Lee, Y. S., Gan, T. Y., (2011). A review of public
35. domain water quality models for simulating dissolved oxygen in rivers and streams. Environmental Modeling and Assessment, Vol. 16(2), pp.183–204.
36. Kezhong, H., and Yu, H. (2000). A New Empirical Equation of Longitudinal Dispersion Co-efficient. Stochastic Hydraulics 2000, Wang and Hu (Eds), Balkema, Rotterdam.
37. Koussis, A. D., and Rodriguez-Mirasol, J. (1998). Hydraulic estimation of dispersion coefficient for streams. J. of Hyraul. Engg., ASCE, 124 (3), 317-320.
38. Lau, Y. L., (1990). Modeling the consumption of dissolved contaminants by biofilm periphyton in open-channel flow. Water Research, 24(10):1269-1274.
39. Li, Y., Huang, G., Huang, Y., and Qin, X., (2014). Modeling of Water Quality, Quantity, and Sustainability. Journal of Applied Mathematics, Article ID 135905, 3 p. http://dx.doi.org/10.1155/2014/135905.
40. Lin, L., Wu, J.L., Wang, S.M., (2006). Evidence from isotopic geochemistry as an indicator of eutrophication of Meiliang Bay in Lake Taihu, China. Science in China Series D-Earth Sciences. 49(s1):62–71. doi: 10.1007/s11430-006-8106-8.
41. Liu, H., (1977). Predicting dispersion co-efficient of streams.Jour. Environ. Eng. Div., Am. Soc. Civil Engrs., 103(1), 59-67.
42. Lund, J.R. and Palmer, R.N. (1997). Water Resource System Modeling for Conflict Resolution," Water Resources Update, Issue No. 108, Summer, pp. 70-82.
43. Madani, K. & Mariño, M. A. (2009). System dynamics analysis for managing Iran’s Zayandeh-Rud river basin. Water Resour Manage, 23(11), 2163-2187, doi: 10.1007/s11269-008-9376-z.
44. Magazine, M.K., (1983), Effect of bed and side roughness on dispersion and diffusion in open channels.Ph. D. thesis, University of Roorkee, Roorkee, India.

45. Marivoet, J. L., and Craenenbroeck, W. V. (1986). Longitudinal dispersion in ship canals. J. of Hydraul. Res., 24 (2), 123-133.
46. Martin, James L. And Steven C. McCutcheon, (1999). Hydrodynamics and Transport for Water Quality Modeling. CRC Press, Inc., Lewis Publishers, Washington Dc., 192p.
47. McCutcheon, S.C. (1989). Water quality modeling (ed. Richard H. French), Volume I: Transport and Surface Exchange in Rivers. CRC Press, Inc.ISBN-0-8493-6971-I. 150 p.
48. McQuivey, R.S., and Keefer, T.N. (1974). Simple method for predictingdispersion in streams. Jour. Env. Eng. Div., Am. Soc. Civil Engrs., 100, 159-71.
49. Murty, M. N., and Surender Kumar, (2011). Water Pollution in India- An Economic Appraisal. India Infrastructure Report. Pp 285-298.
50. Muthukrishnavellaisamy, K., (2007). A study on pollutant transport in a stream. Ph. D. Thesis. Department of Water Resources Development & Management, IIT Roorkee, Roorkee.
51. Ogata, A, and Banks, R. B. (1961). "A solution of the differential equation of longitudinal dispersion in porous media." Profl. Paper No. 411- A, U.S. Geological Survey, Washington, D.C.
52. Omernik, J.M. (1976) The Influence of Land Use on Stream Nutrient Levels. USEPA Ecological Research Series, EPA-60013-76-014. US Environmental Protection Agency, Corvallis, OR.
53. Palmer, M. D. (2001). Water quality modeling: a guide to effective practice. Washington, D.C., World Bank.
54. Ranga Raju, K. G., Kothyari, U. C., and Ahmad, Z. (1997). Dispersion of conservative pollutant. Dept. of Civil Engg. Univ. of Roorkee, Roorkee, India.
55. Riecken, S. (1995). A compendium of water quality models. Water Quality Branch, Environmental Protection Department, Ministry of Environment, Lands and Parks, Canada.
56. Riley, M.J.,and Stefan, H.G. (1988) Development of the Minnesota Lake Water Quality Management Model "MINLAKE", Lake and Reservoir Management, 4:2, 73-83, DOI: 10.1080/07438148809354815
57. Seo, I. W., and Cheong, T. S. (1998). Predicting Longitudinal Dispersion Co-efficient in Natural Streams. J. of Hydraul. Eng., Am. Soc. Civ. Eng., 124(1), pp. 25-32.
58. Sharma, D., and Kansal, A. (2013). Assessment of river quality models: a review. Rev Environ Sci Biotechnol., Vol. 12, pp. 285-311. DOI 10.1007/s11157-012-9285-8
59. Skaggs, R. W. (1980). DRAINMOD reference report. Fort Worth, Tex.: USDA-SCS South National Technical Center. Available at: www.bae.ncsu.edu/soil_water/documents/drainmod/chapter1.pdf.
60. Stefan Heinz G., and Demetracopoulos, (1981). Cells in series simulation of riverine transport. Jour. Hydr. Div.,Am. Soc. Civil Engrs., 107(6), 675-97.
61. Stolarska, A. Z., and Skrzypski, J. (2012).Review of mathematical models of water quality. Ecol chem. engs. Vol. 19(2):197-211.
62. Streeter, H. W., and E. B. Phelps, (1925). A study of the pollution and natural purification of the Ohio River III. Factors concerned in the phenomena of oxidation and reaeration, U. S. Public Health Service, Bulletin No. 146.
63. Sumer, M., (1969). On the longitudinal dispersion coefficient for a broad open channel. Jour. of Hydraul. Res.., 7(1), pp. 129-135.
64. Taylor, G.I., (1921), Diffusion by continuous movements.Proc. London Math. Soc. Ser.,A 20, 196-211.
65. Taylor, G.I., (1954), The dispersion of matter in turbulent flow through a pipe. Proc. R. Soc. London ser., A, 219, 446-68.
66. Thackston, E.L., and P. A. Krenkel, (1967), Longitudinal mixing in natural streams. Jour. Sant. Engrs. Div., Am. Soc. Civil Engrs., 93, 67-90.
67. Tsakiris, G., and Alexakis, D. (2012).Water quality models: An overview, European Water, Vol.37, pp. 33-46.
68. Tsanis, I. K., andJ. Wu, (1994). LMS-an integrated lake modeling system. Environ. Software. Vol. 9, pp 103-113.
69. UL, (2015). Pharmaceuticals and Personal Care Products in Drinking Water. P9. http//:www.library.ul.com/2015.../UL_WP_Final_Pharmaceuticals-and-...
70. UN-Water, (2011). Policy Brief – Water Quality, UNEP, 19p.

71. U.S. EPA (U.S. Environmental Protection Agency). 1988. Quality criteria for water. EPA 440/5-86-001. USEPA, Of- fice of Water Regulations and Standards. U.S. Government Printing Office (PB81-226759), Washington, D.C., USA.
72. Valentine, E.M., andI. R. Wood, (1979), Dispersion in rough rectangular channels. Jour. Hydr. Div., Am. Soc. of Civil Engineers, 105(9), 1537-53.
73. Vanrolleghem, P.A., Schilling, W., Rauch, W., Krebs, P. and Aalderink, H. (1999). Setting up measuring campaigns for integrated wastewater modeling. Water Science & Technology, 39: 257-268.
74. Wang, Q., Shibei, Li, Peng, Jia, Changjun, Qi, and Feng, D. (2013). A Review of Surface Water Quality Models. The Scientific World Journal, ID 231768, pp. 1-7; http://dx.doi.org/10.1155/2013/231768
75. Warn, A. E. (1987). SIMCAT—a catchment simulation model for planning investment for river quality (pp. 211–218). Oxford: IAWPRC, Pergamon.
76. Whitehead, P.G., and T. Lack, (1982). Dispersion and self-purification of pollutants in surface water systems- A contribution to the International Hydrological Programme, UNESCO, 98p.
77. Whitehead, P. G. (1980). Water quality modeling for design. Proceedings of the Helsinki Symposium, June 1980. IAHA Publication No. 130; 1980. p. 465–475.
78. WHO, (2011). Pharmaceuticals in Drinking-water. Report no.: WHO/HSE/WSH/11.05, 35p.
79. Yearsley, J. (1991). A Dynamic River Basin Water Quality Model. EPA 910/9-91-019.
80. Yotsukura, N., andH.B. Fiering, (1964), Numerical solution to a dispersion equation.Jour. Hydr. Div. Am. Soc. Civil Engrs., 90(5), 83-104.
81. Zander, B. and Love, J. (1990). STREAMDO IV and supplemental ammonia toxicity model. water Management Division USEPA, Region VIII, Denver, Colorado, Unpublished Typescript.
82. Zhang, R., Qian X, Li H, Yuan, X., Ye, R. (2012).Selection of optimal river water quality improvement programs using QUAL2K: a case study of Taihu Lake Basin, China. Science of the Total Environment, Vol, 431, pp. 278–285.
83. Zheng, C., and B. Gordon. (1995). Applied Contaminant Transport Modeling. Van Nostrand Reinhold, New York.
84. Zhen-Gang, J., (2008). Hydrodynamic and water Quality-Modeling rivers, lakes and estuaries. Wiley Interscience. John Wiley & Sons, Inc. Publication. Hoboken, New Jersey. 676p.

- Water Quality Research Group of Portland State University, USA (http://www.ce.pdx.edu/w2/)).
- DHI (https://www.dhigroup.com/)
- Deltares (https://www.deltares.nl/en/)
- North American Lake Management, Florida
- Ontario Ministry ofEnvironment, (1991).
- Center for Exposure Assessment Models (CEAM), US-EPA
- Rapid Creek Research, Inc. P.O. Box 2616; Boise,Idaho, 83701-2616, USA
- IHE, TU Delft, Wageningen University and Stowa
- Center for Ecology and Hydrology, UK (http://www.ceh.ac.uk/services/pc-quasar)

CHAPTER 6

WATER RESOURCES SYSTEMS MODELING – STATUS AND FUTURE DIRECTIONS

6.1 Introduction

Comprehensive and rational water management is necessary for social and economic development, particularly in the countries where water resources are limited. Water resources management involves rational use of scarce water and allied resources. Optimal solution of problems involving competitive water demands needs systems approach as a methodological way that takes all the internal and external relationships into account and utilizes new theories of systems and modern computer hardware and software (Votruba1988).

The purpose of this report is to briefly review available software for analysis of water resources systems. This review would help in selection of software to solve the problems Indian systems and to initiate further R&D works. The present report is not intended to be a state-of-the-art report on water resources systems analysis and modeling. Relevant information about the models was obtained from user manuals, published applications, and internet. We have not ourselves applied all the listed models. In case the reader wants more information, he/she is advised to refer to the original model documentation.

6.2 What is a Water Resources System?

A "**water resources system**" (WRS) can be expressed as a set of components associated by interrelationships into a purposeful whole. The elements of the system can be either natural (precipitation, watercourses, ground water, lakes etc.) or artificial (water management facilities, barrages, reservoirs, weirs, channels, hydroelectric power plants, etc.). The interrelationships between the elements are either real (e. g., water diversion) or conceptual (e. g., organization, information). Water Resources Systems are "**open systems**", i.e., their elements allow some relation with the environment of the system (Votruba 1988). If the link between some elements within the system is relatively closer than that between other elements, a relatively independent whole exists inside the system which is called the ***subsystem.***

6.2.1 Classification

WRSs can be categorized on the basis of the objectives: water supply systems, hydroelectric power plant systems, irrigation and drainage systems, flood control systems, etc. A WRS can also be classified as a single purpose or multipurpose system:

Single purpose system serves only a single purpose, e.g., a flood control system, a hydroelectric power generation system, etc.

Multi-purpose system is operated to satisfy a number of purposes, such as irrigation water supply, flood control. Since finances and other resources are limited, it is often helpful to build multipurpose projects.

6.2.2 Approaches for WRS modeling

We discuss here the techniques that are commonly used to analyze WRSs. A classification of the techniques that are most commonly used to solve various problems related to management of WRSs is illustrated in Fig.6.1.

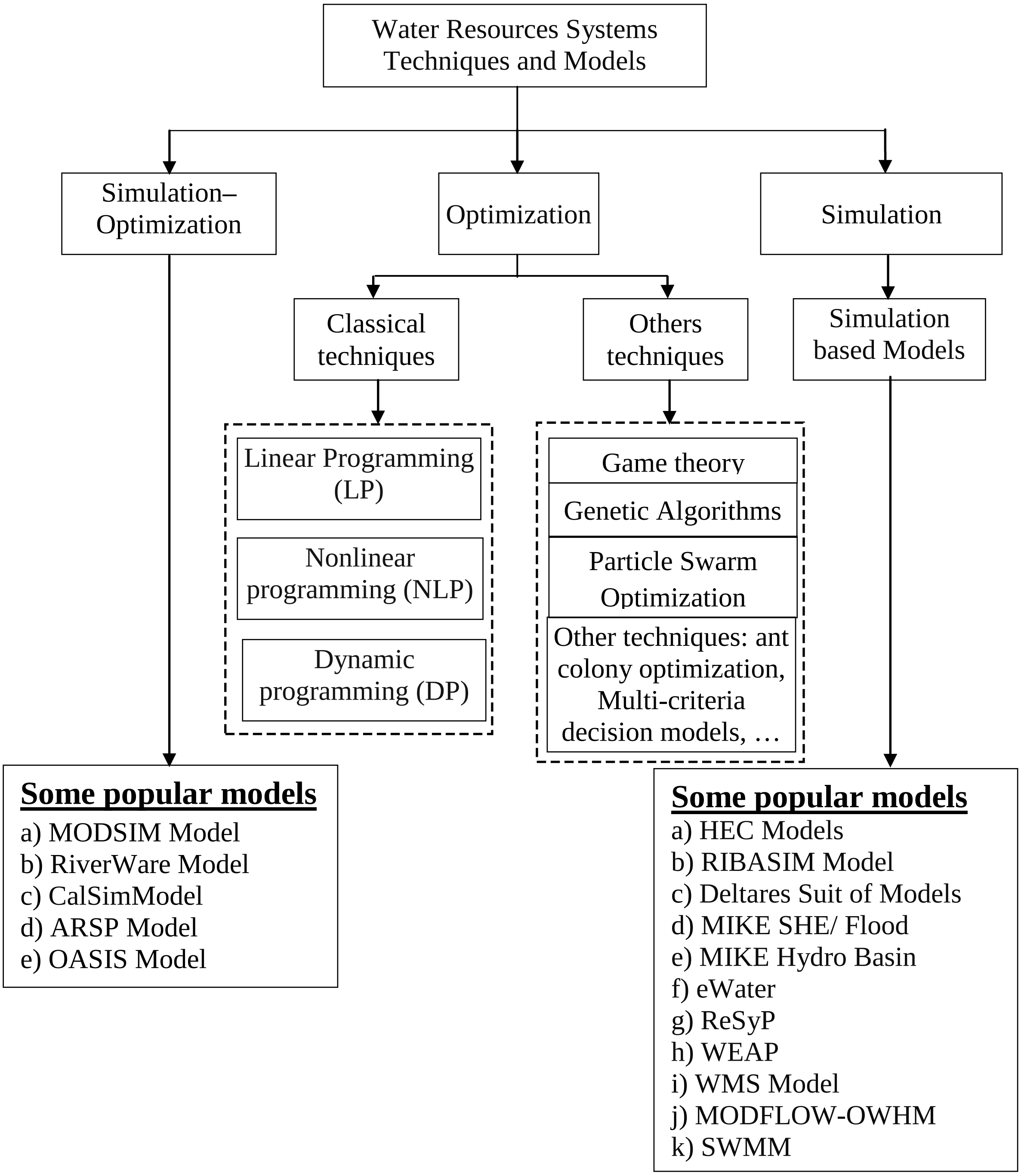


Figure 6.1: Classification of WRS models

6.3 Simulation

Normally, the structure or behavior of the system being studied is so complex that its analytical solution is not possible. Simulation is the process of duplicating the behavior of an existing or proposed system. It consists of designing a model of the system and conducting experiments with this model either for better understanding of the functioning of the system or for evaluating various strategies for its management.

The essence of simulation is to reproduce the behavior of the system in every important aspect to learn how the system will respond to conditions that may be imposed on it or may occur in the future. The main advantage of simulation models lies in their capacity to accurately describe the reality. The proposed configurations of projects can be assessed to judge whether their performance would be adequate or not before investments are made. Likewise, operating policies can be tested before they are implemented in actual situations.

A simulation model of a water resource system simulates its operation with a defined operation policy, using the parameters of physical and control structures, time series of flows, demands, and the variables describing water quality, etc. The evaluation of the design parameters or operation policy is through the objective function (flow or demand related measures or economic indices) or some measure of reliability. Since simulation models do not use an explicit analytical procedure to determine the best combination of the controlling variables, it is necessary to proceed by trial and error or follow a strategy of parameter sampling (Jain and Singh 2003).

Simulation models may be categorized as: a) physical (a scale model of a spillway operated in a hydraulics laboratory), b) analog (a system of electrical components, resistors and capacitors, arranged to act as analog of pipe resistances and storage elements), c) mathematical (a compilation of equations and logical statements that represent the actions of a system's elements). Mathematical simulation models are very useful and popular in the field of water resources.

Simulation models can also be classified as static or dynamic. Dynamic models take into account the changing parameters of the system (structures and facilities) and the variations in their operation. These are assumed as fixed in static models. The development and application of dynamic models is a more involved exercise and often static models give acceptable results.

Many hydrological variables are stochastic in character. Deterministic and stochastic simulation models are distinguished by the way this stochasticity is accounted for. A time-series of gauged flows represents a sample of the stochastic process. Under certain conditions, deterministic simulation models can be used with confidence. For example, if measured monthly flows for a period of 40 years are used as input in simulation and the system has not undergone large changes, a deterministic model may be adequate. If the process is stationary, the sample can be considered a reasonably good characterization of the stochastic process. But a number of model's results with synthetically generated sequences of inflows give a very good indication of the expected system performance.

Simplification in system representation can also be achieved by neglecting variables that do not impart a decisive impact on the system behavior. If the output is not sensitive to the variation of certain variables, these can be considered as constants.

The modeling of a continuous process by a discrete model involves the assumption that the continuous changes during a defined period take place instantly at the end or at the beginning of the period. The decision-making process in water resource systems is discrete; simulation models are also discrete models. The real-life process, however, is continuous. Therefore, the time step size is an important aspect of the model and should be chosen carefully. This choice depends on the degree of aggregation and the time variability of inputs.

Event scanning and periodic scanning are two common ways of time management in simulation models. In the event scan approach, the clock is advanced by the amount necessary to trigger the occurrence of the next, most imminent event, not by some fixed, predetermined interval. The time step size also depends on the water uses. For example, operation of irrigation systems may be simulated with 10-day to 15-day time intervals whereas hydropower systems typically use a daily interval. Flood control systems are simulated with sub-daily intervals such as 3-hour or even smaller. This approach requires some scheme for determining when events are to occur. The periodic scan technique adjusts the simulation clock by one predetermined uniform unit and then examines the system to determine whether any event occurred during that interval. If any occurred, the event or events are simulated; otherwise no action is taken. The simulation clock is then advanced another unit, and the process is repeated. However, it requires some scheme to determine the time when the events take place (Pooch and Wall 1992).

Following are the steps in development and application of a simulation model: a) Define the problem, b) Describe the water resource system and its hydrological relationships, c) Decide the model structure, input, and output, d) Test the model; if it is not suitable, go to step ‘c’, and then e) Apply the model to the problem. If an existing model is being used, then steps ‘c’ to ‘e’ can be skipped. After the model of a system is developed and tested, experiments are conducted with it to investigate various scenarios or answer the question “WHAT IF?". The simulation models are much helpful in understanding the consequences or implications of changing one or more of the decision variables.

A detailed multi-reservoir simulation was executed by Jain et al. (2005) for analysis and design of a large inter-basin water transfer system in India. The authors presented the complexities involved in planning a large inter-basin water transfer scheme and demonstrated the efficacy of simulation modeling approach in finding acceptable and efficient solutions.

Lee et al. (2011) applied a simulation-operation method for finding a trade-off between flood control and reservoir filling objectives under a climatic change scenario in the Columbia River basin. Yang et al. (2015) have analyzed and identified the water-related issues including population, economy, land change, water demand, water supply, wastewater, and water quality. Relationships among and within these issues were formulated based on mathematical models as well as equations of water resource used for effective solution. Calibrated and validated model was used to investigate optimum water-use strategy in Laoshan District of China.

A simulation-based optimization model was proposed to maximize multiple benefits, such as flood control, hydropower generation and navigation by Liu et al. (2015). Using the data of the China’s Three Gorges Reservoir (TGR), the proposed method was demonstrated to provide an effective design for the seasonal flood limited water level (FLWL).

6.4 Optimization

Optimization is a popular subject in water resources studies. It has been widely applied as a solution tool for water resources systems planning and management. The term “optimization” is often used synonymously with mathematical programming to refer to a mathematical expression in which a standard algorithm is applied to calculate a set of decision variables that minimize or maximize an objective function subject to the constraints. Optimization techniques are covered in numerous books (Loucks et al. 1981; Jain and Singh 2003). Although optimization and simulation are alternative modeling approaches with different characteristics, the distinction is somewhat obscured by the fact that most models contain elements of both approaches. All optimization models also simulate some important features of the system. Simulation models are advantageous precisely because optimization models cannot handle all complexities of a system whereas simulation models can, to a great extent. An optimization approach may involve numerous iterative executions of a simulation model, possibly with the iterations being automated to various degrees. Mathematical programming algorithms are embedded within many simulation models to perform certain computations.

The objective function of an optimization model may be a penalty or utility function used to define operating rules based on relative priorities or may be a mathematical expression of a planning or operational objective. The following water management objectives are commonly of interest in WRS optimization: a) minimizing difference between water demand and release, b) reliability of the system, c) maximization the hydroelectric power generation, d) maximum reduction of flood peak, and e) maximization of benefits or minimization of costs.

6.4.1. Optimization techniques

Many optimization techniques have been used to solve problems of water resources systems. Linear programming (LP), nonlinear programming (NLP), dynamic programming (DP) and genetic algorithms are the techniques of optimization which have been commonly used in water resources system studies. Besides these, other optimization techniques such as Ant Colony Optimization, Particle Swarm Optimization, Multi-criteria Decision Models, etc. are also used in WRS studies.

6.4.1.1 Linear Programming (LP)

Linear programming is concerned with maximization or minimization of a linear objective function subject to linear equality or inequality constraints. Although the objective function and the constraints in many real-life water problems are not linearly related, these can be approximately linearized and the LP technique can be used to obtain the solution. LP models have been widely used to solve a variety of industrial, economic, engineering and hydrological problems. More details of LP can be found in Loucks et al. (1981). Many efficient public domain/commercial packages to solve LP problems have been developed, e.g., LINDO (http://www.lindo.com/).

LP technique has been extensively applied in water resources sector. Barlow et al. (2003) presented an LP based conjunctive management model to evaluate the tradeoffs between groundwater withdrawal and stream flow depletion in United States. Khare et al. (2007) used a LP model for investigating the scope of conjunctive use of surface water and groundwater for a link canal command in Andhra Pradesh, India. Li et al. (2010) used an inexact two-stage water management model for irrigation planning. Lu et al. (2011) developed and applied an inexact rough interval fuzzy LP model to generate conjunctive water allocation strategies. Gaur et al. (2011) used similar models for management and planning of surface water and groundwater resources. Sun et al. (2011) reported that irrigation water productivity for the double cropping system can be improved under optimized water management. Singh (2014) formulated linear programming (LP) model with groundwater for the annual farm income maximization in Rohtak district of Haryana, India.

6.4.1.2 Nonlinear programming (NLP)

In Nonlinear Programming (NLP) problems, either the objective function and/or one or more constraints are nonlinear functions of decision variables. Similar to LP, efficient codes to solve NLP problems have been developed. Shuffled Complex Evolution (SCE_UA) algorithm (Duan et al. 1993) is generalized algorithm to solve a NLP problem. It has been widely used in hydrology for tasks such as calibration of hydrologic models.

Benli and Kodal (2003) formulated a crop water benefit function-based NLP model for the determination of irrigation water needs and farm income under adequate and limited water supply conditions in southeast Anatolian Region of Turkey. Ghahraman and Sepaskhah (2004) used LP and NLP models for exploring the irrigation optimization. A similar approach was adopted by Shang and Mao (2006). For the efficient utilization of water resources in a coastal groundwater basin of Orissa in India, NLP and LP models were developed and applied by Rejani et al. (2009). A conjunctive use planning model was formulated by Chiu et al. (2010), considering optimal pumping and recharge strategy. Montazar et al. (2010) developed an integrated soil water balance algorithm and coupled it to an NLP model for carrying out water allocation planning in complex deficit agricultural water resources systems. Huang et al. (2012) developed an integrated two-stage interval quadratic programming model for water resources planning and management in China.

6.4.1.3 Dynamic programming (DP)

Dynamic Programming (DP) is an enumerative technique developed by Richard Bellman in 1953. This technique is used to get the optimum solution to a problem which can be represented as a multistage decision process. DP formulation is based on the Bellman principle of optimality which states that an optimal policy has the property that whatever the initial state and decisions are, the remaining decisions must constitute an optimal policy with respect to the state resulting from first decision. DP is not a class of optimization techniques, but is a powerful procedure to solve sequential decision problems. Many problems in water resources involve a sequence of decisions from one period to the next. Such problems can be decomposed into a series of smaller problems that can be conveniently handled by DP. Unlike LP and NLP, there is no generalized software for DP (except a few attempts).

Use of DP technique is common in irrigation planning and management (Yakowitz 1982) and has been widely used by various researchers worldwide (Shangguan et al. 2002; Tran et al. 2011). Several improvements of DP have been suggested: incremental DP with successive approximation (IDPSA) by Shim et al. (2002); state increment DP (SIDP) by Yurtal et al. (2005); folded DP (FDP) by Kumar and Baliarsingh (2003). Yi et al. (2003) also used modified DP to maximize hydropower generation. Li et al. (2011) have developed and used a robust multistage interval-stochastic programming method and applied it in the regional water management systems planning.

6.4.1.4 Genetic Algorithms (GA)

Genetic algorithms belong to the larger class of evolutionary algorithms (EA) which generate solutions to optimization problems by using techniques inspired by natural evolution, such as inheritance, mutation, selection and crossover. Though GA has been widely used for many water resources optimization problems (Nicklow 2010), its application for irrigation planning is relatively new (Kumar et al. 2006). A GA model was used by Karamouz et al. (2009) to optimize a water allocation scheme considering the conjunctive use of surface water and groundwater resources.

6.4.1.5 Ant Colony Optimization (ACO)

ACO is a discrete combinatorial optimization algorithm based on the collective behavior of ants in their search for food. It is noticed that a colony of ants is able to find the shortest route from their nest to a food source via an indirect form of communication that involves deposition of a chemical substance, called pheromone, on the paths as they travel. Over time, shorter and more desirable paths are reinforced with greater amounts of pheromone thus becoming the dominant path for the colony (Afshar et al. 2015). ACO algorithm has been applied in various fields of water resources, such as(1) reservoir operation and surface water management, (2) water distribution systems, (3) drainage and wastewater engineering, (4) groundwater systems including remediation, monitoring, and management, (5) Environmental and Watershed Management Problems etc (Afshar et al. 2015).

6.4.1.6 Particle Swarm Optimization (PSO)

Particle swarm optimization (PSO) is a swarm intelligence based stochastic optimization technique. It is an efficient approach to optimize a function by using a population-based search method. A population of particles that contains possible solutions evolve in a dynamical way. These particles are initially generated at random and freely fly through the multi-dimensional search space (Kennedy and Eberhart, 1995). This method has been applied in many water resources management studies (Baltar and Fontane 2007; Chang et al. 2013).

6.4.1.7 Multi Criteria Decision Making (MCDM)

MCDM is concerned with structuring and solving decision and planning problems involving multiple criteria. The purpose is to support decision makers facing such problems. Typically, a unique optimal solution does not exist for many problems and it is necessary to use decision maker’s preferences to differentiate between solutions (Majumder 2015). MCDM has been successfully used in various WRS studies such as urban water supply, catchment management, ground water management, water allocation, water policy and supply planning, and water quality management (Hajkowicz and Collins 2007).

6.5 Simulation-Optimization Techniques

Combined use of simulation and optimization models allows us to use the strength of these two techniques. For instance, an optimization can be employed to screen a large number of alternatives and choose a few which can undergo detailed investigation by simulation model.

Wurbs (2005) reviewed generalized river/reservoir simulation and optimization models and concluded: a) The generalized ResSim, RiverWare, MODSIM and WRAP modeling systems are representative of current endeavors of water management community in the United States to improve decision support for a broad spectrum of river basin management activities; and b) Simulation and optimization modeling strategies, measures of system performance, computational methods, time step length, hydrologic period of analysis, and data management schemes vary with the different types of applications. In general, developing and applying a reservoir/river system model involves significant time, effort, and expertise. The worth of a reservoir/river system management modeling system depends upon its capabilities to contribute to actual water management decision-making processes.

An assessment of integrated water resources optimization model by Mayer and Muñoz–Hernandez (2009) compares optimization model applications in various river basins around the world. Rani and Moreira (2010) have surveyed simulation–optimization models as applied to reservoir system operation problems; many models have (simulation–optimization) capability such as MODSIM-DSS (Labadie et al. 2000), CALSIM (Draper et al. 2004 and ARSP (http://www.bossintl.com/html/arsp_details.html).

6.6 Game Theory

Game theory is mainly used in economics, political science, and psychology, as well as logic, computer science, biology and poker. Many researchers have attempted water conflict resolution studies in a game-theoretic framework. Carraro et al. (2005) and Zara et al. (2006) reviewed game theoretic water conflict resolution studies. Game theory has been mainly applied for: (1) water or cost/benefit allocation among users (Lippai and Heaney 2000; Wang et al. 2008); (2) groundwater management (Loaiciga 2004; Raquel et al. 2007); (3) water allocation among trans-boundary users (Madani and Hipel 2007; Elimam et al. 2008); (4) water quality management (Sauer et al. 2003; Schreider et al. 2007).

6.7 Review of selected WRS models

A number of public-domain and commercial software packages are readily available for a broad range of water resources systems analysis and applications. The generalized models discussed here are categorized into pure simulation and simulation-optimization models. Recently, Carter (2015) has compiled the information about hydrologic models.

6.7.1 Generalized pure simulation based models

This section reviews selected pure simulation models.

6.7.1.1 HEC Models

A variety of models and decision support tools have been developed at Hydrologic Engineering Centre (HEC), U.S. Army Corps of Engineers (USACE), Davis, California (link:http://www.hec.usace.army.mil/). The relevant models are Hydrologic Modeling System

(HEC-HMS), River Analysis System (HEC-RAS), Prescriptive Reservoir Model program, HEC-ResPRM, Reservoir System Simulation (HEC-ResSim), Flood Damage Reduction Analysis (HEC-FDA) etc. Spatial database for these models are to be prepared by GIS platform (ArcGIS software). All models can be used for simulation though HEC-ResPRM and HEC-HMS also have optimization function. Software of these models along with user manuals are freely available.

The HEC-HMS software simulates many hydrologic processes such as infiltration, evapo-transpiration, snowmelt, soil moisture accounting etc. for continuous simulation and procedures such as unit hydrograph and hydrologic routing. Advanced capabilities are also provided for gridded runoff simulation using the linear quasi-distributed runoff transform (ModClark). Supplemental analysis tools are provided for model optimization, forecasting streamflow, depth-area reduction, assessing model uncertainty, erosion and sediment transport, and water quality. HEC-RAS allows the user to perform computations for one-dimensional steady flow, one and two-dimensional unsteady flow, sediment transport/mobile bed, and water quality/ temperature modeling. Graphical interface of HEC RAS model displaying some of its capabilities is shown in the Fig. 6.2. Weaver (2016) has reanalyzed records of flood using HEC-2, HEC-RAS, and USGS Gauge Data of the Conestoga River and they have carried out corrections to 2013 HEC-RAS (river analysis system) for simulation.

Applications of HEC’s software for reservoir systems operation simulation are widely reported in literature (Draper et al. 2004; Jenkins et al. 2004; Watkins and Moser 2006). HEC-ResSim is used to model reservoir operations at one or more reservoirs for a different type of operational goals and constraints. The software simulates reservoir operations for flood risk management, low flow augmentation and water supply planning, detailed reservoir regulation plan investigations, and real-time decision support. HEC-ResSim package contains a graphical user interface (GUI) and a computational program for simulation of reservoir operation. The software also has included the capacity of data storage and management capabilities and graphics and reporting facilities (Klipsch and Hurst 2007), see Fig.6.3. Trinh et al (2016) have used HEC-ResSim to reconstruct the historical data on water supply from Shasta Dam to its supply region. HEC-FDA provides the capability to perform an integrated hydrologic engineering and economic analysis during the formulation and evaluation of flood risk management plans.

The Data Storage System, HEC-DSS (HEC, 1995 and HEC, 2009) can be used for storage and retrieval of input and output time-series data.

6.7.1.2 RIBASIM Model

River Basin Simulation Model, RIBASIM is a generic model package for simulating the behavior of river basins under various hydrological conditions. The model package is a comprehensive and flexible tool which links the hydrological water inputs at various locations with the specific water users in the basin. RIBASIM enables the user to evaluate a variety of measures related to infrastructure, operational and demand management and to see the results in terms of water quantity, water quality and flow composition. RIBASIM can also generate flow patterns which provide a basis for detailed water quality and sedimentation analyses in river reaches and reservoirs. RIBASIM can be applied to a river basin, a part of a river basin or a combination of river basins. Detailed documents of RIBASIM model is available in the site https://www.deltares.nl/en/software/ribasim/.

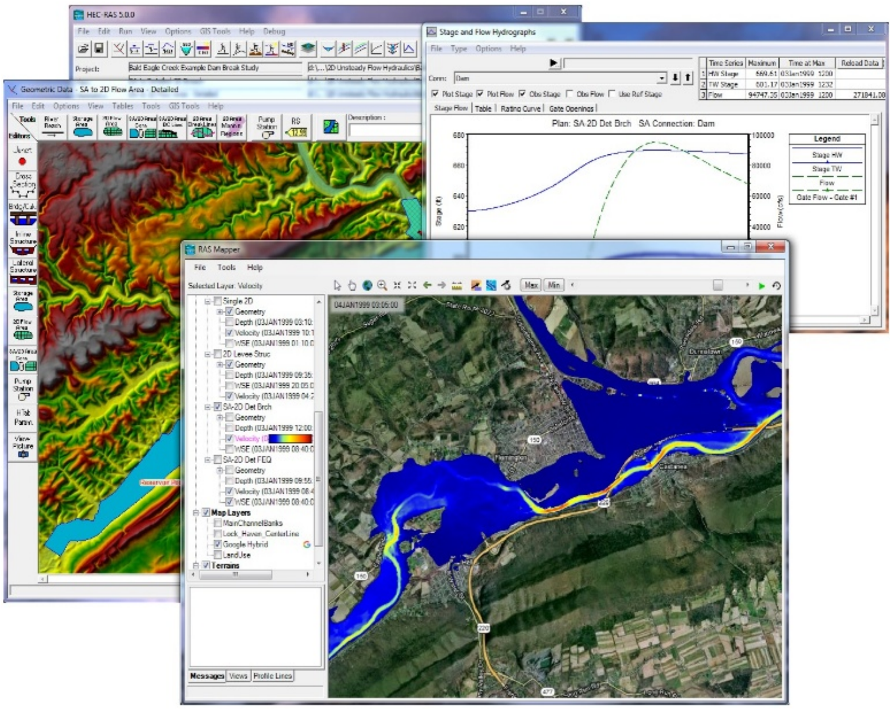


Figure 6.2: HEC RAS model

Figure 6.3: HEC-ResSim Modeling System

Tzoraki et al. (2015) have calculated the potential water allocation, the planning of new water infrastructures and the demand management considering different hydrological conditions (normal, dry, and very dry) using the RIBASIM model in the island of Crete, Greece. They concluded that increasing water scarcity impacts on available water resources due to climate change. Water pricing should be reformed in critical climatic condition.

6.7.1.3 Deltares Models

Deltares (https://www.deltares.nl/en/) has developed simulation software products, such as the Delft3D Flexible Mesh Suite (Delft3D FM) for modeling of coastal waters, estuaries, rivers, lakes, rural and urban areas. SOBEK suite of models has been developed by Deltares for flood forecasting, optimization of drainage systems, control of irrigation systems, sewer overflow design, river morphology, salt water intrusion and surface water quality. The modules within the SOBEK modeling suite simulate the complex flows and the water related processes in almost any system. The modules represent phenomena and physical processes in an accurate way in one-dimensional (1D) network systems and on two-dimensional (2D) horizontal grids. It is the ideal tool for guiding the designer in making optimum use of resources. A policy related long-term fresh water supply and flood risk management has been launched by the government of the Netherlands using Delta models (Prinsen et al. 2015). They have used the Delta models to compute demand in present situation, future scenarios (2050 and 2100) and possible adaptation measurements in national and regional level.

6.7.1.4 MIKE SHE

MIKE SHE is an integrated system to model groundwater, surface water, recharge and evapo-transpiration. MIKE SHE includes all important aspects of hydrology and is a fully integrated model (https://www.mikepoweredbydhi.com/products/mike-she). MIKE SHE can solve the problems related to: a) integrated catchment hydrology, b) conjunctive use and management of surface water and groundwater, c) irrigation and drought management, d) wetland management and restoration, e) environmental river flows, f) floodplain management, g) groundwater-induced flooding, h) land use and climate change impacts on groundwater and surface water, i) nutrient fate and management, and j) integrated mine water management. Sandu & Virsta (2015) have used the MIKE SHE to simulate surface flow as runoff and subsurface flow drainage routed through tile drainage infrastructure within the Argesel River watershed. They have concluded that the structural parameters of the model like grid size significantly influenced the simulation time and the simulated outflow hydrograph while the time step parameters had a moderate influence on river discharge.

6.7.1.5 MIKE HYDRO Basin

MIKE HYDRO Basin is a multipurpose, map-based decision support tool for planning and management of river basins. MIKE HYDRO Basin is designed for analyzing water sharing issues at international, national or local river basin scale. Developed by DHI technologies (https://www.mikepoweredbydhi.com/products/mike-hydro-basin), MIKE HYDRO Basin software can be used for: a) Multi sector solution alternatives to water allocation and water shortage problems; b) Climate change impact assessments on water resources availability and quality; c) Exploration of conjunctive use of groundwater and surface water; d) Optimization of reservoir and hydropower operations; e) Evaluation and improvement of irrigation scheme performance; and f) Integrated water resources management (IWRM) studies. Some of the features available in the software include: rainfall runoff modeling, hydraulic routing, global ranking, water quality, reservoirs, hydropower, reservoir sedimentation, data assimilation, scripting and programming.

MIKE FLOOD

MIKE FLOOD is the unique toolbox for professional flood modelers and information regarding model can be found at https://www.mikepoweredbydhi.com/products/mike-flood. It includes a wide selection of specialized 1D and 2D flood simulation engines, enabling you to model any flood problem - whether it involves rivers, floodplains, flooding in streets, drainage networks, coastal areas, dams, levee and dike breaches, or any combination of these. MIKE FLOOD is applicable at any scale from a single parking lot to regional models offering multiple options for speeding up computation performance through parallelised simulation engines. Applications range from classical flood extent and risk mapping to environmental impact assessments of severe flood events.

MIKE URBAN

MIKE URBAN is the urban water modeling software which can cover all water networks in a city including water distribution systems, storm water drainage systems, and sewer collection in separate and combined systems. For many applications of drinking water, storm water and waste water networks, MIKE URBAN has been successfully used. More information about this software is available at https://www.mikepoweredbydhi.com/products/mike-urban.

6.7.1.6 eWater Source

Australia's National Hydrological Modeling Platform (NHMP) has designed the eWater Source software to simulate all aspects of water resource systems to support integrated planning operations and governance from urban catchment to river basin scales including human and ecological influences (http://ewater.org.au/products/ewater-source/). The software can be used as rainfall-runoff model, groundwater interaction model, nutrient and sediment generation and transport model, crop water use model, etc. It can provide the application of water management rule such as the water sharing rules, resource allocation and environmental flow requirements.

6.7.1.7 NIH_ReSyP Model

National Institute of Hydrology has developed a software package known as NIH_ReSyP (NIH_*Re*servoir *Sy*stems *P*ackage). The package includes modules for reservoir capacity computation using sequent peak analysis, storage-yield-reliability analysis, determination of dependable flows, derivation of trial rule curve levels, simulation of operation of a multipurpose multi-reservoir system for conservation and flood control purposes, hydropower analysis, reservoir routing, and distribution of sediments in reservoir. NIH has developed NIH_ReSyP specifically for deriving operation policies for Indian reservoirs by using the practices being followed in India. The software is free and it has been used in many studies.

6.7.1.8 WEAP Model

Water Evaluation and Planning (WEAP) is a user-friendly software tool that provides an integrated approach to water resources planning (http://www.weap21.org/). WEAP has been developed by the Stockholm Environment Institute's U.S. Center. The software has wide range applications such as rainfall-runoff, groundwater recharge, hydropower generation, water rights and allocation priorities, pollution tracking and water quality, vulnerability assessments, cost-benefit analysis, etc. Mourad and Alshihabi (2015) have used the WEAP model to assess present and future water demand and supply in Syria till 2050. The results have shown that climate change might reduce the inflow from Euphrates, Tigris, and Orontes and water resources will also be affected due to reduced rainfall and increasing evaporation.

6.7.1.9. WMS Model

The Watershed Modeling System (WMS) is a watershed hydrology and hydraulics based graphical interface software. It has been developed by the Environmental Modeling Research Laboratory of Brigham Young University. The main components of WMS include: snowfall accumulation and melting, precipitation and interception, infiltration, evapo-transpiration, surface water retention, surface runoff and flow routing, and groundwater flow (saturated and unsaturated conditions). This software supports other hydrological software such as HEC-RAS, HEC-HMS, TR-20, TR-55, MODRAT, HSPF, Rational Method, and NFF. All these models along with a GIS framework make the task of watershed modeling and mapping easier. Detailed information of WMS is available at http://www.aquaveo.com/software/wms-watershed-modeling-system-introduction.

6.7.1.10 MODFLOW-OWHM

The One-Water Hydrologic Flow Model (MF-OWHM) is a MODFLOW based integrated hydrologic flow model (IHM).The software has been designed by United States Geological Survey (USGS) for analysis of conjunctive-use problems. Detailed information is available at http://water.usgs.gov/ogw/modflow-owhm/.The MODFLOW-OWHM provides the tools for simulating evapo-transpiration (ET), surface water routing (SWR), recharge (RCH), irrigation (FMP), drain and return flow (DRT), unsaturated zone (UZF), and seawater intrusion (SWI). Coupling MODFLOW-OWHM with MODFLOW-LGR (a package for using locally refined grid to simulate groundwater) provides an effective tool for measuring the local influence of tanks and check dams in increasing groundwater levels. This model has been used in many Indian commands for allocating reservoir water through canal systems (Carter, 2015).

6.7.1.11 SWMM

Storm Water Management Model (SWMM) is a dynamic rainfall-runoff simulation model which is used for single event or long-term (continuous) simulation of runoff quantity and quality. The runoff component of SWMM operates on a collection of sub-catchment areas that receive precipitation and estimate runoff and pollutant loads. The routing portion of SWMM transports this runoff through a system of pipes, channels, storage/treatment devices, pumps, and regulators. SWMM tracks the quantity and quality of runoff generated within each sub-catchment and the flow rate, flow depth, and quality of water in each pipe and channel during a simulation period comprised of multiple time steps. The reference manual for SWMM describes the SWMM's hydrologic models, its hydraulic models, and its water quality and low impact development models. Detailed information of SWMM is available at https://www.epa.gov/water-research/storm-water-management-model-swmm.

6.7.2 Generalized simulation–optimization models

6.7.2.1 MODSIM Model

MODSIM is a simulation-optimization model which has been developed jointly by the Colorado State University (CSU) and the Bureau of Reclamation's Pacific North West Region (BRPNWR). The software (MODSIM version 8.5) along with user's manual can be downloaded from (http://modsim.engr.colostate.edu/). The model uses network flow programming (NFP) which employ an efficient Lagrangian relaxation algorithm (RELAX-IV) (Bertsekas and Tseng 1994). MODSIM can be used for developing basin-wide schemes for short-term water management, long-term operational planning, drought contingency planning, water right analysis and environmental concerns. The model has GUI and allows users to create and link reservoirs in network objects (Figure 6.4). Shourian et al. (2008) have used the PSO-MODSIM model to optimize water allocation at basin scale.

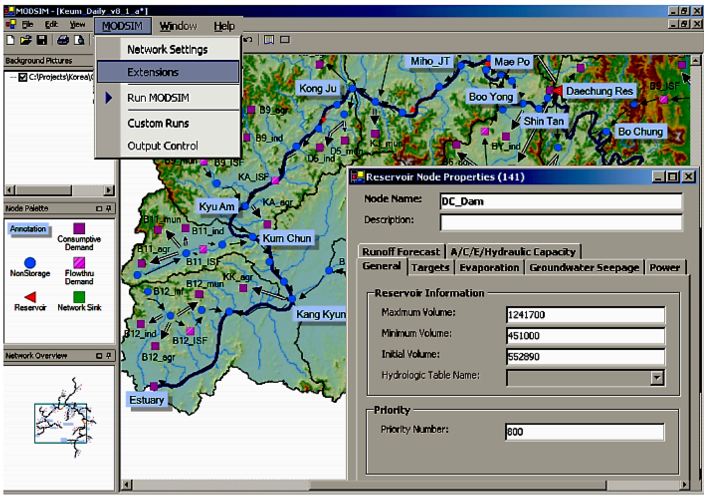


Figure 6.4: MODSIM Model

6.7.2.2 RiverWare Model

RiverWare is a multi-objective river basin modeling tool which has been developed at the Center for Advanced Decision Support for Water and Environmental Systems (CADSWES) of the University of Colorado (http://cadswes.colorado.edu/).The model uses goal programming (GP) with linear programming (LP) as an engine to optimize each of a set of prioritized policy goals, input by the user (Zagona et al. 2001). Management of daily scheduling, mid-term forecasting and long-range planning can be done by this software. A study on water supply has been carried out in the Tarrant Regional Water District (TRWD), Texas in the United States using RiverWare Model (Smith et al. (2015).

6.7.2.3 WRIMS (CalSim Model)

The Water Resource Integrated Modeling System (WRIMS), formally named CALSIM is a graphical based generalized water resources modeling system for measuring operational alternatives of large, complex river basins (Fig. 6.5). The model has been developed by the California State Department of Water Resources (CSDWR) and the U.S.Bureau of Reclamation (USBR) (Draper et al. 2003). Detailed information regarding CalSim model is available at http://baydeltaoffice.water.ca.gov/modeling/hydrology/CalSim/index.cfm. The CalSim utilizes LP/MILP to determine an optimal set of decisions for user defined weights and constraints. The model can also play a flexible foundation for potential future analyses including ensemble forecasting, evaluation of climate change scenarios, assistance with weekly operations forecasts, simulation of water transfers and hydropower operations, etc. A daily time-step planning and operations model is being developed using CalSim-II (Van Lienden et al. 2006). Georgakakos et al. (2012) have used the CalSim model to assess the value of adaptive reservoir management versus traditional operation practices in the context of climatic change in Northern California.

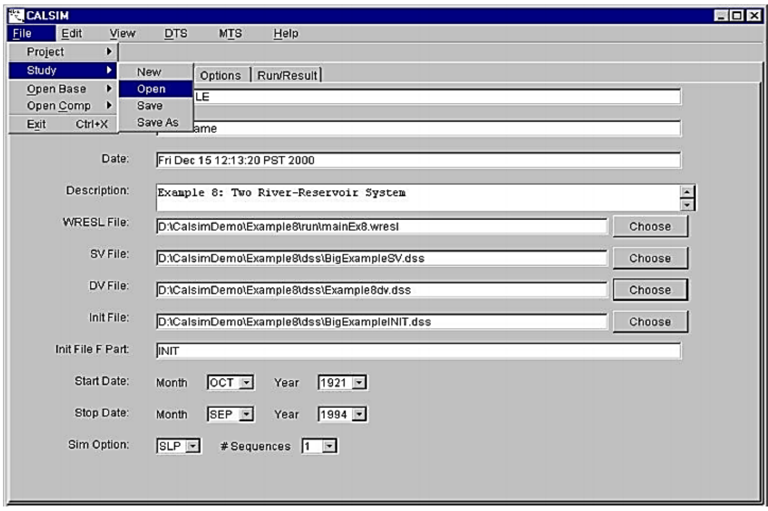


Figure 6.5: CalSim Model

6.7.2.4 ARSP Model

The Acres Reservoir Simulation Program (ARSP) was developed by Acres International Corporation (AIC) and is commercialized and supported by BOSS International. Information regarding model can be found at http://www.bossintl.com/html/arsp_details.html. The ARSP is a Network flow programming (NFP) based model which simulates multi-purpose, multi-reservoir systems. The software can be used in any water resource system incorporating natural inflows, precipitation, evaporation, and evapo-transpiration as input data. The operational features that can be evaluated include storage and release of water by reservoirs, physical discharge controls at reservoir outlets, water flow in channels and consumptive demands. These operational features can be defined as steady-state or time-varying. The reservoir operation policy has been specified using ARSP by prioritizing water requirements (Richter and Barnard 2004; Taghian et al. 2013).

6.7.2.5 OASIS Model

The Operational Analysis and Simulation of Integrated Systems (OASIS) model is a generalized LP-simulation model developed by Hydrologics (http://www.hydrologics.net/). The software has an innovative feature; it simulates the routing of water by solving a linear program. Apart from that, the software can be used to facilitate associations to other simulation models and multi-objective analysis of a water resources system. A drought related problem (McCrodden et al. 2010) and reservoir operations modeling (Rivera et al. 2016) have been studied by this model.

6.8 Evaluation of Models

For this report, detailed information has been collected from various software developers such as Deltares, DHI Water Environment Health (DHI), eWater, India's National Institute of Hydrology (NIH), Stockholm Environmental Institute (SEI), U.S. Army Corps of Engineers (USACE), U.S. Department of Agriculture (USDA), and U.S. Geological Survey (USGS).

The models were assessed on the basis of computational functionality, user interface and capabilities, licensing requirements and software support. Different issues that have been investigated include: water allocation and planning, flood management, groundwater management, conjunctive use, water quality, and sediment transport. This review has been prepared based on a desktop, and is based on review of technical reports, user manuals of the models, tutorials, personal experience with some models, and published studies. However, testing could not be performed on WRS software for validating performance as demonstrated in the literature. Table 6.1 shows the comparative overview of issues addressed by various software's for water resources systems analysis. Carter (2015) carried out a review of currently available hydrological software to identify the packages that can help water resources management in India. Since applications of WRS software are unique in hydrologic setting, institutional setting, and intended use, a detailed review of WRS functionality is recommended before their acquisition for determining suitability in managing the concerned issue of water resources.

6.9 Way Forward

Water resource issues keep changing as growing awareness and exposure uncover unforeseen problems, changes in preferences of society generate new challenges, and new studies may reveal issues that were not important in past. Periodic reviews and updates are necessary to direct research towards emerging issues and problems. The studies need to emphasize on development of models and methods of prediction as well as data collection and monitoring systems. Improvement in the availability of data in terms of the type, coverage and quality may reduce the cost of many water resources projects. Proper management of the constructed projects is essential and is possible by following a scientifically developed operational plan.

Table- 6.1 WRS models evaluated and their relevance to water resources management in India [Adapted from Carter (2015)]

Software Developer	Software Package	Water Allocation	Reservoir Operations	Irrigation Demand Estimation	Flood Mapping and Warning	Conjunctive Use	Water Quality	Simulation	Simulation-Optimization
USACE	HEC-RAS, HEC-HMS	-	-	-	X	-	X	X	-
Deltares	RIBASIM	X	X	X	-	-	X	X	-
Deltares	SOBEK v2.14	X	X	-	X	-	X	X	-
DHI	MIKE SHE	X	X	X	X	X	X	X	-
DHI	MIKE HYDRO Basin	X	X	X	-	-	X	X	-
DHI	MIKE FLOOD	-	-	-	X	-	-	X	-
DHI	MIKE URBAN	-	-	-	X	-	X	X	-
eWater	Source	X	X	X	-	X	X	X	-
NIH	NIH_ReSyP	-	X	-	-	-	-	X	-
SEI	WEAP	X	X	X	-	-	X	X	-
USACE	GSSHA (WMS)	X	X	X	X	X	X	X	-
USGS	MODFLOW-OWHM	X	-	X	-	X	X	X	-
EPA	SWMM	-	-	-	X	-	X	X	-
CSU and BRPNWR	MODSIM Model	X	-	-	-	-	-	-	X
CADSWES	RiverWare Model	X	X	-	-	-	-	-	X
CSDWR and USBR	WRIMS (CalSimModel)	X	X	-	-	X	-	-	X
AIC	ARSP	X	X	-	-	-	-	-	X
Hydrologics	OASIS	-	X	-	-	-	-	-	X

There are many challenges in planning and management of a WRS. A large amount of data needs to be handled and the chosen model/software should be able to work with large dataset. A systematic comparison among possible development and management options is also essential. The models should also be able to interact with other models for the sake of integrated management of WRS.

A challenge with WRS management is to adopt a methodology which can incorporate all the information available to planners and managers into a quantitative framework so as to simulate and predict the outcome of alternative approaches and policies. The modeling framework should be flexible enough to accurately represent the systems; it should be easy to explain it to the decision-makers. Moreover, it should be able to represent the variability and uncertainties inherent in such systems explicitly. For example, the changing climate presents significant challenges to water managers as application of traditional water resources management approaches become questionable due to growing uncertainty and water managers need to adapt or mitigate to these uncertainties. The challenge of climate change is a priority concern for WRS management, where the main issue is to provide better projections of how climate might change water availability and demands in future and then, in accordance, update the operation policies.

A number of generalized models have been developed to study different aspects of WRS. Details of the selected WRS models and their applications are given in the Table 6.1. Some models are open source while others are not available free. Some open source models/software are SWMM, SEAWAT, models from the HEC-family (HEC-HMS, HEC-RAS, HEC-ResSim, HEC-FDA, HEC-DSS etc.), etc. Some of these open source models are very robust and have been tested widely. Generally, open source software has limited manuals, guidelines and test data, user interface, algorithm, upgradation, etc. Due to long history and strong institutional support, HEC group of models do not have these issues and users can easily implement HEC software as per their requirement. Geographical information systems (GISs) are increasingly being included in planning and management models, and hydrologic models can be directly linked to GIS databases. Most of the HEC models have been linked with GIS database.

Based on our experience, it appears that simulation technique is best suited for planning and management of real-life WRSs. For some problems, combined use of simulation and optimization can help in quickly converging to the best solution.

For wider application in India, the WRS models need to have the following features: a) these should preferably be available in public domain; b) adequate documentation (Users' manual, etc.) should be easily available; c) the model/software should be backed up by an active institution or group; and d) there should be adequate expertise in the country to gainfully apply the model.Based on these yardsticks, the models from HEC, USGS, Deltares, and NIH can be picked up for wider application in India. Under NHP, we need to strive to develop expertise in the country, particularly in the State Government organizations, to beneficially use these models. At the same time, indigenous model/software tailored to Indian conditions also needs to be developed.

WRS planning studies need to consider changes in climatic variable since these changes have important implication on fresh water arability of India. Management of floods and droughts is also important in India because different regions of India are routinely affected by floods and droughts every year. Many regions in India have inadequate freshwater resources to meet domestic, economic development and environmental needs. Lack of adequate clean water to meet human drinking water and sanitation needs is indeed a constraint on human health, productivity, and on economic development as well as on the maintenance of a clean environment and healthy ecosystems. Irrigation efficiency needs to be increased by the use of advanced instrumentation and better agricultural water management to save water. Water quality of many rivers in India has degraded substantially and necessary action should be taken to improve quality of water flowing in these rivers.

References

1. Afshar, A., Massoumi, F., Afshar, A., & Mariño, M. A. (2015). State of the art review of ant colony optimization applications in water resource management. Water Resources Management, 29(11), 3891-3904.
2. Baltar, A. M. andD. G. Fontane (2007). "Use of multi objective particle swarm optimization in water resources management." Journal of water resources planning and management 134(3): 257-265.
3. Barlow, P. M., D. P. Ahlfeld and D. C. Dickerman (2003). "Conjunctive-management models for sustained yield of stream-aquifer systems." Journal of Water Resources Planning and Management 129(1): 35-48.
4. Benli, B. and S. Kodal (2003). "A non-linear model for farm optimization with adequate and limited water supplies: application to the South-east Anatolian Project (GAP) Region." Agricultural water management 62(3): 187-203.
5. Bertsekas, D. P. and P. Tseng (1994). RELAX-IV: A faster version of the RELAX code for solving minimum cost flow problems, Massachusetts Institute of Technology, Laboratory for Information and Decision Systems Cambridge, MA.
6. Carraro, C., C. Marchiori and A. Sgobbi (2005). "Applications of negotiation theory to water issues."
7. Carter, B (2015). Water Resource Software overview and review. Centered Consulting International, LLC, created for The World Bank.
8. Chang, J. X., Bai, T., Huang, Q., & Yang, D. W. (2013). Optimization of water resources utilization by PSO-GA. Water Resources Management, 27(10), 3525-3540.
9. Chiu, Y.-C., T. Nishikawa and W. W.-G. Yeh (2009). "Optimal pump and recharge management model for nitrate removal in the Warren Groundwater Basin, California." Journal of Water Resources Planning and Management 136(3): 299-308.
10. Draper, A. J., A. Munévar, S. K. Arora, E. Reyes, N. L. Parker, F. I. Chung and L. E. Peterson (2004). "CalSim: Generalized model for reservoir system analysis." Journal of Water Resources Planning and Management 130(6): 480-489.
11. Draper, A. J., M. W. Jenkins, K. W. Kirby, J. R. Lund and R. E. Howitt (2003). "Economic-engineering optimization for California water management." Journal of water resources planning and management 129(3): 155-164.
12. Duan, Q. Y., Gupta, V. K and Sorooshian, S. (1993). Shuffled complex evolution approach for effective and efficient global minimization. Journal of optimization theory and applications 76(3): 501-521.
13. Elimam, L., D. Rheinheimer, C. Connell and K. Madani (2008). An ancient struggle: a game theory approach to resolving the Nile conflict. Proceeding of the 2008 world environmental and water resources congress. American Society of Civil Engineers. Honolulu, Hawaii.
14. Gaur, S., B. R. Chahar and D. Graillot (2011). "Analytic elements method and particle swarm optimization based simulation–optimization model for groundwater management." Journal of hydrology 402(3): 217-227.
15. Georgakakos, A. P., Yao, H., Kistenmacher, M., Georgakakos, K. P., Graham, N. E., Cheng, F. Y and Shamir, E (2012). Value of adaptive water resources management in Northern California under climatic variability and change: reservoir management. Journal of Hydrology 412: 34-46.
16. Ghahraman, B and A. R. Sepaskhah (2004). "Linear and non-linear optimization models for allocation of a limited water supply." Irrigation and Drainage 53(1): 39-54.
17. Hajkowicz, S., & Collins, K. (2007). A review of multiple criteria analysis for water resource planning and management. Water resources management, 21(9), 1553-1566.
18. Hipel, K. W. and Obeidi, A. (2005). "Trade versus the environment strategic settlement from a systems engineering perspective." Systems Engineering 8(3): 211-233.
19. Huang, Y., Y. Li, X. Chen and Y. Ma (2012). "Optimization of the irrigation water resources for agricultural sustainability in Tarim River Basin, China." Agricultural Water Management 107: 74-85.
20. Jain, S. K and V. P. Singh (2003). Water resources systems planning and management, Elsevier.

21. Jain, S. K., Goel, M. K and Agarwal, P. K (1998). "Reservoir operation studies of Sabarmati system, India." Journal of Water Resources Planning and Management 124(1): 31-37.
22. Jain, S. K., N. Reddy and U. Chaube (2005). "Analysis of a large inter-basin water transfer system in India." Hydrological Sciences Journal 50(1).
23. Jenkins, M. W., J. R. Lund, R. E. Howitt, A. J. Draper, S. M. Msangi, S. K. Tanaka, R. S. Ritzema and G. F. Marques (2004). "Optimization of California's water supply system: Results and insights." Journal of Water Resources Planning and Management 130(4): 271-280.
24. Karamouz, M., A. Ahmadi and S. Nazif (2009). "Development of management schemes in irrigation planning: Economic and crop pattern consideration." Scientia Iranica, Transactions A: Civil Engineering 16(6): 457-466.
25. Kennedy J, Eberhart R (1995) Particle swarm optimization. Proc. IEEE Int. Conf. Neural Networks, Perth, Australia, Dec: 1942–1948.
26. Khare, D., Jat, M. K and Sunder, J. D (2007). "Assessment of water resources allocation options: Conjunctive use planning in a link canal command." Resources, Conservation and Recycling 51(2):487–506
27. Klipsch, J and M. Hurst (2007). "HEC-ResSim reservoir system simulation user's manual version 3.0." USACE, Davis, CA: 512.
28. Kumar, D. N and F. Baliarsingh (2003). "Folded dynamic programming for optimal operation of multireservoir system." Water Resources Management 17(5): 337-353.
29. Kumar, D. N., K. S. Raju and B. Ashok (2006). "Optimal reservoir operation for irrigation of multiple crops using genetic algorithms." Journal of Irrigation and Drainage Engineering 132(2): 123-129.
30. Labadie, J., M. Baldo and R. Larson (2000). "MODSIM: decision support system for river basin management: Documentation and user manual." Colorado State University and US Bureau of Reclamation, Ft Collins.
31. Lee, S. Y., Fitzgerald, C. J., Hamlet, A. F and Burges, S. J (2011). "Daily time-step refinement of optimized flood control rule curves for a global warming scenario." Journal of Water Resources Planning and Management 137(4): 309-317.
32. Li, W., Li, Y. P., Li, C. H and Huang G. H (2010). "An inexact two-stage water management model for planning cultural irrigation under uncertainty." Agricultural Water Management 97:1905–1914.
33. Li, Y. P., Huang, G. H., Nie, S. L and Chen, X (2011). "A robust modeling approach for regional water management under multiple uncertainties." Agricultural Water Management 98:1577–1588
34. Lippai, I and J. P. Heaney (2000). "Efficient and equitable impact fees for urban water systems." Journal of Water Resources Planning and Management 126(2): 75-84.
35. Liu, P., Li, L., Guo, S., Xiong, L., Zhang, W., Zhang, J and Xu, C. Y (2015). Optimal design of seasonal flood limited water levels and its application for the Three Gorges Reservoir. Journal of Hydrology 527: 1045-1053.
36. Loaiciga, H. A (2004). "Analytic game-theoretic approach to ground-water extraction." Journal of Hydrology 297: 22–33.
37. Loucks, D. P., J. R. Stedinger and D. A. Haith (1981). Water Resource Systems Planning and Analysis, Prentice-Hall.
38. Lu, H., G. Huang and L. He (2011). "An inexact rough-interval fuzzy linear programming method for generating conjunctive water-allocation strategies to agricultural irrigation systems." Applied Mathematical Modeling 35(9): 4330-4340.
39. Madani, K (2009). Climate change effects on high-elevation hydropower system in California. Ph.D. Dissertation, Dept. of Civil and Environmental Engg., University of California, Davis. (http://cee.engr.ucdavis.edu/faculty/lund/students/ MadaniDissertation.pdf).
40. Madani, K. and K. W. Hipel (2007). Strategic insights into the Jordan River conflict. Proceeding of the 2007 world environmental and water resources congress. American Society of Civil Engineers, Tampa, Florida.
41. Majumder, M. (2015) Impact of Urbanization on Water Shortage in Face of Climatic Aberrations, Springer Briefs in Water Science and Technology, DOI 10.1007/978-981-4560-73-3_2

42. Mayer, A and A. Muñoz-Hernandez (2009). "Integrated water resources optimization models: an assessment of a multidisciplinary tool for sustainable water resources management strategies." Geography Compass 3(3): 1176-1195.
43. McCrodden, B., S. Nebiker and L. Carreiro (2010). "Drought Management: Probability-Based Operating Rules Improve Water Supply Management (PDF)." Opflow 36(6): 22-24.
44. Montazar, A., H. Riazi and S. Behbahani (2010). "Conjunctive water use planning in an irrigation command area." Water resources management 24(3): 577-596.
45. Mourad, K. A., and Alshihabi, O. (2015). "Assessment of future Syrian water resources supply and demand by the WEAP model." Hydrological Sciences Journal 1-9.
46. Nicklow, J., Reed, P., Savic, D., Dessalegne, T., Harrell, L., Chan-Hilton, A., Karamouz, M., Minsker, B., Ostfeld, A., Singh, A and Zechman, E (2010). "State of the art for genetic algorithm and beyond in water resources planning and management." Journal of Water Resources Planning and Management ASCE 1364:412–432
47. Pooch, U. W and Wall, J. A (1992). Discrete event simulation: a practical approach (Vol. 4). CRC Press.
48. Prinsen, G., Weiland, F. S and Ruijgh, E (2015). "The Delta model for fresh water policy analysis in the Netherlands." Water Resources Management 29(2): 645-661.
49. Raju, K. S and D. N. Kumar (2004). "Irrigation planning using genetic algorithms." Water Resources Management 18(2): 163-176.
50. Rani, D and M. M. Moreira (2010). "Simulation–optimization modeling: a survey and potential application in reservoir systems operation." Water resources management 24(6): 1107-1138.
51. Raquel, S., S. Ferenc, C. Emery and R. Abraham (2007). "Application of game theory for a groundwater conflict in Mexico." Journal of environmental management 84(4): 560-571.
52. Rejani, R., M. K. Jha and S. N. Panda (2009). "Simulation-optimization modeling for sustainable groundwater management in a coastal basin of Orissa, India." Water resources management 23(2): 235-263.
53. Richter, S., and Barnard., J. (2004). Impact of climate change on hydroelectric generation in Newfoundland.CCAF Project A283. Climate Change Impacts and Adaptation Directorate, SGE Acres Limited.
54. Rivera, M., S. Nebiker and B. Wright (2016). "Dynamic Reservoir Operations Support Sustainable Water Management (PDF)." Opflow 42(3): 12-16.
55. Sandu, M. A., and Virsta, A. (2015). "Applicability of MIKE SHE to Simulate Hydrology in Argesel River Catchment." Agriculture and Agricultural Science Procedia 6: 517-524.
56. Sauer, P., Dvorak, A., Lisa, A and Fiala, P (2003). "A procedure for negotiating pollution reduction under information asymmetry. Surface water quality case." Environmental and Resource Economics 24(2): 103–119.
57. Schreider, S., P. Zeephongsekul and M. Fernandes (2007). A game-theoretic approach to water quality management. MODSIM 2007 International Congress on Modeling and Simulation, Modeling and Simulation Society of Australia and New Zealand.
58. Sedki, A. and D. Ouazar (2011). "Simulation-optimization modeling for sustainable groundwater development: A Moroccan coastal aquifer case study." Water resources management 25(11): 2855-2875.
59. Sedki. A., Ouazar, D and E. l. Mazoudi. E (2009). "Evolving neural network using real coded genetic algorithm for daily rainfall-runoff forecasting." Expert Systems with Applications 363(3): 4523–4527
60. Shang, S. and X. Mao (2006). "Application of a simulation based optimization model for winter wheat irrigation scheduling in North China." Agricultural Water Management 85(3): 314-322.
61. Shangguan, Z., Shao, M., Horton, R., Lei, T., Qin, L and Ma, J (2002). "A model for regional optimal allocation of irrigation water resources under deficit irrigation and its applications." Agricultural Water Management 52(1):139–154
62. Shim, K.-C., D. G. Fontane and J. W. Labadie (2002). "Spatial decision support system for integrated river basin flood control." Journal of Water Resources Planning and Management 128(3): 190-201.

63. Shourian, M., S. Mousavi and A. Tahershamsi (2008). "Basin-wide water resources planning by integrating PSO algorithm and MODSIM." Water resources management 22(10): 1347-1366.
64. Singh, A (2012). "An overview of the optimization modeling applications." Journal of Hydrology 466: 167-182.
65. Singh, A (2014). "Optimizing the use of land and water resources for maximizing farm income by mitigating the hydrological imbalances." Journal of Hydrologic Engineering 19(7): 1447-1451.
66. Smith, R., Kasprzyk, J and Zagona, E (2015). "Many-Objective Analysis to Optimize Pumping and Releases in Multireservoir Water Supply Network." Journal of Water Resources Planning and Management 142(2): 04015049.
67. Sun, Q., Kröbel, R., Müller, T., Römheld,V., Cui, Z., Zhang, F., and Chen, X. (2011). "Optimization of yield and water-use of different cropping systems for sustainable groundwater use in North China Plain." Agricultural Water Management 98: 808–814
68. Taghian, M., Rosbjerg, D., Haghighi, A and Madsen, H (2013). "Optimization of conventional rule curves coupled with hedging rules for reservoir operation." Journal of Water Resources Planning and Management 140(5): 693-698.
69. Tran, L. D., Doc, L., Schilizzi, S., Chalak, M and Kingwell, R (2011). "Optimizing competitive uses of water for irrigation and fisheries." Agricultural Water Management 101:42–51
70. Trinh, T., Jang, S., Ishida, K., Ohara, N., Chen, Z. Q., Anderson, M. L., Darama, Y., Chen, J. and Kavvas, M. L (2016). "Reconstruction of Historical Inflows into and Water Supply from Shasta Dam by Coupling Physically Based Hydroclimate Model with Reservoir Operation Model." Journal of Hydrologic Engineering 04016029.
71. Tzoraki, O., Kritsotakis, M and Baltas, E (2015). "Spatial Water Use Efficiency Index towards resource sustainability: application in the island of Crete, Greece." International Journal of Water Resources Development 31(4): 669-681.
72. Van Lienden, B. J., Munévar, A., Field, R and Yaworsky, R (2006). A daily time-step planning and operations model of the American river watershed. Proceedings of operations management 2006 conference: operating reservoirs in changing conditions.
73. Votruba, L (1988). Analysis of water resource systems, Elsevier.
74. Wang, L., L. Fang and K. W. Hipel (2008). "Basin-wide cooperative water resources allocation." European Journal of Operational Research 190(3): 798-817.
75. Watkins Jr., D. W. and D. A. Moser (2006). "Economic-based optimization of Panama Canal system operations." Journal of water resources planning and management 132(6): 503-512.
76. Weaver, A. C (2016). "Reanalysis of Flood of Record Using HEC-2, HEC-RAS, and USGS Gauge Data." Journal of Hydrologic Engineering 21(6): 05016011.
77. Wurbs, R. A (2005). Comparative evaluation of generalized river/reservoir system models, Texas Water Resources Institute.
78. Yakowitz, S. J (1982). "Dynamic programming applications in water resources." Water Resources Research 18(4):673–696.
79. Yang, J., Li, G., Wang, L and Zhou, J (2015). "An integrated model for simulating water resources management at regional scale." Water Resources Management 29(5): 1607-1622.
80. Yi, J., J. W. Labadie and S. Stitt (2003). "Dynamic optimal unit commitment and loading in hydropower systems." Journal of Water Resources Planning and Management 129(5): 388-398.
81. Yurtal, R., G. Seckin and G. Ardiclioglu (2005). "Hydropower optimization for the lower Seyhan system in Turkey using dynamic programming." Water international 30(4): 522-529.
82. Zagona, E. A., T. J. Fulp, R. Shane, T. Magee and H. M. Goranflo (2001). "Riverware: A Generalized Tool for Complex Reservoir System Modeling." Journal of the American Water Resources Association 34(4): 913–929.
83. Zara, S., A. Dinar and F. Patrone (2006). "Cooperative game theory and its application to natural, environmental, and water resource issues: 2. application to natural and environmental resources." Application to Natural and Environmental Resources (November 1, 2006). World Bank Policy Research Working Paper (4073).