Water Resource Software

APPLICATION OVERVIEW AND REVIEW

By Carter Borden, Anju Gaur and Chabungbam R. Singh

March 2016

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Many individuals and organization have supported this analysis. Specific contributions of note include water resources software developers Deltares, DHI, eWater, NIH, SEI, and USGS responded to a software questionnaire outlining the functionality and applications of their products. Individuals at the Government of India's Central Water Commission and National Institute of Hydrology provided valuable comments on their experience of WRS applications in India. Kees Bons provided further clarification of the Deltares software functionality. Apruban Mukherjee and Anil Vyas provided additional information on USACE HEC software. Finally, Dr. Daniele Tonina provided a thorough and comprehensive review of the document.

OVERVIEW

The National Hydrology Project (NHP) is an initiative by the Government of India's Ministry of Water Resources and the World Bank to develop hydro-meteorological monitoring systems and provide scientifically-based tools and design aids to assist implementing agencies in the effective water resources planning and management (http://www.hydrology-project.gov.in/, http://indiawrm.org/). The NHP consists of four components: A) Water Data Acquisition Systems; B) Water Resource Information Systems; C) Water Resources Operation and Management Applications; and D) Institutional Strengthening and Capacity Building. The objective of Component C is to ensure the usefulness of monitored and remotely sensed data sets through the implementation of planning applications for decision support systems (DSS) for river basin planning, water balance assessments, climate risk assessments (for example, climate change, drought management), groundwater resource management, water quality management, scenario analysis for investment planning, and community based water management. Thus, water and water quality modeling software (WRS) for planning and real-time applications will be required to support this initiative.

As many WRS exist to support management a variety of water resources issues, selection of the proper software by water managers with limited experience in these tools can be daunting and confusing. To aid water managers in their selection, this document provides an overview of how WRS are used to manage water resources issues, criteria for WRS selection, and a high level review of WRS currently available that central and state governments of India can use for water management. The water resource issues covered include water allocation and planning, flood management, groundwater management, conjunctive use, water quality, and sediment transport. Selection criteria discussed includes computational functionality, user interface ease or use and capabilities, licensing requirements, and software support. Twenty-two WRS from Aquaveo, Colorado State University (CSU), Deltares, DHI Water Environment Health (DHI), eWater, India's National Institute of Hydrology (NIH), Rockware, Stockholm Environmental Institute (SEI), U.S. Army Corps of Engineers (USACE), U.S. Department of Agriculture (USDA), and U.S. Geological Survey (USGS) were evaluated based on the selection criteria as well as their application to water resource issues in India and globally. In addition, three DSS for flood warning were evaluated. This review is based on software developers' responses to a questionnaire and a desktop review of technical manuals, user guides, tutorials, and studies related to the WRS. No testing was performed on WRS to validate performance as described in the literature. With this information, it is envisioned that water managers can perform a detailed review on a limited set of WRS for determining the package that best suits their unique water resource issue, hydrologic setting, intended use, and institutional setting.

ACRONYMS AND ABBREVIATIONS

AWBM	Australian water balance model
API	Application Programming Interface
BBMB	Bhakra Beas Management Board
CAVI	Control and Visualization Interface
CBOD	carbonaceous biological oxygen demand
COD	chemical oxygen demand
CSU	Colorado State University
C2VSim	California Central Valley Groundwater-Surface Water Simulation Model
CVPM	Central Valley Production Model
CWC	Central Water Commission
CWMS	Corps Water Management System
DB	dam break
DHI	DHI Water Environment Health
DHgM	distributed hydrogeological models
DHM	distributed hydrologic model
DRiFt	Discharge River Forecast
EAC	elevation-area-capacity
EGS	ecosystem goods and services
ELOHA	Ecological Limits of Hydrologic Alteration
ESPA	Eastern Snake Plain Aquifer
FEH	Flood Estimation Handbook
GIS	geographical information system
GUI	graphical user interface
GSSHA	Gridded Surface Subsurface Hydrologic Analysis
HRU	hydrologic response unit
IDWR	Idaho Department of Water Resources
kaf/year	kilo acre feet per year
MFP	Meteorologic Forecast Processor
mm	millimeter
NHP	National Hydrology Project
NIH	National Institute of Hydrology
PGM	Pasture Growth Model
PRMS	Precipitation-Runoff Modeling System
QPF	quantitative precipitation forecast
RBM	river basin model
ReSyP	Reservoir Systems Package
RR	rainfall-runoff
RTC	real time control
RTDAS	real-time data acquisition system
RTDSS	real-time decision support system
RTFWS	real-time flood water system
SEI	Stockholm Environmental Institute
SimHYD	Simplified Hydrology Model
SMARG	Soil Moisture Accounting and Routing Model
SMM	Soil Moisture Model
SO	structure operations
ST	sediment transport
sq km	square kilometer
USACE	U.S. Army Corps of Engineers
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey
WICC	Watershed Information Center and Conservancy
WQ	water quality
WRM	water resource management
WRS	water resources software

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Introduction

Freshwater is a resource crucial to man's existence, affecting all human life. Human need for freshwater resources includes basic consumption such as drinking and sanitation for good health and combating disease; assisting in the production of food and goods humans consume; providing a foundation for cultural services such as community connectivity, spirituality, and recreation; and supporting the ecosystems upon which humans rely.[1,2] Despite the importance of water, freshwater resources are on the decline. The UN Millennium Assessment[3] reports about 5-25 percent of global freshwater use exceeds long-term accessible supply and that freshwater availability is declining due to severe, anthropogenic pollution. An estimated 50 percent of inland waterways have been degraded in the 20th century, and the decline of inland waterways has led to a decrease in the ecosystem goods and services (EGS) for supporting human well-being. This decline in the availability and access to freshwater resources will "lead to problems with food production, human health, and economic development".[3]

Wise management of water resources must take into account hydrologic conditions as well as how the flow and storage of water affects the ecological, social, and economic systems. Due to the complexity of the hydrologic cycle its interaction with socioeconomic and ecological systems in a basin, using numerical model technologies to assist managers in understanding risks and developing water management alternatives greatly adds to the ability to develop and implement water management decisions. Water resources software (WRS) such as hydrologic, hydraulic, hydro-geologic, and water quality simulation and optimization model provide a means to quantitatively test and evaluate the concepts and management strategies addressing water resource issues. Specifically, WRS support water resource management in the following manner:

- Illustrating the fundamental function and operation of systems;
- Identifying and displaying data availability and deficiencies;
- Identifying and quantifying the functional and operational limitations in systems (what is the problem);
- Determining the optimal design for systems;
- Providing water managers a means of testing design, policy, and management strategies prior to implementation; and
- Communicating results for better understanding of water managers, interested stakeholders, and the general public.

Thus, the use of WRS to understand the systems, organize data, predict future conditions, and communicate information is a powerful tool when managing water resources.

Important elements of effective water resource management include the ability to address specific water resource issues, provide a relevant representation of the systems being evaluated, output simulation results related to key indicators in management decisions, and be capable of evaluating a range of decisions (from simple to complex). Thus, the desirable attributes for WRS include the organization of data used in evaluating alternatives; a flexible structure to accommodate evolution of decisions, issues, data, scenarios, and model; and production of reliable and transparent output. Furthermore, the output should be linked to relevant indicators used in evaluating policies and decisions that, directly or indirectly, affect water resources in a basin. This document provides an overview of WRS types, examples of WRS as applied to water management issues, criteria of WRS selection, and review of current WRS available to help water managers in India make more informed decisions.

Modeling in Water Resource Management

Planning, designing, and managing water resources systems involves estimating future conditions. These future scenarios often involve complex relationships between physical conditions and anthropogenic activities that dictate the movement and quality of water. For these complex problems, WRS can be used to predict future changes in a water system given changes in climate, physical conditions, or anthropogenic activities. A range of WRS exists to address different water resource issues and conditions. Correct WRS selection involves matching the software functionality to the water resources issue being addressed, physical conditions and anthropogenic activities of the watershed, available data, expertise of the technical staff, computational capacity, and the institutional role it plays in an organization's water management efforts. Proper selection of the WRS given the issue being addressed, available data, and its role in the management process can make WRS an important tool in water manager's arsenal when managing water resources.

Water Resource Software Types

Four classes of WRS are considered: water resource management (WRM), hydraulic, groundwater, and water quality models. Below is a brief description on each model class.

WRM models simulate the spatial and temporal distribution of water in a basin, given hydrometeorologic conditions and anthropogenic activities, to assist in water resource planning. WRM models provide:

- Water managers and stakeholders with a common understanding of the major active hydrologic processes;
- Illuminate spatial and temporal magnitude of water related issues;
- Forecast the state of water given pressures and drivers such as climate change, drought, or water management strategy scenarios;
- Act as a repository for existing data and illuminate data gaps to guide further collection;
- Provide input data for the analysis of critical ecological, economic, and social systems; and
- Target future, more in-depth research where greater investigation is required.

Therefore, WRM models must simulate the climatic and natural hydrologic cycle as well as the socioeconomic activities that impact human-built infrastructure that store, allocate, and deliver water. WRM models typically support planning and management of water allocation and hydrologic response, thus they tend to be developed over a watershed to basin scale, simulate longer periods to capture meteorological variability, and provide output that is easily understood by water managers and stakeholders. The issues addressed by planning WRM models include surface water distribution considering supply and demand, land-use change impacts, quantification and development of surface water supply, climate change impacts, drought management, infrastructure operations, water quality, and groundwater and conjunctive use studies (Table 1).

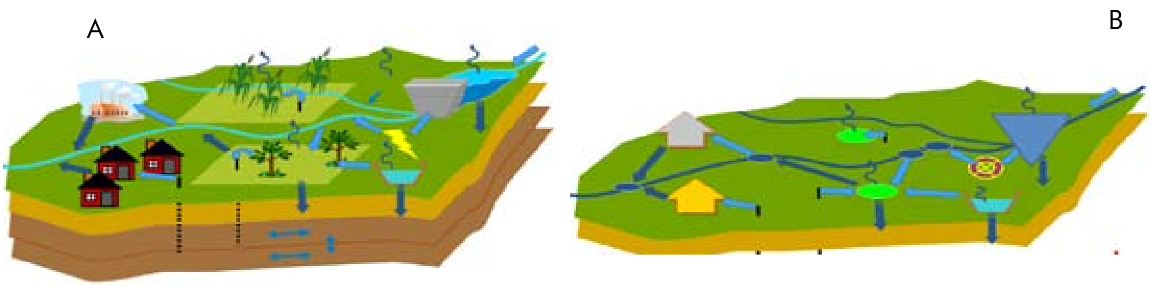
WRM models can be further classified into river basin models (RBMs) and distributed hydrologic models (DHMs). RBMs simulate the water distribution and use in a basin using a network comprised of branches and nodes (Figure 1). In general, nodes represent on-stream water accounting (diversions, bifurcations, catchment inflows, and reservoirs) and off-stream water use activities (domestic, municipal, commercial, industrial, agriculture, and poweruse). Branches route water between nodes and represent rivers, canals, and pipelines. In several packages,

Table 1. WRS types use in addressing to water resources issues

	Time Frame		Water Resource Issue												
WRS Types	Planning/Design	Real-Time	Climate Issues	Land Use Change	Water Allocation	Reservoir Operations	Irrigation	River Flows Routing	Flood Mapping	Real-time Flood Warning	Groundwater	Conjunctive Use	Water Quality	Sediment Transport	Socio-Economic, Ecological
WRM Models	**X**	x	**X**	**X**	**X**	x	**X**	x	x	-	x	x	x	x	A
River Basin Model (RBM)	***X***	*x*	***X***	**-**	***X***	*x*	***X***	-	-	-	-	-	*x*	-	*A*
Distributed Hydrologic Model (DHM)	***X***	-	***X***	***X***	-	-	***X***	*x*	*x*	-	*x*	*x*	*x*	*x*	*A*
Groundwater Models	**X**		x	**X**	-	-	-	-	-	-	**X**	**X**	**X**	-	A
Hydraulic Models	**X**	**X**	x	-	x	**X**	-	**X**	**X**	**X**	-	-	**X**	**X**	A
Water Quality Models	**X**	**X**	x	X	x	-	-	-	-	-	**X**	-	**X**	**X**	A

Note: X = primary applicable, x = secondary applicable, and A = additional analysis.

Figure 1. A conceptual river basin (A) and schematized node and branch version typical of a RBM (B)



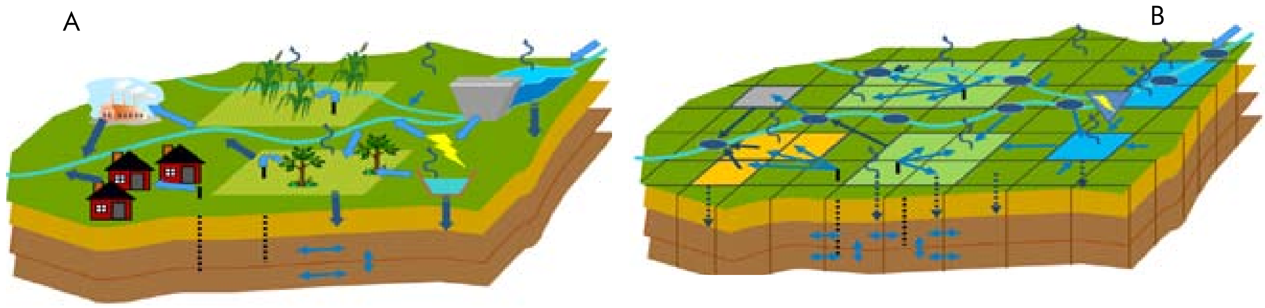
Note: Water uses in A and B include domestic, industrial, agriculture, hydropower, and a reservoir. The blue arrows denote the flux direction of water in the system.

polygons representing catchments are also used to simulate lumped processes (for example, surface runoff, groundwater). While simpler, RBM structures can be very effective at planning water resources as they tend to be easy to operate, have short simulation times, and are conceptually easy to understand.

DHMs are deterministic, fully distributed, physically based modeling system for describing the major flow processes of the hydrological cycle. Generally, the modeling domain is divided into grid cells where the water movement within each hydrologic process is solved (Figure 2). In general, as modeling complexity increases so do the data required and the computational power. As water resource issues and available data vary, software package are available that offer several different approaches for numerically simulating water movement ranging from simple, lumped conceptual models to advanced, distributed, and physically based solutions. Simple and advanced approaches may be combined, which enables the user to compromise between result resolution, time, and data availability constraints.

Hydraulic models simulate the flow of surface water in the riverine systems, lakes and reservoirs, wetlands, floodplains, and canal systems using physical characterization of the channels. Hydraulic model are used in planning as well as real-time water resource management when

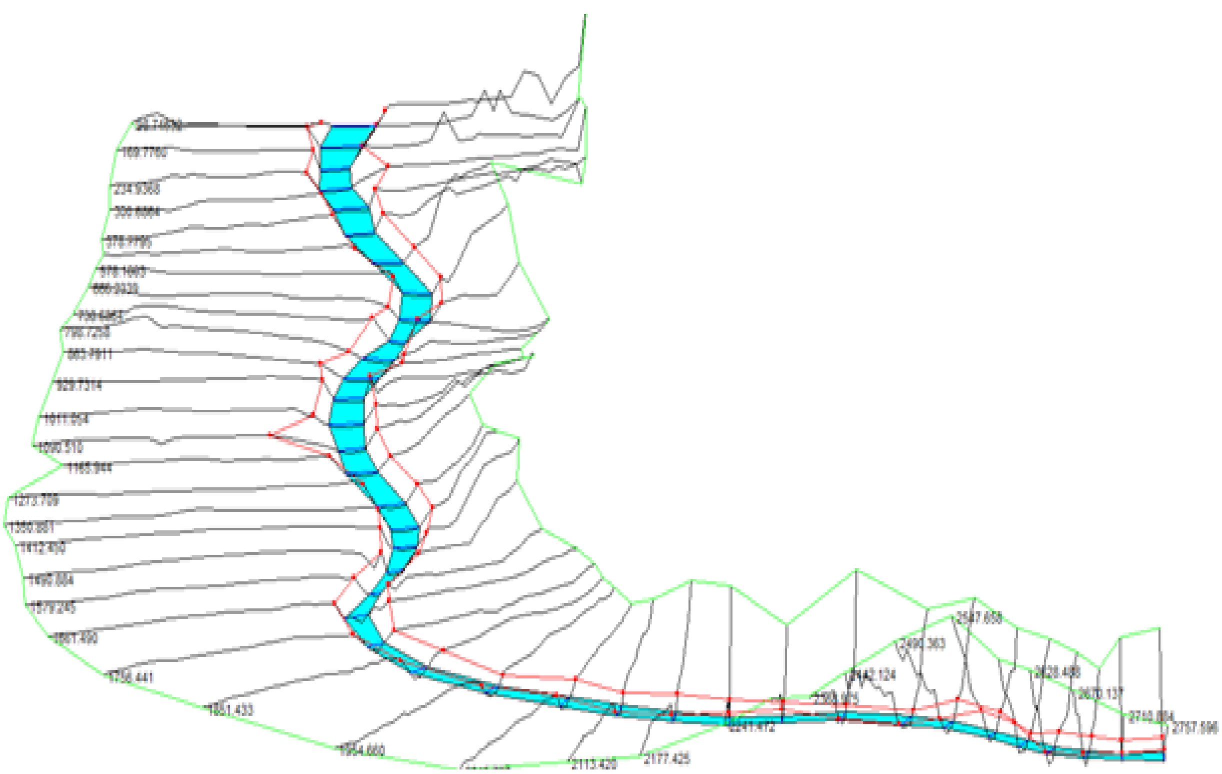
Figure 2. A conceptual river basin (A) and schematized grid based solution typical in a DHM (B)



Note: Water uses in A and B include domestic, industrial, agriculture, hydropower, and a reservoir. The blue arrows denote the flux direction of water in the system. Note, only a representative few of the water fluxes are representing by blue arrows in the figures above as the same calculation is made within each grid cell.

physically based flow estimates are required. Planning issues include, but are not limited to, flood mapping, irrigation networks, river channel and infrastructure design, reservoir planning, emergency management planning, and environmental management (Table 1). Real-time applications include flood warning systems, reservoir operations, and irrigation operations. Hydraulic model can be used in conjunction with hydrologic and groundwater model to provide a more comprehensive view of the hydrologic system.

Figure 3. Cross-sections (black lines) define the river channel and floodplain in a 1-D hydraulic model



Note: Blue area is the water surface profile.[4]

Hydraulic models apply numerical equations that compute the physical movement of water over river, canal, and lake bathymetryas well as floodplain topography to simulate flow (Figure 3). Algorithms are characterized as 1-dimensional (1-D), 2-dimenssional (2-D), and 3-dimensional (3-D). For 2-D hydraulic models, the surface is characterized using a 2-D grid and the vertical dimension as a single layer. Hydraulic WRS used for routing flows and flood mapping are typically 1-D, 2-D, or a combination of both. Lakes and reservoirs may use 3-D hydraulic models where the vertical water movement is important to simulate.

Water Quality models are concerned with the fate and transport of chemicals and sediment movement in water systems. Typical water quality issues include the point source introduction to a water systems through effluent discharge; non-point source contribution to water bodies from surface runoff; eutrophication of lakes and reservoirs; quality of water available for drinking, commercial industrial, and agricultural use; and saline intrusion of groundwater in coastal areas (Table 1). Sediment modeling can further be concerned with changes in the physical dimensions of the river bed or lake leading to increased flooding, channel instability through erosion, or siltation of reservoirs. Typically, water quality algorithms are coupled with the water quantity algorithms as the movement of water is an important component in predicting water quality.

For more in-depth assessment of WRS use in water resource management, Loucks et al.[5] provides a comprehensive volume outlining the use of WRS to support water management.

Water Resource Modeling Application Examples

Modeling applications have been developed to support the management of issues that include water planning, climate change/drought, flooding, reservoir operations, groundwater, water quality, and ecological impacts. Note, that while examples of modeling application may be presented under a single water resource issue, these modeling applications often are used to address multiple issues.

Water Allocation and Planning

Watershed allocation and planning address the allocation of surface water and groundwater supply given demands from domestic, commercial, industrial, agricultural, recreational, power, and ecological uses within a watershed. An example of WRS supporting basin planning is from the Napa County, California.[6] Napa Valley hosts one of the premiere wine growing regions in the United States. As such, there has been pressure to convert nature forests and grasslands to vineyards, raising concerns about how the land use change might affect potential flooding, flows that support irrigation and anadromous fish, and the loading of dissolved chemicals and sediment to the Napa River. To provide an overview of baseline conditions by which planning programs can assess the benefits, constraints, and environmental impacts of future development, the Napa County Baseline Data Report was written. Underlying the surface water, groundwater, and water quality sections of the Baseline Data Report was a fully distributed, physically based DHM that simulated precipitation, evapotranspiration, overland flow, unsaturated flow, stream flow, flow in lakes and reservoirs, groundwater flow, and anthropogenic water use (for example, irrigation to vineyards, surface water diversions, and groundwater abstractions). Water quality analysis was conducted usinga geographical information system (GIS)-based non-point source and erosion calculator, which incorporated the DHM runoff results, to assess loading of chemicals and sediment to the Napa River. Once loaded, a hydraulic model was used to predict the fate and transport of these chemicals and sediment within the Napa River.

The modeling outcome was the baseline characterization of surface water, groundwater, and water quality conditions of 181 sub-basins throughout Napa County. In addition to characterizing existing water quantity and water quality conditions in Napa County, the DHM was used to assess impacts of proposed regional and site-specific changes in land use for the Napa County's General Plan. For each sub-basin, the General Plan provided the recommended threshold of acceptable land development. Results were presented in public meetings and the project report and model data made available at the County Watershed Information Center and Conservancy (WICC) http://www.napawatersheds.org/.

Managing for Climate

Precipitation drives the hydrologic system in watersheds, thus changing climate or drought greatly affect how water is managed. For example, the Okanagan River Basin, British Columbia, Canada receives the preponderance of precipitation in winter. Though the Okanagan Basin currently has sufficient water supply, it is believed that climate change and increased water use may cause future water shortages.[7] In response, the Province of British Columbia and the Okanagan Basin Water Board initiated a project to investigate how projected population growth, agricultural land based expansion, reduction of water supply due to climate change, and mountain pine beetle infestation could affect future water supply and management. A DHM was used to model 23 scenarios of varying projections of population growth, climate impacts, agricultural expansion and irrigation efficiency, and mountain pine beetle infestation. The results showed changes in supply to agricultural land, reduction of water supply due to climate change, and a shift in timing of the spring runoff due to mountain pine beetle infestation and climate change. The DHM results were also used as the inflow time series in a RBM; a model used for rapidly assessing proposed policies and management plans.[8] The Okanagan Basin Water Board used results from both DHM and RBM to plan infrastructure, improve operations, and inform policy decisions.

Drought Planning

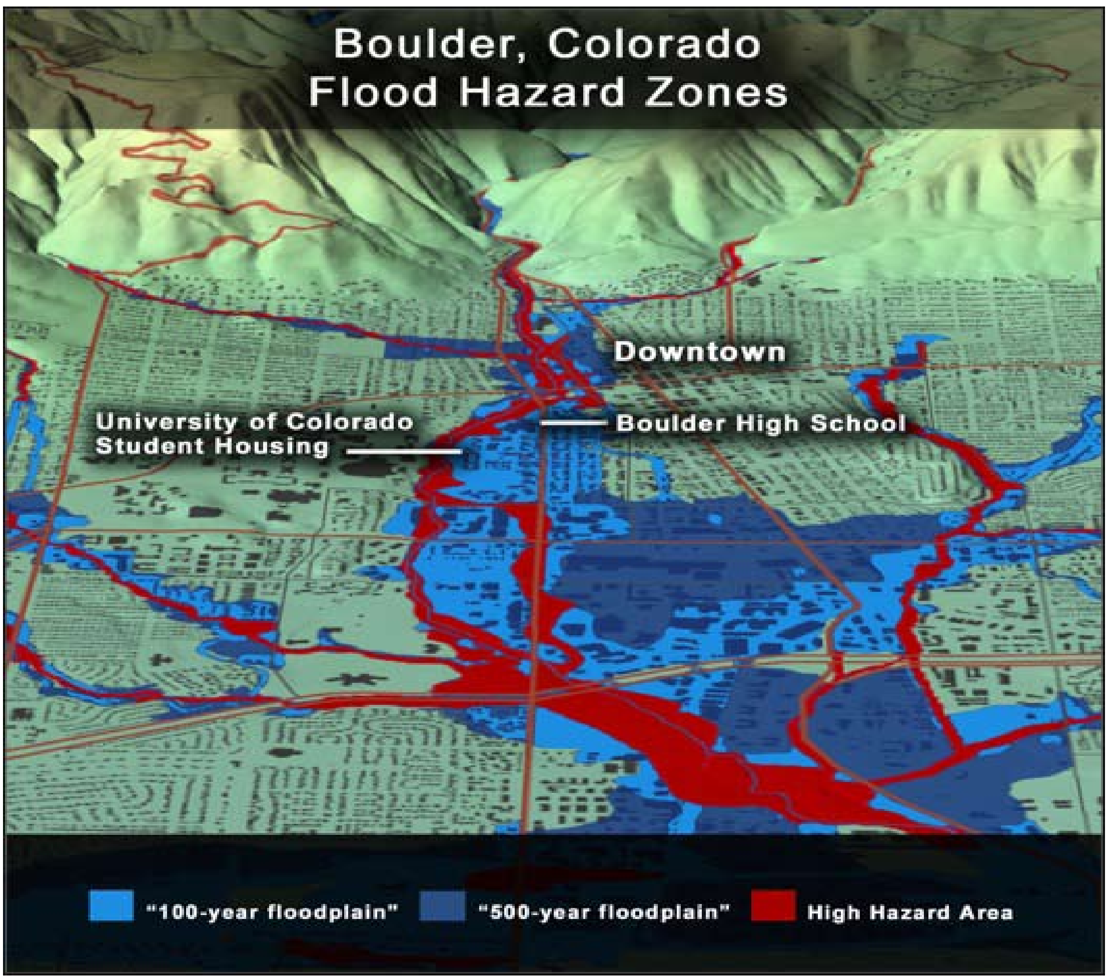
Use of WRS in drought planning is important in creating and testing action plans, reservoir operation strategies, and drought mitigation policies to implement during lean periods of precipitation. California's Central Valley supports 2.8 million hectares of farmland producing crops that are worth 10 percent of the U.S. total cash farm receipts. The irrigation water supply source for farmland is predominately surface water, but is augmented with groundwater during dry periods. Given climate change, there is an increased likelihood of the occurrence of prolonged drought that could have adverse effects on the sustainability of groundwater aquifers and crop production. In order to predict how prolonged drought would impact groundwater supply and crop production, state water managers and federal researchers responsible for water supply in the Central Valley developed CalSim-II (a water allocation and flow model), the California Central Valley Groundwater-Surface Water Simulation Model (C2VSim), and Crop Adaptation Equations derived from the Central Valley Production Model (CVPM).[9] The modeling team ran a series of scenarios with decreased precipitation to determine the impacts on crop acreage, groundwater pumping and level, crop water use, and aquifer recharge. The study found that Central Valley agriculture is resilient to prolonged drought.[9] A 40 percent cut in deliveries to irrigators resulted in only a 10 percent decrease in irrigated area. That said, locally different aquifers within the Central Valley were impacted with varying severity, which could ultimately create locally water stressed areas and may cause land subsidence. State water agencies are using these finding to inform their drought planning efforts.

Flooding

Flooding management has two time horizons: flood planning and real-time flood operations. Planning models are used to develop and map flooding extent, test infrastructure design, and develop emergency action plans to be implemented during flooding events. A model to simulate the hydrologic response to rainfall (rainfall-runoff model) and a coupled 1-D (channel)/2-D (floodplain) hydraulic model were used to generate potential flooding maps of Boulder Creek and South Boulder Creek through the City of Boulder, Colorado, U.S. (Figure 4). The model supported the city's flood mitigation planning,which includes floodplain management and emergency response. Over a five-day period in September 2013, a slow-moving cold front stalled over Colorado, clashing with warm humid monsoonal air from the south and dropping 661 millimeter (mm) of rain in a city that averages 525 mm in year. The 1,000-year event[10] caused extensive flooding throughout the city and surrounding counties. Due to the modeling effort, it is likely that flood damage was significantly reduced during this event.

Real-time operations systems are used to help reservoir and gate operators along with emergency responders determine the flooding timing extent in order to prepare flood defense and evacuate at risk populations. For example, the Bhakra and Beas Reservoirs have been constructed to generate hydroelectricity and supply water to over 40,000 square kilometer (sq km) of irrigated command areas in Punjab, Haryana, and Rajasthan, India, during non-monsoon period and provide downstream flood protection of lives, property, crops, and infrastructure during the

Figure 4. Flood hazard map for Boulder Creek, Boulder, Colorado



Note: The map shows the 100-year floodplain (light blue), 500-year floodplain (dark blue), and high hazard areas as generated from a coupled 1-dimensional/2-dimensional hydraulic model. The map is available for water managers, community planners, and interested stakeholders.[11]

monsoon period.[12] During heavy rainfall periods, operators adjust reservoir gates to increase releases prior to the arrival of a flood wave, creating space in the reservoir in order to retain floodwaters and limit excessive downstream releases. If too little storage water is pre-released, then the flood wave will not be sufficiently retained and downstream flooding will occur. However, if operators release too much storage water in anticipation of a flooding event that does not happen, the remaining storage water will be insufficient to satisfy irrigation demands during the non-monsoon periods. Thus, knowing the quantity and timing of floodwaters arrival to reservoirs improves the operators' abilities to adjust gates to minimize downstream flooding while maintaining sufficient storage to support irrigation during dry periods.

In 2013, a real-time data acquisition system (RTDAS) and a real-time decision support system (RTDSS) were developed for the BBMB system to improve reservoir operations.[12] The RTDAS is a telemetric network of rainfall and snow gages in upstream catchments as well as water levels sensors along rivers, reservoirs and canals that provide inputs to the RTDSS. The RTDSS processes the data and provides decision makers with easily understandable information on the state of their water resources. Flood forecast models within the RTDSS provide predications of the quantity and timing of water discharge that reservoir operators use in gate operations and water managers and emergency responders use to issue flood warnings to downstream communities in order to minimize flood damages. The system is also used to help water managers schedule deliver irrigation water during the Kharif and Rabi seasons. The system has been operated by local officials since 2014.

Groundwater

Groundwater model are used for assessing water quantity and quality issues in aquifers. As groundwater movement is typically much slower than surface water, groundwater models address longer-term planning issues such as inventorying groundwater distribution in aquifers, assessing declining and rising of groundwater levels in irrigated and industrial areas, and identifying of artificial recharge. The Eastern Snake Plain Aquifer (ESPA) extends over a plain 200 miles long by 60 miles wide in southeast Idaho. The aquifer is primarily comprised of fractured basalt lavas with sedimentary interbedded towards the aquifer boundaries[13] and stores 200-300 million acre-foot in the upper 500 feet. The ESPA is the primary drinking water source for many and hosts 809,000 hectares of agricultural lands that, as rainfall ranges between 200-280 mm annually over the aquifer, requires irrigation from surface water diversions and groundwater.[13] The ESPA is hydraulically connected to the Snake River along its eastern and southern boundary, thus groundwater pumping, canal seepage, and irrigation recharge affect river flows that supply water for irrigation, hydropower, industrial, recreation, and ecological use.

Increased groundwater pumping, decreased surface water diversion, increased use of sprinkler irrigation, and changing climate patterns have decreased water levels in the ESPA and flows in the Snake River. To assist in its management, a distributed, hydraulic groundwater model for the ESPA was developed in MODFLOW. The ESPA model has been coupled with a surface water algorithm that simulates how irrigation practices influence groundwater recharge, thus providing a tool for conjunctively managing surface and groundwater. The ESPA model has been used by the Idaho Department of Water Resources (IDWR) to understand the hydrogeological system, delineate areas for water pumping restrictions during dry periods, identify areas to develop recharge zones, and support aquifer planning. A simpler, web-based version of the ESPA model was also developed to assist stakeholders in assessing impacts of water right transfers, saving IDWR staff time in evaluating proposed transfers. IDWR used the model to develop the ESPA Comprehensive Aquifer Management Plan for long-term sustainability of the aquifer.[14] The plan recommends converting 100 kilo acre feet per year (kaf/year) of groundwater use to surface water use; increasing aquifer recharge of 105-205 kaf/year; reducing demand by 250-350 kaf/year by purchasing irrigated land, subordinate agreements, fallowing crop change mixes, and other mechanisms; and conducting a pilot weather modification program such as cloud seeding.

Water Quality

Water quality modeling simulates the fate and transport of chemicals and sediment movement in water systems. Water quality modeling supports planning as demonstrated in the Napa Valley County BDR project where modeling was used to identify and quantify potential pollutant point and non-point sources throughout the county. The City of Bangkok, Thailand is an example of a real-time water quality application. Throughout Bangkok flows the Chao Phraya River and a network of canals that provide drainage, navigation, and conveyance for irrigation water to northern areas. To monitor and forecast water quality conditions in the Chao Phraya River and the main canals, the Bangkok Metropolitan Administration installed a network of 12 real-time monitoring stations.[15] All stations measure water temperature, water level, conductivity, dissolved oxygen, pH and turbidity with select station measuring chemical oxygen demand (COD), nitrate, chlorophyll-A, and trace elements. The real-time monitoring data is transmitted to a RTDSS that allows water managers to visualize water quality conditions and posts conditions on the internet. In addition, water quality models in the RTDSS forecast general water quality conditions and predict the fate and transport of measured chemicals.[14]

Ecological Modeling

Hydro-ecological models assist in understanding and predicting how hydrological conditions influence aquatic and riparian ecosystems and species. Types of hydro-ecological models include aquatic habitat models, agent based models, systems dynamic models, and biologic models. In addition, integrated modeling frameworks link discipline specific models for holistically grasping ecological systems, environmental thresholds (for example, carrying-capacities), and the role of biodiversity in resilience.[16,17] The Ecological Limits of Hydrologic Alteration (ELOHA) is a framework for developing regional environmental flow standards in water resources management.[18] ELOHA uses hydrologic and hydraulic modeling to quantify natural and human altered discharge conditions. Ecologists determine how local species and/or ecosystems respond to a range of discharges. These ecological responses are combined with the natural and altered discharges to determine the flow limiting factors and develop strategies to improve ecological flow conditions.

ELOHA is being applied to the Middle Potomac River (USA) to determine environmental flow needs for rivers and streams that are generally more impaired by land use change than by withdrawals or impoundments.[19] The goals of the project are to:

- Estimate current and future water withdrawals, given population, land use, and climate change projections;
- Determine impacts of water withdrawals, discharges, impoundments, land use, and climate change on flow;
- Characterize flows needed to support healthy biotic communities in smaller streams and rivers; and
- Provide data, information, and analyses to support water and land use planning and decision making at the state level.

To assess flow conditions, the project is using a combination of statistical analysis of gage data and a DHM. Scenario output from the DHM is being post-processed through the Indices of Hydrologic Alteration[20] and the Hydroecological Integrity Tool[21] software to quantify impacts of water management alternatives. The flow alteration-ecological response relationships are being shared with state-level resource managers to support technical assessments and recommendations for protecting and restoring environmental flows and stream health throughout the watershed.

WRS Selection Considerations

WRS selection is a balancing act between complexity of the water resource issue, data availability, computing and technical staff capacity, time, and economic resources. This section provides a brief discussion on the elements and selection criteria to consider when selecting a WRS package to support WRM. A review of individual WRS packages is presented in the *Review of WRS Packages* section below.

Considerations for WRS Selection

Defining the Problem

WRS are intended to support decision-making, thus the WRS type must be selected to address the problems to be addressed. Therefore, the objectives and outputs must first be clearly defined as failure to do so can lead to the adoption of a WRS that does not address the issue or, worse, provides misleading information. Questions to answer include what is the overarching problem, what is causing change, how might the model help in understanding, and what information is needed to make a decision (Table 2). Defining the problem is an important step in identifying how the model will assist water mangers in the business of making decisions, thus making a relevant and useful tool.

Table 2. Questions to address when selecting the WRS model type

Formulating Questions	Example Responses
What is the overarching problem?	The region is experiencing industrial growth. To successfully manage future water supply and demand, a planning report is needed to assess allocation and supply development requirements
What are the pressures driving the change in the hydrologic system?	Industrial production in the basin is expected to increase 25% by the year 2030. Industrial production and employed population will increase water demand for industrial and domestic water sectors
What elements need to be simulated to understand the impact of the water management decision being assessed?	The WRS selected must be able to predict the change in allocation (in time and space) of water in the study area, given changes in domestic and industrial demands. Thus, demand time series need to be editable. To be in compliance with environmental laws, river flows will also need to be reflected in the WRS
What output determines the impact of increasing demand?	Annual delivery, water deficits, instream flows
How will the results be used to address the water resource issue?	Results will be used in planning documents for dissemination within the planning department as well as public presentations to local communities

Planning versus Real-Time Applications

Temporal applicability of WRS types ranges from real-time to long-term planning over decades. As the name implies, real-time WRS assist managers with immediate decisions ranging from minutes to hours. Examples include reservoir operators controlling floodgates, flood warning systems, and irrigation scheme managers allocating water. These simulations need fast solutions as operators and managers do not have time to wait for long simulations to make a decision. Planning applications range from short-term to long-term with short-term simulating several days (operational) into the future and long-term simulating up to hundreds of years (planning). The time horizon of the decisions dictates the WRS selected.

Simulation versus Optimization Algorithms

WRS using optimization algorithms (optimization WRS) are used to determine the maximum benefit or minimum liability given a set of constraints. For example, an optimization WRS could be used to compute the greatest economic output from water allocation to different water sectors. Optimization WRS types are commonly based on optimization algorithms including linear and dynamic programming methods. The limitation with optimization WRS is that assumptions used to formulate and constrain optimization solution can be restrictive. Simulation WRS are more flexible and are used to address "what-if" scenarios. Simulation WRS address what will likely happen at more locations throughout the domain under more varied conditions as they are not as constrained with assumptions as with optimization WRS.

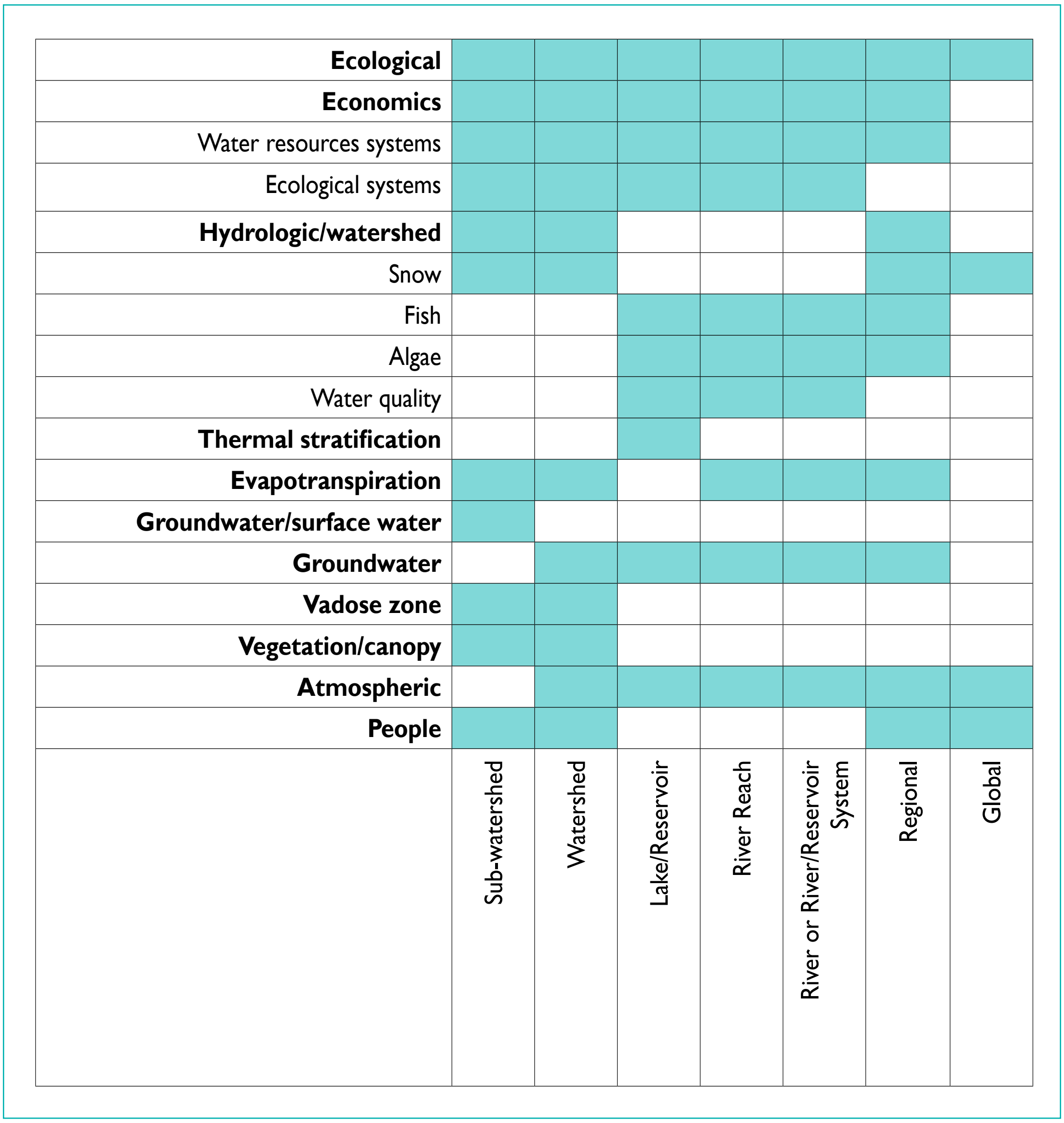
Spatial and Temporal Scales

In WRS consideration, spatial extent (the domain) as well as the internal discretization of processes must be mapped to fit water resource issue complexity, data availability, computational power required, and time and resources available. Domains define what is endogenous and exogenous to the system and include the spatial domain as well as non-spatial elements such as demographic groups, economic sectors, government agencies, and species (Figure 5). The domain extent needs to be large enough to encapsulate the relevant processes, but not so large as to render the system insignificant.[22] For example, if population growth within a watershed is of interest, a reach analysis would be too small as it does not account for development throughout the watershed and a regional analysis would be too large because the watershed population would be lumped into a single figure. For natural resource analyses, the analytical domains are often spatially delineated. For example, hydrologic and ecological processes are tied to the landscape and thus are typically delineated within a watershed boundary. Economic and social systems are generally less directly tied to physical location and thus less likely to follow geographic features.[22]

Different processes operate over different domains within a river basin. How a WRS discretizes the modeling domain to represent the physical processes dictates the issues to be resolved, data requirements, and computer and technical staff capacity required. Often a simpler model can be developed to gain knowledge of the importance of fundamental processes to be considered when modeling with a more sophisticated algorithm, where data is known or missing, and identify spatially and temporally where the limitations in the system occur.

Factors to consider when selecting appropriate temporal scales include the time step and duration of the analysis. Processes operate on different temporal and spatial scales in the fundamental process (for example, computational cell size) and are often linked with finer spatial resolution dictating smaller time steps. Greater variability within a process can also dictate smaller time step length in order to capture rapid change. For example, base flow conditions with constant

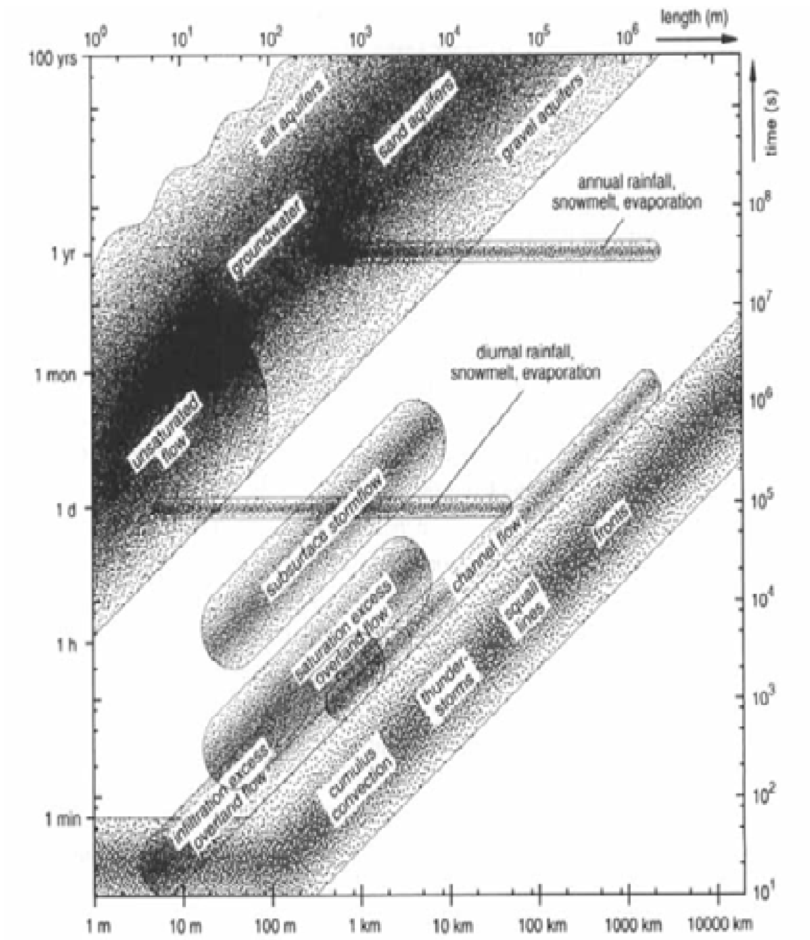
Figure 5. Spatial scales for hydrologic, ecologic, economic systems[23]



flows can be simulated on a daily or weekly basis, whereas flooding events need to be simulated on a minute to hourly basis. In addition, several time scales may be necessary when analyzing multiple processes in a system. For example, in the hydrologic cycle, water movement in a river may be computed on a five-minute time step, the unsaturated zone on a six-hour time step, and the saturated zone on a daily time step (Figure 6). Selecting the fundamental process time step is important for the system's analysis as well as the exchange of data between ecological and socioeconomic systems.

Determining the duration of analysis period includes the disturbance being evaluated and variability of the system. The analysis period needs to encompass both the occurrence and propagation of a disturbance as well as the potential recovery of systems that have been affected.[19] For example, the lag time associated with pumping from a well in an aquifer may

Figure 6. Spatial and temporal scale of meteorological and hydrological systems[24]



not affect river flows until the following year. To account for different conditions that systems may encounter, the analysis period should consider the internal and external variability in driving forces and system behavior. Variability to be considered includes random drivers (for example, annual precipitation amounts) and cycles of processes (for example, decadal cycles in weather patterns).

Important functionality for WRS software is the ability for users to alter input time series and parameters that represent pressures on the hydrologic system and are sensitive to both the changes posed on the hydrologic systems and outcomes to enable decisions. Towards this, conceptual model should be developed to understand the key elements that need to be addressed prior to WRS development.

Parameterization and Measuring Impacts

Output from WRS needs to reflect how the decisions are made towards planning and policy strategies and operations. Therefore, the WRS output must provide relevant results that are easily understandable and pertinent towards the policy or water management scenario being evaluated. WRS outputs are often time series or maps of water quantity and quality distribution within the model domain. To be useful to water managers, these require post-processing to meaningful statistics, graphs, and maps that inform the decision process. For example, in judging the influence of the policy being evaluated, the magnitude and duration of deficits experienced by each city during the scenarios simulation is calculated. In selecting RBM for this application, the software package must generate time series of water delivered to cities throughout the simulation period in order to calculate deficiencies.

Institutional Consideration

WRS is intended to help water managers in their decisions based on information as well as to communicate the results within their organizations and to other agencies, key stakeholders, and the general public. In selecting a WRS, consideration regarding the business, social, and technical infrastructure supporting the WRS must be taken into account. More specifically:

- Business infrastructure focuses on how the software supports the decision making process within the organization used to communicate results. Typical questions involve determining who will define the scenarios to be evaluated, who will use the results, how the WRS supports the decision making process, the communications associated with results, how the software will be maintained and funded, and the measurement feedback on WRS performance;
- Social infrastructure concentrates on the staffing requirements supporting the model. Typical considerations are recruiting, training, and retention of technical staff, as well as contingency plans for staff turnover; and
- Technical infrastructure involves the hardware, facilities, network connection, and technical support available to support the WRS.

Failure to consider these infrastructures when selecting and implementing software can result in limited or failed application of the WRS.

Criteria for Model Selection

The following set of general criteria should be considered when selecting a software package to support the WRM effort. Each application is different in issue complexity, user needs, technical staff capability, data availability, and this specific criterion will have to be further refined and the degree of importance considered for each application. Provided below is a general list to be considered, which may need to be expanded based on WRS' application and purpose.

Software Functionality

Computing Functionality

To be effective, the WRS package being used to address the issue(s) needs to be adjusted to reflect the policies, plans, designs, or conditions to be evaluated; elements of the hydrologic systems (natural and anthropogenic) essential to addressing the issue; and output required to determine the impact of the adjustment (Table 2). Thus, the selected WRS have the following functionality:

- **Input parameters and time series:** In order to test policies, plans, and conditions, the WRS input must be sensitive to the changes to simulate the impacts. For example, if land use change is to be evaluated, parameters such as runoff coefficient, vegetation evapotranspiration rates, and impervious surfaces should be adjustable in the model to reflect changes in the watershed.
- **Simulations:** The constructed system must replicate important components of the hydrologic system. For example, if reservoir operations are important to delivery of water, then these must be simulated in the model

- **Output:** Results must be applicable to the issue being addressed in a format by which water managers typically make decisions. Note, post-processing of raw time-series output may be necessary to present the desired information. WRS should be evaluated if post-processing functionality is available, as it may save time and effort when processing results.
- **Simulation and optimization:** The WRS algorithms tend to support either simulation or optimization. Simulation algorithms are more appropriate for running "what-if" scenarios, whereas optimization algorithms are best for designing systems or optimizing system performance.
- **Complexity:** WRS range from simple to complex representation of the hydrologic, hydraulic, and hydrogeologic systems. In general, the more complex the representation, the more data and computational capacity required. Aspects that define complexity include spatial-temporal scale, modeling domain extent, data requirements, and computational complexity. It is important to note that there is often a tendency to start with a more complex WRS package. However, unless it is very clear that a more complex representation of the hydrologic system is required and that the data to support a more complex model is available, a more prudent method of WRS development is to begin with a simpler model and build complexity when more is known about the system, additional data has been collected, and alternative management solutions are further defined.
- **Automated routines:** Autocalibration, batch and ensemble simulations, pre-processed input data, and post-processed model output are all examples of functionality that make the construction and use of the model easier and more powerful.

User Interface

- **User interfaces:** WRS interfaces range from basic code line prompts to sophisticated graphical user interfaces (GUI). GUIs can greatly expedite model development, simulation execution, and review of output, thus saving time, reducing errors, and reducing human resource usage. A well-designed GUI can lead technical staff through model development and calibrations as well as, depending on the model type, allow individuals unfamiliar with modeling to run simple scenarios and view results.
- **Input data:** Input data is required for model construction as well as developing scenarios. Data used in model construction must be checked, cleaned, and formatted before entering into a model. To expedite this effort, WRS packages can have pre-processing routines. For developing scenarios, input parameter and time series need to reflect the plans, policies, designs, or conditions being evaluated. If a data acquisition system is used, compliance with data exchange protocols should be reviewed.
- **Output format:** Depending on the type of WRS application, the fundamental output can be a time series of points, lines, maps, and animations. The format of the output data can either expedite or limit post-processing, statistical analysis, and use in further analytical models or decision support systems. In addition, post-processing routines within the WRS allow for the automatic calculation of statistics (for example, mean annual flow, map of maximum ground depth, probability of reservoir filling). Output format is very important in presenting meaningful WRS data to support decisions by water managers or communicating with stakeholders and the public.
- **GIS capability:** The ability to use spatial data in model construct as well as display output in relation to other map data is especially beneficial for spatially based issues such as land use change. Functionality for importing, viewing, and exporting GIS data should be considered.
- **Result distribution (web-based, player version):** For modeling applications where stakeholder and public involvement is important, the ability to post results to the internet is

very useful in the dissemination of simulation results. For some WRS packages, a simplified version of the model (a player version) can be distributed allowing stakeholders to control a limited set of inputs to run a select series of simulations and present output in a useful and intuitive display. The player version is very educational for non-modeling water managers and stakeholders and can encourage trust in the model if the results are deemed reasonable.

Additional Software Consideration

- **Licensing cost and maintenance fee:** Proprietary and commercial WRS packages require the purchase of a license. Licensed versions are generally available for either single seat or network licenses, with prices per seat decreasing as more seats are purchased. Prices can differ based on the institution purchasing the software (for example, discounted rates for government or academic institutions). Often, annual maintenance agreements are available for WRS packages allowing access to software updates and limited technical assistance. Non-proprietary and open-source WRS packages do not require users any purchases, but there is a difference between the two. Open-source WRS indicates that the source code for the WRS is available to access, view, and modify. Non-proprietary WRS is free to use (and may need a license), but access to the source code is restricted. If the modeling application is likely to be legally challenged, then non-proprietary WRS packages with restricted access to source code modification is advantageous as the code is known and, thus, investigations of modifications to the underlying computations do not need to be evaluated separately.

  WRS cost should be balanced against functionality and expediting pre-processing, simulation, and post-processing. An inexpensive WRS with limited GUI functionality can require extensive time and effort to format data, calibrate models, formulate scenarios, and run simulations. As such, the cost savings in the aforementioned software purchase may be insignificant when compared to the resources and time to ultimately obtain results. Therefore, the full cost (software plus the effort to obtain results) should be considered in the acquisition and upkeep of the software.

  The intended user group is also a consideration when considering license and maintenance fees. A WRS application that is likely to be used by many departments, agencies, and interested stakeholders is more likely to be widely adopted if the initial cost and maintenance fees are free or inexpensive. For example, flood planning in the United States is primarily conducted using HEC-RAS, freely available hydraulic modeling software. For rivers and streams, the government develops and calibrates "master" flood models in HEC-RAS that are then made available to the public. Individuals interested in simulating flooding for current conditions or proposed development in the channel or floodplain can acquire the "master" model and run analyses in HEC-RAS. As there is no cost barrier for entry, these HEC-RAS models are community-based solutions from which all can evaluate flooding and proposed development. The widespread adoption of these HEC-RAS models has the added benefit of saving regulatory officials time in evaluating the proposed developments as a common WRS is used.
- **Support:** Considerable time can be saved and robust solutions developed if support is available for WRS packages. Types of support include consultation, online support groups, training manuals and classes, and instructional videos. For well-established WRS, this support is often well developed. For newly developed or research software, these support systems are less developed and thus time and effort may be required to learn, apply, and troubleshoot software.
- **Existing application:** Ideally, the WRS has been applied to situations with similar water resource issues; physiographic and hydrologic conditions; regulatory acceptance; and

stakeholder interest. Furthermore, WRS packages that have been in existence for a longer period of time and applied over a wide range of applications are likely to have been vetted both in functionality (for example, free of bugs) and in legal settings. Previous applications of the WRS can provide a roadmap from which to learn during the development and use applying the technology to new water resource issues.

Review of WRS Packages

To identify software packages available for managing India's water resources issues, 22 WRS from 12 software developers were evaluated to provide a high level overview of WRS currently available (Table 3). The software developers include Aquaveo, Colorado State University (CSU), Deltares, DHI Water Environment Health (DHI), eWater, India's National Institute of Hydrology (NIH), Rockware, Stockholm Environmental Institute (SEI), U.S. Army Corps of Engineers (USACE), U.S. Department of Agriculture (USDA), and U.S. Geological Survey (USGS). WRS were evaluated based on computational functionality, user interface ease or use and capabilities,

Table 3. WRS evaluated and their relevance to water resources issues managed in India

Software Developer	Software Package	Water Resources Applications											
		Rainfall-Runoff	Water Allocation	River Flows Routing	General Hydrology*	Reservoir Operations	Irrigation	Flood Mapping	Flood Warning	Groundwater**	Conjunctive Use	Water Quality	Sediment Transport
Aquaveo	GMS	-	-	-	-	-	-	-	-	X	-	X	-
CSU	MODSIM-DSS	-	X	X	-	X	-	-	-	-	-	-	-
Deltares	Delft3D Suite	X	-	X	-	X	-	X	X	-	-	X	X
Deltares	iMod	-	-	-	-	-	-	-	-	X	-	X	-
Deltares	RIBASIM	X	X	X	-	X	X	-	-	-	-	X	-
Deltares	SOBEK v2.14	X	X	X	-	X	-	X	X	-	-	X	X
DHI	MIKE11	X	X	X	-	X	-	X	X	-	-	X	X
DHI	MIKE SHE-MIKE11	X	X	X	X	X	X	X	-	X	X	X	-
DHI	MIKE FLOOD	X	-	X	-	X	-	X	X	-	-	X	X
DHI	MIKE21C	-	-	X	-	-	-	-	-	-	-	X	X
DHI	MIKE HYDRO Basin	X	X	X	-	X	X	-	-	-	-	X	-
eWater	Source	X	X	X	X	X	X	-	-	X	X	X	-
NIH	ReSyP	-	-	-	-	X	-	-	-	-	-	-	-
RockWare	Groundwater Vistas	-	-	-	-	-	-	-	-	X	-	X	-
SEI	WEAP	X	X	X	-	X	X	-	-	-	-	X	-
USACE	GSSHA(WMS)	X	X	X	X	X	X	X	-	X	X	X	-
USACE	HEC-RAS, HEC-HMS, HEC-RESSIM	X	-	X	-	X	-	X	X	-	-	X	X
USDA	SWAT	X	-	X	X	-	X	-	-	X	X	X	X
USGS	MODFLOW	-	-	-	-	-	-	-	-	X	X	X	-
USGS	GSFLOW	X	-	X	X	-	-	-	-	X	-	X	-
USGS	MODFLOW-OWHM	-	X	X	X	-	X	-	-	X	X	X	-
Waterloo Hydrogeologic	Visual MODFLOW	-	-	-	-	-	-	-	-	X	-	X	-

* Simulates the full hydrologic cycle beyond lumped conceptual rainfall-runoff models.
** Simulates groundwater movement using physical equations applied to a discretized grid.

licensing requirements, and software support. The water resource issues considered were water allocation and planning, flood management, groundwater management, conjunctive use,water quality, and sediment transport. Additionally, three DSSs for flood warning were evaluated. This review was based on software vendors' responses to a questionnaire and a desktop review of technical and user manuals, tutorials, and scientific articles related to the WRS. No testing was performed on WRS to validate performance as described in the literature. As WRS applications are unique in hydrologic setting, intended use, and institutional setting, it is recommended that a detailed review of a WRS's functionality and appropriateness for managing the water resources issue be performed before its acquisition.

Water Allocation and Planning

Selection of a WRM model used to support water resource planning is a function of the scale and complexity of the issue to be addressed, acceptable amount of uncertainty, data to support model development, computational capacity, duration of the study, and capacity and availability of the individuals developing, maintaining, and conducting simulations. As stated, types of WRM models used for water allocation and planning range from node and branch models (RBMs) to fully distributed, physically based hydrological models (DHM). RBMs simulate water distribution and use conceptually and therefore require less data, are easier to operate, and experience shorter computational times. However, they are limited in applications that involve impacts of local influences on hydrology. DHMs solve physically based algorithms on a semi-distributed or distributed grid and thus can address more complex, local issues such as land use change. The trade-offs for the increased complexity of DHMs include greater data requirements, increased operational complexity, and considerably more computational time and resources. It is often wise to start with a simple model and build complexity into a WRM model as greater understanding of the issues, hydrologic processes, and available data become revealed. It makes little sense to choose a more complex WRM model if the supporting data, computing power, and technical staff capacity are insufficient to support the increased analytical complexity. Furthermore DHMs and RBMs do not have to be mutually exclusive as both can be applied to provide a more robust solution. For example, a DHM can be used to address fundamental hydrological changes associated with landuse or climate with the RBM incorporating the DHM output to provide a tool for rapidly investigating water distribution and management strategies (see Managing for Climate example). As much of the data used to create a DHM is required for an RBM, the effort to construct a RBM comes in construction and calibration rather than in the arduous task of data collection.

RBMs

The RBM software evaluated includes MIKE HYDRO Basin, MODSIM-DSS, ResSyP, RIBASIM, Source, and WEAP (Tables 4 and 5). A general description of each package is described below:

- **MIKE HYDRO Basin** (DHI) is a multipurpose, map-based decision support tool for integrated water resources analysis, planning, and management in river basins.[25] MIKE HYDRO Basin is designed for analysing water sharing issues at international, national and local river basin levels. This RBM is a comprehensive, easy to use product for those who work in solving water resources and water allocation challenges. MIKE HYDRO Basin compliments the DHI's suite of WRS. MIKE BASIN, the predecessor to MIKE HYDRO Basin, was used in the HP-II DSS (Planning) project. Primary informational sources: DHI vendor response,[25] MIKE HYDRO Basin Technical Manual.[26] Further information regarding MIKE HYDRO Basin can be found at: http://www.mikepoweredbydhi.com/products/mike-hydro-basin[27]

- **MODSIM-DSS** (CSU) is a river basin DSS and network flow model designed specifically for developing improved basin wide and regional strategies for short-term water management, long-term operational planning, drought contingency planning, water rights analysis and resolving conflicts between urban, agricultural, and environmental concerns.[28] Primary informational sources: MODSIM 8.1: River Basin Management Decision Support System User Manual and Documentation.[28] Further information regarding MODSIM can be found at: http://modsim.engr.colostate.edu/[29]

- **ReSyP** (NIH), which stands for *Reservoir Systems Package*, was developed for analyzing reservoir operations.[30] The package includes 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 multireservoir system for conservation and flood control purposes, hydropower analysis, reservoir routing, reservoir sedimentation, and approximation of elevation-area-capacity (EAC) table.[30] NIH developed ReSyP specifically for the management of Indian reservoirs. Primary informational sources: NIH vendor response.[30]

- **RIBASIM** (Deltares) is a generic model package for simulating the behavior of river basins under various hydrological conditions.[31] The software is a comprehensive and flexible tool that links hydrological water inputs at various locations with specific water-uses in the relevant basin. RIBASIM enables users to evaluate a variety of measures related to infrastructure, operational, and demand management as well as see the results in terms of water quantity, water quality, and flow composition. RIBASIM computes water distribution and water balances that provide a basis for detailed water quality, sedimentation, and ecological analyses in reaches and reservoirs. RIBASIM compliments Deltares's suite of WRS. Primary informational sources: Deltares vendor response,[31] RIBASIM Manual.[32] Further information regarding RIBASIM can be found at: https://www.deltares.nl/en/software/ribasim/[33]

- **Source** (eWater) is a river basin and catchment modeling platform with three primary modes of execution: catchment, planning, and "river operations."[34] Across these modes of implementation is a wide range of choices for component model (for example, choice of rainfall-runoff model, nutrient and sediment generation and transport model, groundwater interaction model, crop water use model, and so on) and water management rules (including water sharing rules, resource allocation, environmental flow requirements, and so on). Results of water quantity, water quality, and flow composition are presented in time series plots, plotting data against model, scatter graphs, volume curves, residual mass, and a wide range of statistical tools for analyzing outputs. The full version of Source includes modules for water "Resource Assessment" and "Ownership" to simulate Australian water management practices.[34] Primary informational sources: eWater vendor response,[34] SourceUsers Manual.[35] Further information regarding Source can be found at: http://www.ewater.org.au/products/ewater-source/[36]

- **WEAP** (SEI) operates on the basic principle of a water balance and can be applied to municipal and agricultural systems, a single watershed, or complex transboundary river basin systems.[37] Moreover, WEAP simulates a broad range of natural and engineered components within these systems, including rainfall runoff, base flow, and groundwater recharge from precipitation; sectoral demand analyses; water conservation; water rights and allocation priorities; reservoir operations; hydropower generation; pollution tracking and water quality; vulnerability assessments; and ecosystem requirements. A financial analysis module also allows the user to investigate cost-benefit comparisons for projects.[37] Primary informational sources: SEI vendor response,[37] WEAP User Guide.[38] Further information regarding WEAP can be found at: http://weap21.org/[39]

Computational overview: MIKE HYDRO Basin, MODSIM-DSS, RIBASIM, Source, and WEAP are network models in which the rivers and their main tributaries are represented by a network of branches and nodes (Table 4). Branches represent individual stream sections or canals while nodes represent confluences, diversions, and locations where certain water activities may occur, or important locations where model results are required (for example, diversions, channel bifurcations, gage locations). Supply sources that can be simulated include surface water, groundwater, and reservoirs. Rainfall-runoff models available in each package (except MODSIM-DSS) can be used to compute surface water runoff from precipitation and evaporation records. Demand nodes represent municipal, industrial, reservoir, irrigation, and hydropower water uses (Table 5). All RBMs, including ReSyP, simulate reservoir geometry, infrastructure (for example, gates, canals, spillways), operating rules, and hydropower production. Though these models are primarily surface water accounting models for river basins, they have been applied across a variety of water resource planning issues and are applicable at scales ranging from watershed to transboundary basins.

The primary model inputs to MIKE HYDRO Basin, MODSIM-DSS, RIBASIM, Source, and WEAP are time series data for surface water runoff, diversion, and allocation of water for the off-river nodes. No physical data are required for network construction, though maps are often used in network development as background for spatial representation. Surface runoff is introduced at input or catchment nodes as gage data or simulated hydrologic model results. Water demand time series are required for all nodes representing consumptive water use. For facilitating planning scenarios, WEAP and RIBASIM have calculators that compute the demand from pre-processed modular input, or directly during simulations (for example, if one specifies the number of people and per capita consumption rate, the algorithm generates the demand). Output from MIKE HYDRO Basin, MODSIM-DSS, RIBASIM, Source, and WEAP include maps, time series, and statistics of water availability, movement, and use. MIKE HYDRO Basin, MODSIM-DSS, RIBASIM, Source, and WEAP have additional summary statistical functionality that allows results to be presented by water use sector.

MIKE HYDRO Basin, RIBASIM and Source operate in simulation mode with user defined time steps that are typically single day, 10-day, or monthly (Table 4). WEAP solves optimization simulations based on monthly time steps; MODSIM-DSS solves optimization simulations on monthly, weekly, or daily time steps; and MIKE HYDRO Basin solves optimization simulations on a user defined time step. In the full version, Source has additional functionality to allocate water via modules for water "Resource Assessment" and "Ownership". The Resource Assessment module allows modellers to assess all available water resources for several groups of water users at the start of a water year and, from this assessment, allocate water volumes to all water users using a set of rules. This additional functionality was developed to support Australian water management policies. MODSIM-DSS is adept at simulating complicated, rule-based water allocation such as those found with water rights allocation under the prior appropriation doctrine, storage contracts, rental pools, water service contracts, and exchanges.

Rainfall-runoff algorithms accompany MIKE HYDRO Basin, RIBASIM, Source, and WEAP to predict inflows due to precipitation (Table 4). These algorithms simulate runoff, groundwater recharge, and for some WRMs, contribution to irrigated areas that can thus adjust irrigation requirements. MIKE HYDRO Basin employs NAM (a lumped conceptual model), the Unit Hydrograph Method, SMAP, Urban, Flood Estimation Handbook (FEH), and Discharge River Forecast (DRiFt) to pre-calculate inflow hydrographs at catchment nodes for import to the model. RIBASIM dynamically incorporates the U.S. National Weather Service's Sacramento Soil Moisture

Table 4. General features of MIKE HYDRO Basin, MODSIM-DSS, RIBASIM, Source, and WEAP

Detail	MIKE BASIN Hydro[25,26]	MODSIM[28]	RIBASIM[31,32]	Source[34,35]	WEAP[37,38]
Allocation Algorithm	Simulation, Optimization	Optimization	Simulation	Simulation	Optimization
Time Step	User defined. Typical daily to monthly	Day, week, month	Month, half month, decade, week, day.	User defined. Typical daily to monthly	Monthly
Rainfall-Runoff	Lumped: NAM, Unit Hydrograph, SMAP, Urban, FEH, DRiFt	None	Lumped: Sacramento RR Model Distributed: WFlow	Lumped: Sacramento RR Model, GR4J, SimHYD, SMARG, AWBM	Lumped: Simplified FAO, MABIA, PGM, SMM
Demand Calculator	None	None	Demand calculator dynamically linked	None	Demand calculator dynamically linked
Irrigation	Algorithm based on FAO56	None	• Fixed affirmation demand, • Variable irrigation demand, • DelftAGRI module	Demand computed on soil moisture deficiency	Algorithm based on FAO56
Groundwater	Conceptual Reservoir (Individual)	• None internal • MAPSIM links to MODFLOW	• Conceptual Reservoir (Linked) • Links to MODFLOW	• Conceptual Reservoir • 1-D Groundwater Model, • Links to MODFLOW	• Conceptual Reservoir (Individual) • Links to MODFLOW
Water Quality	• Water Quality Module • ECO Lab Module	None	DELWAQ/WLM Module	• Built-in fully mixed • Built-in particle tracking method	• Built-in • QUAL2k • User plugin
Sediment	Built-in (reservoir sedimentation)	None	RibSERES (reservoir sedimentation)	Dynamic SedNet	• None

Table 5. Evaluation criteria for RBMs to support water allocation and planning

Software Package	GUI Overview (General)							Licensing/ Software Support					Computational Functionality									
	Operating Systems	Workflow Guidance	Pre-Processing Tools	Post-Processing Tools	GIS Interface	Player Version	Animations	Cost	Service Maintenance Agreement	Support	Indian Applications	Worldwide Licenses	Simulation & Optimization	Time Step	Water Demand Calculator	Irrigation Calculator	Groundwater Simulation	Reservoir Simulation	Irrigation Module	WQ Module	Economics	Ecological
RIBASIM	◑	●	●	◑	◑	◍	◑	○	●	●	◑	?	◑	●	●	●	◑	●	●	●	◑	◑
MIKE Hydro BASIN	◑	●	●	◑	●	○	◑	◍	●	●	◑	◑	●	●	◍	●	○	●	●	●	◍	◑
Source	◑	●	●	◑	◑	◍	◑	◑	●	●	○	◑	◑	●	◍	●	●	●	●	●	◑	●
ReSyP	◑	○	○	○	◍	◍	◍	●	◍	◑	◑	◍	◑	○	◍	◍	◍	●	◍	◍	◍	◍
WEAP	◑	●	●	◑	◑	◑	●	◑	●	●	◑	●	◑	○	●	●	◑	●	●	●	◑	◑
MODSIM-DSS	◑	●	◑	◑	◑	◍	◑	●	◍	◑	○	?	◑	○	◍	◍	◍	●	◍	◍	◍	◍

● Best ◑ Good ○ Fair ◍ Poor ? Unknown

Note: Criteria values are defined in Annex Table A1.

Accounting model (a.k.a. Sacramento RR Model) (a lumped conceptual model) or can use WFlow, an open source, command line driven, distributed WRM model to compute effects of land use change within catchments on hydrographs for import into the model.[83] Source provides a variety of lumped conceptual solutions including Sacramento RR Model, GR4J, Simplified Hydrology Model (SimHYD), Soil Moisture Accounting and Routing Model (SMARG), and Australian water balance model (AWBM). WEAP offers the simplified FAO, MABIA, Pasture Growth Model (PGM), and the in-built Soil Moisture Model (SMM). In SMM, effective precipitation is partitioned into evapotranspiration, overland runoff, lateral flows, and vertical flow, by solving an ordinary differential equation for soil moisture. MODSIM-DSS does not have an internal rainfall-runoff module.

Groundwater can be represented using conceptual subsurface reservoirs to illustrate the water available within an area for MIKE HYDRO Basin, RIBASIM, Source, and WEAP (Table 4). All models account for storage, groundwater pumping, groundwater recharge, and base flow to a river network. The lumped conceptual method is effective at assessing the general water availability as a supply source, but cannot be used to evaluate physical groundwater conditions within the area represented by the reservoir. WEAP and MIKE HYDRO Basin represent basins as individual storage reservoirs, while RIBASIM allows for water to be exchanged between subsurface reservoirs thus providing greater flexibility in characterizing subsurface flow. Source has an option to incorporate a 1-D numerical algorithm based on Darcy's law to represent flow in the groundwater system adjacent to, and interacting with a particular river reach. MODSIM-DSS, RIBASIM, Source, and WEAP can be linked to MODFLOW groundwater model for more accurate simulation of the groundwater system (see the Groundwater section). The difficulty and practicality of linking these WRMs with MODFLOW was not evaluated. MODSIM-DSS does not have internal groundwater functionality.

The methods for computing irrigation requirements vary across compared RBMs. In MIKE HYDRO Basin and WEAP, irrigation timing can be determined by soil moisture thresholds, dates, or days since last irrigation based on the FAO56 method. Irrigation amounts can be calculated based on soil moisture thresholds or specified by user. Source computes the irrigation demand based on the daily soil water deficit. RIBASIM has three approaches: 1) fixed irrigation node using explicit time series of net irrigation water requirements and irrigation efficiency; 2) variable irrigation node using explicit time series of gross irrigation water requirements, the actual rainfall time series, and irrigation efficiency; and 3) DelftAGRI which accounts for irrigation requirements based on farming and irrigation practices, physical parameters related to soils and hydro-meteorological characteristics, and crop damage and production costs. Source computes irrigation demand from daily soil water deficit. MODSIM-DSS does not have an internal irrigation module.

All packages, except MODSIM-DSS, have the ability to compute water quality (Table 4). MIKE HYDRO Basin uses ECO Lab, a generic water quality module that allows users to define the water quality algorithm.[25] ECO Lab templates are available for common water quality situations.[40] RIBASIM links with the DELWAQ/WLM[41] to compute water quality. Source offers built-in functionality to account for water quality either as fully mixed, or using a particle tracking method. WEAP has built-in routines for standard water quality parameters and dynamically links to either QUAL2K or a user-defined routine. For sediment, Source incorporates sediment transport and MIKE HYDRO Basin and RIBASIM (using RibSERES) can simulate the impact of reservoir sedimentation.

Finally, RIBASIM, Source and WEAP have economic functionality to assess infrastructure, water demand, hydropower production, and irrigation practices. MIKE HYDRO Basin, RIBASIM, Source, and WEAP can represent environmental demand using a flow requirement at a node. Source has an interface with four rule types for calculating environmental demands. In output, WEAP exports the Indices of Hydrologic Alteration,[20] ecological metrics for estimating impairment to ecosystem based on changes in flow regime.

ResSyP is a package specifically created to assist reservoir operators with reservoir operations specific to needs in India. It takes into account reservoir geometry, infrastructure (for example, gates), operating rules, and downstream demands. Output is in a format that supports reservoir planning and operations in India.

- **GUI:** MIKE HYDRO Basin, MODSIM-DSS, RIBASIM, Source, and WEAP have professional GUIs for data formatting, model development, simulation, and result viewing. These interfaces make changing model inputs to represent water resource scenarios and extracting maps and statistical analyses for displaying outcomeseasy. While free versions are available for Source and WEAP for government officials, no RBM has a "player" versions for distribution to the public with limited functionality; preset scenarios; buttons, dials, sliders, and bars to guide input; and customized output interfaces. WEAP has a Scenario Explorer that allows users to design a group of summary graphs to highlight key system indicators for quick review and comparing of scenarios. While not explicitly developed within MIKE HYDRO Basin, an example of a player version with guided input and a predefined output supporting decision makingis MIKE BASIN embedded within the HP-II DSS(P)[42] software interface. Other packages likely have DSS interfaces to develop player versions.

ReSyP has a simple but functional interface developed in Visual Basic. Input are detailed working tables for each reservoir in the system as well as the time and volume required for meeting different types of demands. Outputs are time series and approximation of EAC tables.

- **Licensing and support:** All RBMs evaluated are proprietary and require a license. At the time of reporting, the prices of the basic license (no additional modules) are:

WRS	Basic Package (lakh INR)	Indian Government (lakh INR)
MIKE HYDRO Basin[25]	2.90	2.90
MODSIM-DSS[28]	0.00	0.00
ReSyP[30]	0.00	0.00
RIBASIM[31,43]	0.00	0.00
Source[34]	1.95	0.00
WEAP[37]	1.95 (2 year license)	0.00

ReSyP, RIBASIM, Source, and WEAP licenses are freely available for government agencies in India. Full priced licenses for MIKE HYDRO Basin, RIBASIM, and Source come with one year of support, and WEAP with two years of support. Additional support can be purchased for an additional fee. All packages have tutorials, reference manuals, and training courses. Contact the software developers for available training courses.

MIKE HYDRO Basin, RIBASIM, and WEAP have been widely used globally as well as in India. In India, MIKE HYDRO Basin (formerly MIKE BASIN) was used to manage water allocation, conjunctive use, reservoir operations, drought, and water quality in nine Indian states as part of Hydrology Project-II DSS Planning.[25,42] RIBASIM was used under Hydrology Project-I to allocate water in the Sabarmati Basin, Gujarat, and the Upper Godavari Basin, Maharashtra; for planning water structures in the Orissa Water Resources Consolidation project; for the analysis of alternative cropping patterns and the introduction of Delft DSS-OMIS software (presently component DelftAGRI) at the Command Area Development Authority and Irrigation Department of the Tungabhadra Irrigation Project; and as a DSS for river basin planning studies to simulate rainfall-runoff, water demand allocations, water quality, and economics for the Mahanadi Basin.[31] Source has been applied in Australia and is being tried within Australian Government funded projects on the Upper Godavari Sub-Basin (in Maharashtra), the Brahamani-Baitarni River Basin, Koshi River Basin, and by the Indian Institute of Technology-Delhi and CWC in the Narmada, Palar, Mahi, and Yamuna Basins.[34] With over 18,000 licenses issued, WEAP has been applied worldwide to assist in water resource planning.[37] In India, WEAP has been used to address water allocation and influence of canals in the Indus and Ganges Basins and in Rajasthan.[37] MODSIM-DSS has been applied to basins in the U.S., the Philippines, South Korea, Egypt, and Brazil.[28] In India, it has recently been applied to the Bhakra and Beas Reservoirs System.[44]

Water Allocation and Planning (RBM) Conclusions: MIKE HYDRO Basin, MODSIM-DSS, RIBASIM, Source, and WEAP support water allocation and planning from a local catchment to international basins, use node and branch network to illustrate flow and use of water, simulate surface and groundwater sources, evaluate demand from multiple sectors, and link with water quality analyses. All can be used to assess a wide variety of water allocation issues on a basin-wide, planning level. None of the applications address changes in water quality and quantity associated with changes in land use, as they are lumped conceptual solutions and not physically based algorithms.

WEAP has been used extensively for optimization problems having over 18,000 licenses with applications in India. For applications interested in optimizing allocation, infrastructure, conservation measures or policy, irrigation, and groundwater, this is the preferred package. With optimization applications with very complicated rule structures, MODSIM should be considered. MIKE HYDRO Basin has both optimization and simulation capabilities, offering flexibility in the algorithm selected.

MIKE HYDRO Basin, RIBASIM, and Source are simulation routines with a wide breadth of capabilities desirable in the India water planning process. RIBASIM incorporates demand calculators into demand nodes for rapidly evaluating population growth, crop changes, and increased industrialization. MIKE HYDRO Basin offers similar functionality minus the economics and demand calculators. Source has more powerful tracking and accounting for water usage in basins, as well as a 1-D built-in groundwater model; however, this functionality is overly complicated for use in most water management decisions in India. Given its widespread use, functionality, ease of use, cost, and support, RIBASIM deserves a good first look in selecting an RBM.

If reservoir planning and operation is the sole focus for the RBM, NIH ReSyP is a good alternative as it supports output tables familiar to reservoir operators in India.

DHMs

As stated, DHMs simulate hydrologic processes on a more detailed, physical basis and thus can be used to assess climate change, land use practices within a watershed or basin, and for several packages, the impact of groundwater recharge and pumping. Five DHM packages were evaluated: GSFLOW, GSSHA (WMS), MIKE SHE, and SWAT (Tables 6 and 7). A general description of each package is given below:

- **GSFLOW** (USGS) is a coupled groundwater and surface-water flow model that integrates MODFLOW and the Precipitation-Runoff Modeling System (PRMS).[45,46] GSFLOW simulates coupled groundwater/surface-water flow in watersheds by simultaneously computing flow across the land surface and within streams and lakes as well as within subsurface saturated and unsaturated materials. Climate data consisting of measured or estimated precipitation, air temperature, and solar radiation, as well as groundwater stresses (such as withdrawals) and boundary conditions are the driving factors for a GSFLOW simulation. The model is appropriate for evaluating effects of land-use change, climate variability, and groundwater withdrawals on surface and subsurface flow for watersheds. Primary informational sources: USGS vendor response,[45] GSFLOW Technical and Methods Report 6-D1.[46] Further information regarding GSFLOW can be found at: http://water.usgs.gov/ogw/gsflow/index.html[47]

- **GSSHA** (USACE), which stands for Gridded Surface Subsurface Hydrologic Analysis, is a physically based, distributed-parameter, structured grid, WRM model that simulates the hydrologic response of a watershed subject to given hydrometeorological input.[48] Major components of the hydrologic cycle simulated in GSSHA include snowfall accumulation and melting, precipitation interception, infiltration, evapotranspiration, surface-water retention, surface runoff routing, channel flow routing, unsaturated zone modeling, and saturated groundwater flow. Typical applications of GSSHA apply to watershed runoff, flash flooding, soil moisture predictions, hydraulic design, determining the effects of wetlands on floods, and land use change. The GUI interface for GSSHA is Aquaveo's WMS software.[49] Primary informational sources: GSSHA Software Primer[48] Aquaveo's WMS website http://www.aquaveo.com/software/wms-watershed-modeling-system-introduction.[49] Further information regarding GSSHA can be found at http://chl.erdc.usace.army.mil/gssha[50]

- **MIKE SHE** (DHI) is an integrated hydrological modelling system for simulating surface water flow and groundwater flow.[25] 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. Primary informational sources: DHI vendor response,[25] MIKE SHEUser Guide.[51] Further information regarding MIKE SHE can be found at: http://www.mikepoweredbydhi.com/products/mike-she[52]
- **SWAT** (USDA) is a river basin scale hydrological transport model that simulates the following components of the hydrologic cycle: weather, surface runoff, return flow, percolation, evapotranspiration, transmission losses, pond and reservoir storage, crop growth and irrigation, groundwater flow, reach routing, nutrient and pesticide loading, and water transfer.[53] SWAT is a public domain model supported by the USDA Agricultural Research Service at the Grassland, Soil and Water Research Laboratory in Temple, Texas, USA. SWAT is used worldwide to quantify the impact of land management practices in large, complex watersheds. Primary informational sources: SWAT Theoretical document,[53] SWAT user software document.[54] Further information regarding SWAT can be found at:http://swat.tamu.edu/[55]

Computational Overview: All packages dynamically simulate components of the hydrologic cycle including evapotranspiration, overland flow, river and lake network, unsaturated zone flow, saturated zone flow, and anthropogenic use (for example, irrigation, ground water pumping, irrigation drains). MIKE SHE and SWAT can also simulate water quality and sediment transport. Differences between these DHMs arise in the algorithm used to simulate the process and the spatial resolution employed. Most DHMs offer multiple algorithms for each hydrological component to match the appropriate complexity level of the water resources issues and data available in simulating the process (Table 6).

GSFLOW, GSSHA (WMS), MIKE SHE, and SWAT use hydrologic response units (HRUs) to compute evapotranspiration, water movement overland flow, and unsaturated zones (Table 6). HRUs are characterized by areas with homogeneous physical characteristics, land use, management practices, and soil types. When combined, the HRUs aggregate to a subwatershed, which then aggregate to form the watershed. In GSFLOW, GSSHA (WMS), MIKE SHE, and SWAT changes in land use or management practices are performed on the HRU through a change in vegetation, soil, or management practices as guided from an extensive documentation on the parameterization.

GSSHA (WMS) and MIKE SHE can also simulate overland flow and unsaturated zone flow using a gridded discretization. For overland flow, both packages solve a finite difference solution and link dynamically with a 1-D hydrodynamic model for simulating the river network (Table 6). For

Table 6. Algorithms and spatial resolution of the hydrologic processes available in the DHMs

Hydrologic Process	GSFLOW[45,46]	GSSHA(WMS)[48,49,50]	MIKE SHE/MIKE11[25,51]	SWAT[53,54]
Evapo-transpiration	Canopy interception, plant transpiration, soil evaporation (HRU*)	• Priestley-Taylor Method (G) • Penman-Monteith with seasonal canopy resistance (G)	Plant transpiration, soil evaporation (HRU*, G)	Canopy interception, plant transpiration, soil evaporation (HRU*)
Overland Flow	3-layer soil model: preferential flow reservoir layer (HRU*)	2-D lateral diffusive wave (G) (options: Explicit, Alternating Direction Explicit, Alternating Direction Explicit with Prediction-Correction	2-D Finite Difference (G)	• SCS runoff (HRU*) • Green-Ampt infiltration equation (HRU*)
Rivers/Lake Network	• Steady-flow and kinematic-wave approaches (1-D), • Diffusive wave approaches (1-D), • Continuity based lake simulation (1-D)	• 1-D longitudinal (options: Explicit, Up-gradient, Diffusive wave) • Lakes: Level pool routing (1-D) • Wetlands: Mixed Darcian and Manning's Flow (1-D)	• Kinematic Wave (1-D), • Steady-state (1-D), • Fully dynamic, 1-D Saint Venant equations (1-D)	• Time of Concentration (HRU*) • Kinematic-wave approaches (1-D)
Unsaturated Zone (UZ)/ Infiltration	3-layer soil model: capillary reservoir layer, gravity reservoir (HRU*)	• Green & Ampt (G) (options: basic, multi-layered, with redistribution), • 1-D vertical Richards' equation (G)	• 2 layer water balance, (G) • Gravity equation, (G) • Richard's equation (G)	3-layer soil model: capillary reservoir layer, gravity reservoir (HRU*)
Saturated Zone (SZ)	3-D Finite Difference (G)	• 2-D lateral Finite Difference (G)	• Linear Reservoir (SD) • 3-D Finite Difference (G)	• Linear Reservoir (SD)
Anthropogenic	Change HRU* parameters for land use, vegetation, nutrient application	• Land use change (G) • Irrigation through precipitation (HRU*, G) • Structure operations (1-D)	• Land use change (G) • Irrigation (SD, G) • Structure operations (1-D)	Change HRU* parameters for land use, vegetation, nutrient application
Water Quality (WQ) Sediment (ST)	Unknown	• WQ: Unknown • ST: Loading: Modified Universal Soil Loss Equation (HRU*). Routing: River/lakes using ST module.	• WQ: River/lakes, UZ, SZ water quality using ECO Lab (G). External program computes loading (HRU*) • ST: Loading: Modified Universal Soil Loss Equation (HRU*). Routing: River/lakes using ST module in MIKE11. (1-D)	• WQ: Extensive computations of chemical processes associated with the storm runoff and return flows (HRU*). • ST: Modified Universal Soil Loss Equation (HRU*)

Note: Spatial discretization is in parentheses: G = gridded, HRU = hydrologic response unit, and 1-D = one dimensional. *Each HRU is assumed to be homogeneous with respect to hydrologic and physical characteristics and to its hydrologic response.*

Table 7. Evaluation criteria for DHMs to support water allocation and planning

Software Package	GUI Overview (General)							Licensing/ Software Support					Computational Functionality							
	Operating Systems	Workflow Guidance	Pre-Processing Tools	Post-Processing Tools	GIS Interface	Player Version	Animations	Licensing/Software Support	Service Maintenance Agreement	Support	Indian Applications	Worldwide Licenses	Surface Water	Overland Flow	Unsatruated Zone	Groundwater	Rainfall-Runoff Link	Irrigation Module	Water Quality	Sediment Transport
MIKE SHE	Good	Best	Best	Best	Good	Poor	Best	Poor	Fair	Best	Good	Good	Best	Best	Best	Best	Good	Best	Good	Good
SWAT	Good	Fair	Good	Good	Good	Poor	Poor	Best	Poor	Good	Best	Best	Good	Good	Good	Good	Best	Good	Best	Best
GSSHA (WMS)	Good	Best	Best	Best	Best	Fair	Best	Poor	Fair	Best	?	Good	Best	Best	Best	Best	Good	Good	Good	Good
GSFLOW	Best	Fair	Fair	Fair	Fair	Poor	Poor	Best	Poor	Good	?	Fair	Good	Good	Good	Best	Best	Fair	Poor	Poor

● Best ◑ Good ○ Fair ● Poor ? Unknown

Note: Criteria values are defined in Annex Table A2.

the unsaturated zone, GSSHA (WMS) uses Green & Ampt (algorithm options include: basic, multi-layered, and with redistribution) to determine infiltration, and a 1-D vertical Richards' equation for computing soil moisture. The unsaturated zone gridded solution in MIKE SHE can use a two-layer water balance, gravity equation, or Richard's equation.

GSFLOW and MIKE SHE employ 3-D finite difference algorithms to simulate groundwater movement. GSSHA (WMS) uses a horizontal 2-D finite difference algorithm to simulate groundwater movement. The finite difference algorithms require data to characterize the subsurface geology and its hydrogeological characteristics. SWAT uses linear reservoirs to predict baseflow contributions to streams. MIKE SHE also can use linear reservoirs if the data to characterize hydrogeological conditions is scant, or if a detailed groundwater simulation is not important for the management issue being addressed.

SWAT's strength is its ability to model and assess the impact of land use and management practices on water, sediments, and agricultural chemicals in irrigation return flows. The model has proven to be an effective tool in assessing non-point source pollution for a wide range of scales and environmental conditions. For MIKE SHE, computations for non-point source loading to the river network, or into the unsaturated zones, are performed with an external calculator that uses hydrologic output from MIKE SHE. A similar tool is available to compute sediment delivery to the river network. MIKE SHE uses ECO Lab,[40] a water quality module for simulating fate and transport in rivers/lakes, unsaturated zone, and saturated zone. For GSFLOW, it is unclear from reviewing the documentation on the water quality and sediment transport capabilities.

GUI Overview: GSFLOW and SWAT historically command line models, but visualization software products for pre-processing and post-processing tools are available through the developer or third party. ArcSWAT has been developed in ESRI's ArcView to support SWAT, MWSWAT, and VIZSWAT are available to visualize SWAT results.[55] GSFLOW uses the USGS ModelMuse and Model Viewer.[45,46] Groundwater portions can be viewed with commercial interfaces, including Groundwater Vistas, GMS, and Visual MODFLOW (see Groundwater Models section). The

GSSHA (WMS) GUI has robust pre-processing and post-processing tools for formatting model input, running simulations, and viewing results. WMS Premium, the version required for GSSHA, also supports HEC-1, HEC-RAS, HEC-HMS, TR-20, TR-55, NFF, Rational, MODRAT, HSPF, CE-QUAL-W2, SMPDBK, and XP-SWMM.[49] MIKE SHE incorporates the DHI suite of pre-processing and post-processing tools and provides a clear workflow for model development, simulation, post-processing, and result visualization. Post-processing tools allow for computation of water budgets, statistics, and animations.[51]

Licensing: GSFLOW and SWAT are public domain software that are free to download and use. GSFLOW GUIs are offered through third party vendors for a fee. The basic MIKE SHE license starts at INR 5.5 lakh/seat for government agencies and INR 7.8 lakh/seat for general purchase excluding the water quality module.[25] With the license fee comes limited support with additional consultation hours available for purchase. The WMS Premium license fee, the version required for running GSSHA, comes for INR 3.7 lakh/seat.[49] All packages have posted their user manuals and tutorials online. Training courses are available for all WRS with listings on the software website.

WRS	Basic Package (lakh INR)	Indian Government (lakh INR)
GSFLOW[45,47]	0.00	0.00
GSSHA[50]	0.00	0.00
GSSHA (WMS)[49]	3.70	3.70
MIKE SHE[25]	7.80	5.50
SWAT[55]	0.00	0.00

SWAT has 30 years of experience and the software's website boasts the publishing of 1,000 peer reviewed articles using SWAT.[53] SWAT was developed to assess the impact of land use and management practices on water, sediments, and agricultural chemicals in irrigation return flows. The model has proven to be an effective tool for assessing nonpoint source pollution for a wide range of scales and environmental conditions.[56] A few applications of SWAT in India include the estimation of water and sediment yield in the Damodar-Barakar basin,[57] mapping of agricultural water productivity in the upper Bhima Catchment,[58] and impact assessment of agricultural water management interventions in Jaldhaka Watershed.[59] Gassman et al.[56] provide an extensive review of SWAT applications.

GSFLOW has been applied by the USGS to simulate surface and ground water hydrology[60,61]as well as climate change impacts,[62] evaluate management alternatives,[63] identify recharge zones in basins,[64] and identify hydrology in a hardrock basin in Spain.[65] The package has also been used to estimate impacts of climate change on stream temperatures.[66] The author is unaware of GSFLOW applications in India.

MIKE SHE has been applied globally for the past 30 years on projects involving a wide range of planning and design applications scaling from local to basin wide,with both surface water and groundwater issues.[25] Applications in India include modelling the impact of irrigation infrastructure on the groundwater regime; studying the impact of waste water on the groundwater quality for the Musi wetland area; using MIKE SHE-MIKE11 to design area drainage and safe ground for the Himavath Thermal Power Station; and assessing impacts of tanks on local groundwater levels in the Vaippar Basin, Tamil Nadu.[ibid]

GSSHA (WMS) has been used around the world for hydrologic and land use projects with applications reported in the U.S., Europe, and the Middle East.[50] The authors are unaware of GSSHA applications in India.

DHM Conclusions: All applications can be used to assess land use change at scales ranging from watershed to basin. SWAT has had numerous applications in India to model water availability, sediment runoff, and water quality (point source and non-point source). For the purpose of evaluating land use and climate changes on stream flow, water quality, and sediment runoff, SWAT is the most widely used of the software evaluated, with many applications and detailed documentation. The downfall is the lumped nature of the HRUs. If land use change within the HRUs cannot be adequately characterized, DHMs using gridded surface algorithms provide a better alternative.

If impacts from land use and management strategies on groundwater are of primary interest, GSFLOW, GSSHA (WMS), and MIKE SHE are more appropriate. MIKE SHE and GSSHA (WMS) offer more capabilities to simulate surface water processes in the routing and operation of water. However, for generalized basin scale changes associated with climate change, GSFLOW is a good option. More detailed operations of surface water networks (for example, canal systems and localized irrigation) are not well suited for SWAT and GSFLOW. MIKE SHE, GSSHA (WMS), and MODFLOW-OWHM (see Conjunctive Use section) are more suitable tools for assessing these applications.

Of the five packages, GSSHA (WMS) and MIKE SHE incorporate the most sophisticated GUI for pre-processing, running simulations, viewing, and post-processing results. The GUIs for these packages guide the workflow making model development straightforward and potentially save time in model development and evaluation of scenarios. If cost is a consideration, GSSHA (WMS) is the more desirable package.

Flood and River Water Quality Management

Flooding in India is a major issue every year, forcing the evacuation of many communities as well as threatening lives and damaging crops, infrastructure, and property. Flood management involves both planning (preventive) and real-time warning (operational response). This section reviews hydraulic WRS for applications and several flood-warning systems to support real-time applications. This section also reviews the water quality and sediment transport simulation capabilities of these hydraulic WRS.

Flood Planning

Flood planning requires WRS to be able to simulate rainfall-runoff, route floodwaters, and compute water levels throughout the river network. Results from the flooding analysis are used to develop inundation maps for different flooding frequencies; develop emergency management plans; establish regulatory guidelines for development (for example, flooding zones); develop operational strategies of dams and other flow control structures; and inform policy makers, stakeholders, and general public of the risk of flooding. WRS software must be able to simulate the propagation of floodwaters as well as effectively map results illustrating the extent of flooding.

In this review, five WRS packages are evaluated that support flood management including Delft3D Suite, HEC-RAS, MIKE11, MIKE Flood, and SOBEK (Table 9). A general description of each package is provided here:

- **Delft3D Suite** (Deltares) is a hydrodynamic model that simulates storm surges, typhoons/ hurricanes, tsunamis, detailed flows and water levels, waves, sediment transport and morphology, water quality and ecology.[31] In addition, the software is capable of handling interactions between these processes. The software can be configured to simulation flow using either a 1-D, 2-D, or 3-D finite difference algorithm. Delft3D is useful for producing local, regional, and multi-regional risk profiles if local risk data are unavailable or of poor quality. Delft3D can be linked to Delft FEWS to perform real-time flood warnings and D-Water Quality for simulating water quality conditions. Primary informational sources: Deltares vendor response,[31] Delft3D FlowUser Manual,[67] D-Water Quality Water Quality and Aquatic Ecology User Manual,[68] D-Water Quality Sediment Water Interaction User Manual.[69] Further information regarding Delft3D Suite can be found at: https://www.deltares.nl/en/software-solutions/[70]

- **HEC-RAS (USACE)** is a 1-D hydraulic model developed by the USACE's Hydrologic Engineering Center to perform hydraulic calculations for natural and constructed channels. Though developed in the U.S., HEC-RAS is used extensively around the world to perform open channel river hydraulics work. The HEC-RAS system contains four 1-D river analyses: (1) steady flow water surface profile computations; (2) unsteady flow simulation; (3) movable boundary sediment transport computations; and (4) water quality analysis. Other applications used with HEC-RAS include HEC-HMS (rainfall-runoff model), ResSim (reservoir simulation model), and FIA (flood impact analyses). HEC-RAS 5.0 Beta includes 2-D hydraulic simulation capabilities, but is not considered in this analysis. HEC-RAS is a component in HEC-WAT system (comprehensive flood planning) and HEC-RTS system (real-time flood warning and systems operations). Primary informational sources: HEC-RAS, River Analysis System, Hydraulics Reference Manual,[71] HEC-WAT Watershed Analysis Tool User's Manual,[72] HEC-RTS/CWMS User's Manual Version 3.0.[73] Further information regarding HEC-RAS can be found at: http://www.hec.usace.army.mil/software/hec-ras/[74]

- **MIKE HYDRO River** (DHI), formerly MIKE11, is a 1-D river modelling software that has been used around the world on application regarding flooding, navigation, water quality, forecasting, sediment transport, a combination of these, or other aspects of river engineering. Modules allow users to expand the simulation capabilities to include rainfall-runoff (RR), water quality (WQ and ECO Lab), sediment transport (ST), structure operations (SO), and dam break (DB). MIKE HYDRO River is dynamically coupled with MIKE21 (a 2-D hydrodynamic package) in MIKE FLOOD, and is the riverine component of the hydrologic cycle in MIKE SHE. MIKE HYDRO River is also used in real-time operations and flood warning systems. Primary informational sources: DHI vendor response,[25] MIKE11 User Manual Manual.[75] Further informationregarding MIKE HYDRO River can be found at: http://www.mikepoweredbydhi.com/products/mike11[76]

- **MIKE FLOOD** (DHI) is a 1-D and 2-D hydrodynamic software package that can be applied to virtually any flood problem, whether it involves rivers; floodplains; street flooding; drainage networks; coastal areas; dam, levee and dike breaches; or any combination of these. MIKE FLOOD dynamically couples MIKE11 and MIKE21(a 2-D flood simulation) to assess flows. In MIKE FLOOD, water quality can be simulated using ECO Lab. The MIKE11 and MIKE21 sediment transport modules can be used independently, but do not apply to MIKE FLOOD. Of note, MIKE21C ST incorporates a curvilinear grid particular suited for sediment transport and river morphologies. Primary informational sources: DHI vendor response,[25] MIKE FLOOD User Manual Manual,[77] MIKE21C ST Manual.[78] Further information regarding MIKE FLOOD can be found at: http://www.mikepoweredbydhi.com/products/mike-flood[79]

- SOBEK (Deltares) is an integrated software package for river, urban, or rural management. Seven program modules work together to give a comprehensive overview of waterway systems that allows users to link river, canal, and sewer systems for a total water management solution. SOBEK incorporates 1-D algorithms for rivers, canals, and sewers, and 2-D for overland flow. Built-in functionality allows users to expand the simulation capabilities to include RR, water quality (1DWAQ, 2DWWAQ, Emissions), sediment transport (1DMOR), and real-time control (RTC). Primary informational sources: SOBEK Technical Manual.[80] Further information regarding SOBEK can be found at: https://download.deltares.nl/en/download/sobek/[81]

Computational Overview: All packages offer 1-D, hydrodynamic simulation for characterizing the flows in rivers and canal systems (Tables 8 and 9). In general, 1-D model are reasonable for rivers with simple floodplain flows and/or simple floodplain topography (e.g. floodplains which only provide storage or flow paths that can be readily predicted). For rivers where flow is more complicated and floodplain topography is known, Delft3D, MIKE FLOOD, and SOBEK have the capability to dynamically couple 1-D and 2-D models which allows the flexibility to model the river in 1-D and floodplains in 2-D.[82] For the 2-D schematization, Delft3D and MIKE FLOOD allow users to employ a flexible mesh for varying the analytical resolution of flow in areas of importance. HEC-RAS 5.0 Beta includes 2-D hydraulic simulation capabilities, however the functionality is still being tested. All packages come with a variety of options to simulate bridges, culverts, dams, gates, pumps, siphons, weirs, and user defined structures. In addition, all packages can simulate operational structures allowing users to vary water control structures with additional logic. Aside from HEC-RAS, these packages require separate modules when simulating operational structures.

Delft3D, MIKE HYDRO River, MIKE FLOOD, and SOBEK are capable of using multicore to decrease computational time. This is important for larger models with more computational points, small time steps, and longer simulation periods. As HEC-RAS is a 1-D code with simpler computational requirements, the ability to access multicores is less important. DHI software are capable of using cloud services to run simulations saving computational time on local resources.

Delft3D, SOBEK, MIKE HYDRO River, and MIKE FLOOD dynamically link with RR modules, allowing for rapid testing of different rainfall events (Table 8). Delft3D and SOBEK dynamically incorporate the U.S. National Weather Service's Sacramento Soil Moisture Accounting model (a lumped conceptual model) or WFlow (an open source, command line driven, distributed DHM model) to compute runoff.[83] MIKE HYDRO River and MIKE FLOOD use NAM (a lumped conceptual model) or the Unit Hydrograph method to pre-calculate inflow hydrographs. MIKE11 is dynamically coupled with MIKE SHE to represent the riverine component of the DHM (see DHM Section). HEC-HMS is a rainfall-runoff module used for computing runoff from precipitation, however, it does not dynamically link to HEC-RAS and thus the pre-run rainfall-runoff results must be transferred for use in HEC-RAS. The transfer can be automated to eliminate manually transferring results between models using HEC-DSS (Data Storage System), HEC-WAT, or HEC-RTS.

All packages have external modules and programs to calculate the flood damages associates to property and infrastructure.

GUI Overview: All software packages have professional GUIs for model development, simulation, and result viewing. Supporting 1-D model construction, model builders in GIS allow users to create and import the model geometry. For 2-D packages, mesh generators are available to aid mesh creation. All packages have internal or modular tools to pre-process the time series and DEM data. In addition, all packages have project management systems to manage files. Of note, HEC-FRA Compute Option and Life-Cycle Cost within HEC-WAT allows users to evaluate uncertainty analysis throughout the entire computation process (rainfall-runoff, hydraulics, food damage impact) using the Monte Carlo Methos.[85]

Creating flood maps and animations is crucial for understanding the flooding extent and conveying its extent to water managers and stakeholders (Table 8). For 1-D applications, HEC-RAS, MIKE HYDRO River, and SOBEK have external GIS programs to build flood maps. For 2-D applications, Delft3D, SOBEK (1-D/2-D) and MIKE FLOOD all have internal mapping features to develop flood maps and animations; 2-D animations are a very convincing format to present flooding results to water managers, interested stakeholders, and the general public.

Licensing and Support: HEC-RAS is a non-proprietary package that requires no license and can be freely downloaded over the Internet. Similarly, Delft3D is open source software for downloading over the Internet, but requires a license that can be acquired through registration

Table 8. Algorithms and functionality of Flood Planning/Warning WRS

Function	Delft3D Flow29,65,66,67	HEC-RAS69,70	MIKE HYDRO River25,72	MIKE FLOOD25,74	MIKE 21C25,75	SOBEK77
Mesh	1-D,2-D,3-D: Curvilinear and sephirical grids	*1-D, Psuedo 2-D with loops *Couple 1-d/2-D (in beta testing)	1-D, Psuedo 2-D with loops	Coupled 1-D/2-D: Cartesian and flexible grid	2-D Curvilinear grid	*1-D, Psuedo 2-D with loops *Coupled 1-D/2-D: rectilinear grid
Discretization	Finite Difference	Finite Difference	Finite Difference	Finite Difference	Finite Difference	Finite Difference
Rainfall-Runoff (RR)	*Sacramento RR Model *WFLOW	HEC-HMS	*NAM, Uniti Hydrograph, SMAP, FEH, DRiFit *MIKE SHE	*NAM, Uniti Hydrograph, SMAP, FEH, DRiFit *MIKE SHE	NAM, Uniti Hydrograph, SMAP, FEH, DRiFit	*SOBEK RR Model *Sacramento RR Model
Structure Types/ Logic Structures (LS)	*Barrier, bridge, culvert, deflection wall, floating structure, gate, weir, user defined *LS: Delft3D (RTC)	*Bridge, culvert, dam, gate, pump, siphon, weir, user defined *LS: Rule structure	*Bridge, culvert, dam, gate, pump, siphon, weir, user defined *LS: Structural Operation (SO) Module	*Bridge, culvert, dam, gate, pump, siphon, weir, user defined *LS: Structural Operation (SO) Module	*Barrier, bridge, culvert, deflection wall, floating structre gate, pump, siphon, weir, user defined *LS: Structural Operation (SO) Module	*Barrier, bridege, culvert, deflection wall, floating structure, gate, weir, user defined *LS: Delft3D (RTC)
Output	*Water levels, water surface profiles, flow velocity, flow quantity *Flood maps *2-D animations *Frequency analysis	*Water levels, water surface profiles, flow velocity, flow quantity *Flood maps (GEO-RAS) *Frequency analysis (HEC-SSP)	*Water levels, water surface profiles, flow velocity, flow quantity *Flood maps *Frequency analysis	*Water levels, water surface profiles, flow velocity, flow quantity *Flood maps *2-D Animations *Frequency analysis	*Water levels, water surface profiles, flow velocity, flow quantity *Flood maps *2-D Animations *Frequency analysis	*Water levels, water surface profiles, flow velocity, flow quantity *Flood maps *Frequency analysis
Program Manager (PM)/ Real-Time (RT)	PM/RT: Delft-FEWS	*PM: HEC-WAT *RT: HEC-RTS	*PM: MIKE HYDRO Interface *RT: MIKE 11 RT	*PM: MIKE HYDRO Interface *RT: MIKE 11 RT	PM: MIKE HYDRO Interface	PM/RT: Delft-FEWS
Water Quality	D-Water Quality Module (Formerly DELWAQ)	Built-In	Advection-Dispersion (AD) Module, ECO Lab Module	Advection-Dispersion (AD) Module, ECO Lab Module	Advection-Dispersion (AD) Module, ECO Lab Module	SOBEDK 1DWAQ
Sediment	DELFT3D-Sed Module	Built-In	Sediment Transport (ST) Module, Advection Dispersion (AD) Module	None	Sediment Transport (ST) Module, Advection Dispersion (AD) Module	Bulit-in (limited functionality)
Ecological	Delft3d-ECO Module	HEC-FIA	ECO Lab Module	ECO Lab Module	ECO Lab Module	None

Table 9. Evaluation matrix for the flood planning WRS.MIKE21C not include for flooding analysis

Software Package	GUI Overview (General)								Licensing/Software Support					Flood Planning								
	Operating Systems	GUI Interface	Workflow Guidance	Pre-Processing Tools	Post-Processing Tools	Error Checking	Animations	3D viewing	Cost Software	Service Maintenance Agreement	Support	India Application	Worldwide License	1D Computation	1D Model Builder	2D Computations	2D Mesh	Structures	Multicore Processing	RR Linkage	Flood Mapping	Flood Impact Calculator
Delft3D Suite*	●	●	●	●	●	●	●	●	●	○	●	●	●	●	◑	●	●	●	●	●	●	Poor
MIKE 11	◑	●	●	●	●	●	●	●	Poor	○	●	○	●	●	◑	Poor	Poor	●	Poor	●	◑	◑
MIKE FLOOD	◑	●	●	●	●	●	●	●	Poor	○	●	○	●	●	◑	●	●	●	●	●	●	◑
HEC - RAS	◑	◑	●	●	●	●	○	Poor	●	Poor	◑	●	●	●	◑	Poor	Poor	●	Poor	◑	◑	◑

● Best ◑ Good ○ Fair Poor

Note: Criteria are defined in Annex, Table A3.

with Deltares.[31,67] When downloaded as open source code, Delft3D must be compiled before using the software; a task that can be complicated depending on the computer's configuration. A fully compiled version is provided with the purchase of the Basic Service Package that costs INR 2.4 lakhs.[31] Non-proprietary water quality and sediment transport modules are available for both packages.

MIKE FLOOD, MIKE HYDRO River, MIKE21C, and SOBEK are proprietary hydraulic WRS that require the purchase of a license.

WRS	Basic Package (lakh INR)	Indian Government (lakh INR)
Delft3D[31]	Uncompiled: 0.00, Compiled: 2.4	Uncompiled: 0.00, Compiled: 2.4
HEC-RAS[74]	0.00	0.00
MIKE HYDRO River[25]	0.00 – 12.9+	0.00 – 12.9+
MIKE FLOOD[25]	Single: 9.7, Network: 24.2	Single: 6.8, Network: 15.76
MIKE21C[25]	Single: 6.6, Network: 16.4	Single: 4.6, Network: 10.7
SOBEK[44]	Single: 2.3+	Single: 2.3+

In India, the basic SOBEK license is INR 2.3 lakh/seat with INR 2.1 lakh/seat for continued annual maintenance support.[43] Network options and hydrology and water quality modules add additional fees. A single seat for the hydrodynamic module of MIKE HYDRO River requires no license, but only comes with very limited capabilities. Versions having greater capacity than the limited version and/or the use of add-on modules require additional fees. For example, the MIKE Hydro River DA Enterprise package which includes four seats of the MIKE11 HD, SO, DB, RR, Advection Dispersion, Auto-calibration, MIKE SHE including 2D overland flow, and Data Assimilation modules costs INR 12.9 lakh.[25] For basic government licenses, MIKE FLOOD for a single seat and INR 15.76 lakh for a network license with optional annual maintenance agreement of INR 2.8 lakh.[25] Modules for simulating rainfall-runoff, water quality, and sediment transport are available at an additional cost for MIKE FLOOD and SOBEK (excluding DELWAQ, which is free). All packages are supported with manuals, tutorials, training courses, and user groups. Training courses and consultancy support is available for an additional fee. The USACE does not provide training courses for HEC-RAS, but third party private and educational firms provide these courses.

All packages have applications in India. The USACE does not consult on projects in India, and therefore, the authors are unaware of number of HEC-RAS applications in India. However, a quick Internet search of HEC-RAS use in India revealed numerous instances of flood modeling and dam break analysis (for example, Lower Tapi River,[86] Mahanadi River,[87] Somb River,[88] Godavari River[89]). In India, Delft3D has primarily been used in 2-D coastal applications of Andhra Pradesh and Tamil Nadu; in Bangladesh it has been used in the Surma River.[31] MIKE FLOOD has been applied for DB analysis for the Ukai Dam and mitigation planning for the downstream Kakrapara weir.[25] MIKE HYDRO River (MIKE11) has been used for evaluating flood risk and determining the safe guard level at the Himavat Thermal Power Plant.[25] SOBEK was used in the Burhi-Gandak, Bihar and Brahmani-Baitarani, Odisha to examine integrated flood management under climate change.[90]

Flood Planning Recommendation: All packages support flood planning and mapping. For systems with simple hydraulics and limited data, HEC-RAS, MIKE HYDRO River (MIKE11) and SOBEK are best applied. Given the widespread use, user-friendly GUI interface, non-proprietary status, and large user community, HEC-RAS is the recommended tool for assessing flood planning in simple systems.

For more complicated systems and where floodplain topography is known, Delft3D Flexible Mesh, MIKE FLOOD and SOBEK are applicable. MIKE FLOOD and SOBEK offer 1-D/2-D modeling of river and floodplain that can provide a more efficient computational solution but have licensing fees for governments of INR 6.8 and 2.3 lakh/seat, respectively. Budget, user familiarity, and support should be considered when choosing between these packages. Delft3D Flexible Mesh is primarily a 2-D/3-D code and thus better suited for 2-D flood mapping, though it can be employed using a 1-D grid. Once HEC-RAS 5.0 has been officially released, the software will handle these complicated systems and be available as a non-proprietary, freely downloadable option to MIKE FLOOD and SOBEK.

Flood Warning

Real-time flood warning systems (RTFWS) require the automation of retrieving and verifying the quality of hydrometeorologic data; incorporation of the data into hydrologic and hydraulic models; determination of the magnitude and timing of flooding; and dissemination of warnings to water resources managers, emergency personnel, hydraulic structure operators, interested stakeholders, and the public. In addition, a RTFWS allows water resource managers to quickly and efficiently test alternative scenarios for managing flooding events. Specific functionality required in RTFWS includes:[91]

- *Data Acquisition and Storage.* The RTFWS automates data collection, verification and storage from real-time sensors, radar information, forecasts, and other data sources. For sensor data, the RTFWS provides quality checks to determine if the values received are within reason and not a function of an erroneous sensor reading. If data signify a potential event, the system can trigger flooding analysis as well as a warning. Real-time and historic data are stored for viewing, analysis, and dissemination.

- *Simulation Models*. Within the RTFWS, WRS are used to predict future conditions and run alternative scenarios. RR models are used to predict the inflows from given precipitation events. Hydraulic models are used to predict flood propagation downstream, providing a prediction of magnitude and timing of waterelevations and volumes. Finally, algorithms are used to simulate the effects and operations of major hydraulic structures, such as reservoirs, which influence river flows. As timing is critical when managing a flooding event, these WRS need to be fast, yet detailed enough to provide relevant information for use in determining scenarios.

- *DSS*. Software is employed for coordinating the data acquisition and validation, providing a means of viewing and evaluating the data, coordinating the transfer of data, controlling simulation runs, and disseminating warnings to water managers, stakeholders, and the public. The DSS must be powerful in capabilities, but not overly complicated to operate, as important decisions are made quickly and efficiently during flooding events. Viewing capabilities need to be customized to fit the varying conditions, as well as the need of the individuals and organizations using the information.

Though RTFWS are designed for assisting in flood management, the data collected, analytic capabilities, and viewing and process functionality make them valuable tools for water management beyond flood warning systems.

Several RTFWS developed to support flood warning systems incorporating these principles are available. The RTFWS reviewed include Delft FEWS, HEC-R RTS, and MIKE11Real-Time Enterprise Package (MIKE11 RT). A general description of each system is given below:

- **Delft FEWS** (Deltares) provides an open shell system for managing forecasting processes and/or handling time series data. The software incorporates a wide range of general data handling utilities, while providing an open interface to any external forecasting model. The modular and highly configurable nature of Delft FEWS allows it to be used effectively for data storage and retrieval tasks, simple forecasting systems, and in highly complex systems utilizing a full range of modeling techniques. Delft FEWS can either be deployed in a standalone, manually driven environment, or in a fully automated, distributed client-server environment. Primary informational sources: Deltares vendor response.[31] For information regarding Delft FEWS, please visit: https://www.deltares.nl/en/software/flood-forecasting-system-Delft FEWS-2/[92]

- **HEC-RTS** (USACE) is the public version of USACE's Corps Water Management System (CWMS) – Control and Visualization Interface (CAVI), a comprehensive data acquisition and hydrologic modeling system used for short-term decision making regarding water control operations in real-time to support the water control management mission. HEC-RTS accompanies HEC's suite of software that encompasses data collection, validation and transformation, data storage, visualization, real-time model simulation for decision-making support, and data dissemination. HEC-RTS is the publicly available, PC version that runs independently of the CWMS database. Primary informational sources: HEC-RTS/CWMS User's Manual Version 3.0 – Draft.[73] For information on HEC-RTS go to: http://www.hec.usace.army.mil/software/[93]

- **MIKE11RT** (DHI) is a subset of DHI software that has been combined into a RTFWS. The suite includes a database, rainfall-runoff model, hydraulic model, data assimilation functionality, and DSS system for viewing data, running simulations, and disseminating information. MIKE11 RT has been implemented around the world with several applications in India. Primary informational sources: DHI vendor response.[25] Information regarding MIKE11 can be found at: http://www.mikepoweredbydhi.com/products/mike11[94]

Computational and GUI Overview: All RTFWS include a DSS that allows coordination between monitoring data, external forecasts, and simulation models to provide customized output. To display conditions in space and time, all systems have map-based capabilities and link to databases for a viewing of time series and capabilities to disseminate warnings to water managers and emergency personnel. All systems require customization as each project has different conditions and different audiences. The differences between these RTFWS are the databases they support, WRS they incorporate, cost, and external support available for customization and implementation.

Delft FEWS is a collection of standard displays, modules, and plug-ins that connect with external databases and models to form a forecasting system. Delft FEWS is model agnostic in that it uses model adapters to connect to a large range of hydrologic, hydraulic, and groundwater models. Delft FEWS supports over 175 import formats and is able to export data in more than 60 export formats.Within Delft FEWS, an Application Programming Interface (API) allows users to develop their own Java plugins for imports, exports, displays, statistical functions, and transformations. The Delft FEWS interface provides advanced graphical and map-based displays. Forecast results can be disseminated through configurable HTML formatted reports, allowing communication to relevant authorities and public through intranet and internet. Standard output formats such as HTML formatted reports are available and can be customized to specific user requirements.

HEC-RTS is an integrated system that begins with the reception of hydro-meteorological data that is then processed, stored, and made available through a user-friendly interface to the water manager for evaluating and modeling hydrologic conditions within the watershed. For incorporating simulation models, HEC-RTS supports the use of HEC software and other products developed by the USACE. HEC-HMS is used to compute runoff based on gaged or radar-based precipitation, quantitative precipitation forecasts (QPF), and other future precipitation scenarios that provide forecasts of uncontrolled flows into and downstream of reservoirs. For loading data into HEC-HMS, HEC-Meteorologic Forecast Processor (MFP) processes meteorological forecasts and HEC-MetVue processes observed precipitation and temperature. Outputs are forecasted meteorological time series formatted for compatibility with HEC-HMS. Slider adjustment options in HEC-HMS allow for more rapid calibration.[91] Data assimilation functionality is used to adjust model input to reflect current conditions from real-time sensor (for example, rain gages, stream levels). Reservoir operations simulations use either HEC-ResSim or CADSWES's RiverWare. HEC-ResSim uses rule-based description of the operational goals and constraints that reservoir operators must consider when making release decisions. River hydraulics uses HEC-RAS to compute river stage and water surface profiles. An inundation boundary and depth map of water in the flood plain can be calculated from the HEC-RAS results using ArcInfo. Economic impacts of different flow alternatives are computed by HEC-FIA. Model and processed data can be displayed and disseminated in tabular, graphical, and/or geo-spatial formats, resulting in an effective DSS.

MIKE11 RT uses DHIs SCADA and geodatabases to receive, verify, store, and disseminate sensor, radar, and forecast data. For predicting inflows, MIKE11 RT uses NAM, a lumped conceptual algorithm solving moisture conditions and water balance in the surface water system, including overland, unsaturated, and saturated zones. As input to NAM, MIKE11 RT supports observed data (precipitation, temperature), remotely sensed data, and forecasts. To route flows through the river systems and simulate reservoir operations, MIKE11hydrodynamic and structural operations modules are employed. The data assimilation model is used to adjust model input to reflect current conditions from real-time sensor (for example, rain gages, stream levels). A DSS interface coordinates the modeling and allows users to view sensor data, maps, and simulation results in standardised or customized interfaces.

Licensing and Support: The Delft FEWS software is open source and freely available for download.[31,92] Deltares supports FEWS through consulting services and has a field office in Delhi to support the Ganges Rejuvenation Project. HEC-RTS and all of the supporting software are public domain and free for download. Similar to HEC-RAS, the USACE does not provide training courses for HEC-RTS, but third party private and educational organizations provide courses and international consulting firms with water management experience using HEC-RTS have offices in India.[94] MIKE11 RT costs INR 16 and 26.6 lakh for a single seat and network license, respectively.[25] For government agencies, these are reduced to INR 11.2 and 17.3 lakh, respectively. Academic and research firms can get a single seat for INR 8.0 lakh and a network license for INR 13.3 lakh.[ibid] Annual software maintenance agreements are available for MIKE11 RT. To support applications, DHI has offices in India.

In India, MIKE11 RT has been the most widely used RTFWS. Applications include real-time stream flow forecasting and reservoir operation system for Krishna and Bhima Basins in Maharashtra, flood forecast and inundation modeling system in the Bagmati-Adhwara Basin, Bihar, flood forecasting and early warning system for Brahmaputra in Assam, and real-time DSS for operational management of the Bhakra-Nangal and Beas Reservoirs in Northwest India.[25] In addition to India, MIKE11 RT has been applied worldwide to assist in flood management. Delft FEWS has been an operational flood forecasting tool in basins in the United States, England, Wales, Scotland, Ireland, Netherlands, Germany, Austria, Spain, Italy, Switzerland, Taiwan, Pakistan, the Zambezi basin, Ghana, Canada, Colombia, Indonesia, Bolivia and by the Mekong River Commission.[31] In India, it is currently being used to coordinate the Ganga Rejuvenation Project. HEC-RTS and CWMS have been used extensively in the United States for operational water management and applied to the BBMB system.[94]

Flood Warning Recommendation: All RTFWSs evaluated have DSS interfaces that link with databases and simulation modeling to support flood management and have been used in flood warning systems. Choice of RTFWS then depends on supporting simulation models, technical support, and license fee.

Delft FEWS is a versatile software allowing for a wide variety of simulation models to be used, including existing models in a basin. Deltares and third party consultancy organizations can provide support for the application of both RTFWSs in India. Delft FEWS is free for government agencies.

HEC-RTS employs a full suite of public domain software, including HEC-HMS, HEC-ResSim, HEC-RAS, HEC-FIA, HEC-MFP, HEC-MetVue, HEC-QFP, which are used to successfully manage water resources both in India and worldwide. HEC-RTS and supporting simulation models are public domain software that require no licensing fee, and thus should be considered when selecting a RTFWS under budgetary considerations.

MIKE11 RTuses MIKE11 and NAM, two programs that have been used throughout India. DHI offices in India provide support for the RTFWS and have experience implementing it in four river basins around India. The primary limitation with MIKE11 RT is the license fee; however, if budgetary constraints are not of great significance then, MIKE11 RT is a proven tool in India. If budgetary constraints are a significant factor in RTFWS selection, Delft FEWS and HEC-RTS should be considered.

Water Quality and Sediment Transport

Though typically not considered in flooding events, all of the hydrodynamic model packages have the capability to simulate water quality (Tables 8 and 10). Delft3DD-Water Quality module and SOBEK 1DWAQ simulates many water quality variables and their related water quality processes. These modules are highly flexible due to the many standard options as well as user-defined options, and have a library of 900 processes and substances, including eutrophication, adsorption, desorption, nutrients, bacteria, oxygen, phytoplankton, heavy metals and micro-pollutants. The interactive processes editor allows users to select the water quality variables and processes to be modeled. Pre-defined sets of water quality variables and processes can be used for particular problems or for the purpose of following the standard set of rules and regulations for a specific region. To analyse the origin of pollutants in any water system, fraction computations make it easy to trace water or a certain pollutant from to its source throughout the network. The software displays mass balances and is fully integrated with the standard Delft3D and SOBEK interfaces.

HEC-RAS incorporates the QUICKEST-ULTIMATE explicit numerical scheme to solve the 1-D advection-dispersion equation using a control volume approach, with a fully implemented heat energy budget. Transport and fate of a limited set of water quality constituents are available in HEC-RAS. The currently available water quality constituents are: dissolved nitrogen (NO3-N, NO2-N, NH4-N, and Org-N); dissolved phosphorus (PO4-P and Org-P); algae; dissolved oxygen (DO); and carbonaceous biological oxygen demand (CBOD).

In MIKE HYDRO River, MIKE FLOOD, and MIKE21C, water quality is calculated through an Advection-Dispersion module or ECO Lab, an open-ended ecological and water quality modeling framework that allows for user-defined equations and water quality models to be defined. The Advection-Dispersion module simulates the fate and transport of standard suite of chemicals and ECO Lab permits the user to simulate the fate and transport of chemicals using user defined equations, ecological processes, agent-based modeling, or other hydraulic influenced processes. ECO Lab templates are available for standard water quality parameters. Both the Advection-Dispersion module and ECO Lab are available for an additional fee. All packages, aside from SOBEK, have modules that specifically conduct ecological analyses (Table 8).

All packages, except MIKE FLOOD, have functionality to compute sediment transport (Table 8). HEC-RAS, MIKE HYDRO River ST, and SOBEK compute 1-D sediment routing of the total load. HEC-RAS and MIKE HYDRO River ST enable equations to calculate suspended sediment and bedload transport loads, compute graded sediment transport (multiple size fractions), and predict changes in riverbed elevation due to erosion or deposition (morphological mode). MIKE HYDRO River can also compute cohesive sediment transport using the AD module. When MIKE HYDRO River is coupled with MIKE 21 in MIKE FLOOD, sediment transport is not an option.

From the 2-D codes, Delft3D D-Water Quality, MIKE21 ST, and MIKE21C ST have multiple equations to compute total load, suspended load, and bedload transport. These models can compute both cohesive and non-cohesive sediment and can simulate morphological changes associated with erosion and deposition. MIKE21 ST and MIKE21C ST also simulate graded sediment classes, which better simulate transport in gravel bed rivers. In riverine environments, Delft3D (curvilinear mode) and MIKE21C ST are specifically tailored for morphology applications through the use of a 2-D curvilinear grid for river flow modelling. These packages simulate bank erosion, scouring and shoaling brought about by activities such as construction and dredging, and seasonal fluctuations in flow. For long stretches of rivers with many grid cells (computational points), neither package is computationally practical.

Table 10. Evaluation matrix for the water quality and sediment transport WRS

Software Package	Water Quality: Processes	Water Quality: Water Quallity CoCs evalauted	Water Quality: HD -WQ Linkage	Water Quality: Customizable	Water Quality: Ecological Module	Sediment Transport: HD -ST Linkage	Sediment Transport: Transport Types	Sediment Transport: Non-Cohsive, Cohesive	Sediment Transport: Available ST Equations	Sediment Transport: Morphological Mode	Sediment Transport: Size Fractions
Delft3D Suite	Best	Best	Best	Best	Best	Best	Best	Best	Best	Best	Poor
MIKE 11	Best	Best	Best	Best	Best	Best	Best	Best	Best	Best	Best
MIKE FLOOD	Best	Best	Best	Best	Best	Poor	Poor	Poor	Poor	Poor	Poor
MIKE 21C	Best	Best	Best	Best	Best	Best	Best	Best	Best	Best	Best
HEC - RAS	Best	Fair	Best	Fair	Best	Best	Best	Best	Best	Best	Best
SOBEK 1D	Best	Fair	Best	Poor	Poor	Best	Fair	Poor	Fair	Poor	Poor

Legend: Best, Good, Fair, Poor

Note: Criteria are defined in Annex, Table A3.

Gravel dominated rivers provide additional challenge when simulating sediment transport. Delft3D D-Water Quality has been used to predict coastal sediment transport, where sand transport dominates, but has very limited applications in gravel bed rivers.[97] The authors are unaware of riverine applications in India. MIKE21C ST has been used in river systems worldwide for both sand dominated and gravel bed rivers.[98] In India, MIKE21C ST has been applied to the Master Plan for Flood and Sediment Management in Kosi River Basin, Amochhu Flood Management and Land Reclamation Project, Integrated Flood and Riverbank Erosion Risk Management Project in Assam, Morphological Study of Vansadhara River, and Design of Bank Protection Measures at Narmada River Crossing.[25] The sediment transport module is an additional fee in MIKE21C ST.

Water Quality and Recommendation: For standard analyses, all packages simulate water quality as a module in the software. For constituents not included in the HEC-RAS simulations, either Delft3D D-Water Quality Module; MIKE HYDRO River, MIKE FLOOD, or MIKE 21C with ECO Lab; or SOBEK 1DWAQ provide greater options. The choice of water quality model should be made with regard to the hydraulic model selected.

Riverine Sediment Transport Recommendations: For 1-D applications, HEC-RAS and MIKE HYDRO River ST have multiple sediment transport equations from which to choose, can simulate mobile boundaries to account for aggradation and erosion along a bed, and can account for graded sediment. These are effective in simulating the loading of sediment to reservoirs from a watershed. Of these, HEC-RAS is the top choice due to the price point. If cohesive sediments are to be considered, MIKE HYDRO River ST should be considered.

For 2-D applications, Delft3D D-Water Quality and MIKE21C ST can be used for sediment management, channel design, and bank erosion in riverine settings where bed and banks are mobile, and the user's purpose is to determine stresses and potential erosion (design scenarios). On price, Delft3D-SED is open source and appropriate for sand dominated rivers. Given the ability to simulate graded sediment, MIKE21C ST better simulates transport in gravel bed rivers, having been successfully applied worldwide and in India.

Groundwater and Conjunctive Use Management

Groundwater management requires determining the quantity and quality of subsurface water movement over time and space as influenced by natural processes and human activities. Unlike surface water conditions, groundwater observations are limited to boreholes water levels and pumping test, thus characterizing the hydrogeological system is more difficult due to a limited set of observations. Therefore, the ability to characterize groundwater systems and to develop and evaluate resource management strategies for sustainable water allocation is greatly enhanced when using groundwater models. 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 (for examples, 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; and
- Communicating groundwater quality and quantity conditions to policy makers and stakeholders.

Often, groundwater models are developed to satisfy multiple uses.

Two types of WRS are used to characterize groundwater: distributed hydrogeological models (DHgM) and RBMs. 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. Typical data requirements for DHgMs include the aquifer thickness, hydrogeological parameters (for example, hydraulic conductivity, transmissivity), boundary conditions (for example, constant flow, fixed head, non-flow), groundwater recharge, and pumping rates. Typical DHgM 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 management issues listed above and have been successfully applied to aquifers in India.

DHgMs, as applied to general groundwater management and conjunctive use, are evaluated in this section. RBMs are not reviewed in this section as groundwater is primarily regarded as supply source in water allocation models (see Water Allocation Model: RBM section).

DHgM: General Groundwater Management

Six DHgMs were evaluated including GMS, Groundwater Vistas, MODFLOW, iMOD,and MIKE SHE, and Visual MODFLOW (Table 11). General descriptions of each package are provided below:

- **GMS** (Aquveo is a groundwater modelling system, based on MODFLOW code, which provides tools for every phase of 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. Primary informational sources: Kumar,[99] GMS website.[100] Information regarding GMS can be found at: http://www.aquaveo.com/software/gms-groundwater-modeling-system-introduction[100]

- **Groundwater Vistas** (Rockware) is a Windows modelling environment for the MODFLOW family of models that allows for the quantification of uncertainty. Groundwater Vistas includes a series of tools for assessing risk using a more complex and real-world groundwater model. Primary informational sources: Kumar,[99] Groundwater Vistas website.[101] Information regarding Groundwater Vistas can be found at:https://www.rockware.com/product/overview.php?id=147[101]

- **iMOD** (Deltares) is an open source, easy to use graphical user interfacethat employs 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). Primary informational sources: Deltares vendor response,[31] the iMOD website.[102] For information regarding iMOD, visit: https://www.deltares.nl/en/software/imod/[102]

- **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. Primary informational sources: Kumar,[99] MODFLOW website.[103] Information regarding MODFLOW can be found at: http://water.usgs.gov/ogw/modflow/[103]

- **MIKE SHE** (DHI): see DHM Section for description.

- **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. Primary informational sources: Kumar,[99] Visual MODFLOW website.[104] Information regarding Visual MODFLOW can be found at: http://www.novametrixgm.com/groundwater-modeling-software/visual-modflow-flex[104]

Computational Overview: 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 (for example, 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 (for example, 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 are available for calibration and quantifying uncertainty. MODFLOW's use of packages allows users to examine specific hydrologic features of the model independently as well as add new packages without modifying existing models. A list of 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. iMOD can employ the MODFLOW packages or couples with WFlow, an open source, command line driven, distributed WRM model to compute effects of land use change within catchments on hydrographs for import into the model.[83]

MIKE SHE includes dynamically linked modules to compute saturated zone flow, evapotranspiration, overland flow, river and lake flow, unsaturated zone flow, and anthropogenic use (for example, irrigation, ground water 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 (Table 6). MIKE SHE can be coupled with the Autocalibration Module to assist in calibration of the groundwater model. Within the Autocalibration 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 water quality. Transport packages associated with MODFLOW include:

- MT3DMS: three-dimensional transport model for simulating advection, dispersion, and chemical reactions of dissolved constituents;
- MT3D99: an enhanced version of MT3DMS, that includes support for implicit solver, TVD

Solution scheme, dual-porosity advection-diffusion, non-equilibrium sorption and monod kinetics, and multispecies reactions, including first-order parent-daughter chain reactions, and instantaneous reactions among species;

- SEAWAT: three-dimensional variable-density groundwater flow coupled with multi-species solute and heat transport;
- RT3D: reactive transport simulations; and
- PHT3D: a multi-component transport model for three-dimensional reactive transport in saturated porous media.

GMS, Visual MODFLOW, and Groundwater Vistas support the use of many of these packages. iMOD uses the D-WQ module that simulates almost any water quality variable and its related water quality processes. iMOD can also use SEAWAT and MT3D.

MIKE SHE addresses water quality with ECO Lab, an open-ended ecological and water quality modelling framework that allows user-defined equations and water quality model to be defined. Templates are available for standard constituents to expedite water quality modeling. A full description of the iMOD D-Water Quality and MIKE SHE ECO Lab is provided in the Water Quality and Sediment Transport sub-section in the Flood and River Water Quality Management Section.

GUI Overview: 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 tools for expediting and enhancing the modeling process. These include site characterization, model development, post-processing, calibration, and visualization. All applications are developed to work on Windows, though MODFLOW also works on 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.

iMOD's interface allows users to build large high resolution groundwater flow models based on a data set expandable to all possible future areas of interest, flexibility to generate high or low resolution models generate, maintain consistency between regional and inlying, and update your data set with the details added in a sub-domain model.[31] All necessary pre- and post-processing tools to prepare, run and visualize input and output for a MODFLOW groundwater model. Subsurface tools allow users to edit 2-D and 3-D subsurface and included borehole information.

MIKE SHE incorporates the DHI suite of pre- and post-processing tools and provides a clear workflow for model development, simulation, post-processing, and result visualization. Post-processing tools allow for computation of water budgets, statistics, and animations.[51]

Table 11. Evaluation matrix for the distributed hydrogeological model WRS

	GUI Overview (General)							Licensing/Software Support												
Software Package	Operating Systems	GUI Interface	Pre-Processing Tools	Post-Processing Tools	GIS Interface	Error Checking	Animations	Cost Government Agency	Service Maintenance Agreement	Support	Indian Applications	Worldwide Licenses	3D Mesh	Ground Water Pumping	Surface Water	Overland Flow	Unsatruated Zone	Water Quality Constituents	GW-WQ Link	Customizable WQ Analysis
GMS	◑	●	●	●	●	?	◑	○	●	●	?	◑	●	◑	○	○	○	●	◑	◑
iMod	◑	●	●	●	●	●	◑	●	●	●	?	◑	●	◑	○	○	○	●	◑	●
MIKE SHE	◑	●	●	●	◑	●	◑	◍	●	●	○	◑	○	●	●	●	●	●	●	●
Groundwater Vistas	◑	●	●	●	●	?	◑	○	●	●	?	◑	●	◑	○	○	○	●	◑	◑
MODFLOW	●	○	○	○	◑	?	◍	●	◍	◍	?	●	●	◑	○	○	○	●	◑	◑
MODFLOW-OWHM	●	○	○	○	◑	?	◍	●	◍	◍	?	○	●	◑	◑	◑	◑	●	◑	◑
Visual MODFLOW Flex	◑	●	●	●	●	?	◑	○	●	●	?	◑	●	◑	○	○	○	●	◑	◑

● Best ◑ Good ○ Fair ◍ Poor ? Unknown

Note: Criteria are defined in Annex, Table A4.

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 that can be purchased are 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 around INR 1 lakh per seat for the 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 autocalibration routines are additional cost. The model is supported with manuals, tutorials, training courses, and online materials. Starting at INR 5.5 lakh/seat, MIKE SHE is the most expensive option of the DHgM packages evaluated.

Groundwater Model Recommendation: 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. iMOD, with the pre-processing and post-processing, strong visualization abilities, strong support, and open source availability, is the strongest candidate of the groundwater model evaluated and thus recommended for groundwater modeling.

Experienced groundwater modellers, 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 a GUI that guides groundwater model development through a straightforward workflow. 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 and ground water (see next section).

DHgM: Conjunctive Management

Conjunctive management is groundwater management that accounts for the dynamic interaction with surface and land use activities such as irrigation. In India, typical applications include command areas, exchange in wetlands/field drains, and influence of tanks and check dams on local infiltration to increase groundwater levels. Three packages support conjunctive management directly: MIKE SHE, MODFLOW-OWHM, and GSSHA (WMS). These packages dynamically link surface water, unsaturated zone, and groundwater activities.

MIKE SHE is the dominant package for these applications due to its existence since 1993 and its worldwide application. As stated, MIKE SHE dynamically couples each component of the hydrologic cycle, making it an excellent tool for conjunctive management. Each module offers several algorithms to select based on the question being addressed in addition to available data. The pre-processing and post-processing tools are robust and make the workflow of model construction, simulation, and viewing straightforward. The model is scalable in its ability to address both local and regional problems.

MIKE SHE and FEFLOW (not evaluated here) have been used in the Saph Pani-Enhancement of Natural Water Systems and Treatment Methods for the Safe and Sustainable Water Supply in India project.[25] The project is a collaborative research project for 10 pilot study sites across India investigating the application of integrated surface and ground water modeling. One pilot study examined the efficacies of a water retaining structure, such as check dams/ponds near Chennai, to arrest or reduce the salinity ingress on groundwater system. A second study used MIKE SHE to examine the impact of irrigation infrastructure on groundwater regime as well as the impact of wastewater on the groundwater quality for the Musi Wetland.[25] For demonstration, DHI created a MIKE SHE application to assess the impact of small tanks on surface and ground water availability in the Vaippar Basin, Tamil Nadu.[25]

The USGS software package used for conjunctive use studies is MODFLOW-OWHM: an integrated hydrologic flow model for the analysis of human and natural water movement within a supply-and-demand framework.[105] MODFLOW-OWHM dynamically simulates hydrologic process packages for evapotranspiration, surface water routing, rivers, lakes and reservoirs, wells, recharge, irrigation, drain and return flow, unsaturated zone, and seawater intrusion. The package has been largely applied in western U.S. for the conjunctive management of river and reservoir diversion as well as groundwater use for irrigation, most notably applied to the Central Valley in California.[9] Water management in Central Valley is analogous to many Indian command areas in that storage water from reservoirs is routed through a distributary canal system to satisfy crop requirements, and farmers supplement irrigation deficiencies with groundwater.

Coupling MODFLOW-OWHM with MODFLOW-LGR (a package for using a locally refined grid to simulate groundwater flow) would be an effective tool for evaluating the local influence of tanks and check dams on local infiltration in increasing groundwater levels.

GSSHA (WMS) is a physically based, distributed-parameter, structured grid, WRM model that simulates the hydrologic response of a watershed subject to a given hydrometeorological input.[9] The software fully couples 2-D overland flow, 1-D stream flow, 1-D infiltration, and 2-D groundwater to simulate flow between the groundwater, vadoze zone, streams, and overland flow. The user interface for GSSHA is Aquaveo's WMS, which provides pre-processing and post-processing tools that make the workflow of model construction, simulation, and viewing straightforward.

A major difference between GSSHA and MODFLOW-OWHM is that, in GSSHA, the groundwater is simulated as a horizontal 2-D finite difference grid and thus not suitable for projects where complex groundwater conditions are required to be simulated. Applications in India are unknown at this time, but the software has been applied for conjunctive management of water and land use in the Wadi El-Arish Watershed, Egypt.[106]

Although it is a powerful tool set, the disadvantage of using MODFLOW-OWHM over MIKE SHE is that MODFLOW-OWHM has a more limited set of control structure options for application to the distributary network, offering a time series of operations or fixed structures (for example, weir) and the interface (as discussed above). In MIKE SHE, control structure options in MIKE11 allow for more nuanced control over the water control structure operations, which may be important in simulating conditional logic. For the interface, ModelMuse and ModelViewer supports MODFLOW-OWHM, but beyond the groundwater and unsaturated zone packages, the other packages are not supported with iMOD, GMS, Visual MODFLOW, and Groundwater Vistas. Experienced modellers may not be limited in the applications, but uninitiated modellers may find it difficult to implement without training and experience.

In addition to the aforementioned WRS, MODFLOW models have been adapted to simulate groundwater, surface water, and unsaturated zone interaction. IDWR has developed a surface water flow, irrigation, and unsaturated zone module for the purpose of working with MODFLOW in both planning and actively managing groundwater in the ESPA.[107] The tool is complex, requiring very detailed hydrogeological and water use data, but has proven to be very effective in characterizing the aquifer's hydrology, planning recharge augmentation zones, evaluating proposed water rights transfers and groundwater well development, and determining the curtailment of surface and groundwater operations during periods with low flow in rivers. However, expertise in model development is required for building the model, and requires continued attention to maintain and update the supporting software.

Several applications have illustrated how a DHgM can be used with an optimization algorithm to optimize conjunctive use of ground and surface water. Czarnecki et al.[108] optimized the conjunctive use of surface water and groundwater in 9,910 km^2 area in the Mississippi River Valley in southeastern Arkansas, USA. The effort used MODFLOW-2000 to develop the physical characterization of groundwater flow and a modified MODMAN 4.0 to determine the optimal extraction rates to support maintenance of hydraulic heads and streamflow in both the Arkansas River and Bayou Bartholomew.[ibid] The effort produced the optimal sustainable yield, unmet demand, and groundwater level.

Conjunctive Use Recommendation: GSSHA (WMS), MIKE SHE, and MODFLOW-OWHM are suitable for integrated surface and ground water simulations required for conjunctive management. MIKE SHE and GSSHA (WMS) have better GUI interfaces and more capabilities stemming from their more complex operations of surface water control structures. However, their limitations are the cost per license, which provides a barrier to their widespread adoption, and their inability to change the mesh density near areas of concern (for example, groundwater pumping wells, tanks and check dams for groundwater recharge). That being said, GSSHA (WMS) is significantly less expensive than MIKE SHE, but is restricted in simulating groundwater movement in 2-D.

For the MODFLOW-OWHM, a sub-model model can be readily developed from the larger regional model, but the two are not dynamically linked. MODFLOW-OWHM offers a full suite of MODFLOW packages to simulate integrated surface and groundwater interactions. Due to the lack of a GUI interface for MODFLOW-OWHM, developing a conjunctive use model would require more modeling expertise.

MIKE SHE and GSSHA (WMS) are preferred if budgets are not limited, technical staff have limited experience with modeling, or if complicated control of surface water is required. If technical staff are familiar with creating, calibrating, and using MODFLOW packages, the MODFLOW-OWHM is good solution.

Conclusions

A variety of WRS are available to assist Indian water managers in managing the water resources of their state or basin. Selecting the WRS that best suites this management of water resources involves understanding the water resources issues being managed, alternative scenarios to be evaluated, and outcomes from the model required to make decisions. These needs are matched with the algorithm, spatial and temporal resolution, inputs/outputs, viewing functionality, data requirements, cost, support, and experience of the available technologies reviewed to determine the best alternative to employ when managing their water resources. Successful selection can help inform water managers and support their decisions, and can ultimately significantly contribute to successful management of the water resources within a state or basin.

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Annex

WRS Review Criteria

Table A1. Metrics for the RBMs in Water Allocation and Planning in Table 5

Metrics	Poor	Fair	Good	Best	Notes
Software GUI (General)					
Operating Systems	One platform, not Windows	Linux, Unix Only	Windows	Windows + 1 option	Options: Windows, OSX, Linux, Unix
Workflow Guidance	None		Data input check	Scenario manager	
Pre-Processing Tools	None	TS formatter	TS formatter, Map tool	Demand	Time series (TS) format, map tool
Post-Processing Tools	None	TS Viewer	TS Viewer, TS Stats, Mapping	Customizable DSS Interface	Time series (TS) viewer, mapping, TS statistics (stats). Custom interface a DSS for creating output template
GIS Interface	None	Background maps	Digitize network on map and DEM tools	Integration of full GIS	Full includes input and simulation dialogue describing the item and error
Player Version	None	Predefined scenario viewing	Free, choose from several scenarios to run model	Free, interface with input controls, customizable output interface	Versions for distribution to the public with limited functionality; preset scenarios; buttons, dials, sliders bars to guide input; and customized output interface.
Animations	None		Map	Map and Fly By	
Licensing/Support					
Cost Software	>1 Lakh/seat	<=1 Lakh/ seat	Free Agency, Private Parties Fee	Free, Public Domain	Open Source not considered a factor as public domain is the main
Service Maintenance Agreement	None	Consultancy only (project based)	>1 Lakh/seat	<=1 Lakh/seat	
Support	None	1 Option	2-3 Option	4 Options	Options: Online help, training courses, tutorials, user groups
Indian Licenses	<25	25-50	50-250	>250	License (assumes seats), network licenses counts as 5 seats
Worldwide License	<100	100-500	500-1000	>1000	

Table A1 continued

Metrics	Poor	Fair	Good	Best	Notes
WA&P (RBM)					
Simulation & Optimization			Simulation or Optimization	Simulation & Optimization	
Time Step	None	Monthly only	Daily Only	User Defined	
Demand Calculator	None		Precalculated within tool	Dynamically linked, influences water allocation	
Irrigation Calculator	None	Demand Only	Preset Types + User Defined	Dynamically linked, influences water allocation	
Groundwater Simulation	None	Simple Reservoir	Connect to MODFLOW	1D Simulation near River, connect to MODFLOW	
Reservoir Simulation	None		Direct Import	Dynamic Link	
Water Quality	None	Limited Suite	Standard Suite	Extended Suite	Suite = temperature, nitrogen; phosphorus; algae; dissolved oxygen; pH, and BOD
HD -WQ Linkage	None	External Program, Post-processed	Internal Module dynamically linked	Built-in	
Economics	None	External Program, Post-processed	Internal Module, Post-processed	Hydro-econoomic link, influences water allocation	
Ecological	None	External Program, Post-processed	Internal Module, Post-processed	Hydro-ecological link, influences water allocation	

Table A2. Metrics for the DHMs in Water Allocation and Planning in Table 7

Metrics	Poor	Fair	Good	Best	Notes
Software GUI (General)					
Operating Systems	One platform, not Windows	Linux, Unix Only	Windows	Windows + 1 option	Options: Windows, OSX, Linux, Unix
Workflow Guidance	None		Data input check	Scenario manager	
Pre-Processing Tools	None	TS formatter	TS formatter, Map tool	Demand	Time series (TS) format, map tool
Post-Processing Tools	None	TS Viewer	TS Viewer, TS Stats, Mapping	Customizable DSS Interface	Time series (TS) viewer, mapping, TS statistics (stats). Custom interface a DSS for creating output template
GIS Interface	None	Background maps	Digitize network on map and DEM tools	Integration of full GIS	Full includes input and simulation dialogue describing the item and error
Player Version	None	Predefined scenario viewing	Free, choose from several scenarios to run model	Free, interface with input controls, customizable output interface	Versions for distribution to the public with limited functionality; preset scenarios; buttons, dials, sliders bars to guide input; and customizd output interface.
Animations	None		Map	Map and Fly By	
Licensing/Support					
Cost Software	>1 Lakh/seat	<=1 Lakh/ seat	Free Agency, Private Parties Fee	Free, Public Domain	Open Source not considered a factor as public domain is the main
Service Maintenance Agreement	None	Consultancy only (project based)	>1 Lakh/seat	<=1 Lakh/seat	
Support	None	1 Option	2-3 Option	4 Options	Options: Online help, training courses, tutorials, user groups
Indian Licenses	<25	25-50	50-250	>250	License (assumes seats), network licenses counts as 5 seats
Worldwide License	<100	100-500	500-1000	>1000	
WA&P (DHM)					
Surface Water	None	Kinematic only	Steady State Energy, Kinematic	Hydrodynamic 1D	
Overland Flow	None		Linear Reservoir HRU	2D Grid Based	
Unsatruated Zone	None	2 Layer Water Balance HRU	2 Layer Water Balance Grid	2D Grid Gravity or Richard's equation	
Groundwater	None	Linear Reservoir watershed	Linear Reservoir, HRU	3D Grid Based	

Table A2 continued

Metrics	Poor	Fair	Good	Best	Notes
Rainfall-Runoff Link	None		Preprocessed in Module	Dynamic Link	
Reservoir Simulation	None	Simple Mass Balance	Mass Balance with Reservoir Geometry	Mass Balance with Reservoir Geometry& Operations	
Irrigation Module	None	Option 1 or 2	Options 1 and 2	Options 1-3	Options 1) Fixed irrigation demand, 2) variable irrigation demand 3) dynamically calculated irrigation demand
Water Quality	None	Loading and routing external	Loading or routing external, other process dynamic link	Dynamic link for both loading and routing	
Sediment Transport	None	Loading and routing external	Loading or routing external, other process dynamic link	Dynamic link for both loading and routing	

Table A3. Metrics for the Flood Planning in Table 9 and Water Quality and Sediment Transport in Table 10

Metrics	Poor	Fair	Good	Best	Notes
Software GUI (General)					
Operating Systems	One platform, not Windows	Linux, Unix Only	Windows	Windows + 1 option	Options: Windows, OSX, Linux, Unix
GUI Interface	Command Line	Simple dialogue box for specific tasks	Simple dialogue support all processes	Professionally developed	
Workflow Guidance	None		Data input check		
Pre-Processing Tools	None	TS formatter	TS formatter, Map tool		Time series (TS) format, map tool
Post-Processing Tools	None	TS Viewer	TS Viewer, TS Stats, Mapping	Customizable Interface	Time series (TS) viewer, mapping, TS statistics (stats), custom interface
Error Checking	None	Input or simulation only	Full Check on select modules	Full Check, all packages and modules	Full includes input and simulation dialogue describing the item and error

Table A3 continued

Metrics	Poor	Fair	Good	Best	Notes
Animations	None		Map	Map and Fly By	Map is a static view, fly by allows the video to "fly along" a path similar to being in a plane
Licensing/Support					
Cost Software	>1 Lakh/ seat	<=1 Lakh/ seat	Free Agency, Private Parties Fee	Free, Public Domain	Open Source not considered a factor as public domain is the main
Service Maintenance Agreement	None	Consultancy only (project based)	>1 Lakh/seat	<=1 Lakh/seat	
Support	None	1 Option	2-3 Option	4 Options	Options: Online help, training courses, tutorials, user groups
India Application	1	1-4	5-10	>10	License (assumes seats), network licenses counts as 5 seats
Worldwide License	<25	25-50	50-250	>250	
Flood Planning					
1D Computation	Kinematic only	Steady State Energy, Kinematic	Hydrodynamic 1D	High Diffuse Hydrodynamic 1D	
1D Model Builder	None		GIS External Import Geometry	GIS Internal Module	
2D Computations	None		Hydrodynamic 2D	Couple with 1D	
2D Mesh	None	Fixed Grid	Variable rectilinear	rectilinear cells, curvilinear meshes, triangles, pentagons	
Structures	None	Preset Types	Preset Types + User Defined	Types, User Defined, Control structures	Types: Bridges, culverts, weirs. Control structures allows for additional logic to be introduced on the operation of the structure (e.g., gate logic)
Multicore Processing	None			Yes	
Cloud Processing	None		Upon Request	User Defined	
RR Linkage	None		Direct Import	Dynamic Link	
Ensemble Forecast, Uncertainty Calculations	None		Batch	Integrated	

Table A3 continued

Metrics	Poor	Fair	Good	Best	Notes
Modular Expansion	None	Limited Suite	Full*		* Full denotes all the modules desired to support modeling effort. Will vary depending on water resource issue
Flood Mapping	None	Map View*	GIS External Export Results	GIS Internal Module	
Flood Impact Calculator	None	Map View*	GIS External Calculate	GIS Internal Module	
Water Quality					
Processes	None	Advection or Dispersion		Advection and Dispersion	
Water Quality Constituents	None	Limited Suite	Standard Suite	Extended Suite	Suite = temperature, nitrogen; phosphorus; algae; dissolved oxygen; pH, and BOD
HD -WQ Linkage	None	External Program, Post-processed	Internal Module, Post-processed	Dynamic Link	
Customizable	None	Choose CoCs	Change equation parameters	Customize Equations	CoCs = constituents of concern
Sediment Transport					
HD -ST Linkage	None	External Program, Post-processed	Internal Fixed Boundary	Dynamic Boundary	
Transport Types	None	One type	Two types	All types	Types: Suspended, bedload, and total load equations (eqn.)
Available ST Equations	1	2	5	5+	
Size Fractions	None	Only sand	Sand + Gravel	Multiple size fractions	
Cohesive, Non-Cohesive	None	Only cohesive	Only non-cohesive	Cohesive, non-cohesive	Cohesive and non-cohesive sediment

Table A4. Metrics for the Groundwater in Table 11

Metrics	Poor	Fair	Good	Best	Note
Software GUI (General)					
Operating Systems	One platform, not Windows	Linux, Unix Only	Windows	Windows + 1 option	Options: Windows, OSX, Linux, Unix
GUI Interface	Command Line	Simple dialogue box for specific tasks	Simple dialogue support all processes	Professionally developed	
Pre-Processing Tools	None	TS formatter	TS formatter, Map tool		Time series (TS) format, map tool
Post-Processing Tools	None	TS Viewer	TS Viewer, TS Stats, Mapping	Customizable Interface	Time series (TS) viewer, mapping, TS statistics (stats), custom interface
GIS Interface	None	Background maps	Import/export GIS coverages	Integration of full GIS	
Error Checking	None	Input or simulation only	Full Check on select modules	Full Check, all packages and modules	Full includes input and simulation dialogue describing the item and error
Animations	None		Map	Map and Fly By	Map is a static view, fly by allows the video to "fly along" a path similar to being in a plane
Licensing/Support					
Cost Software	>1 Lakh/seat	<=1 Lakh/seat	Free Agency, Private Parties Fee	Free, Public Domain	Open Source not considered a factor as public domain is the main
Service Maintenance Agreement	None	Consultancy only (project based)	>1 Lakh/seat	<=1 Lakh/seat	
Support	None	1 Option	2-3 Option	4 Options	Options: Online help, training courses, tutorials, user groups
India Application	1	1-4	5-10	>10	License (assumes seats), network licenses counts as 5 seats
Worldwide License	<25	25-50	50-250	>250	
Groundwater					
3D Mesh	None	Fixed Grid	Variable rectilinear	Variable rectilinear cells, triangles, pentagons	
Ground Water Pumping	None	User defined	Irrigation demand	User Defined and Irrigation demand	
Surface Water Connection	None	Boundary Condition	Linked but different programs	Hydrodynamic-ally linked	
Overland Flow	None	Boundary Condition	Linked but different programs	Hydrodynamic-ally linked	
Unsaturated Zone	None	2 Layer Water Balance HRU	2 Layer Water Balance Grid	2D Grid Gravity or Richard's equation	
Water Quality					
Water Quality Constituents	None	Limited Suite	Standard Suite	Extended Suite	Suite = temperature, nitrogen; phosphorus; algae; dissolved oxygen; pH, and BOD
GW -WQ Linkage	None	External Program, Post-processed	Internal Module, Post-processed	Dynamic Link	
Customizable WQ Analysis	None	Choose CoCs	Change equation parameters	Customize Equations	CoCs = constituents of concern

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