Central Water Commission

Hydrological Design Aids (Surface Water) Developed Under Hydrology Project-II

HDA-Y Draft Final Report

Part C: Technical Manual - 2

Revision-R_0

March 2015

Consulting Engineering Services (India) Private Limited
New Delhi, India

EXECUTIVE SUMMARY

The objective of Hydrological Design Aids Project under HP-II aims to improve upon current design practices and to standardize them for uniform use all over the country, in the three key areas of Hydrological Planning and Design namely;

i. *Assessment of Resource Potential for sizing the water resource development project (HDA-Y)*
ii. *Estimation of Design Flood for safety of Hydraulic structures (HDA-F)*
iii. *Sedimentation estimate to assess the economic life of the Project (HDA-S)*

The Draft Final Report of HDA Y comprises of two broad components. First, a Software Package with Design Aids, Software Interface and Manuals pertaining to Yield Assessment required for planning and design of water storage projects. The second, Regional relations aimed to develop yield series at the project site, where the flow information is not available.

HDA- Y Software Package

HDA-Y Interface has been developed on a modular Framework and integrated with Relational Database structure (HDA – head). The modules have been designed on the lines of BIS Guidelines and Standard Practice recommended to be followed in Hydrological yield Assessment. The Software Package includes :

Technical Reference Manual

The Technical Manual contains the detailed Technical background of all the functions of yield analysis and flow simulation used in developing the HDA-Y Module of the HDA Package. Test Examples have been provided to guide and support the user in developing a better understanding of the underlying processes. Part 1 of the Report includes 4 chapters which cover the Data Validation and Completion, Data Compilation and Data Analysis Functions of Data Validation Module. A brief overview of HDA–Y is presented in Chapter 1 of this Manual. Snowmelt related study has been included in a separate section. Part 2 of the Technical Manual covers the contents from Chapter 5 *onwards. The Flow Naturalisation Module (FNM) provides a set of optional routines for developing natural flow:*

- *Water Balance Routine - Naturalisation of observed flow when multiple Irrigation (major/medium/minor) storage projects exist u/s of gauging site in the basin*
- *Reservoir Operation Routine - Estimation of flow u/s of a reservoir when observed flow is located d/s of a reservoir*

The technical background of FNM has been discussed in Chapter 5 with Test Example.

The other modules of HDA-Y are Rainfall-Runoff Models (RRM), Flow Measurement (FM) and Time Series Model (TSM). RRM comprises of three sub-modules PROM, MODEL E and REGM. PROM and MODEL E represent various components of the rainfall-runoff process by continuously accounting for the water content for a range of flow. REGM is based on Regression analysis, which is a black-box approach of Rainfall-Runoff modeling. While in the PROM procedure, accounting of processes are on daily basis, MODEL E and REGM are workable at monthly time period. RRM sub-module algorithm, process, approach, sensitivity analysis and Test Examples have been described in Chapter 6.

The Flow measurement sub-module of Data Validation deals on development of Rating Curves, their Validation, Extrapolation and Transformation. The output is the continuous record of discharge under various measurement conditions which include development of Simple Rating curve, Compound Rating curve, Backwater curve, Measurement structures like weir, spillway and Flumes and the associated Uncertainty analysis. The methodology has been provided in Chapter 7 with Test Example.

Chapter 8 describes the methodology involved in stochastic streamflow generation to develop streamflow dataset that is derived to represent the most relevant statistical characteristics of the historic series The essential process is to capture the various statistical properties inherent to the

natural historical streamflow sequence, achieved in TSM by selecting the appropriate statistical distribution models and parameter sets of ARMA and is best described in four steps : Normalization of series, Standardization, Identification of model form and Testing of Model Goodness of Fit.

User Manual and Installation Manual

The HDA-Y software user manual gives step by step guidance for using the software package. Part 1 of this Manual includes Data Validation and Completion, Data Compilation, Data Analysis, WINSRM and HEC HMS user support. User Manual Part 2 includes the step by step approach for DVM-Flow Measurement sub modules, FNM, Rainfall Runoff Models and Time series simulation.

Regional Analysis

The other Component of studies presented in the Draft Final Report of HDA- Y is the Regional Analysis. The study aims to develop relationships to enable computation of monthly yield series for monsoon season for small ungauged sub-basins in the different river systems in India. The specific objective of the Regional study was to provide yield series for ungauged locations using data on climatic parameters, sub-basin characteristics and land use/land cover.

This Regional Analysis Report gives a comprehensive assessment of the water resource availability through spatial and temporal analysis for some selected basins of India. A detailed sub-basin wise assessment has been undertaken using Soil and Water Assessment Tool (SWAT) for those basins viz. Godavari, Tapi, Damanganga, Kannadipuzzha. Satluj, Lohit and Barak. Empirical relation has been developed using data on soil, sub-basin characteristics, land use and spatially distributed climate parameters with flow. The Regional analysis is an attempt to provide a set of equations linking monthly yield with parameters of the sub-basins. Precipitation data is one of the important independent variables in the equations. Other parameters can be derived from the topographic maps, land use/land cover maps, soil maps, and hydro-meteorological data. These equations can be used by a water

resources engineer to assess time series of water yield for an un-gauged catchment in the selected sub-basins.

The output of Godavari, Tapi and Damanganga Regional modelling were by and large encouraging. Most of the sub-basins analysed have shown acceptably good performance. Exception is Upper Godavari (G2) which did not give satisfactory results. The sub-basins Sabari (G10) and Lower Godavari (G12) also yielded acceptability on a borderline range in model simulation. However, Empirical relationship have been developed for G10 and G12 which are proposed to be used with caution.

The Regional modelling of Kannadipuzha sub-basin of Bharatpuzza has been undertaken amid data scarcity. The basin has high utilization which requires assessment through data collection from project authorities before an acceptable rainfall-runoff modelling can be simulated. Empirical Relationship has not been developed for the sub-basin due to data severity.

The development of Regional model for Barak sub-basin of Brahmaputra basin has been carried out and simulated yield has been found to be within acceptable range. The Goodness of fit measure indicate correlation coefficient of 0.83, NSI of 0.73 at B. P. Ghat on annual scale and correlation coefficient of 0.86, NSI of 0.86 at monthly scale.

Lohit has about 43% snowmelt contribution at Hayuliang G&D station. The spatial modeling of Lohit posed challenges in calibration and validation, due to the limitations of good quality Global Data and absence of IMD climate information. The Correlation coefficient and NSI value for the simulation at Hayuliang is 0.76 and 0.71 respectively. A better representation of Lohit Indian part of the catchment can be achieved when concurrent flow series for Kibithoo and downstream flow station at Hayuliang is available for adequate period of time along with precipitation records in the basin.

For Satluj sub-basin, similar data constraints exist as the major portion of the catchment lies beyond the Indian territory and reliance on Global data for spatial modelling cannot be underrated. Simulation and Analysis of flow show snowmelt contribution of 89% at Kasol. Empirical relation has been

developed for the Upper Satluj sub-basin, with the given data availability scenario. The Goodness of fit measure derived at Kasol, Seoni and Rampur indicate correlation coefficient in range of 0.73-0.75 and NSI in range of 0.57-0.66 at monthly scale.

Notwithstanding the limited acceptability of model performance measure, Empirical relations have been developed for all the basins. However, it is recommended to exercise caution while applying Empirical relations with snowmelt parameters.

Contents

5. FLOW NATURALIZATION MODEL....1
5.1. GENERAL....1
5.2. WATER BALANCE ROUTINE....1
5.3. PARAMETER EVALUATION....2
5.4. MODEL STRUCTURE....6
5.5. RESERVOIR OPERATION.... 10

List of Figures

Figure 5. 1: Schematic depiction of Water Balance Model of FNM....3
Figure 5. 2: Dialogue Box for calculating Reservoir evaporation....6
Figure 5.3 : Dialogue Box for incorporating Project information related to the basin....7
Figure 5.4 : Dialogue Box for incorporating basin level Project information....8
Figure 5.5 : Dialogue Box for incorporating basin level Project information....8
Figure 5.6 : Interface supporting D&I computation....9

5. FLOW NATURALIZATION MODEL

5.1. GENERAL

Changes in water management practices, land use and Climate affect the flow pattern over time. A river basin is typically characterised by the development and utilization of hydropower, irrigation and other water supply systems through construction of major or medium storage dams. A large number of diversion schemes and pumped schemes may also be in operation. In such situation, the flow in the basin needs to be adjusted to remove the non-homogeneity caused by abovementioned human activities. A natural flow represents a specified uniform condition of watershed and river system under long term climate and water use. The objective of Flow Naturalisation Model (FNM) is to develop a homogenous flow representing natural river basin hydrology. The extent to which observed historical flow are naturalised is based largely on judgment. FNM provides a set of optional routines for developing natural flow:

- Water Balance Routine - Naturalisation of observed flow when multiple Irrigation (major/medium/minor) storage projects exist u/s of gauging site in the basin
- Reservoir Operation Routine - Estimation of flow u/s of a reservoir when observed flow is located d/s of a reservoir

This Chapter presents the theoretical background of the Flow Naturalisation Model.

5.2. WATER BALANCE ROUTINE

Assessment of natural flow is complex in view of the upstream utilization, reservoir storages, regenerated flows and return flows, etc. Apart from basic need of drinking for sustaining human life, water is also used for other beneficial purposes such as irrigation for increasing crop productivity, industrial processing, etc. India, with monsoon climate is characterized by rainfall, which mainly occurs in three to four months of a year with large variations from year to year.

The natural flow at the location of any site is the summation of observed flow, upstream utilization for irrigation, domestic and industrial uses, change in storage of reservoirs in the basin and evaporation losses in reservoirs and deducting return flows from different uses from surface water and ground water sources. The following equation describes the computation of natural flow from observed runoff in the proposed naturalization model.

$R(N) = R(O) + R(IR) + R(DI) + S + E - R(R\text{-}IR) - R(R\text{-}DI) - R(I) + R(E)$

Where,

R (N) = Natural Flow

R (O) = Observed Flow

R (IR) = Withdrawal for irrigation from the river

R (D) = Withdrawal for domestic and industrial requirements from the river

S = Increase in storage of the reservoirs in the basin

E = Net evaporation from the reservoirs

R (RI) = Return flow from Irrigated areas

R (RD) = Return flow from domestic and industrial withdrawals both from surface and ground water discharging in to the river

R (I) = Import

R (E) = Export

For working out upstream abstractions for various uses, assumptions have been made in FNM. The Schmetic Diagram as shown in ***Figure 5.1*** illustrates the water balance components in defining the flow naturalization series and the overall picture of the various parmeters considerd in FNM. Uniform procedure cannot naturally be adopted for all river basins. Particularly for estimating withdrawals for irrigation which is major consumer of water, varying assumptions are made. In many cases while diversions from major and medium irrigation projects were available, those from minor schemes are seldom available.

5.3. PARAMETER EVALUATION

The methodology involved to estimate natural flow from observed series on monthly time scale is discussed as follows:

i) Observed Flow R(O)

It is the observed flow at a particular site which will be available as monthly time series.

ii) Irrigation Withdrawal R (IR)

The flow data of irrigation supply from diversion or storage structures can be obtained from the records maintained by irrigation project authorities. FNM gives the provision to import the measured irrigation diversion flow series directly. In the absence of above data, R IR) can be derived by simulation, by providing the details of various projects located in the catchment of the flow observation point. The data as user input for each of the project located in the catchment are as follows :

- Project Name
- Irrigable Command Area in sq. km(ICA)
  - Cropping pattern in the command (C %)
  - Monthly Gross Water Requirement of crops (GWR)

The above inputs are used to calculate the GWR for each of the projects on a monthly time scale which is the water demand for Irrigation R(IR').

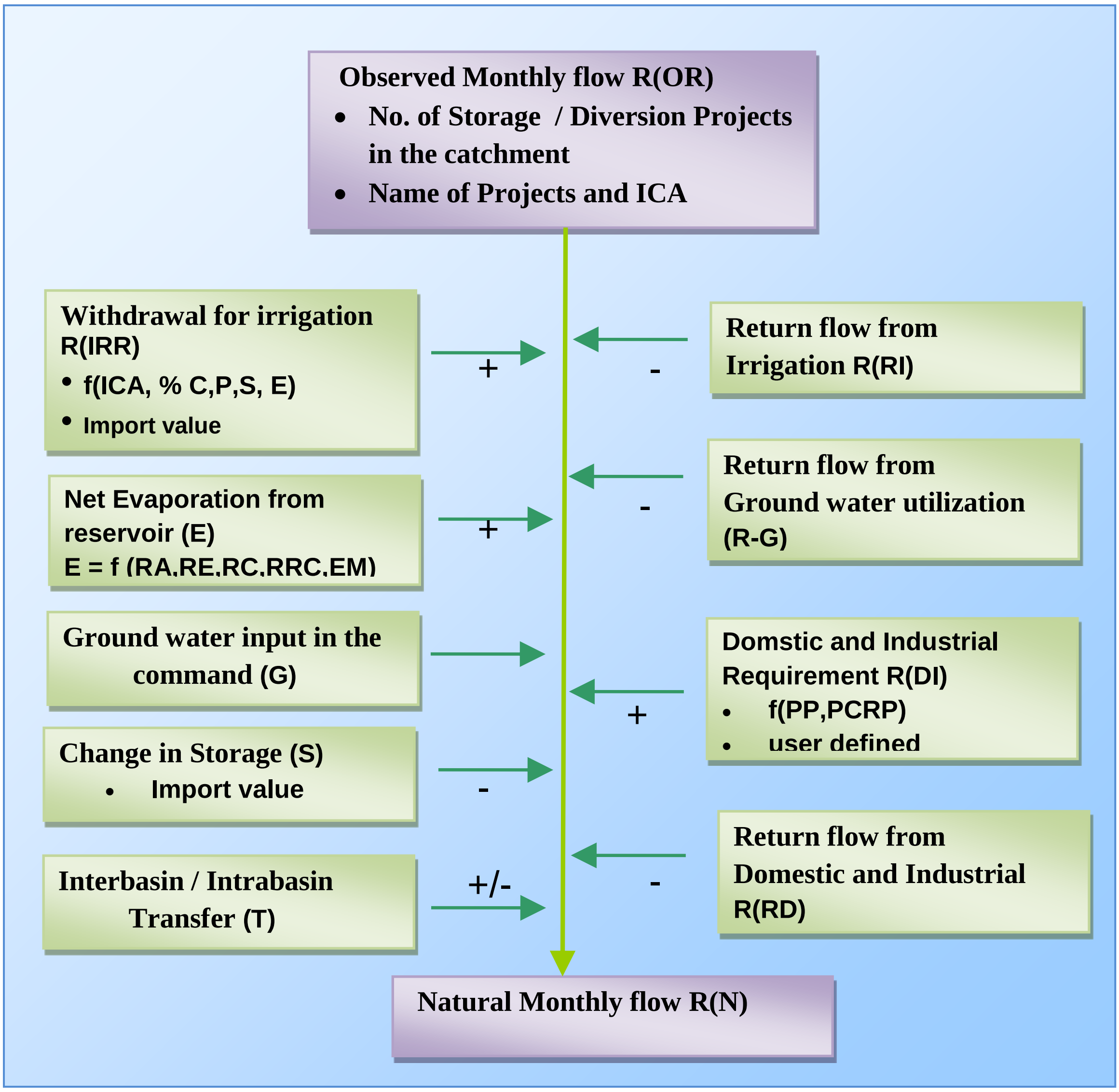


Figure 5. 1: Schematic depiction of Water Balance Model of FNM

FNM has been designed considering general and widely divergent requirement of the user. CROPWAT, FAO public domain software computes crop wise Gross Water requirement for a wide range of crops listed at a Global level. Various Regions have their own local cropping practice and crop coefficients. To accommodate the wide spectrum of variations in practices, the monthly GWR of the crops in the command, usually available as design parameter for irrigation network, can be provided as a direct input to FNM. The GWR value can be directly imported as an Excel file in a defined format, after computation by any procedure or interfaced with CROPWAT.

Basin level annual utilization is available in Reports on Water Balance. For instance, NWDA basin Reports are a useful information source for this kind of application for some basins. FNM allows to capture basin level annual utilization pattern to evaluate the project level utilization on a pro rata, in the absence of measured information.

For assessment of monthly irrigation Release R(IR), the computation have been made considering Crop Water Demand/utilization under two time periods :

1. Monsoon Period utilization R(IR1) - The water released from the Project during the

monsoon month is equal to the GWR during that month.

2. Non-monsoon Period utilization R(IR2)– The Crop water demand during this period is assumed to be met from the water released from the structure stored from the inflow during the preceding monsoon season. With this in view, the utilization of non-monsoon months are added to the observed flow of monsoon months in proportion of the ratio of rainfall in that month and total monsoon rainfall received in the catchment of the Gauging station for yield assessment.

The Irrigation Release R (IR) for a particular month is the summation of Irrigation Releases during that month comprising of monsoon and non-monsoon utilization components R(IR1) and R(IR2).

Naturalization is typically determined for observed flow at gauging station to remove the effects of human water management. It is therefore imperative to state that this procedure does not account for the natural channel losses occurring in its catchment. However, the channel losses occurring from Irrigation release through infiltration and evapotranspiration are considered in the efficiency factor applied on the calculation of Gross Crop Water Requirement.

iii) Domestic and Industrial Release from the project R(D)

The release for domestic or industrial usage can be imported in FNM as flow series directly if available. The other alternative is to compute the release. FNM enables this by providing the following parameters as user input :

- Population in the beneficiary area
- % Rural and Urban Population
- Livestock Population

R(D) is calculated as :

$$R(D) = P(N_R \frac{P_R}{100} + N_U \frac{P_U}{100}) + P_L N_L$$

Where,

P = Population

P_R = Percentage of rural population

P_U= Percentage of urban population

N_R = Per Capita rural requirement

P_U = Per Capita urban requirement

P_L = Livestock population

N_L = Per capita livestock requirement

Under a default setting, the industrial water requirement is assumed to be same as the domestic water requirement in FNM and it identifies water need in litre per Capita daily (lpcd) as per CPHEEO norms given below.

Category	Per capita daily need (litre)
Rural N_R	70
Urban P_U	200
Livestock N_L	50

iv) Net evaporation from the reservoirs (E)

The net evaporation can be estimated from the reservoir level records, Elevation-area-storage information maintained by project authorities and the evaporation measurements in the area. In addition to facilitate import of reservoir evaporation series, FNM calculates monthly evaporation loss from the average water surface area of the storage structure using the following input (Refer ***Figure 5.2***) :

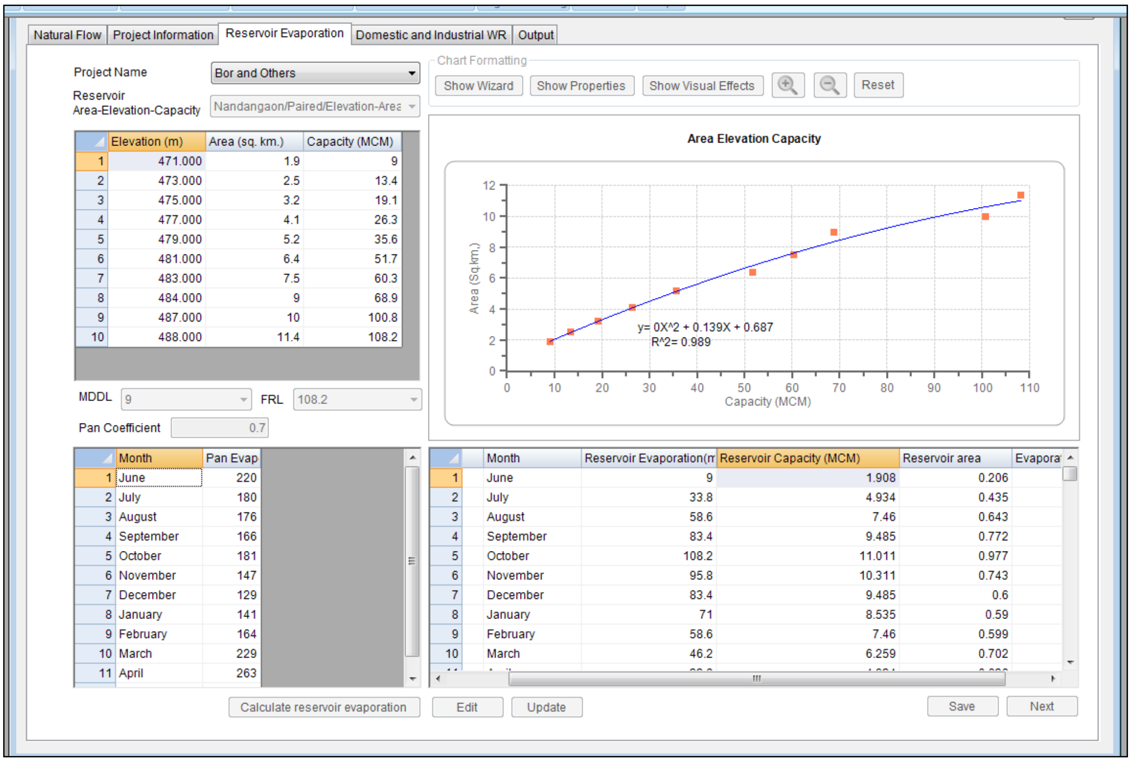
- Elevation-Area-Capacity of reservoir from MDDL to FRL (E-A-C)
- Monthly Pan evaporation (PE)
- Rule curve information on monthly basis (RC)

Seasonal Rule curve operation is commonly used in allocation of storage capacity in multiple purpose reservoir between Full Reservoir level and Minimum Drawdown level, based on seasonally varying characteristics of water supply and flood risk. A seasonal rule curve consists of varying the specified top of conservation pool elevation over the year. Monthly varying upper limit on reservoir storage capacity are specified as rule curve. The monthly evaporation from the surface of the reservoir is calculated by multiplying the surface area of reservoir corresponding to elevation according to the rule curve with observed average monthly evaporation rate and pan evaporation coefficient.

v) Return flow

Return flow represent water discharged back into the stream after use such as municipal and industrial wastewater treatment plant effluent or irrigation return flows. It can represent water transported through open drains or pipelines. A constant percentage of return flow is specified which occurs in the same month as diversion.

Return flows have been assumed to be 10% in case of irrigation (major and medium) and 80% in case of domestic and industrial supplies which are only approximate (reference : NWDA water balance study of Basins).Hydropower releases are also treated as return flow. The default for irrigation, domestic and industrial, hydropower is to return 10%, 80% and 100% of the respective releases.



Project Name: Bor and Others

Reservoir Area-Elevation-Capacity: Nandangaon/Paired/Elevation-Area

	Elevation (m)	Area (sq. km.)	Capacity (MCM)
1	471.000	1.9	9
2	473.000	2.5	13.4
3	475.000	3.2	19.1
4	477.000	4.1	26.3
5	479.000	5.2	35.6
6	481.000	6.4	51.7
7	483.000	7.5	60.3
8	484.000	9	68.9
9	487.000	10	100.8
10	488.000	11.4	108.2

MDDL: 9 FRL: 108.2

Pan Coefficient: 0.7

	Month	Pan Evap
1	June	220
2	July	180
3	August	176
4	September	166
5	October	181
6	November	147
7	December	129
8	January	141
9	February	164
10	March	229
11	April	263

	Month	Reservoir Evaporation(m	Reservoir Capacity (MCM)	Reservoir area	Evapora
1	June	9	1.908	0.206	
2	July	33.8	4.934	0.435	
3	August	58.6	7.46	0.643	
4	September	83.4	9.485	0.772	
5	October	108.2	11.011	0.977	
6	November	95.8	10.311	0.743	
7	December	83.4	9.485	0.6	
8	January	71	8.535	0.59	
9	February	58.6	7.46	0.599	
10	March	46.2	6.259	0.702	

Figure 5. 2: Dialogue Box for calculating Reservoir evaporation

vi) Interbasin transfer of water

Interbasin transfer are manmade conveyance schemes wherein water is diverted to another basin where it can be utilized for human development. The purpose of design schemes is to alleviate water shortage of the receiving basin. Interbasin transfer is explicitely defined as import and export of water from one basin to another as an effective way to enhance irrigation potential, mitigation of flood or drought and reduce regional imbalance of water resource.

5.4. MODEL STRUCTURE

The water balance routine has been executed under five Tabs :

a) Natural Flow

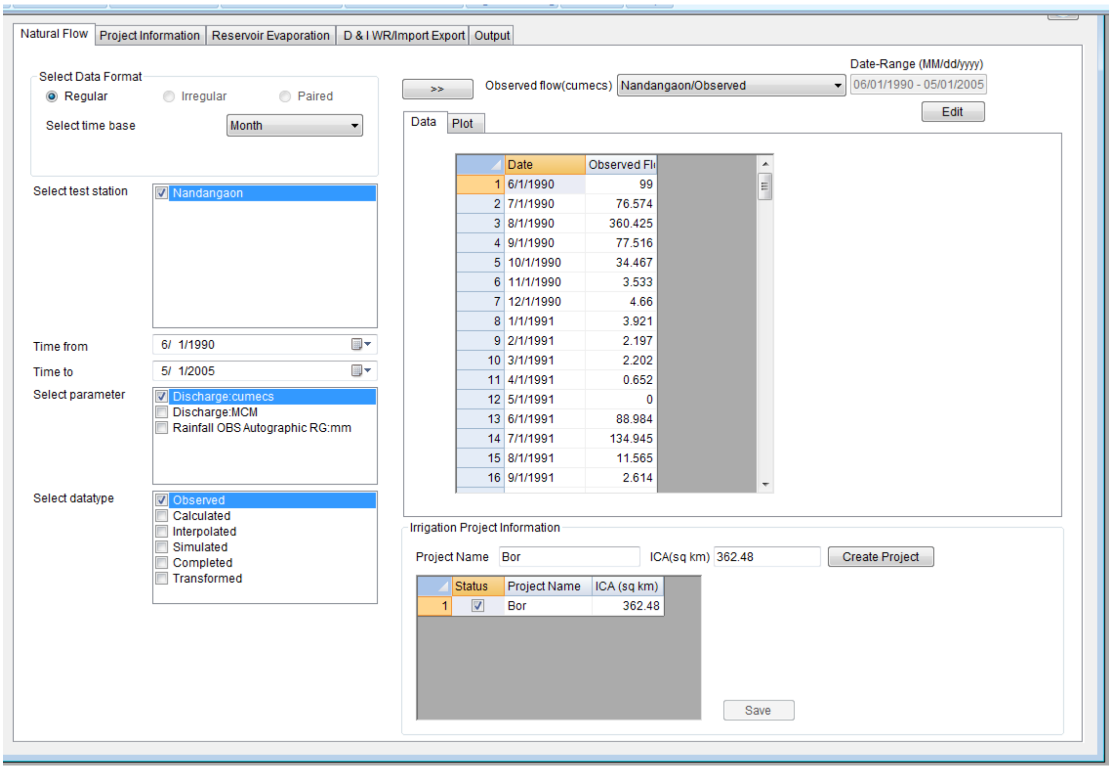
b) Project Information

c) Reservoir Evaporation

d) D& I WR/Import Export

e) Output

'Natural Flow' Tab (Refer *Figure 5.3*) supports selection of observed Flow Series to be taken for developing Natural flow. Information of Irrigation projects located in the catchment of observation site during the simulation period viz. Identification name and the Irrigable Command Area (ICA) in sq km are provided in the Tab.



Select Data Format: ● Regular ○ Irregular ○ Paired

Select time base: Month

Select test station: ☑ Nandangaon

Time from: 6/ 1/1990

Time to: 5/ 1/2005

Select parameter: ☑ Discharge:cumecs ☐ Discharge:MCM ☐ Rainfall OBS Autographic RG:mm

Select datatype: ☑ Observed ☐ Calculated ☐ Interpolated ☐ Simulated ☐ Completed ☐ Transformed

Observed flow(cumecs): Nandangaon/Observed

Date-Range (MM/dd/yyyy): 06/01/1990 - 05/01/2005

	Date	Observed Fl
1	6/1/1990	99
2	7/1/1990	76.574
3	8/1/1990	360.425
4	9/1/1990	77.516
5	10/1/1990	34.467
6	11/1/1990	3.533
7	12/1/1990	4.66
8	1/1/1991	3.921
9	2/1/1991	2.197
10	3/1/1991	2.202
11	4/1/1991	0.652
12	5/1/1991	0
13	6/1/1991	88.984
14	7/1/1991	134.945
15	8/1/1991	11.565
16	9/1/1991	2.614

Irrigation Project Information

Project Name: Bor ICA(sq km): 362.48

	Status	Project Name	ICA (sq km)
1	☑	Bor	362.48

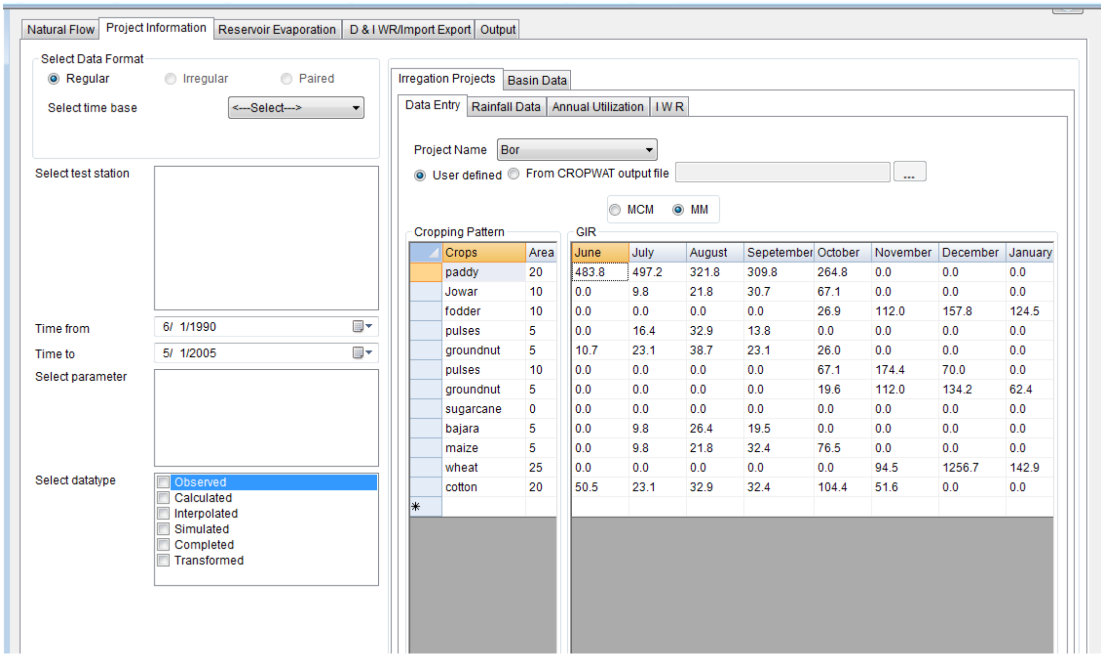
Figure 5.3 : Dialogue Box for incorporating Project information related to the basin

The 'Project information' stores project related details in two sub-tabs viz. irrigation project and Basin data. The project wise Cropping Pattern and Gross Irrigation Requirement, monthly rainfall and Annual Utilization is provided in the 'Project Information' sub-tab (Refer ***Figure 5.4***). The 'basin data' sub-tab (refer ***Figure 5.5***) contains the details of storage of the basin, ground water use, return flows from irrigation and ground water usage.

Reservoir Elevation Area Capacity, Monthly Rule Curve and Evaporation is provided for individual storage structures in the 'Reservoir Evaporation' Tab.

The 'D&I/Export Import' Tab supports the information on import to the basin or export from the basin. The domestic and Industrial requirement is calculated under this Tab. (refer ***Figure 5.6***). The release for domestic or industrial usage can also be imported in FNM as series directly if available.

The 'output' Tab contains the Tabular output of all components of Naturalisation series with standard Plot of yield.



Select Data Format: ● Regular ○ Irregular ○ Paired

Select time base: <---Select--->

Time from: 6/ 1/1990

Time to: 5/ 1/2005

Select datatype: ☐ Observed ☐ Calculated ☐ Interpolated ☐ Simulated ☐ Completed ☐ Transformed

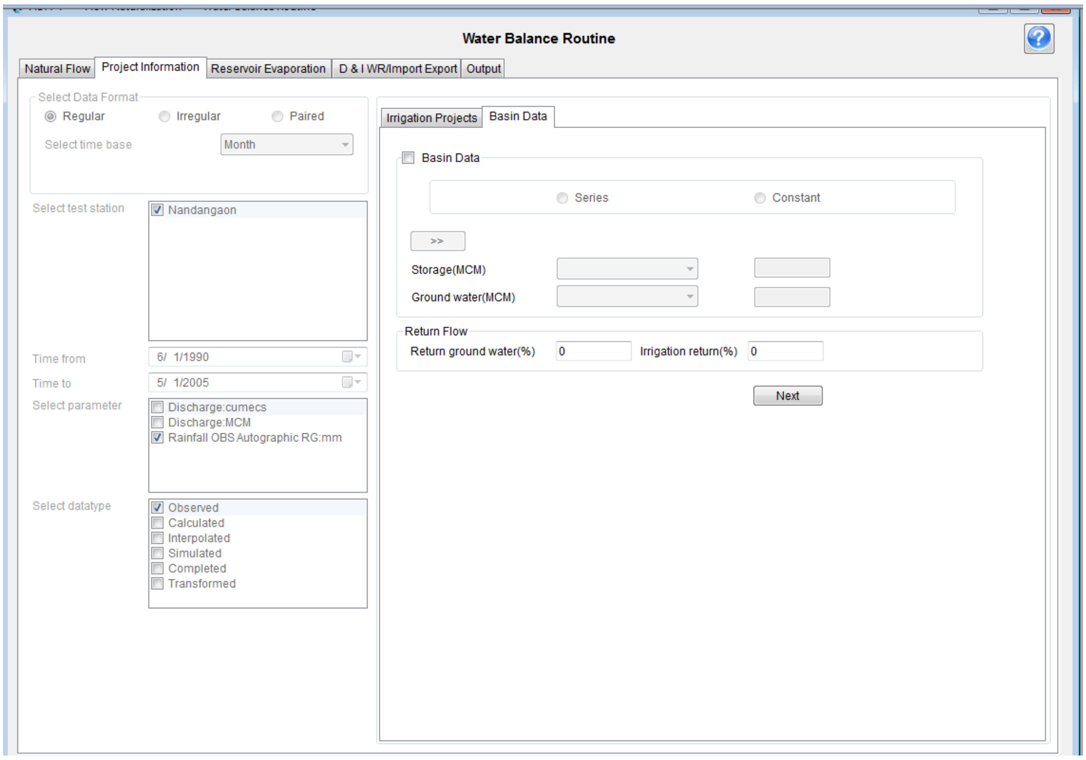
Project Name: Bor

● User defined ○ From CROPWAT output file

○ MCM ● MM

Crops	Area	June	July	August	Sepetember	October	November	December	January
paddy	20	483.8	497.2	321.8	309.8	264.8	0.0	0.0	0.0
Jowar	10	0.0	9.8	21.8	30.7	67.1	0.0	0.0	0.0
fodder	10	0.0	0.0	0.0	0.0	26.9	112.0	157.8	124.5
pulses	5	0.0	16.4	32.9	13.8	0.0	0.0	0.0	0.0
groundnut	5	10.7	23.1	38.7	23.1	26.0	0.0	0.0	0.0
pulses	10	0.0	0.0	0.0	0.0	67.1	174.4	70.0	0.0
groundnut	5	0.0	0.0	0.0	0.0	19.6	112.0	134.2	62.4
sugarcane	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
bajara	5	0.0	9.8	26.4	19.5	0.0	0.0	0.0	0.0
maize	5	0.0	9.8	21.8	32.4	76.5	0.0	0.0	0.0
wheat	25	0.0	0.0	0.0	0.0	0.0	94.5	1256.7	142.9
cotton	20	50.5	23.1	32.9	32.4	104.4	51.6	0.0	0.0

Figure 5.4 : Dialogue Box for incorporating basin level Project information



Select Data Format: ● Regular ○ Irregular ○ Paired

Select time base: Month

Select test station: ☑ Nandangaon

Time from: 6/ 1/1990

Time to: 5/ 1/2005

Select parameter: ☐ Discharge:cumecs ☐ Discharge:MCM ☑ Rainfall OBS Autographic RG:mm

Select datatype: ☑ Observed ☐ Calculated ☐ Interpolated ☐ Simulated ☐ Completed ☐ Transformed

☐ Basin Data

○ Series ○ Constant

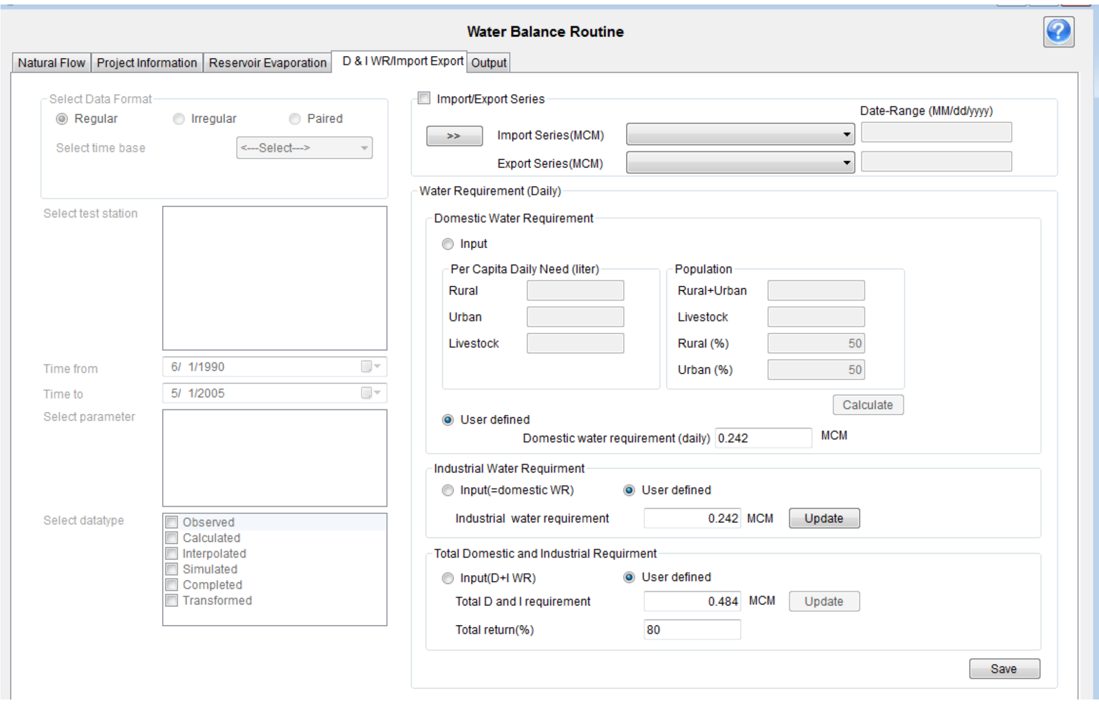
Storage(MCM)

Ground water(MCM)

Return ground water(%): 0

Irrigation return(%): 0

Figure 5.5 : Dialogue Box for incorporating basin level Project information



Select Data Format: ● Regular ○ Irregular ○ Paired

Time from 6/ 1/1990

Time to 5/ 1/2005

Rural (%) 50

Urban (%) 50

● User defined

Domestic water requirement (daily) 0.242 MCM

○ Input(=domestic WR) ● User defined

Industrial water requirement 0.242 MCM

○ Input(D+I WR) ● User defined

Total D and I requirement 0.484 MCM

Total return(%) 80

Figure 5.6 : Interface supporting D&I computation

The implementation of the FNM Model is explained with the help of an example problem in which the monthly stream flow data from Nandgaon station, Godavari River, India has been employed. The report also contains the procedures to be adopted for running of the FNM model. The result shows the plot of naturalized flow calculated from observed flow.

Reference: Test Example 5.1

5.5. RESERVOIR OPERATION

Each month, prior to reservoir simulation loop, Equation used for calculating inflow to reservoir QI(I) from observed outflow from reservoir QO(I)

QO(I) = QI(I) + B-RS(I)- EV(I) – IWR(I) – DI(I) –E-RS(I)-EN(I)

Where,

QO(I) = Outflow from reservoir

QI(I = Inflow to reservoir

B-RS(I) = Reservoir storage in the beginning of the period

E-RS(I) = Reservoir storage at the end of the period

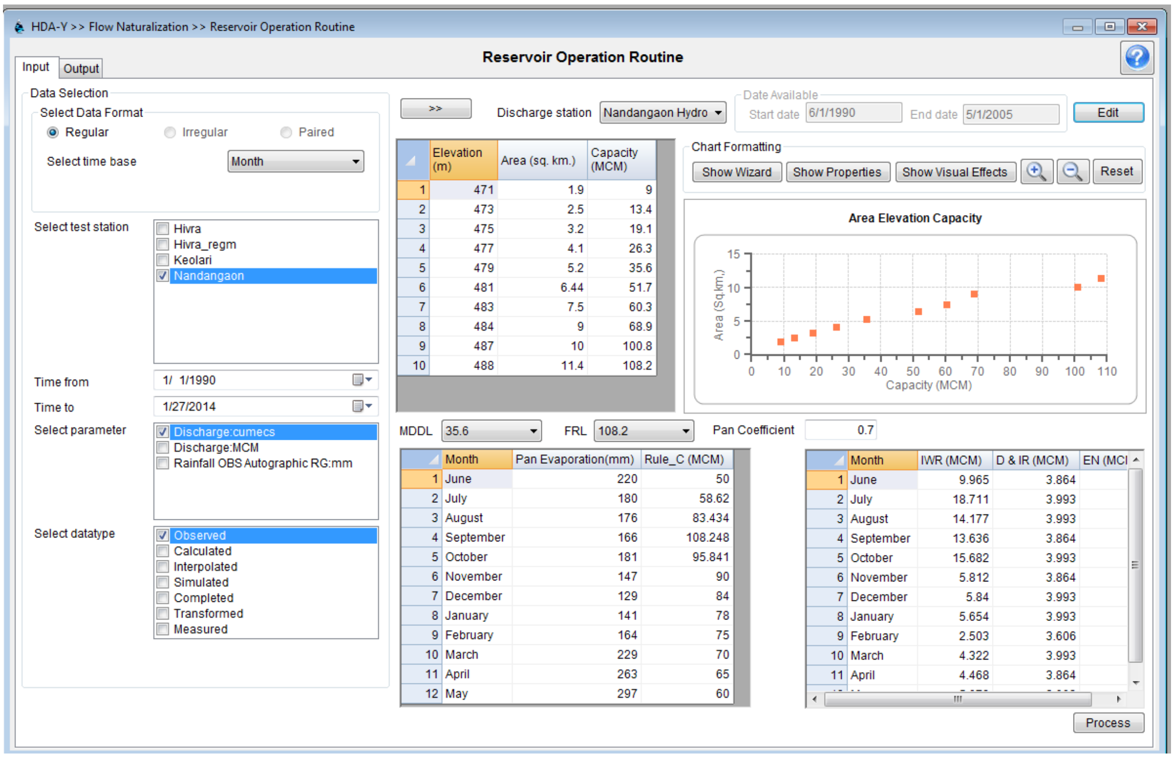
IWR(I) = Irrigation release from the reservoir

EV(I) = Net evaporation from the reservoirs

DI(I) = Release for Domestic and Industrial requirement

EN(I) = Release for Environmental needs

Estimation of QI(I) in FNM has been achieved by optimization with trial and error approach. *Figure 5.6* and *Figure 5.7* show the Dialogue Box of Input and Output tabs of Reservoir Operation Routine respectively.



● Regular ○ Irregular ○ Paired

Select time base: Month

Select test station:
☐ Hivra
☐ Hivra_regm
☐ Keolari
☑ Nandangaon

Time from: 1/ 1/1990

Time to: 1/27/2014

Select parameter:
☑ Discharge:cumecs
☐ Discharge:MCM
☐ Rainfall OBS Autographic RG:mm

Select datatype:
☑ Observed
☐ Calculated
☐ Interpolated
☐ Simulated
☐ Completed
☐ Transformed
☐ Measured

Discharge station: Nandangaon Hydro

Start date: 6/1/1990 End date: 5/1/2005

	Elevation (m)	Area (sq. km.)	Capacity (MCM)
1	471	1.9	9
2	473	2.5	13.4
3	475	3.2	19.1
4	477	4.1	26.3
5	479	5.2	35.6
6	481	6.44	51.7
7	483	7.5	60.3
8	484	9	68.9
9	487	10	100.8
10	488	11.4	108.2

MDDL: 35.6 FRL: 108.2 Pan Coefficient: 0.7

	Month	Pan Evaporation(mm)	Rule_C (MCM)
1	June	220	50
2	July	180	58.62
3	August	176	83.434
4	September	166	108.248
5	October	181	95.841
6	November	147	90
7	December	129	84
8	January	141	78
9	February	164	75
10	March	229	70
11	April	263	65
12	May	297	60

	Month	IWR (MCM)	D & IR (MCM)	EN (MCI
1	June	9.965	3.864	
2	July	18.711	3.993	
3	August	14.177	3.993	
4	September	13.636	3.864	
5	October	15.682	3.993	
6	November	5.812	3.864	
7	December	5.84	3.993	
8	January	5.654	3.993	
9	February	2.503	3.606	
10	March	4.322	3.993	
11	April	4.468	3.864	

Figure 5.7 : Input Tab of Reservoir Operation Routine

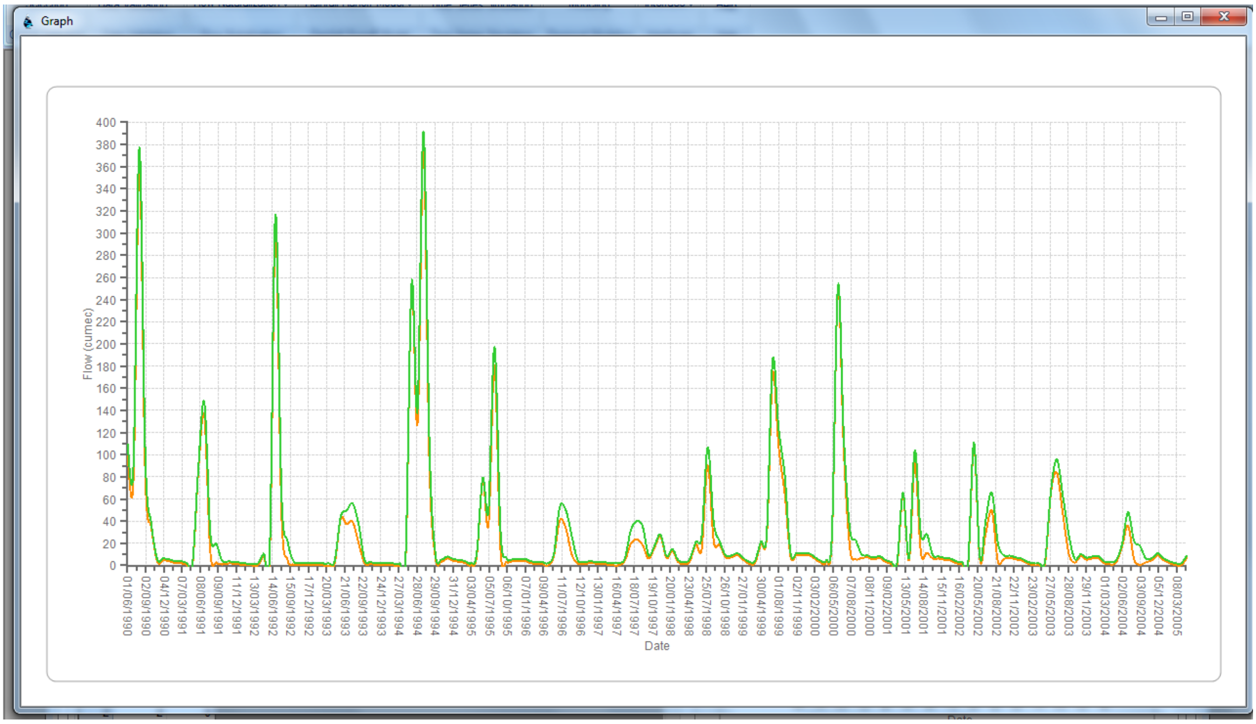
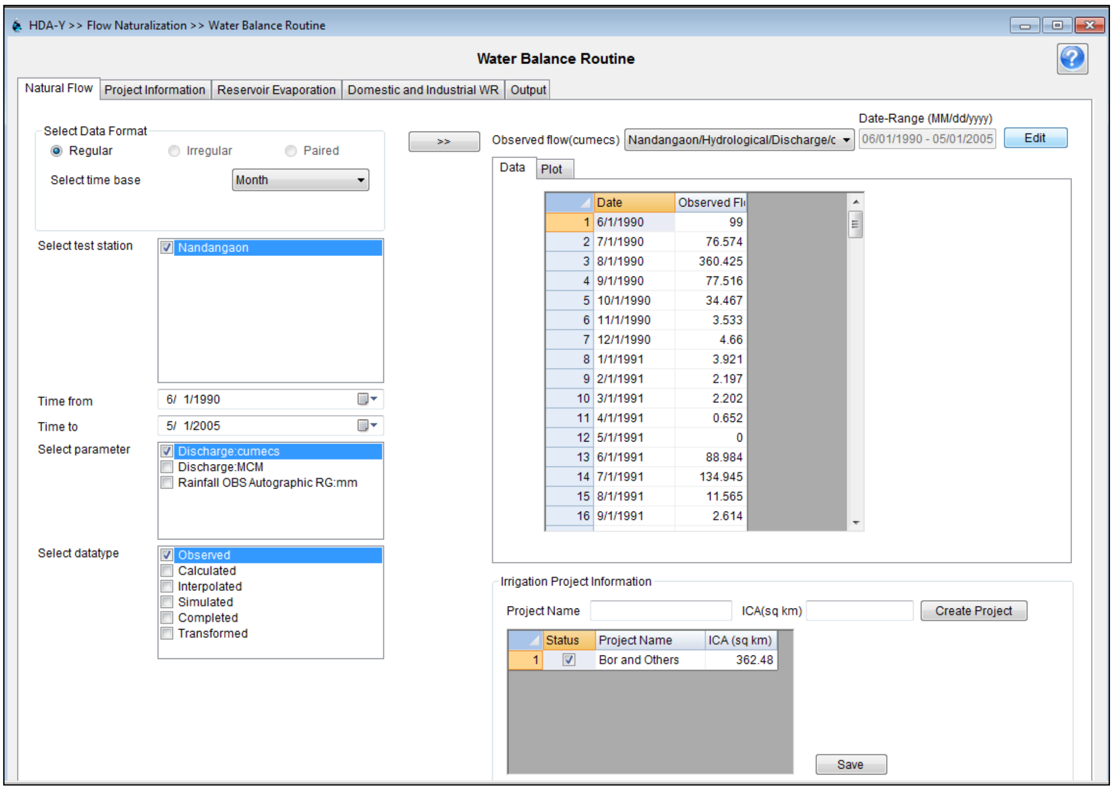


Figure 5.8 : Output Plot of Reservoir Operation sub-module

Test Example – 5.1 Demonstrating FNM-Water Balance

This example illustrates the application of FNM in studies undertaken for flow naturalisation. Data for the example are adopted from Godavari basin. The illustration is designed with the objective of developing yield series, which is the primary input for reservoir design, canal and drainage planning and network analysis.

Considering the monthly data set of observed flow of Nandgaon in Wardha sub-basin of Godavari, with catchment area 4580 sq km. There are five medium irrigation projects in the catchment viz. Bor, Kanholibara, Panchadhara, Dongargaon and Dham covering the Irrigable command area (ICA) of 362.48 sq km. The projects also cater to the Domestic and Industrial requirements in the Command



Select Data Format: ● Regular ○ Irregular ○ Paired

Select time base: Month

Select test station: ☑ Nandangaon

Time from: 6/ 1/1990

Time to: 5/ 1/2005

Select parameter: ☑ Discharge:cumecs ☐ Discharge:MCM ☐ Rainfall OBS Autographic RG:mm

Select datatype: ☑ Observed ☐ Calculated ☐ Interpolated ☐ Simulated ☐ Completed ☐ Transformed

Observed flow(cumecs): Nandangaon/Hydrological/Discharge/c

Date-Range (MM/dd/yyyy): 06/01/1990 - 05/01/2005

	Date	Observed Fl
1	6/1/1990	99
2	7/1/1990	76.574
3	8/1/1990	360.425
4	9/1/1990	77.516
5	10/1/1990	34.467
6	11/1/1990	3.533
7	12/1/1990	4.66
8	1/1/1991	3.921
9	2/1/1991	2.197
10	3/1/1991	2.202
11	4/1/1991	0.652
12	5/1/1991	0
13	6/1/1991	88.984
14	7/1/1991	134.945
15	8/1/1991	11.565
16	9/1/1991	2.614

Irrigation Project Information

Project Name:
ICA(sq km):

	Status	Project Name	ICA (sq km)
1	☑	Bor and Others	362.48

Figure 5. 1: FNM main Dialogue Box showing data series selection

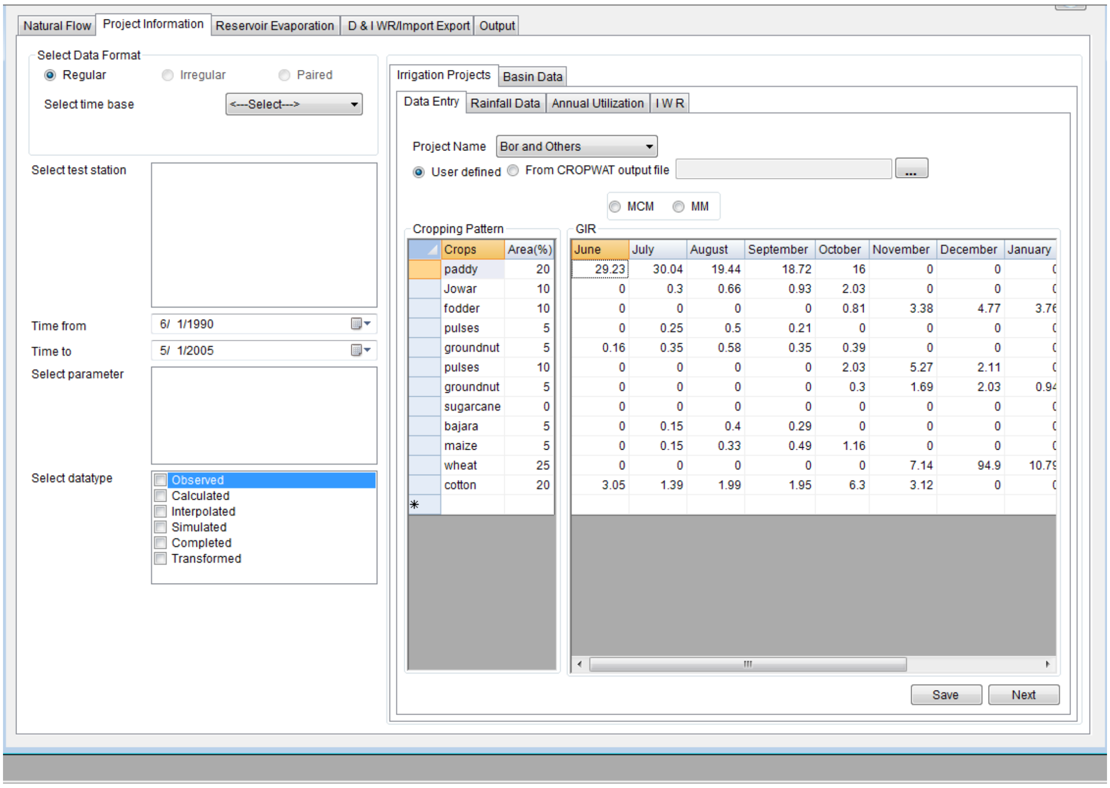
Monthly dischrge data of Nandgaon is selected as shown in the left selection panel in *Figure 5.1*. With the 'Edit' button, the project changes to edit mode to incorporate the informations relation to projects in the catchment.

Identification of upstream projects and calculation of monthly Water utilized for irrigation

The next step is to identify and incorporate the list of existing major, medium and minor irrigatioon project at upstream of the Nandgaon station. There are five medium irrigation projects in the catchment viz. Bor, Kanholibara, Panchadhara, Dongargaon and Dham covering the Irrigable command area (ICA) of 362.48 sq km.

Cropping pattern for Major and Medium projects in the sub-basin

The cropping pattern and the monthly Gross Irrigation requirement (mm) of each crop can be provided in the 'Data entry' sub-tab of Project Information Tab as shown in ***Figure 5.2***.



Select Data Format
● Regular ○ Irregular ○ Paired

Select time base: <---Select--->

Select test station

Time from: 6/ 1/1990

Time to: 5/ 1/2005

Select parameter

Select datatype:
☐ Observed
☐ Calculated
☐ Interpolated
☐ Simulated
☐ Completed
☐ Transformed

Project Name: Bor and Others

● User defined ○ From CROPWAT output file

○ MCM ○ MM

Cropping Pattern / GIR

Crops	Area(%)	June	July	August	September	October	November	December	January
paddy	20	29.23	30.04	19.44	18.72	16	0	0	0
Jowar	10	0	0.3	0.66	0.93	2.03	0	0	0
fodder	10	0	0	0	0	0.81	3.38	4.77	3.76
pulses	5	0	0.25	0.5	0.21	0	0	0	0
groundnut	5	0.16	0.35	0.58	0.35	0.39	0	0	0
pulses	10	0	0	0	0	2.03	5.27	2.11	0
groundnut	5	0	0	0	0	0.3	1.69	2.03	0.94
sugarcane	0	0	0	0	0	0	0	0	0
bajara	5	0	0.15	0.4	0.29	0	0	0	0
maize	5	0	0.15	0.33	0.49	1.16	0	0	0
wheat	25	0	0	0	0	0	7.14	94.9	10.79
cotton	20	3.05	1.39	1.99	1.95	6.3	3.12	0	0

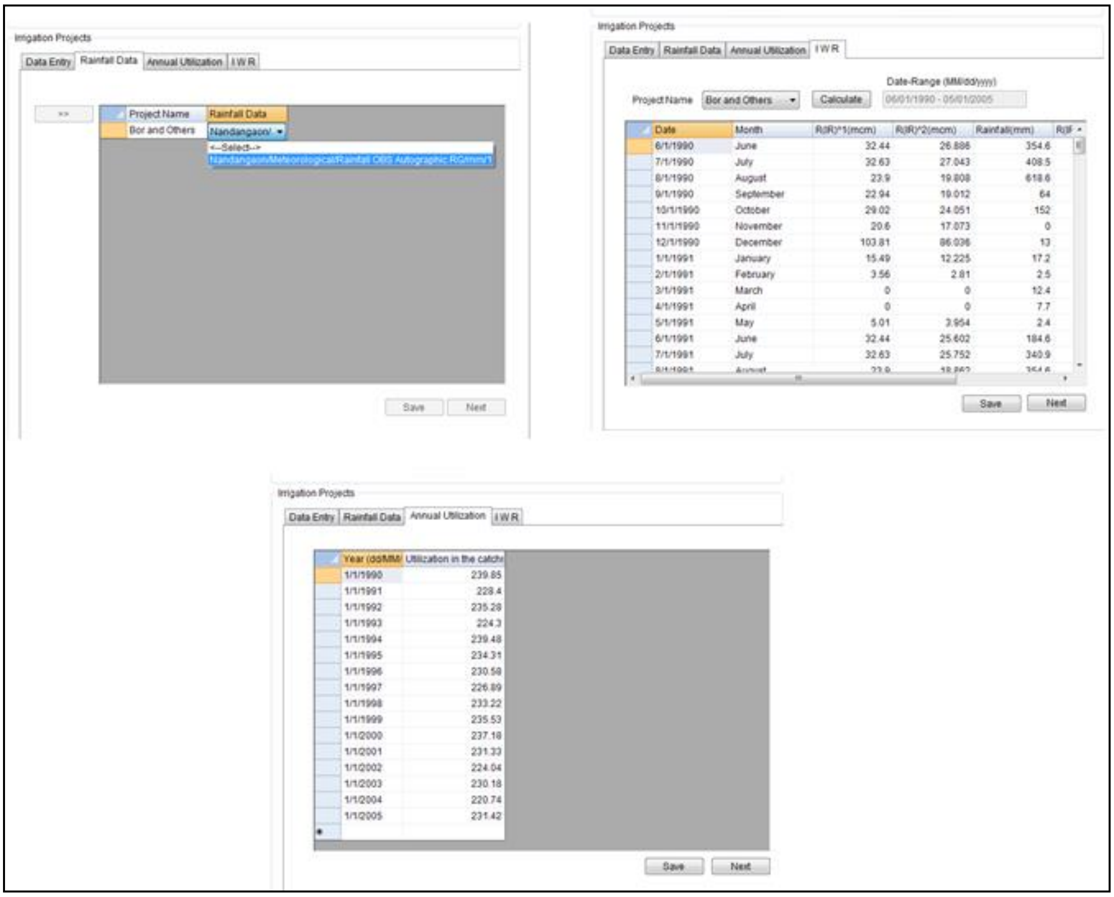
Figure 5.2: 'Data entry' sub-tab to incorporate Cropping informations for projects

Using the input as shown in ***Figure 5.2***, the model calculates the Monthly water needed for each project for irrigation in MCM. The values can also be imported directly from CROPWAT.

In the next step, monthly rainfall of the catchment area is provided to assess the inflow pattern in the river (refer sub-tab 'Rainfall data' in ***Figure 5.3***). Annual utilization of water for irrigation is provide in the Sub-tab 'Annual Utilization' (Refer ***Figure 5.3***).

Calculation of Evaporation from the reservoirs

The reservoir evaporation is calculated monthly by multiplying pan evaporation coefficient to evaporation observed during the month. The area of reservoir is expected to be corresponding to the elevation maintained according to the rule curve. For this the inputs are Elevation-Area-Capacity of the reservoir, monthly evaporation and rule curve specified level of reservoir. The interface is seen from ***Figure 5.4***.



Project Name	Rainfall Data
Bor and Others	Nandangaon/

<--Select-->
Nandangaon/Meteorological/Rainfall OBS Autographic RG/mm/1

Project Name: Bor and Others
Date-Range (MM/dd/yyyy): 06/01/1990 - 05/01/2005

Date	Month	R(IR)^1(mcm)	R(IR)^2(mcm)	Rainfall(mm)
6/1/1990	June	32.44	26.886	354.6
7/1/1990	July	32.63	27.043	408.5
8/1/1990	August	23.9	19.808	618.6
9/1/1990	September	22.94	19.012	64
10/1/1990	October	29.02	24.051	152
11/1/1990	November	20.6	17.073	0
12/1/1990	December	103.81	86.036	13
1/1/1991	January	15.49	12.225	17.2
2/1/1991	February	3.56	2.81	2.5
3/1/1991	March	0	0	12.4
4/1/1991	April	0	0	7.7
5/1/1991	May	5.01	3.954	2.4
6/1/1991	June	32.44	25.602	184.6
7/1/1991	July	32.63	25.752	340.9

Year (dd/MM/	Utilization in the catch
1/1/1990	239.85
1/1/1991	228.4
1/1/1992	235.28
1/1/1993	224.3
1/1/1994	239.48
1/1/1995	234.31
1/1/1996	230.58
1/1/1997	226.89
1/1/1998	233.22
1/1/1999	235.53
1/1/2000	237.18
1/1/2001	231.33
1/1/2002	224.04
1/1/2003	230.18
1/1/2004	220.74
1/1/2005	231.42

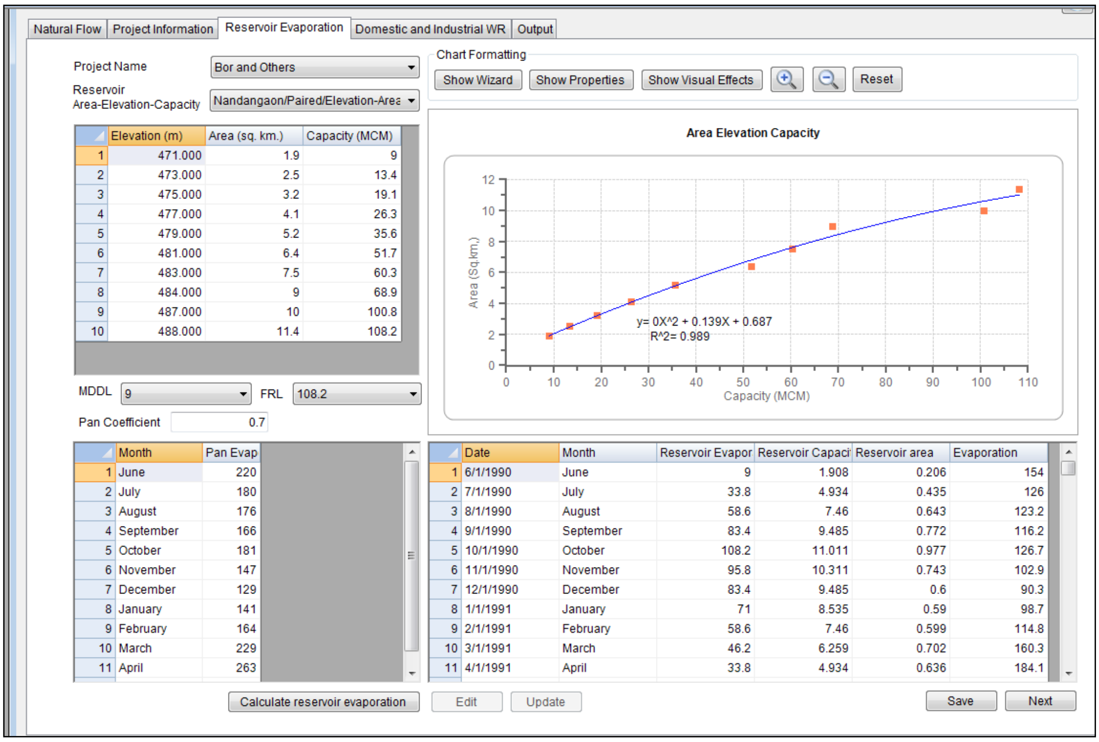
Figure 5. 3: Sequence of Irrigation water Release compution

Calculation of Domestic and Industrial Requirement

The Domestic and Industrial requirement has been calculated as 0.484 Mcm/day in ‘Domestic and Industrial’ Tab.

Return flow

In the current analysis, Irrigation return flow of 0% and D&I Return flow of 80% has been provided for assessment of yield.



Project Name: Bor and Others

Reservoir Area-Elevation-Capacity: Nandangaon/Paired/Elevation-Area

	Elevation (m)	Area (sq. km.)	Capacity (MCM)
1	471.000	1.9	9
2	473.000	2.5	13.4
3	475.000	3.2	19.1
4	477.000	4.1	26.3
5	479.000	5.2	35.6
6	481.000	6.4	51.7
7	483.000	7.5	60.3
8	484.000	9	68.9
9	487.000	10	100.8
10	488.000	11.4	108.2

MDDL: 9

FRL: 108.2

Pan Coefficient: 0.7

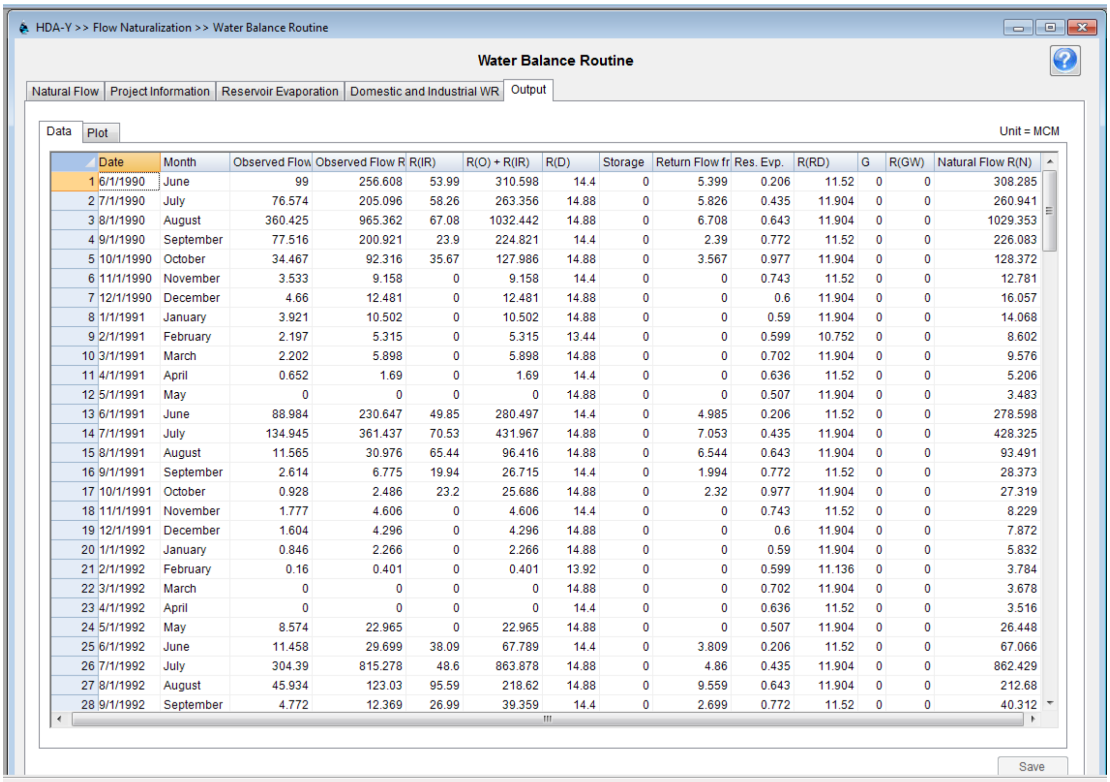
	Month	Pan Evap
1	June	220
2	July	180
3	August	176
4	September	166
5	October	181
6	November	147
7	December	129
8	January	141
9	February	164
10	March	229
11	April	263

	Date	Month	Reservoir Evapor	Reservoir Capaci	Reservoir area	Evaporation
1	6/1/1990	June	9	1.908	0.206	154
2	7/1/1990	July	33.8	4.934	0.435	126
3	8/1/1990	August	58.6	7.46	0.643	123.2
4	9/1/1990	September	83.4	9.485	0.772	116.2
5	10/1/1990	October	108.2	11.011	0.977	126.7
6	11/1/1990	November	95.8	10.311	0.743	102.9
7	12/1/1990	December	83.4	9.485	0.6	90.3
8	1/1/1991	January	71	8.535	0.59	98.7
9	2/1/1991	February	58.6	7.46	0.599	114.8
10	3/1/1991	March	46.2	6.259	0.702	160.3
11	4/1/1991	April	33.8	4.934	0.636	184.1

Figure 5.4: Input to calculate reservoir evaporation

Output

The execution of FNM results in generation of Tabular and Graphical Output is shown in ***Figure 5.5*** and ***Figure 5.6***. ***Table 5.1*** gives the detailed output.



Unit = MCM

	Date	Month	Observed Flow	Observed Flow R	R(IR)	R(O) + R(IR)	R(D)	Storage	Return Flow fr	Res. Evp.	R(RD)	G	R(GW)	Natural Flow R(N)
1	6/1/1990	June	99	256.608	53.99	310.598	14.4	0	5.399	0.206	11.52	0	0	308.285
2	7/1/1990	July	76.574	205.096	58.26	263.356	14.88	0	5.826	0.435	11.904	0	0	260.941
3	8/1/1990	August	360.425	965.362	67.08	1032.442	14.88	0	6.708	0.643	11.904	0	0	1029.353
4	9/1/1990	September	77.516	200.921	23.9	224.821	14.4	0	2.39	0.772	11.52	0	0	226.083
5	10/1/1990	October	34.467	92.316	35.67	127.986	14.88	0	3.567	0.977	11.904	0	0	128.372
6	11/1/1990	November	3.533	9.158	0	9.158	14.4	0	0	0.743	11.52	0	0	12.781
7	12/1/1990	December	4.66	12.481	0	12.481	14.88	0	0	0.6	11.904	0	0	16.057
8	1/1/1991	January	3.921	10.502	0	10.502	14.88	0	0	0.59	11.904	0	0	14.068
9	2/1/1991	February	2.197	5.315	0	5.315	13.44	0	0	0.599	10.752	0	0	8.602
10	3/1/1991	March	2.202	5.898	0	5.898	14.88	0	0	0.702	11.904	0	0	9.576
11	4/1/1991	April	0.652	1.69	0	1.69	14.4	0	0	0.636	11.52	0	0	5.206
12	5/1/1991	May	0	0	0	0	14.88	0	0	0.507	11.904	0	0	3.483
13	6/1/1991	June	88.984	230.647	49.85	280.497	14.4	0	4.985	0.206	11.52	0	0	278.598
14	7/1/1991	July	134.945	361.437	70.53	431.967	14.88	0	7.053	0.435	11.904	0	0	428.325
15	8/1/1991	August	11.565	30.976	65.44	96.416	14.88	0	6.544	0.643	11.904	0	0	93.491
16	9/1/1991	September	2.614	6.775	19.94	26.715	14.4	0	1.994	0.772	11.52	0	0	28.373
17	10/1/1991	October	0.928	2.486	23.2	25.686	14.88	0	2.32	0.977	11.904	0	0	27.319
18	11/1/1991	November	1.777	4.606	0	4.606	14.4	0	0	0.743	11.52	0	0	8.229
19	12/1/1991	December	1.604	4.296	0	4.296	14.88	0	0	0.6	11.904	0	0	7.872
20	1/1/1992	January	0.846	2.266	0	2.266	14.88	0	0	0.59	11.904	0	0	5.832
21	2/1/1992	February	0.16	0.401	0	0.401	13.92	0	0	0.599	11.136	0	0	3.784
22	3/1/1992	March	0	0	0	0	14.88	0	0	0.702	11.904	0	0	3.678
23	4/1/1992	April	0	0	0	0	14.4	0	0	0.636	11.52	0	0	3.516
24	5/1/1992	May	8.574	22.965	0	22.965	14.88	0	0	0.507	11.904	0	0	26.448
25	6/1/1992	June	11.458	29.699	38.09	67.789	14.4	0	3.809	0.206	11.52	0	0	67.066
26	7/1/1992	July	304.39	815.278	48.6	863.878	14.88	0	4.86	0.435	11.904	0	0	862.429
27	8/1/1992	August	45.934	123.03	95.59	218.62	14.88	0	9.559	0.643	11.904	0	0	212.68
28	9/1/1992	September	4.772	12.369	26.99	39.359	14.4	0	2.699	0.772	11.52	0	0	40.312

Figure 5. 5: Natural Flow computed from observed flow

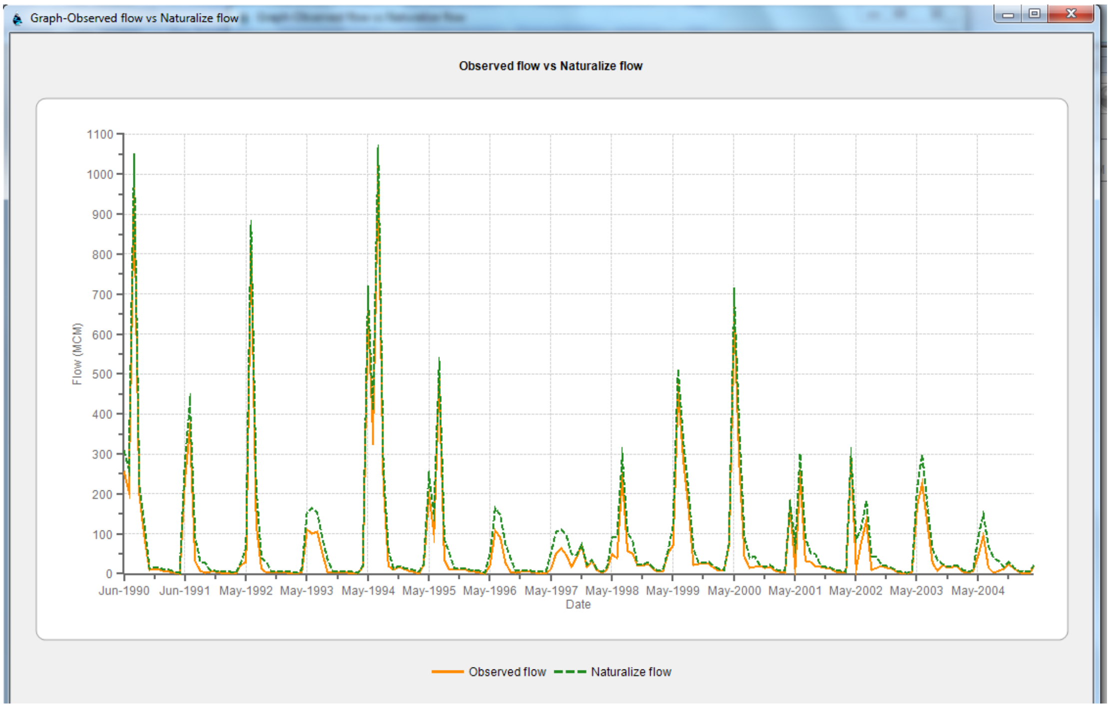


Figure 5. 6: Time series plot of Observed and Naturalised flow

Table 5.1 : Detailed Output of FNM (Unit : MCM)

Date	Month	R(O)-cms	Days	R(O)	R(IRR)	R(O) + R(IR)	R(DI)	STO	R(R-IRR)	EVAP	R(R-DI)	G	R(GW)	IMP	EXP	R(N)	R(N) (cms)
6/1/1990	June	99	30	256.608	53.99	310.598	14.52	0	0	0.004	11.616	0	0	0	0	313.506	120.951
7/1/1990	July	76.574	31	205.096	58.26	263.356	15.004	0	0	0.016	12.003	0	0	0	0	266.373	99.452
8/1/1990	August	360.425	31	965.362	67.08	1032.442	15.004	0	0	0.027	12.003	0	0	0	0	1035.47	386.6
9/1/1990	September	77.516	30	200.921	23.92	224.841	14.52	0	0	0.033	11.616	0	0	0	0	227.778	87.877
10/1/1990	October	34.467	31	92.316	35.66	127.976	15.004	0	0	0.044	12.003	0	0	0	0	131.021	48.918
11/1/1990	November	3.533	30	9.158	0	9.158	14.52	0	0	0.033	11.616	0	0	0	0	12.095	4.666
12/1/1990	December	4.66	31	12.481	0	12.481	15.004	0	0	0.026	12.003	0	0	0	0	15.508	5.79
1/1/1991	January	3.921	31	10.502	0	10.502	15.004	0	0	0.025	12.003	0	0	0	0	13.528	5.051
2/1/1991	February	2.197	28	5.315	0	5.315	13.552	0	0	0.025	10.842	0	0	0	0	8.05	3.328
3/1/1991	March	2.202	31	5.898	0	5.898	15.004	0	0	0.028	12.003	0	0	0	0	8.927	3.333
4/1/1991	April	0.652	30	1.69	0	1.69	14.52	0	0	0.024	11.616	0	0	0	0	4.618	1.782
5/1/1991	May	0	31	0	0	0	15.004	0	0	0.017	12.003	0	0	0	0	3.018	1.127
6/1/1991	June	88.984	30	230.647	49.86	280.507	14.52	0	0	0.004	11.616	0	0	0	0	283.415	109.342
7/1/1991	July	134.945	31	361.437	70.53	431.967	15.004	0	0	0.016	12.003	0	0	0	0	434.984	162.404
8/1/1991	August	11.565	31	30.976	65.44	96.416	15.004	0	0	0.027	12.003	0	0	0	0	99.444	37.128
9/1/1991	September	2.614	30	6.775	19.96	26.735	14.52	0	0	0.033	11.616	0	0	0	0	29.672	11.448
10/1/1991	October	0.928	31	2.486	23.2	25.686	15.004	0	0	0.044	12.003	0	0	0	0	28.731	10.727
11/1/1991	November	1.777	30	4.606	0	4.606	14.52	0	0	0.033	11.616	0	0	0	0	7.543	2.91
12/1/1991	December	1.604	31	4.296	0	4.296	15.004	0	0	0.026	12.003	0	0	0	0	7.323	2.734
1/1/1992	January	0.846	31	2.266	0	2.266	15.004	0	0	0.025	12.003	0	0	0	0	5.292	1.976
2/1/1992	February	0.16	29	0.401	0	0.401	14.036	0	0	0.025	11.229	0	0	0	0	3.233	1.29
3/1/1992	March	0	31	0	0	0	15.004	0	0	0.028	12.003	0	0	0	0	3.029	1.131
4/1/1992	April	0	30	0	0	0	14.52	0	0	0.024	11.616	0	0	0	0	2.928	1.13
5/1/1992	May	8.574	31	22.965	0	22.965	15.004	0	0	0.017	12.003	0	0	0	0	25.983	9.701

Table 5.1 : Detailed Output of FNM (Unit : MCM)

Date	Month	R(O)-cms	Days	R(O)	R(IRR)	R(O) + R(IR)	R(DI)	STO	R(R-IRR)	EVAP	R(R-DI)	G	R(GW)	IMP	EXP	R(N)	R(N) (cms)
6/1/1992	June	11.458	30	29.699	38.1	67.799	14.52	0	0	0.004	11.616	0	0	0	0	70.707	27.279
7/1/1992	July	304.39	31	815.278	48.59	863.868	15.004	0	0	0.016	12.003	0	0	0	0	866.885	323.658
8/1/1992	August	45.934	31	123.03	95.59	218.62	15.004	0	0	0.027	12.003	0	0	0	0	221.648	82.754
9/1/1992	September	4.772	30	12.369	27	39.369	14.52	0	0	0.033	11.616	0	0	0	0	42.306	16.322
10/1/1992	October	0.91	31	2.437	25.09	27.527	15.004	0	0	0.044	12.003	0	0	0	0	30.572	11.414
11/1/1992	November	0.789	30	2.045	0	2.045	14.52	0	0	0.033	11.616	0	0	0	0	4.982	1.922
12/1/1992	December	0.622	31	1.666	0	1.666	15.004	0	0	0.026	12.003	0	0	0	0	4.693	1.752
1/1/1993	January	0.811	31	2.172	0	2.172	15.004	0	0	0.025	12.003	0	0	0	0	5.198	1.941
2/1/1993	February	0.757	28	1.831	0	1.831	13.552	0	0	0.025	10.842	0	0	0	0	4.566	1.887
3/1/1993	March	0.078	31	0.209	0	0.209	15.004	0	0	0.028	12.003	0	0	0	0	3.238	1.209
4/1/1993	April	0.025	30	0.065	0	0.065	14.52	0	0	0.024	11.616	0	0	0	0	2.993	1.155
5/1/1993	May	1.918	31	5.137	0	5.137	15.004	0	0	0.017	12.003	0	0	0	0	8.155	3.045
6/1/1993	June	42.162	30	109.284	45.84	155.124	14.52	0	0	0.004	11.616	0	0	0	0	158.032	60.969
7/1/1993	July	37.349	31	100.036	67.65	167.686	15.004	0	0	0.016	12.003	0	0	0	0	170.703	63.733
8/1/1993	August	39.554	31	105.941	48.53	154.471	15.004	0	0	0.027	12.003	0	0	0	0	157.499	58.803
9/1/1993	September	20.293	30	52.599	34.52	87.119	14.52	0	0	0.033	11.616	0	0	0	0	90.056	34.744
10/1/1993	October	2.213	31	5.927	29.02	34.947	15.004	0	0	0.044	12.003	0	0	0	0	37.992	14.185
11/1/1993	November	1.075	30	2.786	0	2.786	14.52	0	0	0.033	11.616	0	0	0	0	5.723	2.208
12/1/1993	December	0.762	31	2.041	0	2.041	15.004	0	0	0.026	12.003	0	0	0	0	5.068	1.892
1/1/1994	January	0.803	31	2.151	0	2.151	15.004	0	0	0.025	12.003	0	0	0	0	5.177	1.933
2/1/1994	February	0.623	28	1.507	0	1.507	13.552	0	0	0.025	10.842	0	0	0	0	4.242	1.753
3/1/1994	March	0.01	31	0.027	0	0.027	15.004	0	0	0.028	12.003	0	0	0	0	3.056	1.141
4/1/1994	April	0	30	0	0	0	14.52	0	0	0.024	11.616	0	0	0	0	2.928	1.13
5/1/1994	May	6.468	31	17.324	0	17.324	15.004	0	0	0.017	12.003	0	0	0	0	20.342	7.595

Table 5.1 : Detailed Output of FNM (Unit : MCM)

Date	Month	R(O)-cms	Days	R(O)	R(IRR)	R(O) + R(IR)	R(DI)	STO	R(R-IRR)	EVAP	R(R-DI)	G	R(GW)	IMP	EXP	R(N)	R(N) (cms)
6/1/1994	June	253.356	30	656.699	43.11	699.809	14.52	0	0	0.004	11.616	0	0	0	0	702.717	271.11
7/1/1994	July	128.559	31	344.332	69.56	413.892	15.004	0	0	0.016	12.003	0	0	0	0	416.909	155.656
8/1/1994	August	374.951	31	1004.269	47.23	1051.499	15.004	0	0	0.027	12.003	0	0	0	0	1054.527	393.715
9/1/1994	September	88.035	30	228.187	40.87	269.057	14.52	0	0	0.033	11.616	0	0	0	0	271.994	104.936
10/1/1994	October	7.188	31	19.252	38.29	57.542	15.004	0	0	0.044	12.003	0	0	0	0	60.587	22.621
11/1/1994	November	3.457	30	8.961	0	8.961	14.52	0	0	0.033	11.616	0	0	0	0	11.898	4.59
12/1/1994	December	6.333	31	16.962	0	16.962	15.004	0	0	0.026	12.003	0	0	0	0	19.989	7.463
1/1/1995	January	4.195	31	11.236	0	11.236	15.004	0	0	0.025	12.003	0	0	0	0	14.262	5.325
2/1/1995	February	3.361	28	8.131	0	8.131	13.552	0	0	0.025	10.842	0	0	0	0	10.866	4.492
3/1/1995	March	2.275	31	6.093	0	6.093	15.004	0	0	0.028	12.003	0	0	0	0	9.122	3.406
4/1/1995	April	0.085	30	0.22	0	0.22	14.52	0	0	0.024	11.616	0	0	0	0	3.148	1.215
5/1/1995	May	8.066	31	21.604	0	21.604	15.004	0	0	0.017	12.003	0	0	0	0	24.622	9.193
6/1/1995	June	76.772	30	198.993	48.58	247.573	14.52	0	0	0.004	11.616	0	0	0	0	250.481	96.636
7/1/1995	July	37.581	31	100.657	53.14	153.797	15.004	0	0	0.016	12.003	0	0	0	0	156.814	58.548
8/1/1995	August	180.725	31	484.054	36.04	520.094	15.004	0	0	0.027	12.003	0	0	0	0	523.122	195.311
9/1/1995	September	13.594	30	35.236	51.86	87.096	14.52	0	0	0.033	11.616	0	0	0	0	90.033	34.735
10/1/1995	October	3.242	31	8.683	44.38	53.063	15.004	0	0	0.044	12.003	0	0	0	0	56.108	20.948
11/1/1995	November	3.671	30	9.515	0	9.515	14.52	0	0	0.033	11.616	0	0	0	0	12.452	4.804
12/1/1995	December	3.616	31	9.685	0	9.685	15.004	0	0	0.026	12.003	0	0	0	0	12.712	4.746
1/1/1996	January	4.387	31	11.75	0	11.75	15.004	0	0	0.025	12.003	0	0	0	0	14.776	5.517
2/1/1996	February	2.207	29	5.53	0	5.53	14.036	0	0	0.025	11.229	0	0	0	0	8.362	3.337
3/1/1996	March	1.415	31	3.79	0	3.79	15.004	0	0	0.028	12.003	0	0	0	0	6.819	2.546
4/1/1996	April	1.235	30	3.201	0	3.201	14.52	0	0	0.024	11.616	0	0	0	0	6.129	2.365
5/1/1996	May	0	31	0	0	0	15.004	0	0	0.017	12.003	0	0	0	0	3.018	1.127

Table 5.1 : Detailed Output of FNM (Unit : MCM)

Date	Month	R(O)-cms	Days	R(O)	R(IRR)	R(O) + R(IR)	R(DI)	STO	R(R-IRR)	EVAP	R(R-DI)	G	R(GW)	IMP	EXP	R(N)	R(N) (cms)
6/1/1996	June	8.454	30	21.913	30.13	52.043	14.52	0	0	0.004	11.616	0	0	0	0	54.951	21.2
7/1/1996	July	40.62	31	108.797	59	167.797	15.004	0	0	0.016	12.003	0	0	0	0	170.814	63.775
8/1/1996	August	33.716	31	90.305	60.1	150.405	15.004	0	0	0.027	12.003	0	0	0	0	153.433	57.285
9/1/1996	September	9.993	30	25.902	47.48	73.382	14.52	0	0	0.033	11.616	0	0	0	0	76.319	29.444
10/1/1996	October	1.859	31	4.979	33.56	38.539	15.004	0	0	0.044	12.003	0	0	0	0	41.584	15.526
11/1/1996	November	1.373	30	3.559	0	3.559	14.52	0	0	0.033	11.616	0	0	0	0	6.496	2.506
12/1/1996	December	1.987	31	5.322	0	5.322	15.004	0	0	0.026	12.003	0	0	0	0	8.349	3.117
1/1/1997	January	1.71	31	4.58	0	4.58	15.004	0	0	0.025	12.003	0	0	0	0	7.606	2.84
2/1/1997	February	1.652	28	3.997	0	3.997	13.552	0	0	0.025	10.842	0	0	0	0	6.732	2.783
3/1/1997	March	0.808	31	2.164	0	2.164	15.004	0	0	0.028	12.003	0	0	0	0	5.193	1.939
4/1/1997	April	0.091	30	0.236	0	0.236	14.52	0	0	0.024	11.616	0	0	0	0	3.164	1.221
5/1/1997	May	0.295	31	0.79	0	0.79	15.004	0	0	0.017	12.003	0	0	0	0	3.808	1.422
6/1/1997	June	4.315	30	11.184	43.07	54.254	14.52	0	0	0.004	11.616	0	0	0	0	57.162	22.053
7/1/1997	July	19.334	31	51.784	55.41	107.194	15.004	0	0	0.016	12.003	0	0	0	0	110.211	41.148
8/1/1997	August	23.555	31	63.09	47.29	110.38	15.004	0	0	0.027	12.003	0	0	0	0	113.408	42.342
9/1/1997	September	18.308	30	47.454	49.36	96.814	14.52	0	0	0.033	11.616	0	0	0	0	99.751	38.484
10/1/1997	October	6.177	31	16.544	32.3	48.844	15.004	0	0	0.044	12.003	0	0	0	0	51.889	19.373
11/1/1997	November	16.18	30	41.939	0	41.939	14.52	0	0	0.033	11.616	0	0	0	0	44.876	17.313
12/1/1997	December	26.255	31	70.321	0	70.321	15.004	0	0	0.026	12.003	0	0	0	0	73.348	27.385
1/1/1998	January	6.788	31	18.181	0	18.181	15.004	0	0	0.025	12.003	0	0	0	0	21.207	7.918
2/1/1998	February	13.032	28	31.527	0	31.527	13.552	0	0	0.025	10.842	0	0	0	0	34.262	14.163
3/1/1998	March	3.361	31	9.002	0	9.002	15.004	0	0	0.028	12.003	0	0	0	0	12.031	4.492
4/1/1998	April	0.992	30	2.571	0	2.571	14.52	0	0	0.024	11.616	0	0	0	0	5.499	2.122
5/1/1998	May	3.776	31	10.114	0	10.114	15.004	0	0	0.017	12.003	0	0	0	0	13.132	4.903

Table 5.1 : Detailed Output of FNM (Unit : MCM)

Date	Month	R(O)-cms	Days	R(O)	R(IRR)	R(O) + R(IR)	R(DI)	STO	R(R-IRR)	EVAP	R(R-DI)	G	R(GW)	IMP	EXP	R(N)	R(N) (cms)
6/1/1998	June	19.212	30	49.798	42.77	92.568	14.52	0	0	0.004	11.616	0	0	0	0	95.476	36.835
7/1/1998	July	14.667	31	39.284	57.04	96.324	15.004	0	0	0.016	12.003	0	0	0	0	99.341	37.09
8/1/1998	August	90.219	31	241.643	53.27	294.913	15.004	0	0	0.027	12.003	0	0	0	0	297.941	111.238
9/1/1998	September	21.707	30	56.265	48.27	104.535	14.52	0	0	0.033	11.616	0	0	0	0	107.472	41.463
10/1/1998	October	18.872	31	50.547	32.06	82.607	15.004	0	0	0.044	12.003	0	0	0	0	85.652	31.979
11/1/1998	November	7.093	30	18.385	0	18.385	14.52	0	0	0.033	11.616	0	0	0	0	21.322	8.226
12/1/1998	December	7.307	31	19.571	0	19.571	15.004	0	0	0.026	12.003	0	0	0	0	22.598	8.437
1/1/1999	January	9.301	31	24.912	0	24.912	15.004	0	0	0.025	12.003	0	0	0	0	27.938	10.431
2/1/1999	February	4.917	28	11.895	0	11.895	13.552	0	0	0.025	10.842	0	0	0	0	14.63	6.047
3/1/1999	March	1.682	31	4.505	0	4.505	15.004	0	0	0.028	12.003	0	0	0	0	7.534	2.813
4/1/1999	April	2.221	30	5.757	0	5.757	14.52	0	0	0.024	11.616	0	0	0	0	8.685	3.351
5/1/1999	May	19.286	31	51.656	0	51.656	15.004	0	0	0.017	12.003	0	0	0	0	54.674	20.413
6/1/1999	June	27.529	30	71.355	50.95	122.305	14.52	0	0	0.004	11.616	0	0	0	0	125.213	48.307
7/1/1999	July	173.296	31	464.156	50.15	514.306	15.004	0	0	0.016	12.003	0	0	0	0	517.323	193.146
8/1/1999	August	106.39	31	284.955	49.6	334.555	15.004	0	0	0.027	12.003	0	0	0	0	337.583	126.039
9/1/1999	September	64.467	30	167.098	44.8	211.898	14.52	0	0	0.033	11.616	0	0	0	0	214.835	82.884
10/1/1999	October	8.121	31	21.751	40.17	61.921	15.004	0	0	0.044	12.003	0	0	0	0	64.966	24.256
11/1/1999	November	9.351	30	24.238	0	24.238	14.52	0	0	0.033	11.616	0	0	0	0	27.175	10.484
12/1/1999	December	9.035	31	24.199	0	24.199	15.004	0	0	0.026	12.003	0	0	0	0	27.226	10.165
1/1/2000	January	9.456	31	25.327	0	25.327	15.004	0	0	0.025	12.003	0	0	0	0	28.353	10.586
2/1/2000	February	6.157	29	15.427	0	15.427	14.036	0	0	0.025	11.229	0	0	0	0	18.259	7.287
3/1/2000	March	2.746	31	7.355	0	7.355	15.004	0	0	0.028	12.003	0	0	0	0	10.384	3.877
4/1/2000	April	2.795	30	7.245	0	7.245	14.52	0	0	0.024	11.616	0	0	0	0	10.173	3.925
5/1/2000	May	26.743	31	71.628	0	71.628	15.004	0	0	0.017	12.003	0	0	0	0	74.646	27.87

Table 5.1 : Detailed Output of FNM (Unit : MCM)

Date	Month	R(O)-cms	Days	R(O)	R(IRR)	R(O) + R(IR)	R(DI)	STO	R(R-IRR)	EVAP	R(R-DI)	G	R(GW)	IMP	EXP	R(N)	R(N) (cms)
6/1/2000	June	250.39	30	649.011	46.87	695.881	14.52	0	0	0.004	11.616	0	0	0	0	698.789	269.595
7/1/2000	July	103.52	31	277.268	92.59	369.858	15.004	0	0	0.016	12.003	0	0	0	0	372.875	139.216
8/1/2000	August	16.004	31	42.865	49.71	92.575	15.004	0	0	0.027	12.003	0	0	0	0	95.603	35.694
9/1/2000	September	5.739	30	14.875	23.46	38.335	14.52	0	0	0.033	11.616	0	0	0	0	41.272	15.923
10/1/2000	October	6.804	31	18.224	24.08	42.304	15.004	0	0	0.044	12.003	0	0	0	0	45.349	16.931
11/1/2000	November	7.138	30	18.502	0	18.502	14.52	0	0	0.033	11.616	0	0	0	0	21.439	8.271
12/1/2000	December	5.386	31	14.426	0	14.426	15.004	0	0	0.026	12.003	0	0	0	0	17.453	6.516
1/1/2001	January	6.628	31	17.752	0	17.752	15.004	0	0	0.025	12.003	0	0	0	0	20.778	7.758
2/1/2001	February	3.24	28	7.838	0	7.838	13.552	0	0	0.025	10.842	0	0	0	0	10.573	4.37
3/1/2001	March	1.601	31	4.288	0	4.288	15.004	0	0	0.028	12.003	0	0	0	0	7.317	2.732
4/1/2001	April	1.08	30	2.799	0	2.799	14.52	0	0	0.024	11.616	0	0	0	0	5.727	2.209
5/1/2001	May	63.253	31	169.417	0	169.417	15.004	0	0	0.017	12.003	0	0	0	0	172.435	64.38
6/1/2001	June	4.856	30	12.587	61.06	73.647	14.52	0	0	0.004	11.616	0	0	0	0	76.555	29.535
7/1/2001	July	91.618	31	245.39	59.3	304.69	15.004	0	0	0.016	12.003	0	0	0	0	307.707	114.885
8/1/2001	August	11.896	31	31.862	60.08	91.942	15.004	0	0	0.027	12.003	0	0	0	0	94.97	35.458
9/1/2001	September	11.382	30	29.502	19.73	49.232	14.52	0	0	0.033	11.616	0	0	0	0	52.169	20.127
10/1/2001	October	6.296	31	16.863	30.57	47.433	15.004	0	0	0.044	12.003	0	0	0	0	50.478	18.846
11/1/2001	November	6.239	30	16.171	0	16.171	14.52	0	0	0.033	11.616	0	0	0	0	19.108	7.372
12/1/2001	December	5.153	31	13.802	0	13.802	15.004	0	0	0.026	12.003	0	0	0	0	16.829	6.283
1/1/2002	January	4.427	31	11.857	0	11.857	15.004	0	0	0.025	12.003	0	0	0	0	14.883	5.557
2/1/2002	February	1.901	28	4.599	0	4.599	13.552	0	0	0.025	10.842	0	0	0	0	7.334	3.032
3/1/2002	March	1.182	31	3.166	0	3.166	15.004	0	0	0.028	12.003	0	0	0	0	6.195	2.313
4/1/2002	April	0.706	30	1.83	0	1.83	14.52	0	0	0.024	11.616	0	0	0	0	4.758	1.836
5/1/2002	May	108.611	31	290.904	0	290.904	15.004	0	0	0.017	12.003	0	0	0	0	293.922	109.738

Table 5.1 : Detailed Output of FNM (Unit : MCM)

Date	Month	R(O)-cms	Days	R(O)	R(IRR)	R(O) + R(IR)	R(DI)	STO	R(R-IRR)	EVAP	R(R-DI)	G	R(GW)	IMP	EXP	R(N)	R(N) (cms)
6/1/2002	June	4.827	30	12.512	77.66	90.172	14.52	0	0	0.004	11.616	0	0	0	0	93.08	35.91
7/1/2002	July	29.569	31	79.198	34.98	114.178	15.004	0	0	0.016	12.003	0	0	0	0	117.195	43.756
8/1/2002	August	49.316	31	132.088	54.09	186.178	15.004	0	0	0.027	12.003	0	0	0	0	189.206	70.641
9/1/2002	September	3.73	30	9.668	33.63	43.298	14.52	0	0	0.033	11.616	0	0	0	0	46.235	17.838
10/1/2002	October	5.939	31	15.907	24.19	40.097	15.004	0	0	0.044	12.003	0	0	0	0	43.142	16.107
11/1/2002	November	7.103	30	18.411	0	18.411	14.52	0	0	0.033	11.616	0	0	0	0	21.348	8.236
12/1/2002	December	5.564	31	14.903	0	14.903	15.004	0	0	0.026	12.003	0	0	0	0	17.93	6.694
1/1/2003	January	4.441	31	11.895	0	11.895	15.004	0	0	0.025	12.003	0	0	0	0	14.921	5.571
2/1/2003	February	1.635	28	3.955	0	3.955	13.552	0	0	0.025	10.842	0	0	0	0	6.69	2.765
3/1/2003	March	0.383	31	1.026	0	1.026	15.004	0	0	0.028	12.003	0	0	0	0	4.055	1.514
4/1/2003	April	0	30	0	0	0	14.52	0	0	0.024	11.616	0	0	0	0	2.928	1.13
5/1/2003	May	1.496	31	4.007	0	4.007	15.004	0	0	0.017	12.003	0	0	0	0	7.025	2.623
6/1/2003	June	66.243	30	171.702	44.83	216.532	14.52	0	0	0.004	11.616	0	0	0	0	219.44	84.66
7/1/2003	July	83.723	31	224.244	78.69	302.934	15.004	0	0	0.016	12.003	0	0	0	0	305.951	114.229
8/1/2003	August	46.554	31	124.69	47.04	171.73	15.004	0	0	0.027	12.003	0	0	0	0	174.758	65.247
9/1/2003	September	10.466	30	27.128	33.76	60.888	14.52	0	0	0.033	11.616	0	0	0	0	63.825	24.624
10/1/2003	October	2.672	31	7.157	25.08	32.237	15.004	0	0	0.044	12.003	0	0	0	0	35.282	13.173
11/1/2003	November	8.295	30	21.501	0	21.501	14.52	0	0	0.033	11.616	0	0	0	0	24.438	9.428
12/1/2003	December	5.258	31	14.083	0	14.083	15.004	0	0	0.026	12.003	0	0	0	0	17.11	6.388
1/1/2004	January	6.414	31	17.179	0	17.179	15.004	0	0	0.025	12.003	0	0	0	0	20.205	7.544
2/1/2004	February	6.604	29	16.547	0	16.547	14.036	0	0	0.025	11.229	0	0	0	0	19.379	7.734
3/1/2004	March	1.839	31	4.926	0	4.926	15.004	0	0	0.028	12.003	0	0	0	0	7.955	2.97
4/1/2004	April	0.932	30	2.416	0	2.416	14.52	0	0	0.024	11.616	0	0	0	0	5.344	2.062
5/1/2004	May	2.713	31	7.266	0	7.266	15.004	0	0	0.017	12.003	0	0	0	0	10.284	3.84

Contents

6. RAINFALL RUNOFF MODEL 1
6.1. INTRODUCTION 1
6.2. PRECIPITATION RUNOFF MODEL 1
  6.2.1. Model Structure 2
  6.2.2. Basic Modeling Components 3
  6.2.3. Description of Model Parameters 4
  6.2.4. Data Requirements 8
  6.2.5. PROM Structure in RRM of HDA-Y 9
  6.2.6. PROM : Parameter Sensitivity 15
6.3. MODEL E 21
  6.3.1. Model Structure 21
  6.3.2. Model Algorithm 22
  6.3.3. Basic Modeling Components 23
  6.3.4. Data Requirements 24
  6.3.5. Model Structure of MODEL E in HDA 24
  6.3.5.1 Time Series 25
  6.3.5.2 Calibration 25
  6.3.5.3 Validation 28
  6.3.5.4 Simulate 29
  6.3.5.5 Final Output 29
  6.3.6. MODEL E : Parameter sensitivity 30
6.4. REGRSSION MODEL 32
  6.4.1 Model structure 32
  6.4.2 Regression Theory 35
  6.4.3 Limitations 37
6.5. CALIBRATION AND TESTS OF MODEL FITNESS 38

List of Figures

Figure 6. 1: Land phase of hydrological cycle 2
Figure 6. 2: Dialogue Box for selection of time series for PROM 10
Figure 6. 3: Calibration Tab of PROM 11
Figure 6. 4: Comparison of observed and simulated discharge (Monthly and Annual) during 13
Figure 6.5: Validation Tab of PROM with output 14
Figure 6.6: Result statistics of model under simulate Tab in PROM 14
Figure 6.7: Yield series Data Table and Plot as Final Output in PROM 15

Figure 6. 8: Changes in Model TWY , Monsoon and Non-Monsoon flow response to most sensitive parameters of PROM 19

Figure 6.9: Schematic diagram of Model E 21

Figure 6.10: Project Configuration in Model E 26

Figure 6.11: Calibration in Model E 26

Figure 6.12: Data plot comparison of observed and simulated discharge 28

Figure 6.13: Validation of model and comparison plot of observed and simulated flow 28

Figure 6.14 : Summary Report of the model 29

Figure 6.15: Data plot of model 29

Figure 6.16: Changes in Model TWY , Monsoon and Non-Monsoon flow response to most sensitive parameters of MODEL E 31

List of Tables

Table 6. 1: Calibration Parameters in PROM 12

Table 6. 2: Relative Sensitivity of PROM Parameters 19

Table 6. 3: Relative Sensitivity of MODEL E Parameters 31

6. RAINFALL RUNOFF MODEL

6.1. INTRODUCTION

Reliable results for a basin system study can be obtained only when streamflow data are available for a minimum period of 30-35 years. This makes it necessary to use long rainfall records locally or from adjacent catchments, to estimate the streamflow hydrograph which would have corresponded to a long hyetograph, termed as “extending” the streamflow record (Clark,1973).

The nature of Rainfall-Runoff model suitable for any purpose depends on several factors such as i) Time scale of modeling ii) measurements of physical parameters of the basin iii) Reliability and the type of data forming the hydrometeorological network of the basin. The models in HDA-Y are :

PROM

MODEL E

REGM

MWSWAT (interface)

Being a lumped model, PROM, MODEL E and REGM treat each catchment as a single unit. The parameters and variables represent, therefore, average values for the entire catchment. MWSWAT is semi-distributed in nature. It divides the catchment into watersheds which are assigned unique climate, soil and landuse characteristics. It can therefore be used for watershed as well as river basin system.

PROM, MODEL E and MWSWAT represent various components of the rainfall-runoff process by continuously accounting for the water content for a range of flow. REGM is based on Regression analysis, which is a black-box approach of Rainfall-Runoff modeling. It involves establishing a relation between a dependent variable runoff for which an estimate is made, and one or more independent variables like precipitation, weather data, catchment parameters etc.

While PROM and MWSWAT accounting of processes are on daily basis, MODEL E and REGM are workable at monthly time period.

6.2. PRECIPITATION RUNOFF MODEL

The Precipitation Runoff model PROM is a lumped, conceptual precipitation-runoff model, simulating the overland, inter-flow, and base-flow components on a catchment scale. PROM is the abbreviation for Precipitation Run-Off Model based on the Model NAM "Nedbør-Afstrømnings-Model", originally developed by the Department of Hydrodynamics and Water Resources at the Technical University of Denmark. Being a continous simulation model, PROM can be used either for continuous hydrological modeling over a range of flows or for simulating single events.

6.2.1. Model Structure

A conceptual model like PROM is based on physical structures and equations used together with semi-empirical ones. As a result some of the model parameters can be evaluated from physical catchment data, but the final parameter estimation must be performed by calibration against time series of hydrological observations. The model structure of PROM is shown in ***Figure 6.1 .***

PROM simulates the rainfall-runoff process by continuously accounting for the water content in three different and mutually interrelated storages that represent different physical elements of the catchment.

- Surface storage
- Lower or root zone storage
- Groundwater storage

Each storage represents different physical elements of the catchment and are defined by semi-empirical equations . The model is described by 9 parameters connected by the three storages.

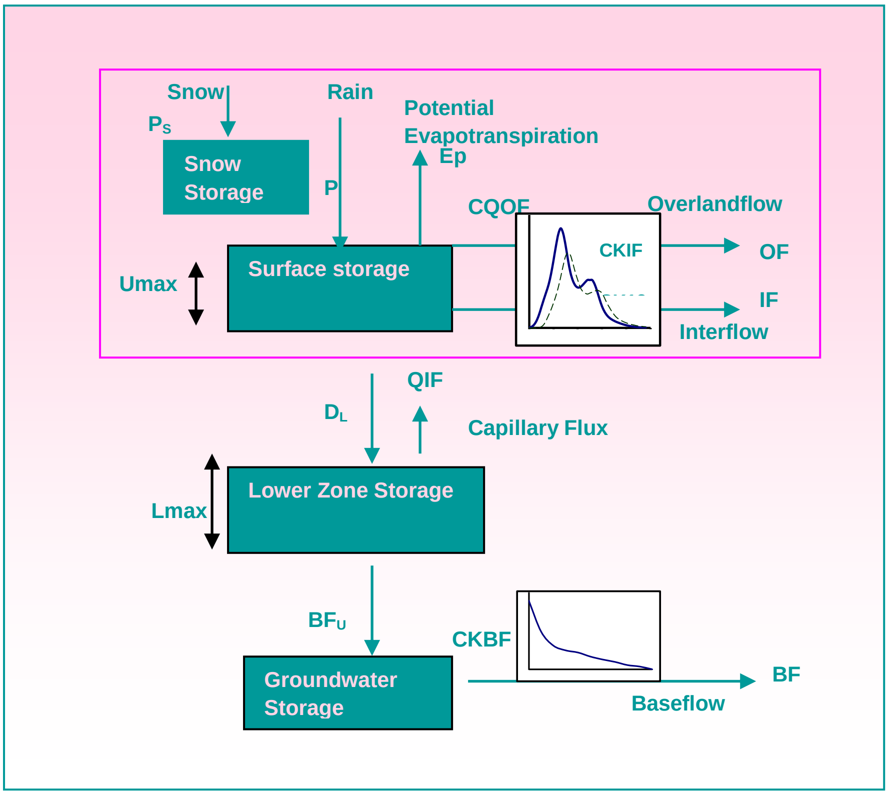


Figure 6. 1: Land phase of hydrological cycle

6.2.2. Basic Modeling Components

a. Surface storage

Moisture intercepted on the vegetation as well as water trapped in depressions and in the uppermost, cultivated part of the ground is represented as surface storage. Umax denotes the upper limit of the amount of water in the surface storage.

The amount of water U in the surface storage is continuously diminished by evaporative consumption as well as by horizontal leakage (interflow). When there is maximum surface storage, some of the excess water P_N will enter the streams as overland flow, whereas the remainder is diverted as infiltration into the lower zone and groundwater storage.

b. Lower zone or root zone storage

The soil moisture in the root zone, a soil layer below the surface from which the vegetation can draw water for transpiration, is represented as lower zone storage. Lmax denotes the upper limit of the amount of water in this storage. Moisture in the lower zone storage is subject to consumptive loss from transpiration. The moisture content controls the amount of water that enters the groundwater storage as recharge and the interflow and overland flow components.

c. Evapotranspiration

Evapotranspiration demands are first met at the potential rate from the surface storage. If the moisture content U in the surface storage is less than these requirements (U < Ep), the remaining fraction is assumed to be withdrawn by root activity from the lower zone storage at an actual rate Ea. Ea is proportional to the potential evapotranspiration and varies linearly with the relative soil moisture content L/Lmax, of the lower zone storage

$$Ea = (Ep - U)\frac{L}{Lmax}$$

d. Overland flow

When the surface storage spills, i.e. when U > Umax, the excess water P_N gives rise to overland flow as well as infiltration. QOF denotes the part of PN that contributes to overland flow. It is assumed to be proportional to PN and varies linearly with the relative soil moisture content, L/Lmax, of the lower zone storage

$$QOF = \left(\left[\quad CQOF \frac{\frac{L}{Lmax} - TOF}{1 - TOF} PN \quad \right] \quad \begin{matrix} For\,\frac{L}{Lmax} > TOF \\ \\ For\,\frac{L}{Lmax} \leq TOF \end{matrix} \right)$$

Where

CQOF is the overland flow runoff coefficient (0 ≤ CQOF ≤ 1) and TOF is the threshold value for overland flow (0 ≤ TOF ≤ 1) .

The proportion of the excess water P_N that does not runoff as overland flow infiltrates into the lower zone storage. A portion, ΔL, of the water available for infiltration, (P_N -QOF), is assumed to increase the moisture content L in the lower zone storage. The remaining amount of infiltrating moisture, G, is assumed to percolate deeper and recharge the ground water storage.

e. Interflow

The interflow contribution, QIF, is assumed to be proportional to U and varies linearly with the relative moisture content of the lower zone storage.

$$QIF = \left\{ \begin{bmatrix} (CKIF)^{-1} \dfrac{\dfrac{L}{Lmax} - TIF}{1 - TIF} U \\ 0 \end{bmatrix} \begin{matrix} For \dfrac{L}{Lmax} > TIF \\ For \dfrac{L}{Lmax} \le TIF \end{matrix} \right\}$$

Where CKIF is the time constant for interflow, and TIF is the root zone threshold value for interflow (0 ≤ TIF ≤ 1).

f. Interflow and overland flow routing

The interflow is routed through two linear reservoirs in series with the same time constant CK12. The overland flow routing is also based on the linear reservoir concept but with a variable time constant.

g. Groundwater recharge

The amount of infiltrating water G recharging the groundwater storage depends on the soil moisture content in the root zone. The Baseflow BF from the ground water storage is calculated as the outflow from the linear reservoir with time constant CKBF.

$$G = \left[(P_N - QOF) \frac{L/Lmax - TG}{1 - TG} \right] \qquad For \frac{L}{Lmax} > TG$$

$$= 0 \qquad For \frac{L}{Lmax} \le TG$$

Where

TG is the root zone threshold value for groundwater recharge (0 ≤ TG ≤ 1).

6.2.3. Description of Model Parameters

Model parameters play a significant part in physical interpretation of the process and require adjustments during calibration and validation of the model.

Surface and root zone parameters

a. Maximum water content in surface storage(Umax)

Umax [mm] defines the maximum water content in the surface storage. This storage is the water content in the interception storage (on vegetation), in surface depression storages, and in the uppermost ground layer. Typical values of Umax are in the range 10-20 mm.

One important characteristic of the model is that the surface storage must be at its maximum capacity, i.e. U ≥ Umax before any excess water, PN, occurs. In dry periods, the amount of net rainfall that must occur before any overland flow occurs can be used to estimate Umax.

b. Maximum water content in root zone storage (Lmax)

Lmax [mm] defines the maximum water content in the lower or root zone storage. Lmax is the maximum soil moisture content in the root zone available for the evapotranspiration. Ideally, Lmax can then be estimated by multiplying the difference between field capacity and wilting point of the actual soil within effective root zone. The difference between field capacity and wilting point is referred to as the available water holding capacity (AWHC).

It may be noted that Lmax represents the average value for an entire catchment, i.e. an average value for the various soil types and root depths of the individual vegetation types. Hence, Lmax cannot in practice be estimated from field data, but an expected interval can be defined. Typically, values are between 50-300 mm.

Since the actual evapotranspiration is highly dependent on the water content of the surface and root zone storages, Umax and Lmax are the primary calibration parameters. In the preliminary stages of the model calibration, it is recommended to fix the relation between Umax and Lmax, leaving only one storage parameter to be estimated. As a rule, Umax = 0.1Lmax can be used unless special catchment characteristics or hydrograph behavior indicate otherwise.

c. Overland flow runoff coefficient (CQOF)

CQOF is a very important parameter which estimates the extent to which excess rainfall becomes overland flow or infiltration. CQOF is dimensionless with values between 0 and 1. Physically, it reflects the magnitude of infiltration and recharge. Small values of CQOF are expected for a flat catchment having coarse, sandy soils and a large unsaturated zone, whereas large CQOF-values are expected for catchments having low, permeable soils such as clay or bare rocks. CQOF values in the range 0.01-0.90 are proposed.

It should be noted that during periods where the groundwater table is at the ground surface, the model excludes the infiltration component and hence, CQOF becomes redundant.

d. Time constant for interflow (CKIF)

((CKIF)-1 is the quantity of the surface water content U that is drained to interflow every hour). CKIF [hours] together with Umax, determines the amount of interflow. It is the dominant routing parameter of the interflow because CKIF >> CK12.

Physical interpretation of the interflow is difficult. Since interflow is seldom the dominant stream flow component, CKIF is not, in general, a very important parameter. Usually, CKIF-values are in the range 500-1000 hours.

e. Time constant for routing interflow and overland flow (CK12)

The time constant for routing interflow and overland flow CK12 [hours] determines the shape of hydrograph peaks. The value of CK12 depends on the size of the catchment and how fast it responds to rainfall. Typical values are in the range 3-48 hours.

The time constant can be inferred from calibration on peak events. If the simulated peak discharges are too low or arriving too late, decreasing CK12 may correct this, and vice versa.

f. Root zone threshold value for overland flow (TOF)

TOF is a threshold value for overland flow in the sense that no overland flow is generated if the relative moisture content of the lower zone storage, L/Lmax, is less than TOF. Similarly, the root zone threshold value for interflow TIF and recharge TG act as threshold values for generation of interflow and recharge, respectively.

Parameter	Range of value	Description	Calibration
Umax (mm)	10 - 25	Maximum water content in the surface storage – This is the water content in the interception storage, depression storages and in the uppermost layer.	Large value causes less overland flow and infiltration and high evapotranspiration and interflow
Lmax (mm)	50 - 250	Maximum water content in the lower zone storage. Lmax can be interpreted as the maximum soil water content in the root zone available for the vegetative transpiration.	Large value causes higher evapotranspiration and infiltration and less in overland flow and base flow.
CQOF [-]	0.01 – 0.99	Overland flow runoff coefficient CQOF determines the distribution of excess rainfall into overland flow and infiltration.	Large value causes high overland flow and small infiltration.
TOF [-]	0.0 – 0.7	Threshold value for overland flow . Overland flow is only generated if the relative moisture content in the lower zone storage is larger than TOF.	Large value causes the delay of the threshold of overland flow in wet period and high infiltration.
TIF [-]	0.0 – 0.7	Threshold value for interflow. Interflow is only generated if the relative moisture content in the lower zone storage is larger than TIF.	Large value creates delay of the threshold of interflow in wet period, high infiltration and overland flow.
TG [-]	0.0 – 0.7	Threshold value for recharge. Recharge to the ground water storage is only generated if the relative moisture content	Large value causes delay of the threshold of ground water flow in wet period

Parameter	Range of value	Description	Calibration
		in the lower zone storage is larger than TG.	and quicker filling of root zone.
CKif [hours]	500 - 1000	Time constant for interflow from the surface storage. It is the dominant routing parameter of the interflow because CKif >>CK12	Large value causes higher interflow and less infiltration and interflow.
CK1,2 [hours]	3 - 48	Time constant for overland flow and interflow routing. Overland flow and interflow are routed through two linear reservoirs in series with the same time constant CK12.	Increasing CK12 cause longer duration and lower peaks
CKBF	500-5000	Baseflow time constant. Baseflow from the groundwater storage is generated using a linear reservoir model with time constant CKBF.	Changing CKBF has no effect on generated flow volumes over long time but in changing the shape of hydrographs.

Physically, the three threshold values should reflect the degree of spatial variability in the catchment characteristics, so that a small homogeneous catchment is expected to have larger threshold value than a large heterogeneous catchment.

For catchments with alternating dry and wet periods, the threshold values determine the onset of the flow components in the periods where the root zone is being filled up. This can be used in model calibration. It should be noted that the threshold values have no importance in wet periods. The significance of the threshold value varies from catchment to catchment and is usually larger in semi-arid regions.

In areas with alternating dry and wet seasons, TOF can be estimated on the basis of situations where even very heavy rainfall does not give rise to the quick response of the overland flow component. The parameter has an impact only during the first, few weeks of the wet season. Values of TOF in the range 0-0.7 have been experienced.

g. Root zone threshold value for interflow (TIF)

The root zone threshold value for interflow has the same function for interflow as TOF has for the overland flow. It is usually not a very important parameter, and it can in most cases be given a value equal to zero.

Groundwater parameters

a. Baseflow time constant (CKBF)

The time constant for baseflow, CKBF [hours], determines the shape of the simulated hydrograph in dry periods. According to the linear reservoir description the discharge in such periods is given by an exponential decay.

CKBF can be estimated from hydrograph recession analysis. CKBF-values in the range 500-5000 hours have been experienced. If the recession analysis indicates that the shape of the hydrograph changes to a slower recession after a certain time, an additional (lower) groundwater storage can be added to improve the description of the baseflow.

b. Root zone threshold value for groundwater recharge (TG)

The root zone threshold value for recharge has the same effect on recharge as TOF has on the overland flow. It is an important parameter for simulating the rise of the groundwater table in the beginning of a wet season.

Initial conditions

The initial conditions required by the PROM model consist of the initial water contents in the surface and root zone storages, together with initial values of overland flow, interflow, and base flow.

If a lower groundwater reservoir is specified, the initial base flow from both the upper and the lower reservoir should be specified. If the snow module is included, the initial value of the snow storage should be specified.

If a simulation commences at the end of a dry period, it is often sufficient to set all initial values to zero, except the water content in the root zone and the base flow. The water content in the root zone should be about 10- 30% of the capacity and the base flow should be given a value close to the observed discharge.

Improved estimates of the initial conditions may be obtained from a previous simulation, covering several years, by noting the appropriate moisture contents of the root zone and base flow at the same time of the year as the new simulation will start.

In general it is recommended to disregard the first few months of the PROM simulation in order to eliminate the influence of erroneous initial conditions.

6.2.4. Data Requirements

The PROM model can be characterized as a deterministic, lumped, conceptual model with moderate input data requirements. A description of the classification of hydrological models is given in Abbott and Refsgaard (1996), Refsgaard and Knudsen (1997), where a number of hydrological model, including the NAM model, have been compared in terms of both data requirements and model performance. The Data requirements of PROM are :

Rainfall (mm)

In continuous simulation for yield analysis by PROM, daily rainfall values is a pre-requisite. PROM is not designed for simulation by monthly precipitation.

Potential Evapotranspiration (mm)

The time resolution of Potential Evapotranspiration data is daily.

Temperature (C^0)

Temperatures data (mean daily) are required if snow accumulation and melt are included in the simulations. During the snow season, the time increments in the temperature data should reflect the length of the time step in the simulation, e.g. daily mean temperatures.

Discharge (m3/s)

Observed discharge data at the catchment outlet are required for comparison with the simulated runoff for model calibration and validation.

PROM calibration statistics are available at daily, monthly and annual time scale. The time resolution of the flow depends on the objective of the study and on the time scale of the catchment response.

6.2.5. PROM Structure in RRM of HDA-Y

Model PROM is a sub module of Rainfall Runoff Model module of HDA. This sub module includes the following Tabs to execute the simulation :

- Time Series
- Calibrate
- Validate
- Data Plots
- Summary Report

i. Time Series

The 'Time Series' Tab allows the user to configure the Rainfall-Runoff simulation. As a basin level model, the number of sub-catchment can be identified at this level, each associated with a flow series for calibration, so thst the PROM parameters can be assigned as averaged value reflecting the characteristic of the sub-basin. As seen in ***Figure 6.2***, a sub-catchment named 'Keolari' has been created with time series selected from the left panel. The time period of data considered for Modeling comprising of Calibration, Validation and Simulation processes is assigned at this level in the "Time From/To" in the Left panel. While the availability of flow series is a pre-requisite for calibration and Validation periods, the Simulation/extension period does not require the associated flow. The data selected for PROM consists of :

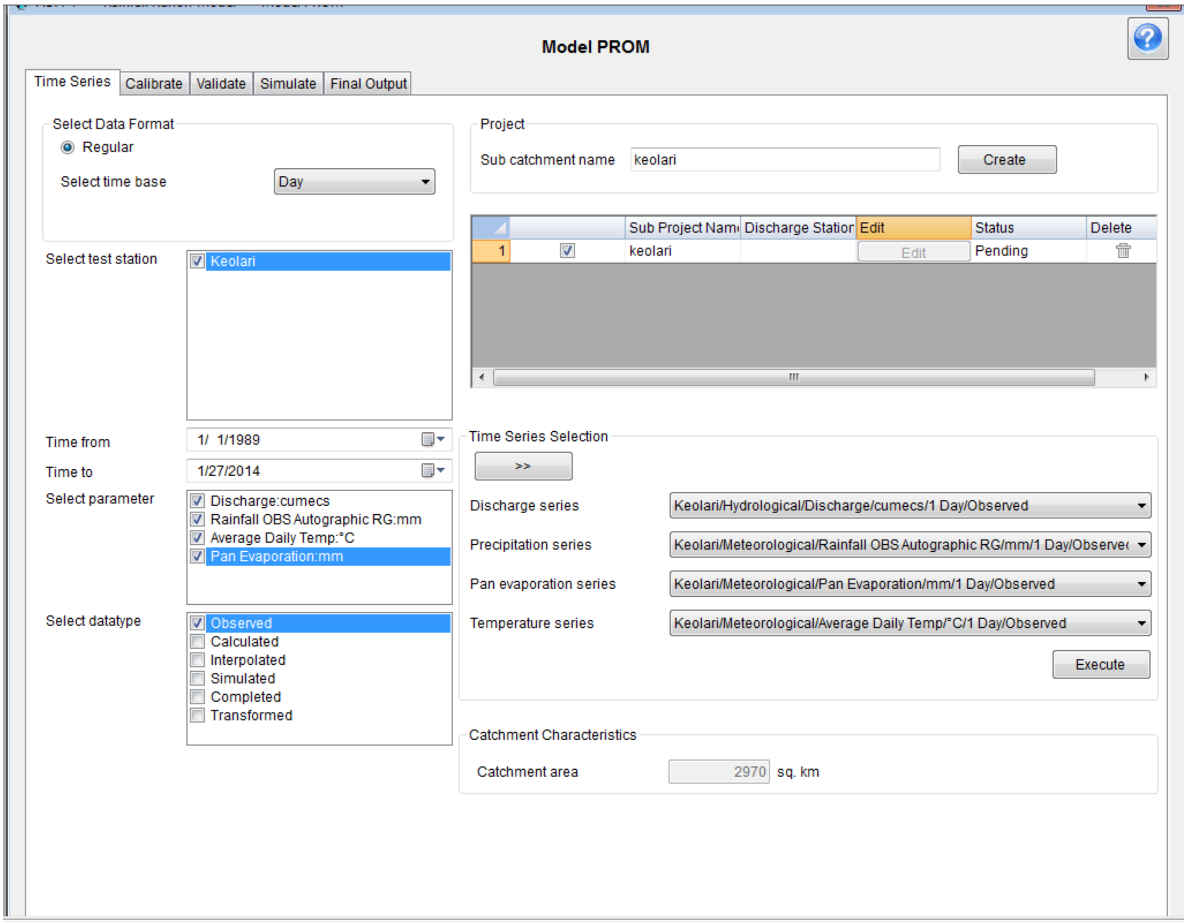
Discharge : Time series of flow in cumec at daily time interval. The record length of selected series should cover calibration and validation period

Precipitation : Time series of precipitation in mm at daily time interval for record period covering calibration, validation and simulation.

Potential Evaporation: Daily time series data of Potential evapotranspiration in mm for record period covering calibration, validation and simulation.

Temperature Time Series: Daily time series data of temperature in ^{0}C for record period covering calibration, validation and simulation.

Catchment Area: Area of the catchment for rainfall-runoff modeling, This is read only field, which correspond to the catchment area of the selected discharge station.



Select Data Format
● Regular
Select time base: Day

Project
Sub catchment name: keolari

		Sub Project Nam	Discharge Statior	Edit	Status	Delete
1	☑	keolari		Edit	Pending	🗑

Select test station: ☑ Keolari

Time from: 1/ 1/1989
Time to: 1/27/2014

Select parameter:
☑ Discharge:cumecs
☑ Rainfall OBS Autographic RG:mm
☑ Average Daily Temp:°C
☑ Pan Evaporation:mm

Select datatype:
☑ Observed
☐ Calculated
☐ Interpolated
☐ Simulated
☐ Completed
☐ Transformed

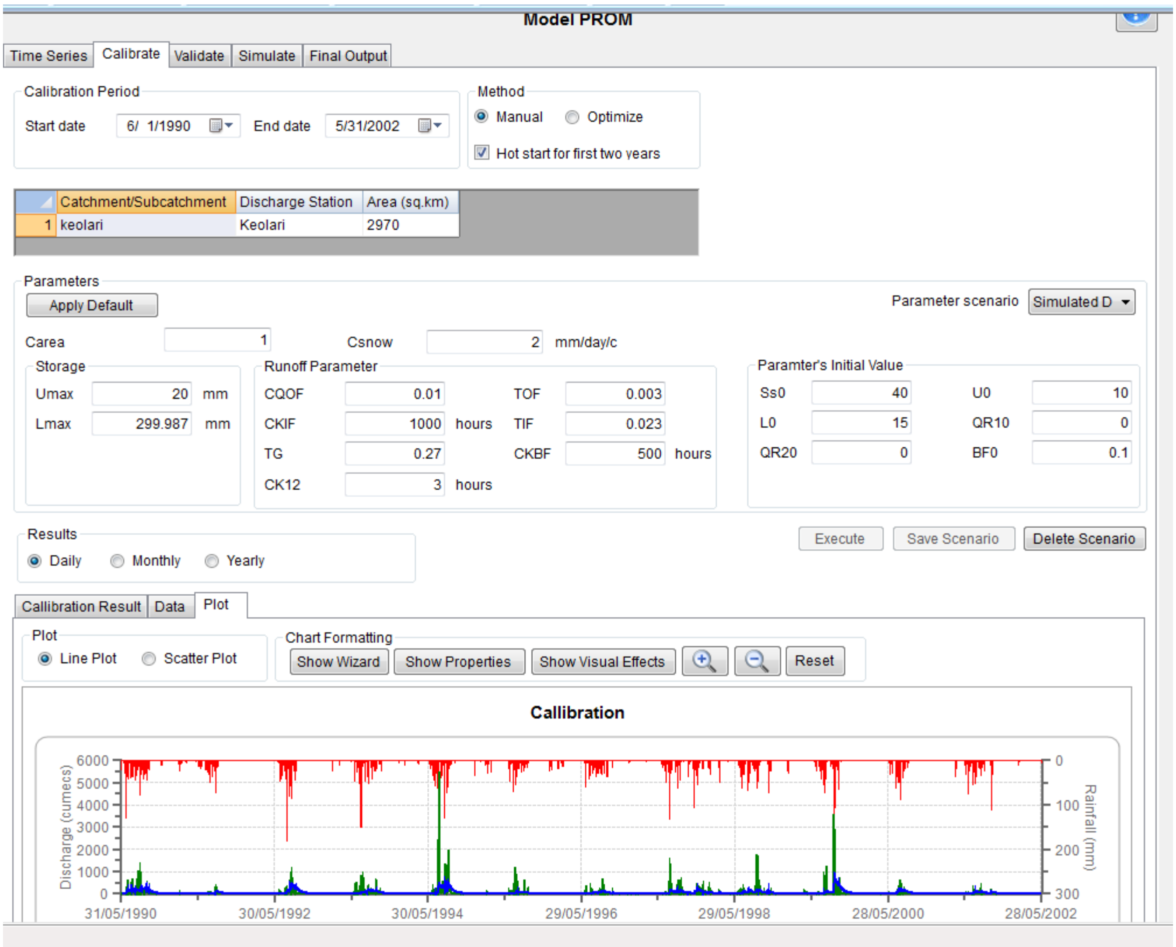
Time Series Selection
Discharge series: Keolari/Hydrological/Discharge/cumecs/1 Day/Observed
Precipitation series: Keolari/Meteorological/Rainfall OBS Autographic RG/mm/1 Day/Observe
Pan evaporation series: Keolari/Meteorological/Pan Evaporation/mm/1 Day/Observed
Temperature series: Keolari/Meteorological/Average Daily Temp/°C/1 Day/Observed

Catchment Characteristics
Catchment area: 2970 sq. km

Figure 6. 2: Dialogue Box for selection of time series for PROM

ii. Calibrate

The composite water balance is achieved by adjusting the model parameters in order to obtain a good match between the observed record of flows and the corresponding model computed flows. The coefficient of determination R^2 and Nash Sutcliffe Index (NSI) are used to evaluate model performance. The entries under 'calibrate' Tab as seen in *Figure 6.3* are :



Calibration Period
Start date 6/ 1/1990
End date 5/31/2002

Method
● Manual ○ Optimize
☑ Hot start for first two years

	Catchment/Subcatchment	Discharge Station	Area (sq.km)
1	keolari	Keolari	2970

Parameters
Parameter scenario Simulated D

Carea 1
Csnow 2 mm/day/c

Storage
Umax 20 mm
Lmax 299.987 mm

Runoff Parameter
CQOF 0.01
TOF 0.003
CKIF 1000 hours
TIF 0.023
TG 0.27
CKBF 500 hours
CK12 3 hours

Paramter's Initial Value
Ss0 40
U0 10
L0 15
QR10 0
QR20 0
BF0 0.1

Results
● Daily ○ Monthly ○ Yearly

Plot
● Line Plot ○ Scatter Plot

Figure 6. 3: Calibration Tab of PROM

Calibration Period: This is the time period for which the selected input data time series have contiguous data. 'Start Date' by default will be start date of the Simulation period assigned in the 'Time series' Tab.

Hot Start: This date is provided to warm up the model (before calibration). This is optional field. Model will warm up picking up two years of initial data series. The statistical summary output does not include the results calculated for the warm up period.

Method of calibration : Manual and optimization technique based on Generalized Reduced Gradient method (GRG in Excel Solver) is available for the user to derive the best parameter set.

Parameters Scenario's: The calibration process requires several reruns to set the model. In order to use and compare the results of various runs, parameter sets can be saved as Scenarios. This option will store the list of the scenarios (which contains the calibrated parameters values).

Calibration Parameters : It is proposed to start calibration with default values by clicking 'apply default' setting. The default values of all the Calibration parameters and their range are shown in *Table 6.1.* This may be followed by manual calibration by selection of 'Manual' in method of optimization. In the final step, execution with selection of 'optimize' provides the optimal result for the model.

Table 6. 1: Calibration Parameters in PROM

Parameter		Default
Ratio of ground water catchment to topographical catchment area (0-1)	Carea	**1**
Constant Degree-day coefficient (2 - 4 mm/day/C)	Csnow	**2**
Maximum water content in surface storage (10 - 20 mm)	Umax	**20**
Maximum water content in root zone storage (50 - 500 mm)	Lmax	**120**
Overland flow runoff coefficient (0.01 - 0.99)	CQOF	**0.9**
Time constant for Interflow (500 - 1000 hours)	CKIF	**1000**
Root zone threshold value for overland flow (0 – 0.99)	TOF	**0.6**
Root zone threshold value for interflow (0 – 0.99)	TIF	**0.7**
Root zone threshold value for groundwater recharge (0 – 0.99)	TG	**0.25**
Time constant for routing Interflow and overland flow (3 - 48 hours)	CK12	**48**
Baseflow time constant (500 - 5000 hours)	CKBF	**500**
Initial water content in Surface storage	Ss_0	**40**
Initial water content in Surface storage	U_0	**10**
Initial water content in root zone	L_0	**15**
Initial Overland flow	QR10	**0**
Initial Interflow	QR20)	**0**
Initial Base flow	BF_0	**0.1**

Results: The coefficient of determination R^2 and Nash Sutcliffe Index (NSI) were used to evaluate model performance. The calibration output can be viewed and saved on daily, monthly, and annual time scale in the Results panel. The output comprises of statistical summary, data table and plots of simulation (refer ***Figure 6.4***).

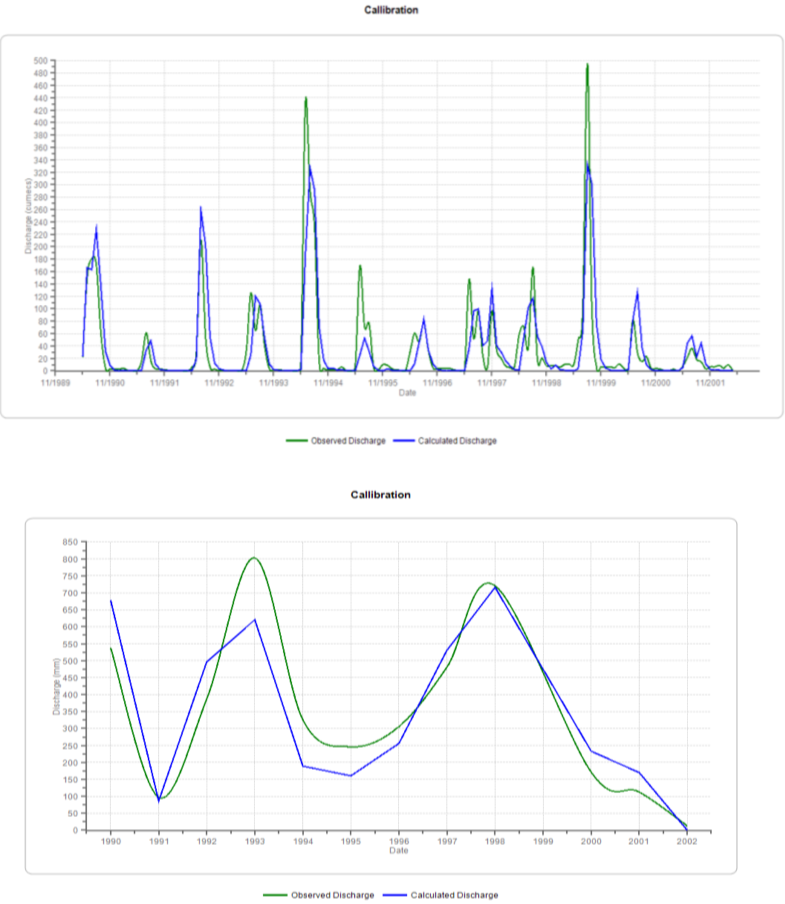


Figure 6. 4: Comparison of observed and simulated discharge (Monthly and Annual) during Calibration in PROM

iii. Validate

Model validation is in reality an extension of the calibration process. Its purpose is to assure that the calibrated model properly assesses all the variables and conditions which can affect model results, and demonstrate the ability to predict field observations for periods beyond the calibration time. The Validation of model is executed after assigning the Time period of simulation in the 'Validate' Tab as shown in ***Figure 6.5***. The Start date of 'Validate' corresponds to the end date following calibration. The end date of 'Validate' corresponds to the end date of flow record available. The output can again be viewed and saved in the form of Summary statistics, Data Table and plot.

iv. Simulate

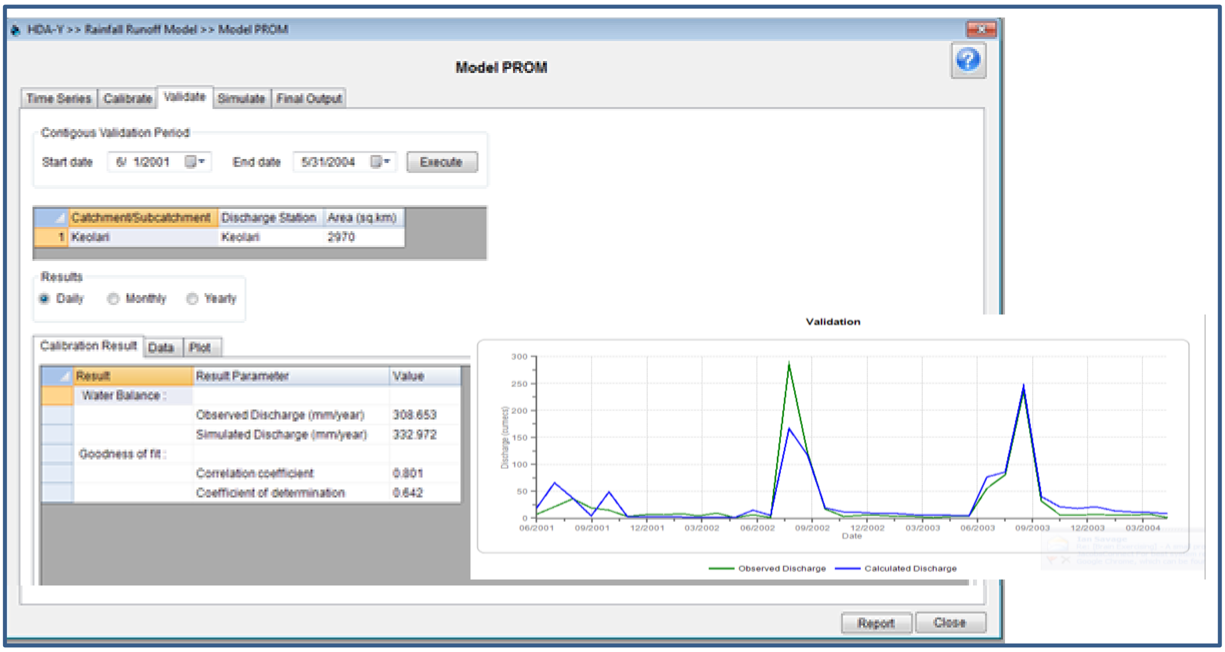
The 'Simulate' Tab extends the flow series with calibrated parameters applied on Time series selected for simulation. By default, the assigned time period are as follows :

- Start date of 'Simulate' Tab corresponds to the End date following Validation
- End date of 'Simulate' Tab corresponds to the End date selected during project configuration and Time series selection.

The complete model output statistics, data and plot are presented in sub-tabs under results panel indicated in ***Figure 6.6***

v. Final Output

The monthly Simulated output on sub-basin level and overall catchment level is available as Final Output Data Table and plot on this tab as shown in ***Figure 6.7***.



Contigous Validation Period

Start date 6/ 1/2001 End date 5/31/2004

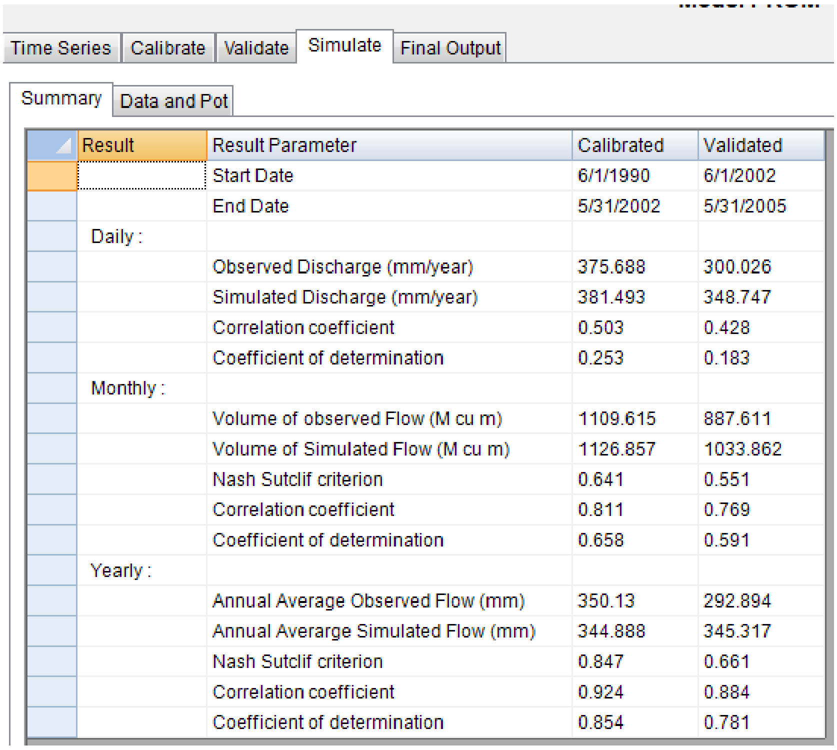
	Catchment/Subcatchment	Discharge Station	Area (sq.km)
1	Keolari	Keolari	2970

Results
● Daily ○ Monthly ○ Yearly

Calibration Result | Data | Plot

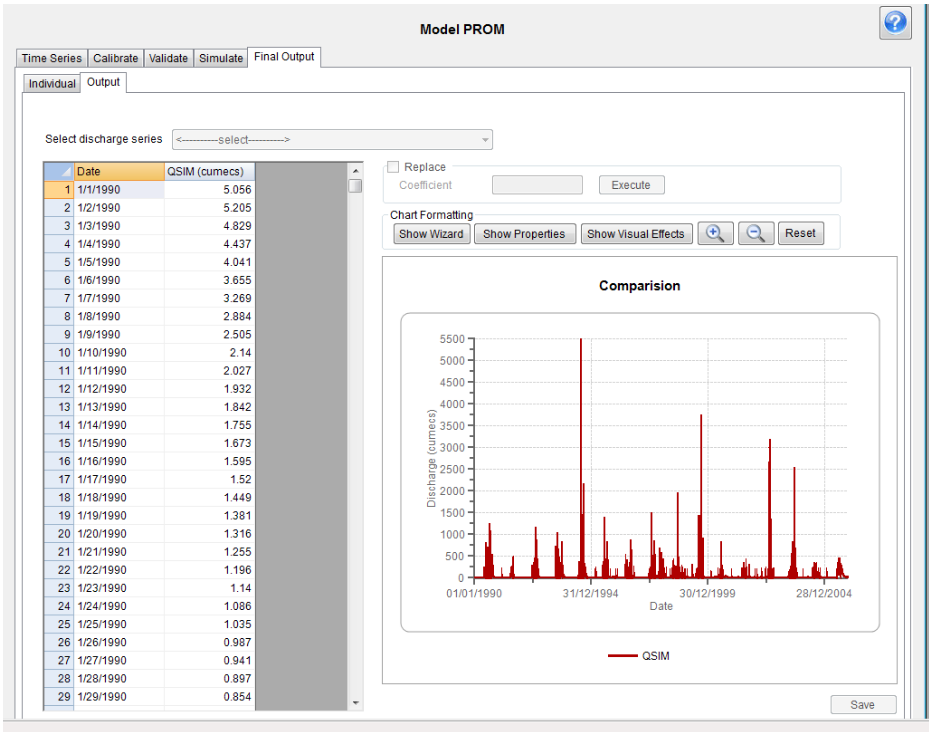
Result	Result Parameter	Value
Water Balance :		
	Observed Discharge (mm/year)	308.653
	Simulated Discharge (mm/year)	332.972
Goodness of fit :		
	Correlation coefficient	0.801
	Coefficient of determination	0.642

Figure 6.5: Validation Tab of PROM with output



Result	Result Parameter	Calibrated	Validated
	Start Date	6/1/1990	6/1/2002
	End Date	5/31/2002	5/31/2005
Daily :			
	Observed Discharge (mm/year)	375.688	300.026
	Simulated Discharge (mm/year)	381.493	348.747
	Correlation coefficient	0.503	0.428
	Coefficient of determination	0.253	0.183
Monthly :			
	Volume of observed Flow (M cu m)	1109.615	887.611
	Volume of Simulated Flow (M cu m)	1126.857	1033.862
	Nash Sutclif criterion	0.641	0.551
	Correlation coefficient	0.811	0.769
	Coefficient of determination	0.658	0.591
Yearly :			
	Annual Average Observed Flow (mm)	350.13	292.894
	Annual Average Simulated Flow (mm)	344.888	345.317
	Nash Sutclif criterion	0.847	0.661
	Correlation coefficient	0.924	0.884
	Coefficient of determination	0.854	0.781

Figure 6.6: Result statistics of model under simulate Tab in PROM



Select discharge series <----------select---------->

	Date	QSIM (cumecs)
1	1/1/1990	5.056
2	1/2/1990	5.205
3	1/3/1990	4.829
4	1/4/1990	4.437
5	1/5/1990	4.041
6	1/6/1990	3.655
7	1/7/1990	3.269
8	1/8/1990	2.884
9	1/9/1990	2.505
10	1/10/1990	2.14
11	1/11/1990	2.027
12	1/12/1990	1.932
13	1/13/1990	1.842
14	1/14/1990	1.755
15	1/15/1990	1.673
16	1/16/1990	1.595
17	1/17/1990	1.52
18	1/18/1990	1.449
19	1/19/1990	1.381
20	1/20/1990	1.316
21	1/21/1990	1.255
22	1/22/1990	1.196
23	1/23/1990	1.14
24	1/24/1990	1.086
25	1/25/1990	1.035
26	1/26/1990	0.987
27	1/27/1990	0.941
28	1/28/1990	0.897
29	1/29/1990	0.854

Figure 6.7: Yield series Data Table and Plot as Final Output in PROM

6.2.6. PROM : Parameter Sensitivity

The purpose of sensitivity analysis is to identify the parameters that have the greatest influence on model results. This enables and guides in calibration of the model. The present methodology of input parameter sensitivity analysis is based on calculation of sensitivity coefficient (S) defined as the ratio of the rate of change of the output function vs. the rate of change of the input parameter under study (Haan et al.,1995):

$S = \delta O / \delta P$

where, O is model output and P represents the input parameter.

The relative sensitivity (Sr) is a unitless measure (Haan, 2002) and is defined as :

$$S_r = \frac{(O_{P+\Delta P} - O_{P-\Delta P})/O_P}{2\Delta P/P}$$

where, (Sr) is relative sensitivity.

OP is the model output with input parameters set at base value equal to the calibrated value. ΔP represents the absolute change in value of the parameter from the calibrated value. The base value of the input parameter for the sensitivity analysis were obtained by manually calibrating the model to obtain the closest match of simulated water budget components to observed values for the total period of analysis, while maximizing the agreement between the observed and predicted Total Water Yield at the annual and monthly level. In the present analysis, the model outputs of TWY (Total Water Yield) as the objective function has been considered.

The division of parameters into various degrees of sensitivity is subjective. Lenhart et al. (2002) ranked sensitivity coefficients into four classes : small to negligible (0.00 ≤ ISrI ≤ 0.05), medium ((0.05 ≤ ISrI ≤ 0.2), high (0.2 ≤ ISrI ≤ 1.0), and very high (ISrI > 1.0).

Approach

The sensitivity analysis for PROM calibration parameters involves execution of model runs, where each of the sensitive input parameters have been set to values near at the limit of the range expected for that parameter. For a typical catchment, the effect of change in model parameter on Total Water yield (TWY), monsoon yield and non-monsoon yield have been analysed. The PROM parameters corresponding to calibrated value is allowed to vary in the range from -100% to 100%. The % change in TWY, monsoon and non-monsoon yield is noted. The The analysis does not account for interactions among parameters.

Parameter CKBF	% of base value	TWY		Monsoon Y		Non-Monsoon Y	
		mm	%	mm	%	mm	%
435	75%	135.53	100%	126.75	104%	8.78	66%
500	86%	135.52	100%	124.82	102%	10.71	80%
580	100%	135.53	100%	122.21	100%	13.32	100%
600	103%	135.53	100%	121.52	99%	14	105%
700	121%	135.53	100%	118	97%	17.53	132%
725	125%	135.53	100%	117.1	96%	18.43	138%
800	138%	135.53	100%	114.4	94%	21.13	159%
900	155%	135.53	100%	110.85	91%	24.69	185%
1000	172%	135.53	100%	107.41	88%	28.13	211%

Parameter CK12	% of base alue	TWY		Monsoon Y		Non-Monsoon Y	
		mm	%	mm	%	mm	%
3.75	75%	135.53	100%	122.2	100%	13.32	100%
5	**100%**	**135.53**	**100%**	**122.21**	**100%**	**13.32**	**100%**
6.25	125%	135.53	100%	122.2	100%	13.32	100%
10	200%	135.53	100%	122.2	100%	13.32	100%
15	300%	135.53	100%	122.2	100%	13.32	100%
20	400%	135.53	100%	122.19	100%	13.33	100%
25	500%	135.53	100%	122.19	100%	13.33	100%
30	600%	135.53	100%	122.18	100%	13.34	100%
35	700%	135.53	100%	122.17	100%	13.35	100%
40	800%	135.53	100%	122.17	100%	13.36	100%
45	900%	135.53	100%	122.16	100%	13.36	100%

Parameter TG	% of base value	TWY		Monsoon Y		Non-Monsoon Y	
		mm	%	mm	%	mm	%
0.1	40%	148.36	109%	133.41	109%	14.95	112%
0.1875	75%	140.75	104%	126.7	104%	14.05	105%
0.2	80%	139.7	103%	125.78	103%	13.91	104%
0.25	100%	135.53	100%	122.21	100%	13.32	100%
0.3	120%	131.2	97%	118.54	97%	12.67	95%
0.3125	125%	130.1	96%	117.61	96%	12.5	94%
0.4	160%	122.67	91%	111.4	91%	11.27	85%
0.5	200%	114.68	85%	104.83	86%	9.85	74%
0.6	240%	107.23	79%	98.65	81%	8.58	64%
0.7	280%	101.06	75%	93.82	77%	7.24	54%

Parameter TIF	% of base value	TWY		Monsoon Y		Non-Monsoon Y	
		mm	%	mm	%	mm	%
0.1	50%	136.07	100%	122.78	100%	13.29	100%
0.15	75%	135.8	100%	122.5	100%	13.3	100%
0.2	100%	135.53	100%	122.21	100%	13.32	100%
0.25	125%	135.25	100%	121.91	100%	13.35	100%
0.3	150%	134.97	100%	121.59	99%	13.38	100%
0.4	200%	134.33	99%	120.87	99%	13.45	101%
0.5	250%	133.64	99%	120.09	98%	13.54	102%
0.6	300%	133.02	98%	119.38	98%	13.63	102%
0.7	350%	132.53	98%	118.85	97%	13.68	103%

Parameter CKIF	% of base value	TWY		Monsoon Y		Non-Monsoon Y	
		mm	%	mm	%	mm	%
375	75%	136.71	101%	123.56	101%	13.14	99%
400	80%	136.41	101%	123.23	101%	13.19	99%
500	100%	135.53	100%	122.21	100%	13.32	100%
600	120%	134.93	100%	121.52	99%	13.41	101%
625	125%	134.81	99%	121.38	99%	13.43	101%
700	140%	134.5	99%	121.03	99%	13.48	101%
800	160%	134.18	99%	120.65	99%	13.53	102%
900	180%	133.93	99%	120.36	98%	13.56	102%
1000	200%	133.73	99%	120.13	98%	13.6	102%

Parameter CQOF	% of base value	TWY		Monsoon Y		Non-Monsoon Y	
		mm	%	mm	%	mm	%
0.2	67%	135.5	100%	122.13	100%	13.36	100%
0.225	75%	135.5	100%	122.15	100%	13.35	100%
0.3	100%	135.53	100%	122.21	100%	13.32	100%
0.375	125%	135.55	100%	122.26	100%	13.29	100%
0.4	133%	135.56	100%	122.28	100%	13.28	100%
0.5	167%	135.59	100%	122.35	100%	13.24	99%

0.6	200%	135.63	100%	122.42	100%	13.2	99%
0.7	233%	135.66	100%	122.49	100%	13.16	99%
0.8	267%	135.69	100%	122.56	100%	13.13	99%
0.9	300%	135.72	100%	122.63	100%	13.09	98%

Parameter value TOF	% of base value	TWY		Monsoon Y		Non-Monsoon Y	
		mm	%	mm	%	mm	%
0.2	22%	143.81	106%	132.6	109%	11.22	84%
0.3	33%	142.1	105%	130.65	107%	11.44	86%
0.4	44%	140.34	104%	128.64	105%	11.7	88%
0.5	56%	138.75	102%	126.72	104%	12.03	90%
0.6	67%	137.38	101%	125.03	102%	12.35	93%
0.675	75%	136.61	101%	124.03	101%	12.58	94%
0.7	78%	136.43	101%	123.77	101%	12.66	95%
0.9	100%	135.53	100%	122.2	100%	13.32	100%
1.13	126%	135.43	100%	121.98	100%	13.45	101%

Parameter UMAX	% of base value	TWY		Monsoon Y		Non-Monsoon Y	
		mm	%	mm	%	mm	%
7	64%	146.03	108%	130.9	107%	15.13	114%
8.25	75%	142.39	105%	127.89	105%	14.49	109%
9	82%	140.35	104%	126.22	103%	14.13	106%
11	100%	135.53	100%	122.2	100%	13.32	100%
13	118%	131.38	97%	118.78	97%	12.6	95%
13.75	125%	129.88	96%	117.55	96%	12.33	93%
15	136%	127.45	94%	115.56	95%	11.89	89%
18	164%	122.46	90%	111.49	91%	10.96	82%
20	182%	119.74	88%	109.32	89%	10.42	78%

Parameter IMAX	% of base value	TWY		Monsoon Y		Non-Monsoon Y	
		mm	%	mm	%	mm	%
90	50%	183.76	136%	169.99	139%	13.77	103%
110	61%	170.41	126%	156.67	128%	13.74	103%
130	72%	159.13	117%	145.42	119%	13.71	103%
135	75%	156.57	116%	142.87	117%	13.69	103%
150	83%	149.22	110%	135.62	111%	13.6	102%
180.88	100%	135.53	100%	122.2	100%	13.32	100%
210	116%	123.91	91%	110.99	91%	12.91	97%
226	125%	118.03	87%	105.38	86%	12.65	95%
230	127%	116.62	86%	104.04	85%	12.58	94%
250	138%	109.89	81%	97.67	80%	12.22	92%
270	149%	103.7	77%	91.9	75%	11.83	89%

The S_r and Degree of S_r for PROM parameters are shown in ***Table 4.2.***

Table 6. 2: Relative Sensitivity of PROM Parameters

Parameter	Sensitivity Index (Sr)					
	Overall(TWY)		Monsoon		Non-Monsoon	
Lmax	-0.57	High	-0.61	High	-0.16	Medium
Umax	-0.18	Medium	-0.17	Medium	-0.32	High
TOF	-0.02	Small to Neg.	-0.03	Small to Neg.	0.13	Medium
CQOF	0.00	Small to Neg.	0.00	Small to Neg.	-0.01	Small to Neg
CKIF	-0.03	Small to Neg.	-0.04	Small to Neg.	0.04	Small to Neg
TIF	-0.01	Small to Neg.	-0.01	Small to Neg.	0.01	Small to Neg
TG	-0.16	Medium	-0.15	Medium	-0.23	High
CK12	0.00	Small to Neg.	0.00	Small to Neg.	0.00	Small to Neg
CKBF	0.00	Small to Neg.	-0.16	Small to Neg.	1.45	Very High

The plot of % changes in model parameters from base value to % changes in flow response from base value response is shown in ***Figure 6.8.***

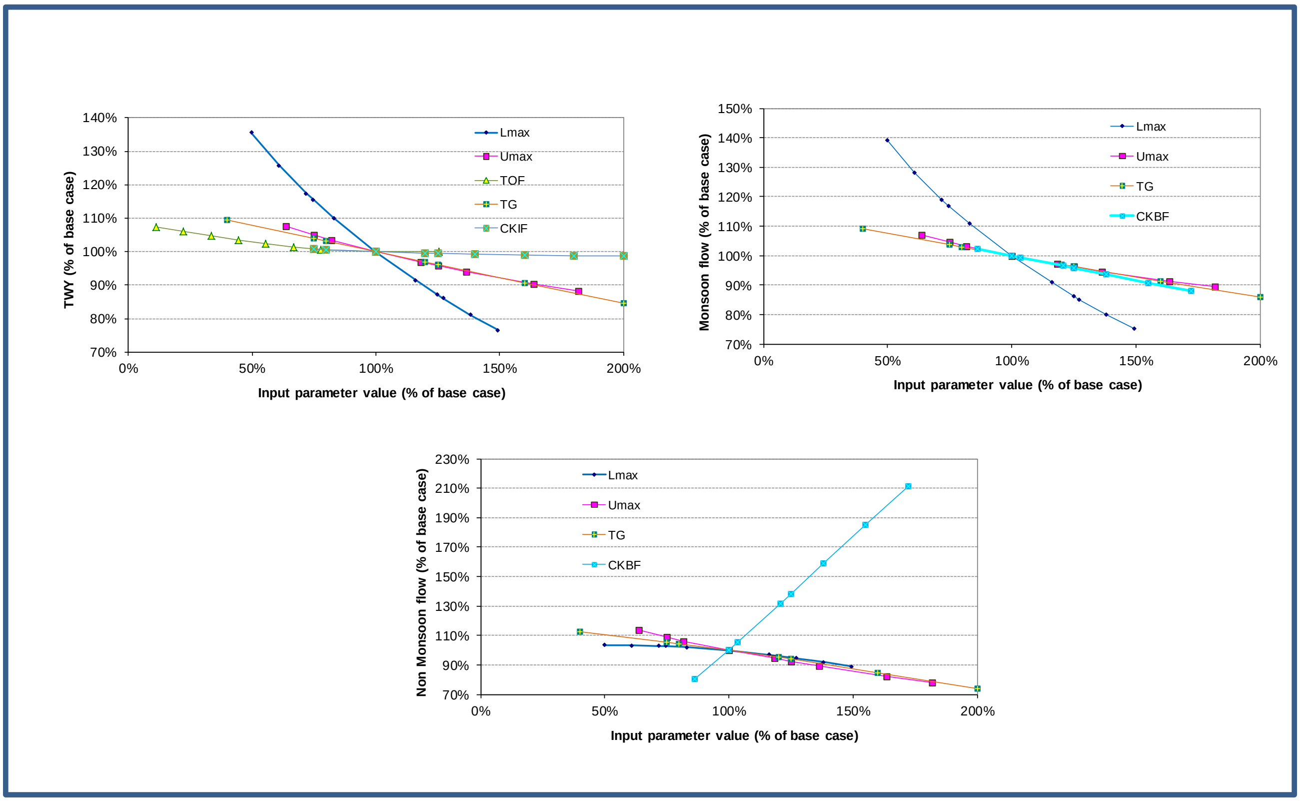


Figure 6. 8: Changes in Model TWY , Monsoon and Non-Monsoon flow response to most sensitive parameters of PROM

Conclusion

The Relative Sensitivity Sr indicate that Lmax is the only parameter which shows high sensitivity with respect to overall yield as well as yield during monsoon period. Umax and TG show medium sensitivity. As the values of these parameters increase, yield were observed to decrease. CKBF is highly sensitive during the non-monsoon period. Other parameters can be categorized as negligibly sensitive. The parameters in order of sensitivity are tabulated below :

Parameters in order of sensitivity (Sr)		
TWY	**Monsoon**	**Non-monsoon**
Lmax	Lmax	CKBF
Umax	Umax	Umax
TG	CKBF	TG
CKIF	TG	Lmax

Reference :

Danish Hydraulic Institute (2003) MIKE BASIN : Rainfall-Runoff modeling Reference manual. DHI, Denmark

MAIDMENT, D. R. (1993) Handbook of Hydrology, 1st Edn. New York : Mc Graw Hill Publication

Haan, C. T., B. Allred, D. E. Storm, G. J. Sabbagh, and S. Prabhu. 1995. Statistical procedure for evaluating hydrologic/water quality models. Trans. ASAE 38(3): 725-733

6.3. MODEL E

MODEL E is a lumped conceptual rainfall-runoff model designed to work on the basis of monthly input data. As compared to PROM which requires a daily time series data, MODEL E is a simple model designed to take into account the heterogeneity of catchment by dividing the catchment into irrigated and un-irrigated area.

6.3.1. Model Structure

Observed flow comprises of two components ; Run-off from precipitation and Return flows due to anthropogenic influences. Flow arise due to exceedance of water in storage capacity of the soil and rise in the ground water table. In Model E, it is assessed by modeling the irrigated and un-irrigated area separately.

In non-irrigated area however, runoff occurs when soil moisture level exceed maximum soil moisture capacity. In the irrigated agriculture sub-basin, rainfall in the basin is directed through diversion schemes to the irrigation command to provide the evapotranspiration requirement of crops. The structure of Model E is shown as *Figure 6.9*.

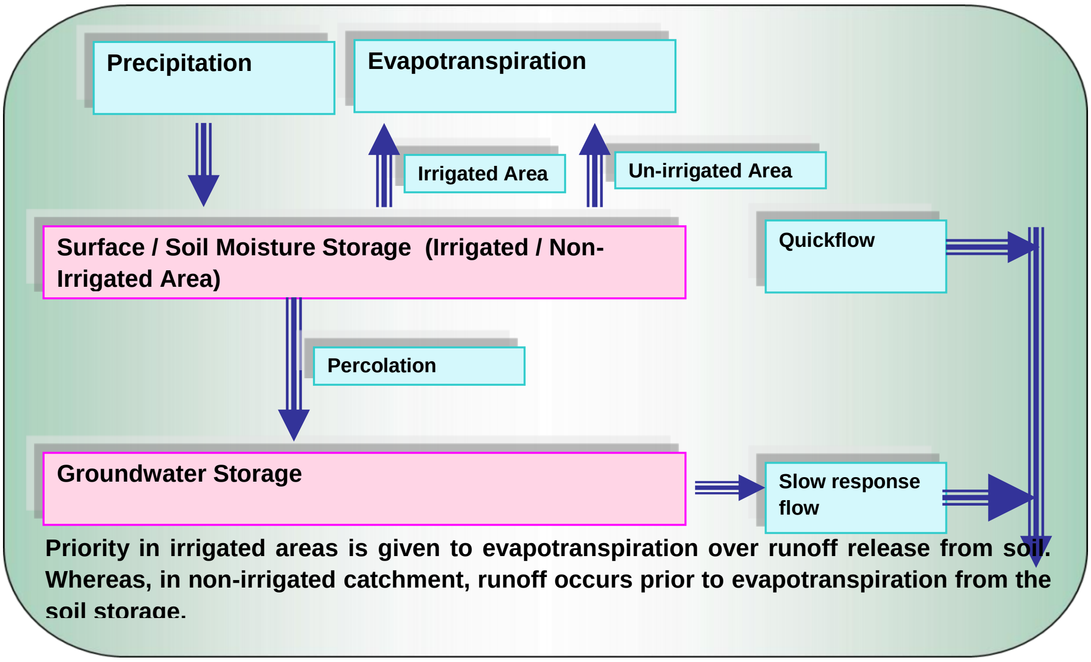


Figure 6.9: Schematic diagram of Model E

During the event of precipitation, the process of runoff generation and evapotranspiration losses occur more or less spontaneously. In Model E, priority in irrigated areas is given to evapotranspiration over runoff release from soil. However for non-irrigated area, priority is given to runoff from the soil over evapotranspiration.

It is a two storage model. The total water drained from soil pores, which would be available as runoff is also assumed to be partitioned into two components namely

1. Quick flow component (QIF) : Calculated by $QIF = VDS * K_1$; $K_1 < 1$
   Where, VDS is Volume drained from soil pores;

2. Percolation to ground water store component (PGW)

   $PGW = VDS * [1-K_1]$

The quick flow component is assumed to be the basin's immediate response to water application and the percolation component is assumed to add to the ground water store, from which water is released to the river in proportion to the available ground water storage which later joins the river system.

6.3.2. Model Algorithm

1. Divides a basin into irrigated and un-irrigated areas
2. Accords priority to evapotranspiration over runoff in irrigated areas.
3. Accords priority to runoff generation in un-irrigated areas, the soil moisture that remains is then apportioned to meet evapo-transpiration requirements
4. Un-irrigated areas
   a. Runoff is assumed to occur when soil moisture levels exceed assumed Maximum Soil moisture Capacity.(MSM)
   b. Runoff occurs when precipitation + initial soil moisture (ISM) is greater than MSM and is = Precipitation + ISM(t) - MSM and ASM = MSM otherwise Runoff = 0.0 and ASM = precipitation + ISM(t)
   c. When runoff occurs
      i. ASM=MSM
      ii. Potential Actual evaporation ETP = (.5 (ISM(t) + ISM (t+1)) / MSM) * Dni * EP (Pan Evaporation Coeff.)
   d. When runoff does not occu r
      i. ASM = Precipitation + ISM(t)
      ii. Potential Actual Evaporation ETP = (.5 (ISM(t) + ASM / MSM) * Dni * EP (Pan Evaporation coeff)
   e. Comparing Evaporation potential with availability of water
      i. If ETP <= ASM then
         Actual Evaporation AET = ETP and
         ISM (t+1) = ASM - AET
         Else
         AET = ASM and
         ISM (t+1) = 0.0
5. Irrigated Areas
   a. Water availability
      Total Water =Precipitation + Irr + ISM(t)
   b. If Total water is <= Dir*EP(Pan Evap.)
      Actual Evaporation AET = Total water
      ASM=0.0 that is runoff is 0.0
      Else
      AET=Dir*EP
      ASM= Total water-Dir*EP
   c. Soil moisture Threshold for runoff Computation is MSM

If ASM <= MSM
Runoff =0.0
ISM(t+1) = ASM
Else
Runoff = ASM-MSM
ISM(t+1) = MSM

d. Runoff computed in 4(b) and 5(c) is assumed to consist of two components
   i. Quick flow component
   ii. Flow from Ground water Storage

e. Quick Flow component
   i. QIF = Runoff*K1 where K1,1

f. Flow from Ground water
   i. Percolation to ground water PGW = Runoff *(1-K1)
   ii. Available GW Storage AGW = Initial storage IGW(t) + PGW
   iii. Flow from GW Storage FGW = 0.5(IGW(t)+AGW)*K2 where K2<1
   iv. IGW(t+1) = AGW - FGW
   v. Total flow in the river = QIF + FGW

g. Parameters
   i. Dni Pan coefficient for un-irrigated arteas
   ii. Dir Pan coefficient for Irrigated Areas
   iii. MSM Maximum soil moisture storage capacity
   iv. K1Coefficient of Quick flow recession
   v. K2 coefficient of Ground water Recession

h. Start simulation from a month when ISM(t) and IGW(t) are 0.0

Runoff (F) from irrigated area can be written as

F = Quick flow component + Delayed flow component

F = QIF+FGW

Or ,

$$QIF = VDS * K_1 ; \qquad [K_1 < 1]$$

And $$FGW = [IGW+AGW]*0.5*K_2 \qquad [K_2<1]$$

6.3.3. Basic Modeling Components

Model E consists of five parameters which are :

1. **Evapo-transpirative Loss Parameter for Irrigated area (Dir)**
   Determines the pan coefficient of evapotranspiration to determine the evaporative demand of the atmosphere in irrigated area.
2. **Pan Coefficient for Un-irrigated Area (Dni)**
   It represents the coefficient of evapotranspiration to determine evapotranspiration demands of the atmosphere in un-irrigated area
3. **Maximum Soil Moisture Storage Capacity (MSM)**

It represents the maximum water content at saturation in 'mm' of the interception storage and surface depression storage in the upper layer of soil. Typical values ranges between 90-650mm. Since interception and surface depression is not accommodated in model separately, magnitude of MSM should be higher than the field capacity

4. **'K_1' Coefficient of Quick Flow Recession**
   The model calculates quick flow as a fraction of excess runoff generated after soil moisture reaches saturation level and evapotranspiration requirements are met. Typical value ranges between 0.1 to 0.7
5. **'K_2' Coefficient of Ground Water Recession**
   The water which percolates to ground water storage denotes coefficient for ground water recession. This water joins runoff as slow response flow. The value varies between 0.1 to 0.8 where 0.1 denotes low ground water contribution and 0.8 implies high ground water flow usually in rocky terrain.

6.3.4. Data Requirements

The Time series input for MODEL E are :

Rainfall (mm)

Monthly values (mm) are used in running the model. In case of daily rainfall , Aggregation sub-module of Data Validation Model is used to develop monthly series for running the simulation.

Evaporation (mm)

Monthly (mm) Potential evapotranspiration is provided as input to run the model.

Irrigation Water

Since Model E has been conceived as a monthly rainfall-runoff for irrigated and non-irrigated catchment, Irrigation water depth (in mm) is required for simulation. This is a user input data which reflects the depth of water already available in the field and retained through field bunds, a characteristic of rice cultivation. To incorporate the time variability, this needs to be prepared as a data time series which can be imported into Model E module.

Discharge (m3/s)

Observed discharge data at the catchment outlet or sub-basin outlets on monthly resolution are required for comparison with the simulated runoff for model calibration and validation.

6.3.5. Model Structure of MODEL E in HDA

MODEL E designed to run on 'average' or a lumped set of parameters for the catchment considered can further be allowed to use spatially disaggregated information. While the default set-up works with the catchment considered for the Project, further sub-catchment inputs can be provided with representative flow series with selection of sub-catchment button. The number of sub-catchment with their identity can be created in the model only with the associated flow series, which provides the calibration reference for the lumped inputs of the sub-catchment. The routing procedure is specified at the final stage. Under the most common at-site situation faced during the planning of the project is the absence of flow information at the site considered, measurement of flow for limited time period is mostly recommended in those scenarios. RRM suitably incorporates those measured flow information in the yield series after final analysis has been made.

Model E is a sub module of Rainfall Runoff Model module of HDA. Model E sub module includes the following Tabs reflecting processes of simulation similar to PROM:

- Time Series
- Calibrate
- Validate
- Simulate
- Data Plots
- Summary Report

6.3.5.1 Time Series

The Project specifications and input time series are defined at this stage (Refer ***Figure 6.10***) to simulate the flow. THe selected series comprise of

Precipitation Time Series: Monthly time series data of precipitation in mm

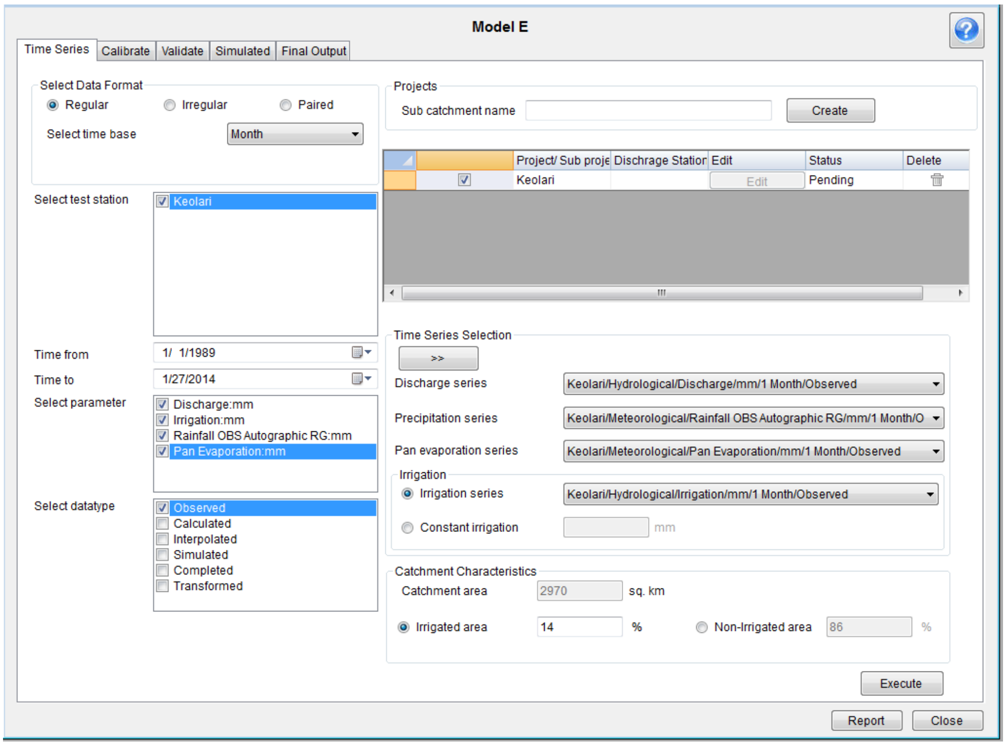
Potential Evaporation: Monthly potential evaporation in mm

Irrigation depth : Two options, time series and constant value can be provided to incorporate the irrigation depth in mm.

Flow Time Series : Flow in mm corresponding to the sub-catchment used for calibrating the model.

6.3.5.2 Calibration

The composite water balance will be calibrated in the 'Calibrate' tab by adjusting the calibration parameters in order to obtain a good match between the observed record of flows and the corresponding model computed flow. Model E will be calibrated using naturalized discharge data.



Select Data Format: ● Regular ○ Irregular ○ Paired

Select time base: Month

Projects
Sub catchment name:

	Project/ Sub proje	Dischrage Station	Edit	Status	Delete
☑	Keolari		Edit	Pending	

Select test station: ☑ Keolari

Time from: 1/ 1/1989

Time to: 1/27/2014

Select parameter:
☑ Discharge:mm
☑ Irrigation:mm
☑ Rainfall OBS Autographic RG:mm
☑ Pan Evaporation:mm

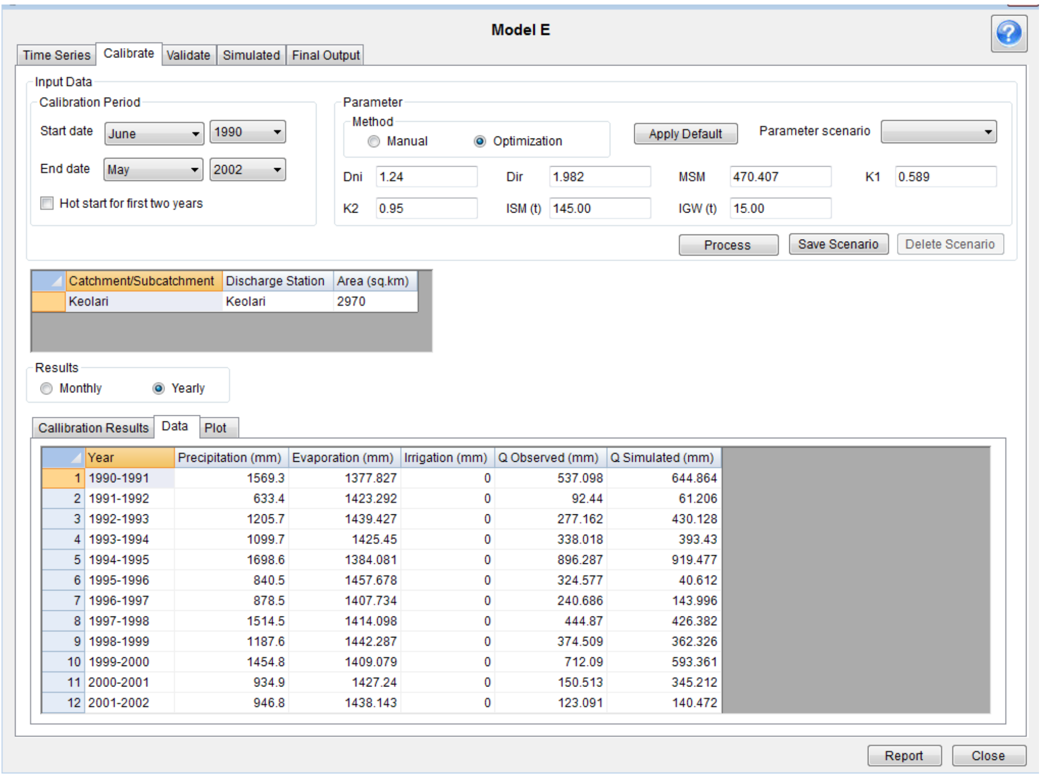
Select datatype:
☑ Observed
☐ Calculated
☐ Interpolated
☐ Simulated
☐ Completed
☐ Transformed

Time Series Selection
Discharge series: Keolari/Hydrological/Discharge/mm/1 Month/Observed
Precipitation series: Keolari/Meteorological/Rainfall OBS Autographic RG/mm/1 Month/O
Pan evaporation series: Keolari/Meteorological/Pan Evaporation/mm/1 Month/Observed

Irrigation
● Irrigation series: Keolari/Hydrological/Irrigation/mm/1 Month/Observed
○ Constant irrigation: mm

Catchment Characteristics
Catchment area: 2970 sq. km
● Irrigated area: 14 %
○ Non-Irrigated area: 86 %

Figure 6.10: Project Configuration in Model E



Input Data

Calibration Period
Start date: June 1990
End date: May 2002
☐ Hot start for first two years

Parameter
Method: ○ Manual ● Optimization
Parameter scenario:

Dni: 1.24
Dir: 1.982
MSM: 470.407
K1: 0.589
K2: 0.95
ISM (t): 145.00
IGW (t): 15.00

Catchment/Subcatchment	Discharge Station	Area (sq.km)
Keolari	Keolari	2970

Results: ○ Monthly ● Yearly

	Year	Precipitation (mm)	Evaporation (mm)	Irrigation (mm)	Q Observed (mm)	Q Simulated (mm)
1	1990-1991	1569.3	1377.827	0	537.098	644.864
2	1991-1992	633.4	1423.292	0	92.44	61.206
3	1992-1993	1205.7	1439.427	0	277.162	430.128
4	1993-1994	1099.7	1425.45	0	338.018	393.43
5	1994-1995	1698.6	1384.081	0	896.287	919.477
6	1995-1996	840.5	1457.678	0	324.577	40.612
7	1996-1997	878.5	1407.734	0	240.686	143.996
8	1997-1998	1514.5	1414.098	0	444.87	426.382
9	1998-1999	1187.6	1442.287	0	374.509	362.326
10	1999-2000	1454.8	1409.079	0	712.09	593.361
11	2000-2001	934.9	1427.24	0	150.513	345.212
12	2001-2002	946.8	1438.143	0	123.091	140.472

Figure 6.11: Calibration in Model E

Hydrological Year Starting Month: According to the available records for the selected data-set, the start time for calibration is automatically selected. The user can change the time at this stage if he chooses. THe module sets the hydrological years for continuous simulation in accordance with the standard practice. Option to provide the name of the month from here hydrological year is started. Default month selected is 'June'. The data considered for calibration is started from this month.

Catchment Area: Area of the catchment under consideration. This is read only field, this is the area respective to the selected time series of the discharge station.

Contiguous Calibration Period: This is the time period for which the selected input data time series have contiguous data. Start Date and End Dates will populate automatically after the selection of input time series data.

Hot Start: This date is provided to warm up the model (before calibration). This is optional field. Model will warm up for the calibration Start Date to this Hot Start date, and calibrate from Hot Start date to calibration End Date. "hot start check box' enables the user to provide the number of years the data can be selected for warming up.

Parameters Scenario's: This option will store the list of the scenarios (which contains the calibrated parameters values).

Calibrated Parameters: The calibration parameters are available to the user at this stage. The default values for the parameters are given below :

Parameter		Default value
Pan coefficient for un-irrigated area	D_{ni}	0.5
Pan coefficient for irrigated area	D_{ir}	0.5
Maximum soil moisture content	MSM	350
Coefficient for quick flow recession	K1	0.5
Coefficient for ground water component	K2	0.5
Initial soil moisture level	ISM (t)	145
Initial ground water storage	IGW (t)	15

The calibration is achieved by two procedure :

i. Manual

ii. Optimization

In manual calibration process, it requires many reruns to calibrate the model. The GUI enables parameter adjustment and simultaneous view of results and plot. For best results, it is recommended to make manual adjustment followed by parameter adjustment by optimization.

Calibrated Results: The coefficient of determination R^2 and Nash Sutcliffe Index (NSI) were used to evaluate model performance. The calibrated results can be viewed on monthly and annual time resolution.

In order to use and compare the results of various runs, data table and data plots facility is provided here. Facility to plot the results on monthly and annual basis are available under Results panel in well identified Tabs.

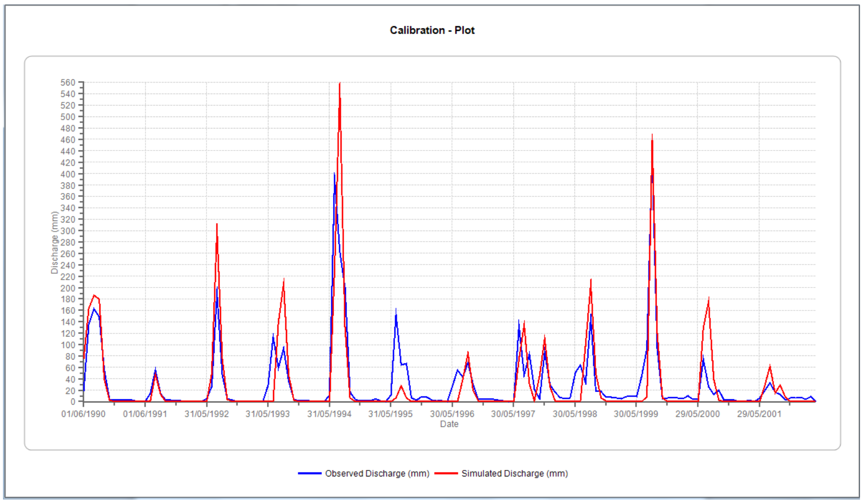
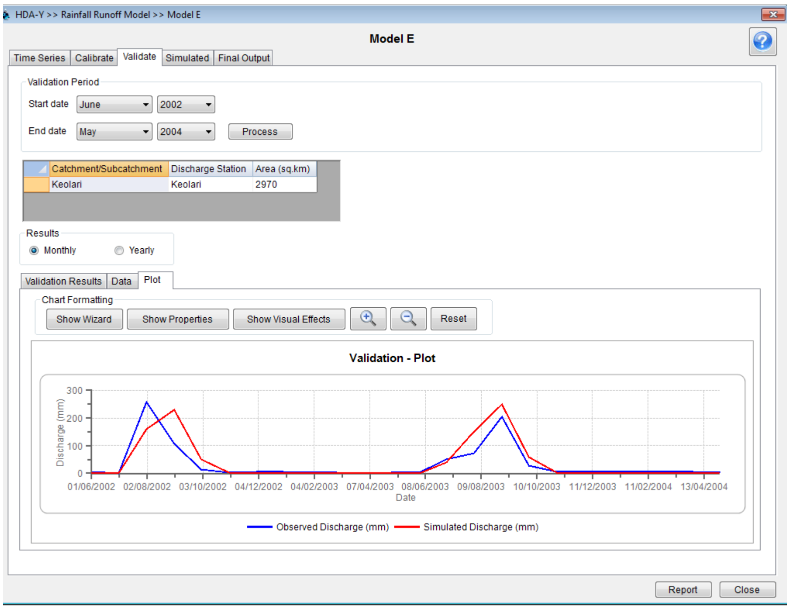


Figure 6.12: Data plot comparison of observed and simulated discharge

6.3.5.3 Validation

Model validation is in reality an extension of the calibration process. Its purpose is to assure that the calibrated model properly assesses all the variables and conditions which can affect model results, and demonstrate the ability to predict field observations for periods separate from the calibration effort. Here the model is validated for the period June 2001 to May 2004.



Validation Period

Start date June 2002

End date May 2004

Catchment/Subcatchment	Discharge Station	Area (sq.km)
Keolari	Keolari	2970

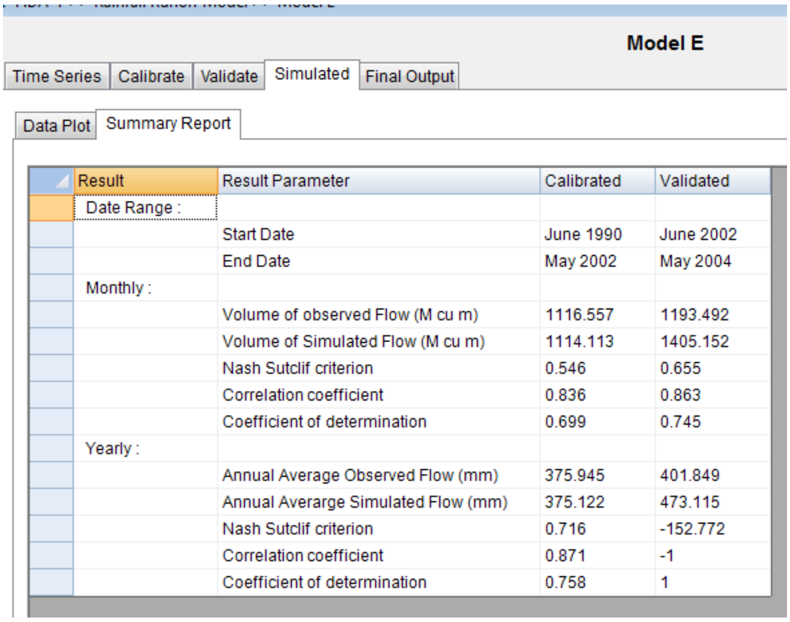
Results

● Monthly ○ Yearly

Figure 6.13: Validation of model and comparison plot of observed and simulated flow

6.3.5.4 Simulate

Under the Simulate Tab, the model is executed for hindcasting with available input time series. The output of the model in terms of summary statistics (*Figure 6.15*) , data table and plot can be obtained at this stage.

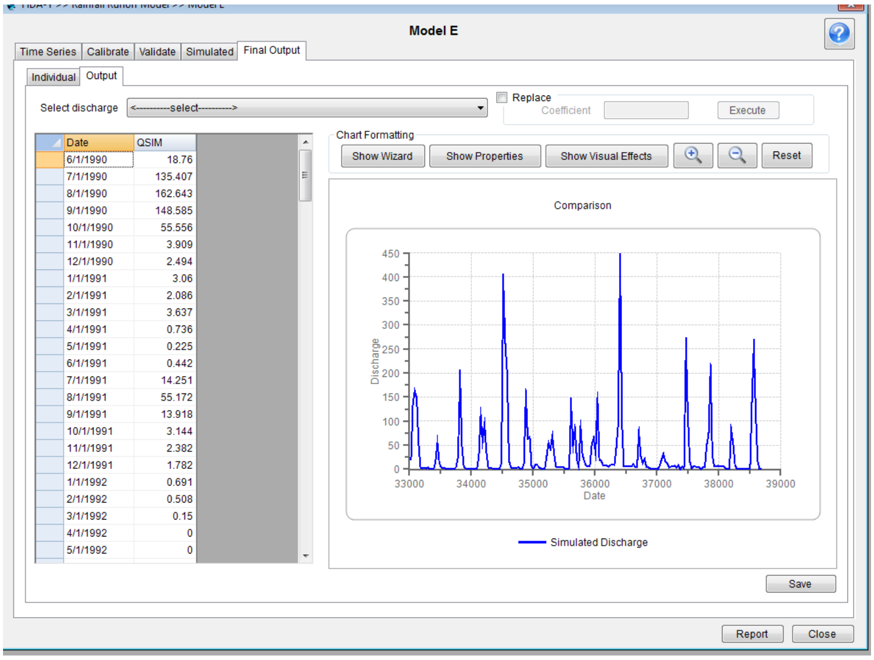


Result	Result Parameter	Calibrated	Validated
Date Range :			
	Start Date	June 1990	June 2002
	End Date	May 2002	May 2004
Monthly :			
	Volume of observed Flow (M cu m)	1116.557	1193.492
	Volume of Simulated Flow (M cu m)	1114.113	1405.152
	Nash Sutclif criterion	0.546	0.655
	Correlation coefficient	0.836	0.863
	Coefficient of determination	0.699	0.745
Yearly :			
	Annual Average Observed Flow (mm)	375.945	401.849
	Annual Averarge Simulated Flow (mm)	375.122	473.115
	Nash Sutclif criterion	0.716	-152.772
	Correlation coefficient	0.871	-1
	Coefficient of determination	0.758	1

Figure 6.14 : Summary Report of the model

6.3.5.5 Final Output

7 The monthly simulated output on sub-basin level and overall catchment level is available as Final Output Data Table and plot in this tab as shown in *Figure 6.7*.



Date	QSIM
6/1/1990	18.76
7/1/1990	135.407
8/1/1990	162.643
9/1/1990	148.585
10/1/1990	55.556
11/1/1990	3.909
12/1/1990	2.494
1/1/1991	3.06
2/1/1991	2.086
3/1/1991	3.637
4/1/1991	0.736
5/1/1991	0.225
6/1/1991	0.442
7/1/1991	14.251
8/1/1991	55.172
9/1/1991	13.918
10/1/1991	3.144
11/1/1991	2.382
12/1/1991	1.782
1/1/1992	0.691
2/1/1992	0.508
3/1/1992	0.15
4/1/1992	0
5/1/1992	0

Figure 6.15: Data plot of model

6.3.6. MODEL E : Parameter sensitivity

The objective of sensitivity analysis is to provide guidance to the user in developing a better understanding about the input parameter which has greater effect on model output. The approach for Sensitivity Analysis of MODEL E parameters have been followed as described in para 6.2.6, on similar lines of PROM. The details of analysis showing change in parameter value with change in yield are tabulated below :

Parameter value K1	% of base value	TWY		Monsoon Y		Non-Monsoon Y	
		mm	%	mm	%	mm	%
0.40	68%	134.6	100%	126.3	104%	8	63%
0.44	75%	134.6	100%	125.0	103%	10	72%
0.50	85%	134.6	100%	123.4	102%	11	84%
0.59	100%	134.5	100%	121.3	100%	13	100%
0.70	119%	134.5	100%	120.3	99%	14	107%
0.74	125%	134.5	100%	120.7	99%	14	105%
0.80	136%	134.5	100%	122.1	101%	12	93%

Parameter value MSM	% of base value	TWY		Monsoon Y		Non-Monsoon Y	
		mm	%	mm	%	mm	%
140.00	68%	214.5	159%	194.2	160%	20.4	153%
155.25	75%	189.9	141%	171.8	142%	18.0	136%
180.00	87%	162.3	121%	146.8	121%	15.5	117%
207.00	100%	134.5	100%	121.3	100%	13.3	100%
220.00	106%	122.2	91%	110.0	91%	12.3	93%
240.00	116%	105.5	78%	94.5	78%	11.0	83%
258.75	125%	92.3	69%	82.4	68%	9.9	75%

Parameter value Dir	% of base value	TWY		Monsoon Y		Non-Monsoon Y	
		mm	%	mm	%	mm	%
1.13	75%	134.7	100%	121.4	100%	13.3	100%
1.40	93%	134.6	100%	121.3	100%	13.3	100%
1.50	100%	134.5	100%	121.3	100%	13.3	100%
1.60	107%	134.6	100%	121.3	100%	13.3	100%
1.88	125%	134.6	100%	121.3	100%	13.2	100%

Parameter value Dni	% of base value	TWY		Monsoon Y		Non-Monsoon Y	
		mm	%	mm	%	mm	%
0.90	75%	179.5	133%	160.8	133%	18.8	142%
1.20	100%	134.5	100%	121.3	100%	13.3	100%
1.40	117%	117.7	87%	106.6	88%	11.2	84%
1.50	125%	111.7	83%	101.3	83%	10.4	79%

The Relative Sensitivity derived from the analysis are provided in ***Table 6.3.***

Table 6. 3: Relative Sensitivity of MODEL E Parameters

Parameters	**Sensitivity Index (Sr)**					
	TWY		**Monsoon**		**Non-monsoon**	
Dni	-1.01	High	-0.98	High	-1.26	High
Dir	0.00	Small to Neg.	0.00	Small to Neg.	-0.01	Small to Neg.
MSM	-4.00	High	-4.06	High	-3.43	High
K1	0.00	Small to Neg.	-0.07	Small to Neg.	0.66	High

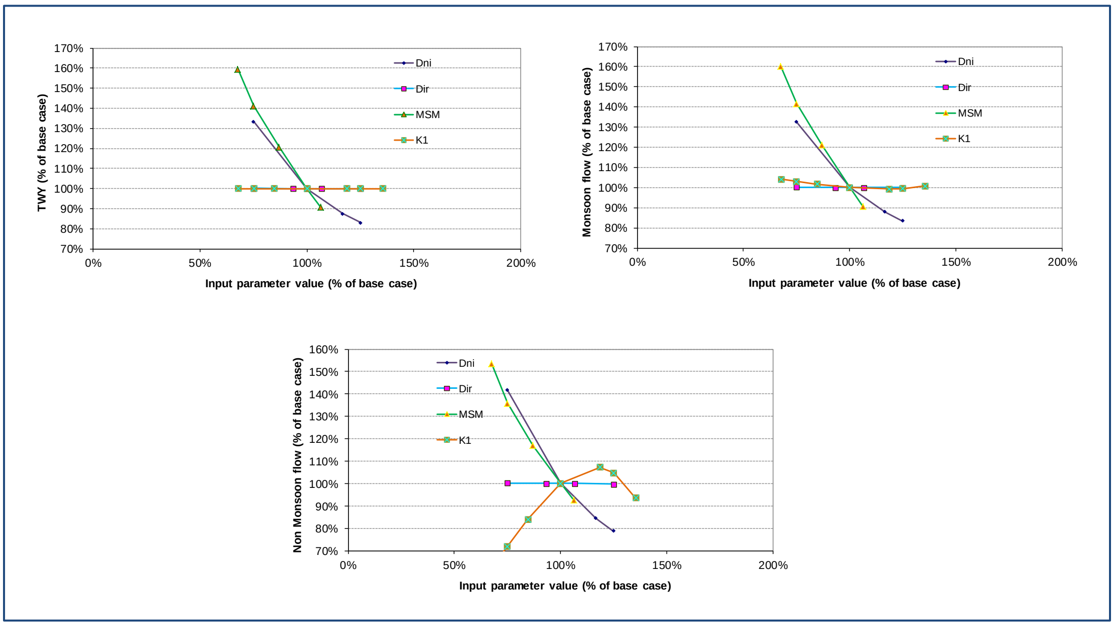


Figure 6.16 : Changes in Model TWY , Monsoon and Non-Monsoon flow response to most sensitive parameters of MODEL E

The sensitive parameters of MODEL E ordered according to the Relative Sensitivity are tabulated below

Parameters in order of sensitivity (Sr)		
TWY	**Monsoon**	**Non-monsoon**
MSM	MSM	MSM
Dni	Dni	Dni
		K1
		Dir

Figure 6.16 shows the slope of the curves representing the relative sensitivity coefficient indicating how sensitivity changes through the range of parameter values. MSM is the most sensitive parameter for Yield assessment, both for Monsoon and Non-Monsoon periods. Dni is second most sensitive.

6.4. REGRSSION MODEL

During period of low rainfall , the relation between rainfall and its response is highly non-linear in view of the high evaporation and infiltration rate. For rainfall in the wet period, the abstraction becomes constant as it reaches its potential level. The rainfall-runoff relation is therefore, linear. Experience has shown that when the time scale of modeling is long, such as a month, simple regression model is adequate to represent the relation between rainfall and runoff. The Rainfall-Runoff Regression Model (RegM) in HDA Y has been developed with the following objectives :

Hind-casting of streamflow records (partially available) where long term precipitation data series is available

Simple Linear / Non-linear Regression models are used for developing monthly/ seasonal/ annual relationship between the concurrent rainfall and naturalized flows of homogenous basin. The applicability of regression model are :

i) Long term precipitation record at the proposed site and concurrent rainfall and flow data of reasonable duration at neighbouring basin.

ii) Rainfall data of longer duration for the catchment of the proposed site and flow data of specific duration with concurrent rainfall data located at upstream or downstream of the proposed site.

Catchment homogeneity is an important prerequisite for application of record augmentation technique. The discharge gauging sites should belong to the basins which experience similar / same meteorological event.

River flow reconstructions from flow series (Discharge – discharge correlation) or Record Augmentation of series

The above procedure is useful when :

i) Flow is estimated from discharge records available in sub-basins belonging to different time period.

ii) In a basin, two gauging sites are available in series in which one has short record and other is a long record site. The relation is used to develop flow records of concurrent period between two or more stations, one with short term data and other with long term records.

6.4.1 Model structure

The models which have been provided in RegM are:

1. Runoff Coefficient Model (RCM) – In the Runoff Coefficient Model, the monthly rainfall and runoff are related as

$$Q_t = CP_t$$

where, C = coefficient of runoff, P_t = monthly rainfall in period t, Q_t = monthly runoff in period t. The model does not take into account the periodic nature of the series and is intended to derive runoff coefficient in order to give a preliminary information of the catchment and its response. No goodness of fit criterion is applicable for this model.

2. Single Regression Model (SRM) – In the single regression model, the monthly rainfall and runoff are related as

   $Q_t = a_0 + a_1.P_t$

   where, a_0, a_1 = regression coefficients, P_t = monthly rainfall in period t, Q_t = monthly runoff in period t. Like RCM, this model also does not take into account the periodic nature of the series as the same coefficient is used for all months.
3. Range Dependent Single Regression Model (RRM) – Range based regression is based on the premise that :
   - In Rainfall-runoff modeling, a given set of processes are active during high precipitation and a different set of processes are active during low precipitation period as can be seen from schematics of any Continous Simulation Rainfall-Runoff model .
   - High precipitation event can also occur during non-seasonal period which influences the overall coefficient of that period.
   - The non-linearity in flow vs flow relation can be accounted for by segmenting them in ranges.
4. Range Dependent Multiple Regression Model (RRM1) – This is similar to RRM except the fact that two parameters can be taken for modeling where the range is governed by the first parameter, which is more significant .
5. Monthly Linear Regression Model (MLM) - In the monthly linear model, the monthly rainfall and runoff are related as

   $Q_{i,t} = a_{t,0} + a_{t,1}. P_{i,t}$

   where, a_0, a_1 = regression coefficients for month t, $P_{i,t}$ = monthly rainfall for month t and year i, $Q_{i,t}$ = monthly runoff for month t and year i. This model has 12 equations, for each month.
6. Monthly Linear Regression Model for monsoon season (MLM1) – A monthly Regession model developed for monsoon months June, July, August, September and October. The non – monsoon months are treated as SRM model.

   Double Regressed model (DRM) – When the precipitation series for the study catchment is inadequate, it is extended with respect to adjacent catchment precipitation. The rainfall runoff regression is then made with the extended precipitation series as :

   $P_{i,t} = a_{t,0} + a_{t,1}. PB_{i,t}$
   $Q_{i,t} = b_{t,0} + b_{t,1}. P_{i,t}$

   where, $P_{i,t}$ and $PB_{i,t}$ = monthly rainfall for month t and year i for project catchment and longer precipitation station respectively. $Q_{i,t}$ = monthly runoff for month t and year i, $a_{t,0}$, $a_{t,1}$ = regression coefficients for rainfall relation between precipitation stations and $b_{t,0}$, $b_{t,1}$ = regression coefficients for rainfall and discharge stations.
7. Multiple Regression Model

   The monthly rainfall and runoff are related as

   $Q_{i,t} = a_{t,0} + a_{t,1}. P_{i,t} + a_{t,2}. P_{i,t-1}$

where, a_0, a_1, a_2 = regression coefficients for month t, $P_{i,t}$, $P_{i,t-1}$ = monthly rainfall for month t and t-1 and year i respectively, $Q_{i,t}$ = monthly runoff for month t and year i. This model has 12 equations, for each month.

RegM model has been designed for specific purpose, which is rainfall-runoff modeling. A typical problem lies in developing a rational relation between runoff and rainfall on monthly time period. The selection of relationship as a first step is achieved by making the following selections :

a. Dependent and independent parameter
b. On the 'type' of relationship
c. Time period for Calibration
Verification
Simulation

With the given user defined inputs in the RegM of HDA1, relationship can be developed between :

i) Runoff Coefficient Model (RCM)
ii) Monthly rainfall and runoff series as Single Regression Model (SRM)
iii) Range Dependant monthly rainfall and runoff series (RRM)
iv) Range Dependant multiple Regression Model (RRM1)
v) Month-wise rainfall and runoff series as Monthly Linear Regression Model (MLM)
vi) Monthly Linear Regression Model for monsoon season (MLM1)
vii) Double Regressed model (DRM)
viii) Multiple Regression Model (MRM)

Model Type	**Regression Type**	**Dependant and Independent variables**	**Form of curve**
RCM	Simple Linear	Discharge R(t) and catchment rainfall P(t)	$R(t) = \beta P(t)$
SRM, MLM RRM,MLM1, DRM	Simple Linear	Discharge R(t) and catchment rainfall P(t)	$R(t) = \alpha + \beta P(t)$
SRM	Simple Linear	Discharge R(t) and Discharge $R_1(t)$ (upstream / downstream / adjacent catchment)	$R(t) = \alpha + \beta R_1(t)$
MRM	Multiple Linear	Discharge R(t) and Discharge of two upstream tributaries $R_1(t)$ and $R_2(t)$	$R(t) = \alpha + \beta_1 R_1(t) + \beta_2 R_2(t)$
MRM	Multiple Linear	Discharge R(t) and Discharge of upstream flow station $R_1(t)$ and rainfall P(t)	$R(t) = \alpha + \beta_1 R_1(t) + \beta_2 P(t)$
MRM	Multiple Linear	Discharge R(t) and Discharge of downstream flow station $R_1(t)$ and intervening tributary $R_2(t)$	$R(t) = \alpha + \beta_1 R_1(t) + \beta_2 R_2(t)$

Model Type	**Regression Type**	**Dependant and Independent variables**	**Form of curve**
MRM,RRM1	Multiple Linear	Discharge R(t) and catchment Precipation P(t) and P(t-1)	R(t) = α + β1P(t) + β2P(t-1)

RegM provides the facility to simulate linear and non-linear relation in the following form

○ linear
○ Exponential

However, Ms Excel is being popularly applied for developing a wide range of relation in Hydrology. To enable and preserve the already widely used procedure, the capability to export the processed data to Ms Excel has been provided in a desired format. This will facilitate the modeling of following relationships as a part of Excel package without going into the rigours of fresh data processing and getting the advantage of plots facilities and regression algorithms already existing :

- linear
- logarithmic
- polynomial (user defined order)
- Power
- Exponential
- Multi linear Regression

6.4.2 Regression Theory

Regression analysis gives the ability to summarize a collection of sampled data by fitting it to a model that will accurately describe the data. This method fits a set of data points to a function which is a dependent variable Y as a linear combination of one or more number of functions of the independent variable(s) X. They are broadly categorized into two : **linear** and **non-linear regression**. Linear regression models with more than one independent variable are referred to as **multiple linear models,** as opposed to **simple linear models** with one independent variable.

Multiple linear model

Consider the following as an example:

$Y = a_1 + a_2 X_1 + a_3 X_2 + a_4 X_3 + \ldots\ldots\ldots a_m X_{m-1}$

or

$Y = a_1 + \sum a_{i+1} X_i \;\; i=1,\ldots \mathbf{m}$

Polynomial $Y = a_1 + a_2 X + a_3 X^2 + a_4 X^3 + \ldots\ldots\ldots a_m X^{m-1}$

which is just a specific case of (1) with $X_1 = X, X_2 = X^2, \ldots\ldots X_{m-1} = X^{m-1}$

The estimators of the regression coefficients are determined by minimizing the merit function by Least Squares method given by :

$$M = \sum \varepsilon_i^2 = \sum (X_i - \hat{X}_i)^2$$

which implies minimizing the sum of the squares of the distances between the actual data points and the regression line.

Linear Regression

$Y = a_1 + a_2 X_1$

It is obvious that simple linear model is just specific case of multiple one with m=1 .

Assumptions of Linear Regression

- Linearity - the relationships between the predictors and the outcome variable should be linear
- Normality - the errors should be normally distributed
- Homogeneity of variance (homoscedasticity) - the error variance should be constant
- Independence - the errors associated with one observation are not correlated with the errors of any other observation
- Model specification - the model should be properly specified (including all relevant variables, and excluding irrelevant variables)

Non-Linear Regression

For regression models whose dependence on its parameters is linear, this is a straightforward process. Note, however, that some models that appear nonlinear may be re-arranged as to appear linear. For example, the equation

$$Y = a X^{b}$$

may be 'linearized' by taking the natural log of both sides of the equation and re-arranging it:

$$\ln(Y) = \ln(a X^{b}) = \ln(a) + \ln(X^{b}) = \ln(a) + b \ln(X)$$

Once the model is linearized, it has the form of the general least squares regression model as shown above. The error minimization is carried out on the logarithm rather than the original values.

Similar to linear regression, the goal of multilinear regression is to determine the best-fit parameters for a model by minimizing a chosen merit function. Where multilinear regression differs is that the process of merit function minimization is an iterative approach. The process is to start with some initial estimates and incorporate algorithms to improve the estimates iteratively. The new estimates then become a starting point for the next iteration. These iterations continue until the merit function effectively stops decreasing.

The proposed practice in selecting a multiple regression model is to perform several regressions on a given set of data using different combinations of the independent variables. As a first step, a correlation matrix is computed. The regression that “best” fits the data is then selected. A commonly used criterion for the best fit is to select the equation yielding the largest value of Coefficieny of Determination R^2. It may be noted that the variables in a regression equation that are highly correlated makes the interpretation of regression coefficient difficult. Many a times, the sign of regression coefficient may be just the opposite of what is expected if the corresponding variable is highly correlated with another independant variable in the equation.

6.4.3 Limitations

The variance of the regression estimate is always biased downward since regression estimates lie on the regression line while the actual data are scattered about the regression line.

Effect of Outlier data

A single or individual observation that is substantially different from all other observations can make a large difference in the results of your regression analysis. Outlier can exert undue influence on the coefficients. An outlier may indicate a sample peculiarity or may indicate a data entry error or other problem.

Collinearity

The term collinearity implies that two variables are near perfect linear combinations of one another. Predictors that are highly collinear, i.e. linearly related, can cause problems in estimating the regression coefficients. When there is a perfect linear relationship among the predictors, the estimates for a regression model cannot be uniquely computed.

When more than two variables are involved it is often called multicollinearity. The primary concern is that as the degree of multicollinearity increases, the regression model estimates of the coefficients become unstable and the standard errors for the coefficients can get wildly inflated.

6.5. CALIBRATION AND TESTS OF MODEL FITNESS

The total water yield (TWY) is calculated on monthly, annual, monsoon and non-monsoon time interval. The objective of calibration is to minimize the Standard error between the observed and simulated water budget components while maximizing the monthly and annual model efficiencies. The composite water balance in calibration is achieved by adjusting the parameters in order to obtain a close match of simulated water budget components to observed values while maximizing the agreement between the observed and predicted record of flows at annual and monthly time interval. During calibration, it is important to test the goodness of fit. The measures for the goodness of fit are :

1. Coefficient of determination (R^2). :

A measure of association between variables is given by the coefficient of correlation "σ". It is defined as a ratio of covariance to the root of the product of variances given by.

$$\sigma = \frac{S_{XY}}{\sigma_X \sigma_Y}$$

Coefficient of determination (R^2) is defined by

$$R^2 = \sigma^2 = \frac{\left[\left(Q_m - \overline{Q}_m\right)\left(Q_s - \overline{Q}_s\right)^2\right]}{\sum\left(Q_m - \overline{Q}_m\right)^2 \sum\left(Q_s - \overline{Q}_s\right)^2}$$

Where,

Q_m = Measured discharge , Q_s= Simulated discharge

R^2 is an appropriate measure for the quality of regression fit to the observations. The closer R^2 is to 1, the better the regression equation is in making predictions of Y given X. The R^2 value measures how well the simulated versus observed regression line approaches an ideal match and ranges from 0 to 1, with the value of 0 indicating no correlation and value of 1 represents that the computed value equals the observed value.

The development of reliable regression requires a fairly large data series. The scale of correlation values for an acceptable relationship can be :

0.00 to 0.25 - Doubtful
0.25 to 0.6 - Not Good
0.6 to 0.75 - Fair
0.75 to 1.00 - Acceptable

2. Nash Sutcliffe Index (NSI) :

$$NSI = 1 - \frac{\sum(Q_m - Q_s)^2}{\sum(Q_m - \overline{Q}_m)^2}$$

The NSI ranges from –α to 1 and measures how well the simulated verses observed data match. Improved model performance is indicated as the NS approaches 1, while a value of zero indicates that simulated values are no better than the mean of observed values.. While there is no consensus on specific Nash-Sutcliff coefficient values that must be obtained for SWAT predictions to be considered good, a value greater than 0.5 is considered acceptable. NS values greater than 0.75 signify good model performance, while those between 0.36 and 0.75 signify acceptable model performance. Value of NS greater than 0.4 have also been considered to indicate acceptable model performance.

3. Standard error (S)

$$S = \sqrt{\frac{\sum (Q_m - Q_s)^2}{N}}$$

Where N = no of observations , Q_m = Measured discharge , Q_s= Simulated discharge

The relation having a minimum value of 'S' should be preferred. Standard error with respect to peak flow and time to peak have been calculated as :

a) Standard Error of observed and simulated Peak flows

b) Standard Error of observed and simulated time of Peak flows

Test Example – 6.1

PROM

This example illustrates the application of PROM in studies undertaken for yield analysis. Data for the example are adopted from Godavari basin. The illustration is designed with the objective of developing yield series, which is the primary requirement for planning and design of water resource structures, canal and drainage planning and network analysis.

Consider the Keolari G&D site located on Wainganga stream in Godavari basin having catchment area 2970 sq km as seen in ***Figure 6.1***. The daily observed flow is available from 1st June 1990 to 31st May 2004. The model input viz. precipitation, temperature and evaporation series (daily) have been developed as catchment averaged series for the site from 1st June 1990 to 31st May 2005 using IMD Gridded data

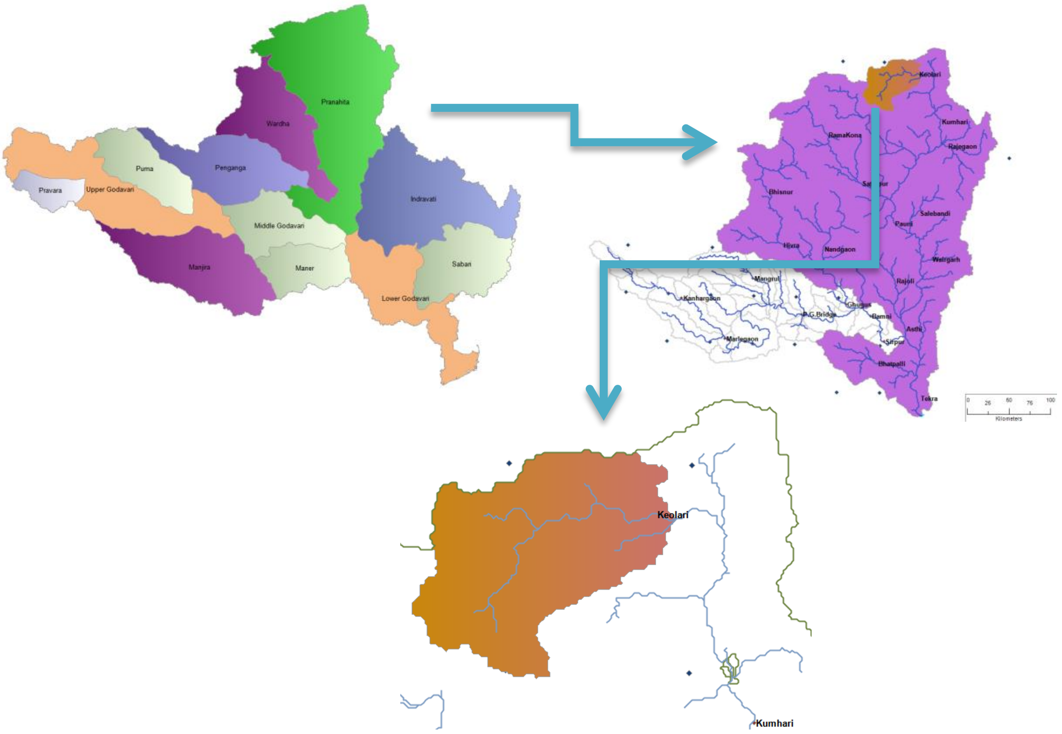


Figure 6.1 : Project Specifications in Model PROM

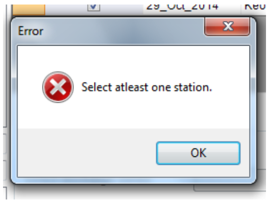
The current example describes the methodology adopted for modelling Keolari sub-basin with the following time period considered in simulation. In a real application, model simulation is undertaken to extend the flow information for a longer period. In the absence of observed climate data beyond 2005 from the same source, the simulation shown in the example is limited to one year.

Calibration	
Initial Period	June -1990
Final Period	May – 2001
No of years	11

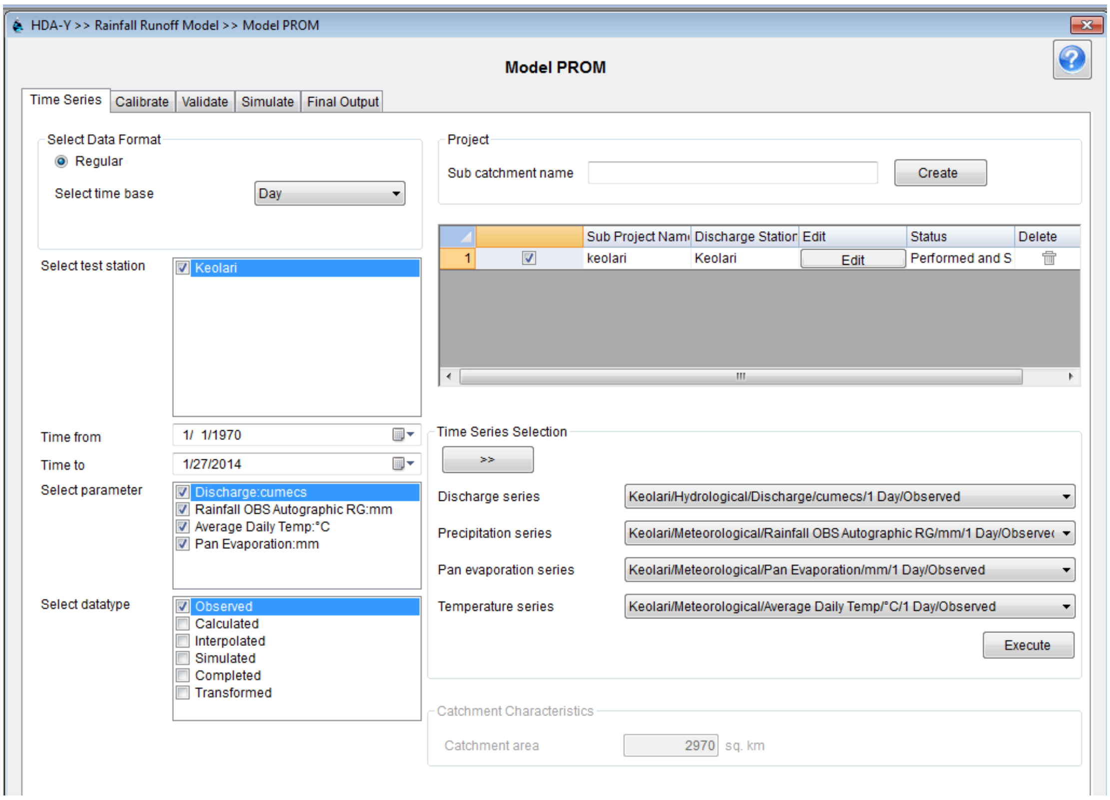
Validation	
Initial Period	June -2001
Final Period	May – 2004
No of years	3
Simulation	
Initial Period	June – 2004
Final Period	May – 2005
No of years	1

Selection of Project specifications and Time series

First step towards developing the model scenario is to decide on the catchment and sub-catchments for running the module on a lumped scale. With the time base 'day', a set of discharge series, the precipitation, pan evaporation and temperature series from the Global selection set of series specified in the left panel of the model main Dialogue Box is selected as shown in Figure 6.9. In case of Keolari, a single catchment is created with Keolari G&D station as the controlling point. In the absence of flow, the model asks to include the relevant reference flow series



Select atleast one station.



Select Data Format: ● Regular

Select time base: Day

Select test station: ☑ Keolari

Time from: 1/ 1/1970

Time to: 1/27/2014

Select parameter:
- ☑ Discharge:cumecs
- ☑ Rainfall OBS Autographic RG:mm
- ☑ Average Daily Temp:°C
- ☑ Pan Evaporation:mm

Select datatype:
- ☑ Observed
- ☐ Calculated
- ☐ Interpolated
- ☐ Simulated
- ☐ Completed
- ☐ Transformed

Project

Sub catchment name:

		Sub Project Nam	Discharge Statior	Edit	Status	Delete
1	☑	keolari	Keolari	Edit	Performed and S	

Time Series Selection

Discharge series: Keolari/Hydrological/Discharge/cumecs/1 Day/Observed

Precipitation series: Keolari/Meteorological/Rainfall OBS Autographic RG/mm/1 Day/Observe

Pan evaporation series: Keolari/Meteorological/Pan Evaporation/mm/1 Day/Observed

Temperature series: Keolari/Meteorological/Average Daily Temp/°C/1 Day/Observed

Catchment Characteristics

Catchment area: 2970 sq. km

Figure 6.2 : Project Specifications in Model PROM

The selected series can be further allocated to each lumped unit of simulation through the dropdown in the Time series selection panel. In the catchment characteristics panel, the drainage area (sq km) and % irrigation area is provided for each unit sub-catchment.

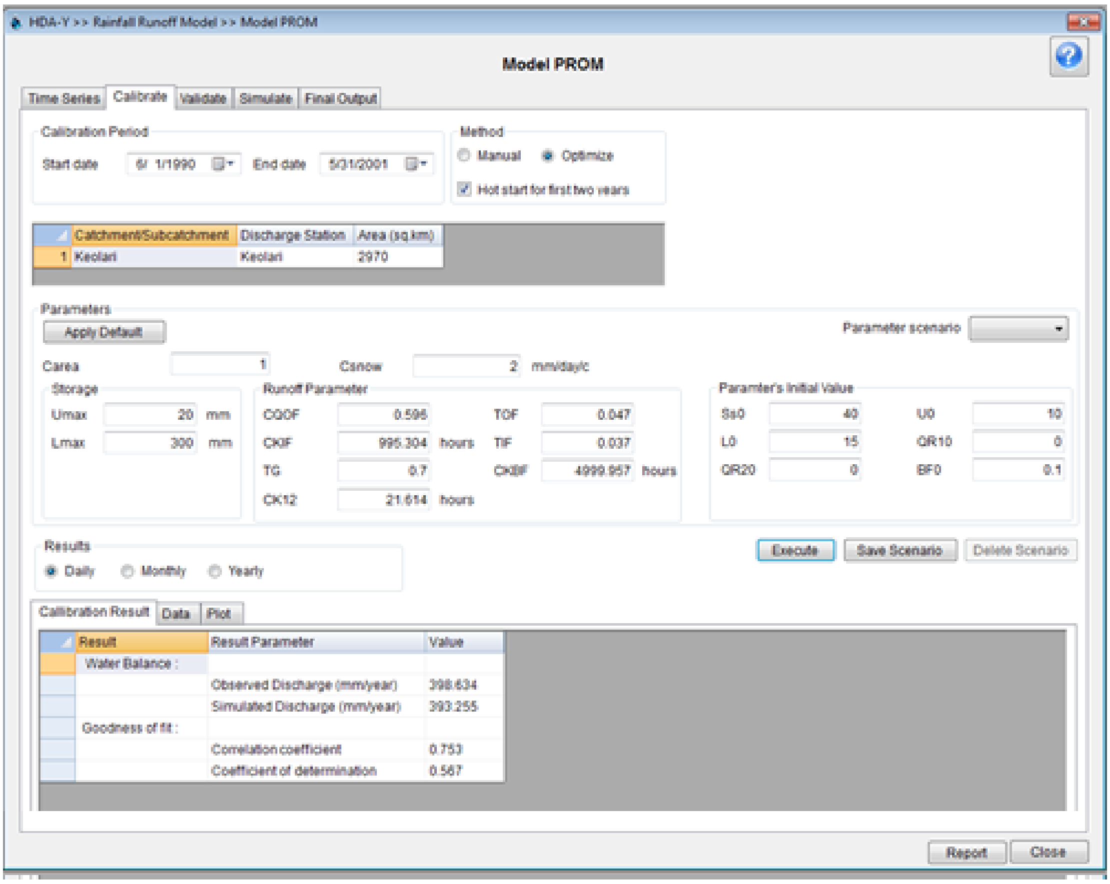
Calibration in PROM

Referring to the GUI as shown in ***Figure 6.3***, calibration period of the model is specified at this stage. According to the records available for the selected data-set, the start time of calibration automatically appears in the selected time. The user can change the time at this stage if he chooses. Selection of optional "hot start check box' enables the user to provide the number of years the data can be selected for warming up.

The calibration parameters are available to the user at this stage. As a rule, for optimum results, it is proposed to do calibration in three steps : Initially set the default values. Next, perform manual calibration with some most sensitive parameters. Finally, adopt optimisation technique for the best parameter set. The PROM parameters are shown in ***Table 6.1*** below :

Table 6.1*:* PROM calibration parameters

Parameter		Default	Calibrated
Ratio of ground water catchment to topographical catchment area	Carea	1	1
Constant Degree-day coefficient (mm/day/C)	Csnow	2	-
Maximum water content in surface storage (mm)	Umax	20	20
Maximum water content in root zone storage (mm)	Lmax	120	300
Overland flow runoff coefficient	CQOF	0.9	0.596
Time constant for Interflow (hour)	CKIF	1000	995.3
Root zone threshold value for overland flow	TOF	0.6	0.047
Root zone threshold value for interflow	TIF	0.7	0.037
Root zone threshold value for groundwater recharge	TG	0.25	0.7
Time constant for routing Interflow and overland flow (hour)	CK12	48	21.6
Baseflow time constant (hour)	CKBF	500	5000
Initial water content in Surface storage	Ss_0	40	40
Initial water content in Surface storage	U_0	10	10
Initial water content in root zone	L_0	15	15
Initial Overland flow	QR10	0	0
Initial Interflow	QR20)	0	0
Initial Base flow	BF_0	0.1	0.1



Calibration Period
Start date 6/ 1/1990
End date 5/31/2001

Method
○ Manual ● Optimize
☑ Hot start for first two years

	Catchment/Subcatchment	Discharge Station	Area (sq.km)
1	Keolari	Keolari	2970

Parameters
Parameter scenario

Carea 1
Csnow 2 mm/day/c

Storage
Umax 20 mm
Lmax 300 mm

Runoff Parameter
CQOF 0.596
CKIF 995.304 hours
TG 0.7
CK12 21.614 hours
TOF 0.047
TIF 0.037
CKBF 4999.957 hours

Paramter's Initial Value
Ss0 40
L0 15
QR20 0
U0 10
QR10 0
BF0 0.1

Results
● Daily ○ Monthly ○ Yearly

Result	Result Parameter	Value
Water Balance :		
	Observed Discharge (mm/year)	398.634
	Simulated Discharge (mm/year)	393.255
Goodness of fit :		
	Correlation coefficient	0.753
	Coefficient of determination	0.567

Figure 6.3 Calibration dialog box for Model PROM

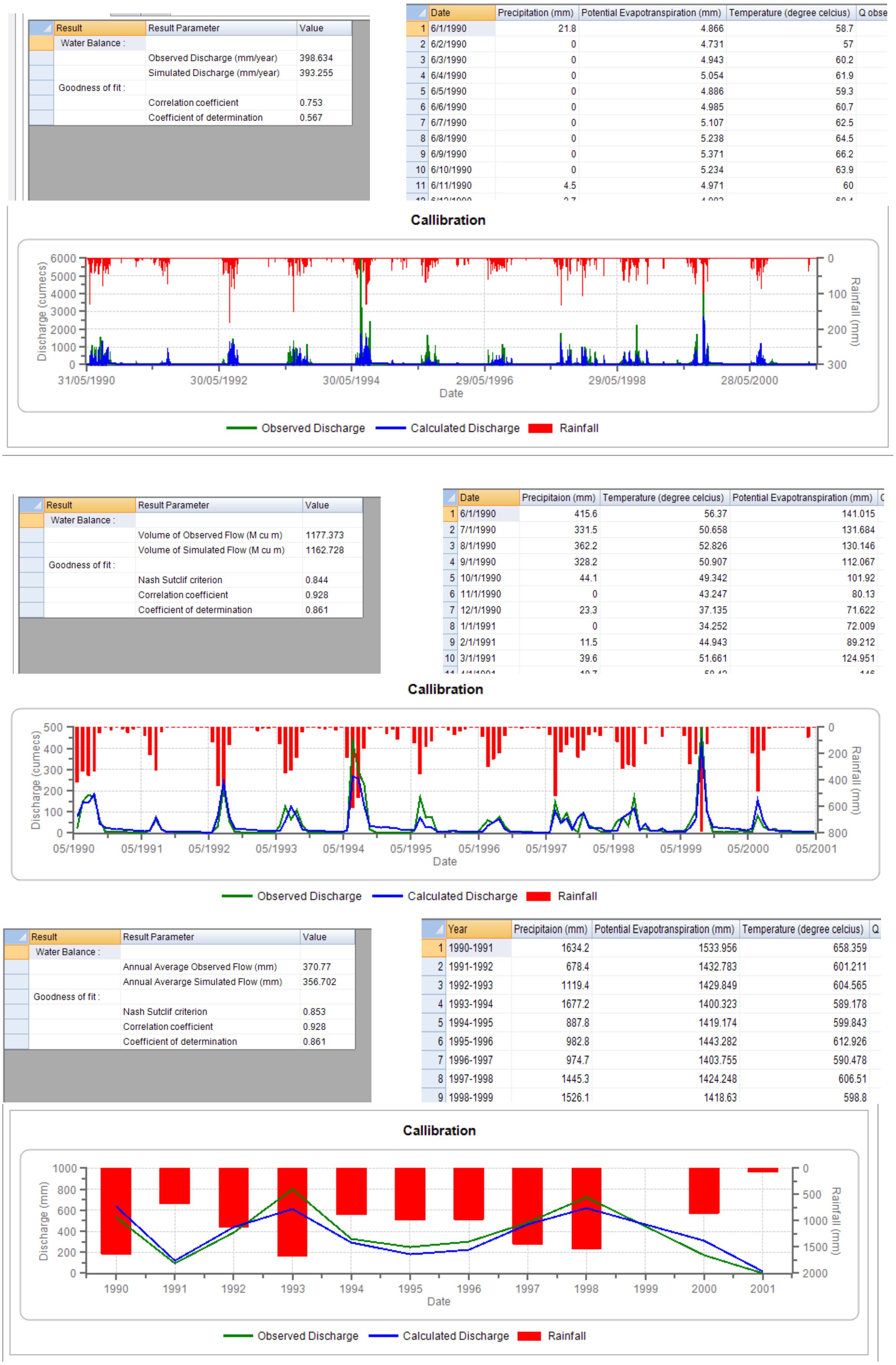
Figure 6.4 shows the output of PROM in the form of Statistical results, Tabular and Plot on daily, monthly and annual time scale.

Validation in PROM

The Model is validated for the period from June, 2001 to May, 2004.*Figure 6.5* and *Figure6.6* show the Validation Dialogue Box and Validation output respectively.

Simulation in PROM

Model is simulated for the period from June, 2004 to December, 2005. The Simulation Tabular Output can be seen in *Figure 6.7* and Summary Report is seen as *Figure 6.8*.



Result	Result Parameter	Value
Water Balance :		
	Observed Discharge (mm/year)	398.634
	Simulated Discharge (mm/year)	393.255
Goodness of fit :		
	Correlation coefficient	0.753
	Coefficient of determination	0.567

	Date	Precipitation (mm)	Potential Evapotranspiration (mm)	Temperature (degree celcius)	Q obse
1	6/1/1990	21.8	4.866	58.7	
2	6/2/1990	0	4.731	57	
3	6/3/1990	0	4.943	60.2	
4	6/4/1990	0	5.054	61.9	
5	6/5/1990	0	4.886	59.3	
6	6/6/1990	0	4.985	60.7	
7	6/7/1990	0	5.107	62.5	
8	6/8/1990	0	5.238	64.5	
9	6/9/1990	0	5.371	66.2	
10	6/10/1990	0	5.234	63.9	
11	6/11/1990	4.5	4.971	60	

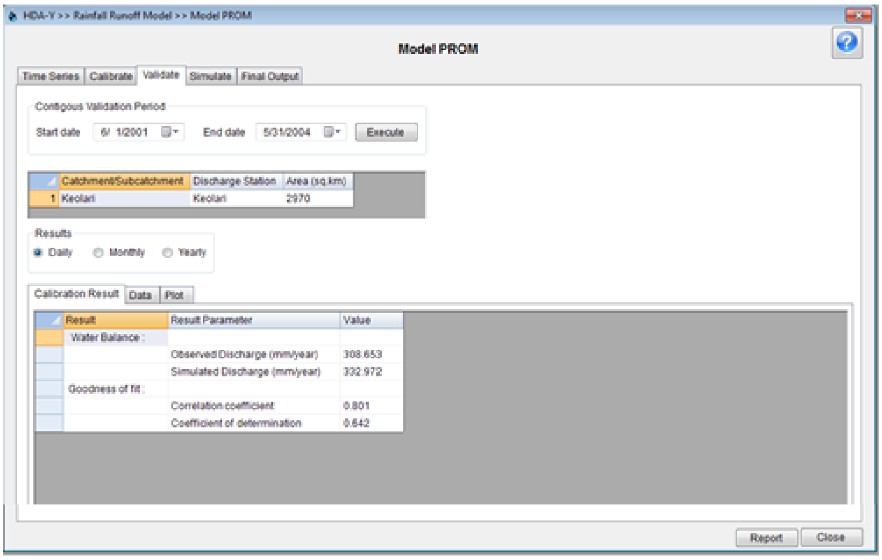
Result	Result Parameter	Value
Water Balance :		
	Volume of Observed Flow (M cu m)	1177.373
	Volume of Simulated Flow (M cu m)	1162.728
Goodness of fit :		
	Nash Sutclif criterion	0.844
	Correlation coefficient	0.928
	Coefficient of determination	0.861

	Date	Precipitaion (mm)	Temperature (degree celcius)	Potential Evapotranspiration (mm)
1	6/1/1990	415.6	56.37	141.015
2	7/1/1990	331.5	50.658	131.684
3	8/1/1990	362.2	52.826	130.146
4	9/1/1990	328.2	50.907	112.067
5	10/1/1990	44.1	49.342	101.92
6	11/1/1990	0	43.247	80.13
7	12/1/1990	23.3	37.135	71.622
8	1/1/1991	0	34.252	72.009
9	2/1/1991	11.5	44.943	89.212
10	3/1/1991	39.6	51.661	124.951

Result	Result Parameter	Value
Water Balance :		
	Annual Average Observed Flow (mm)	370.77
	Annual Average Simulated Flow (mm)	356.702
Goodness of fit :		
	Nash Sutclif criterion	0.853
	Correlation coefficient	0.928
	Coefficient of determination	0.861

	Year	Precipitaion (mm)	Potential Evapotranspiration (mm)	Temperature (degree celcius)	Q
1	1990-1991	1634.2	1533.956	658.359	
2	1991-1992	678.4	1432.783	601.211	
3	1992-1993	1119.4	1429.849	604.565	
4	1993-1994	1677.2	1400.323	589.178	
5	1994-1995	887.8	1419.174	599.843	
6	1995-1996	982.8	1443.282	612.926	
7	1996-1997	974.7	1403.755	590.478	
8	1997-1998	1445.3	1424.248	606.51	
9	1998-1999	1526.1	1418.63	598.8	

Figure 6.4 Calibration Results – Daily, Monthly and Annual time step



Contigous Validation Period

Start date 6/ 1/2001 End date 5/31/2004

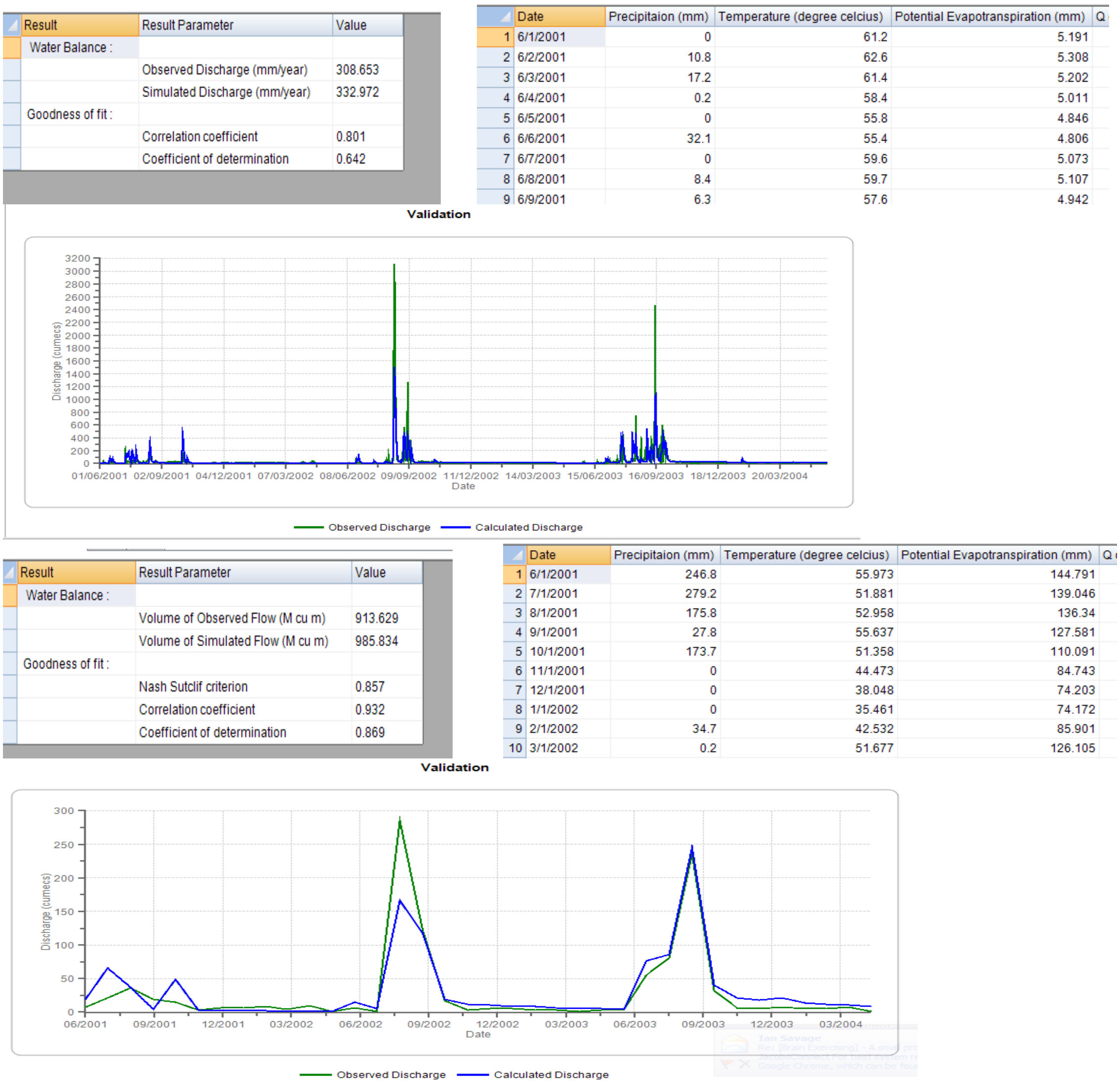
	Catchment/Subcatchment	Discharge Station	Area (sq.km)
1	Keolari	Keolari	2970

Results

● Daily ○ Monthly ○ Yearly

Result	Result Parameter	Value
Water Balance :		
	Observed Discharge (mm/year)	308.653
	Simulated Discharge (mm/year)	332.972
Goodness of fit :		
	Correlation coefficient	0.801
	Coefficient of determination	0.642

Figure 6.5 Validation dialog box for Model PROM



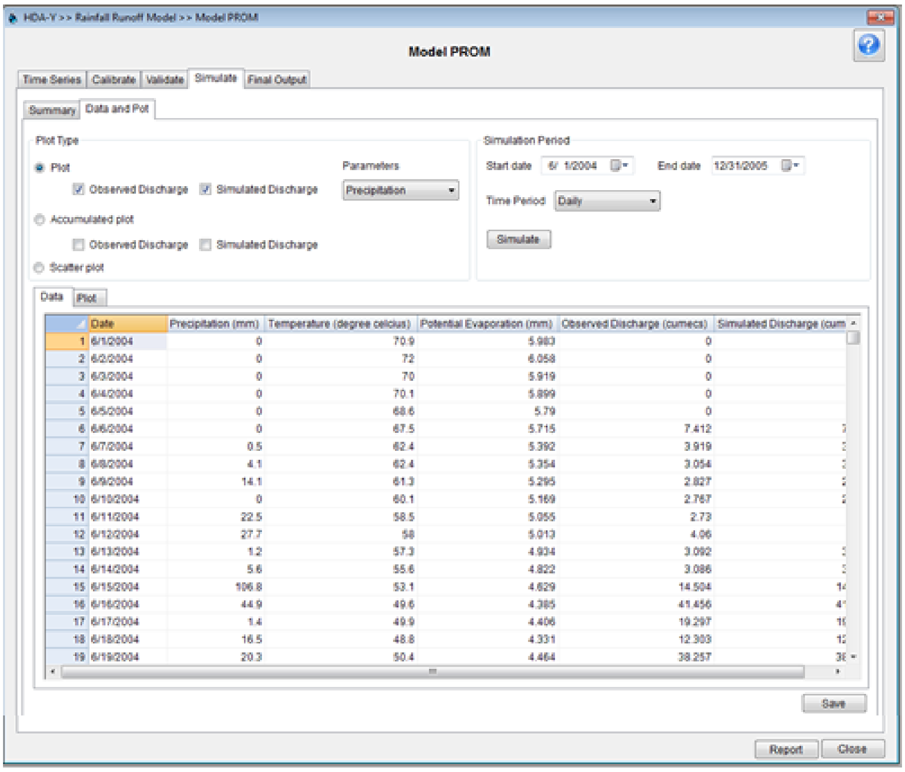
Result	Result Parameter	Value
Water Balance :		
	Observed Discharge (mm/year)	308.653
	Simulated Discharge (mm/year)	332.972
Goodness of fit :		
	Correlation coefficient	0.801
	Coefficient of determination	0.642

	Date	Precipitaion (mm)	Temperature (degree celcius)	Potential Evapotranspiration (mm)	Q
1	6/1/2001	0	61.2	5.191	
2	6/2/2001	10.8	62.6	5.308	
3	6/3/2001	17.2	61.4	5.202	
4	6/4/2001	0.2	58.4	5.011	
5	6/5/2001	0	55.8	4.846	
6	6/6/2001	32.1	55.4	4.806	
7	6/7/2001	0	59.6	5.073	
8	6/8/2001	8.4	59.7	5.107	
9	6/9/2001	6.3	57.6	4.942	

Result	Result Parameter	Value
Water Balance :		
	Volume of Observed Flow (M cu m)	913.629
	Volume of Simulated Flow (M cu m)	985.834
Goodness of fit :		
	Nash Sutclif criterion	0.857
	Correlation coefficient	0.932
	Coefficient of determination	0.869

	Date	Precipitaion (mm)	Temperature (degree celcius)	Potential Evapotranspiration (mm)	Q
1	6/1/2001	246.8	55.973	144.791	
2	7/1/2001	279.2	51.881	139.046	
3	8/1/2001	175.8	52.958	136.34	
4	9/1/2001	27.8	55.637	127.581	
5	10/1/2001	173.7	51.358	110.091	
6	11/1/2001	0	44.473	84.743	
7	12/1/2001	0	38.048	74.203	
8	1/1/2002	0	35.461	74.172	
9	2/1/2002	34.7	42.532	85.901	
10	3/1/2002	0.2	51.677	126.105	

Figure 6.6 Validation results – Daily and Monthly time step



● Plot

☑ Observed Discharge ☑ Simulated Discharge

Parameters: Precipitation

○ Accumulated plot

☐ Observed Discharge ☐ Simulated Discharge

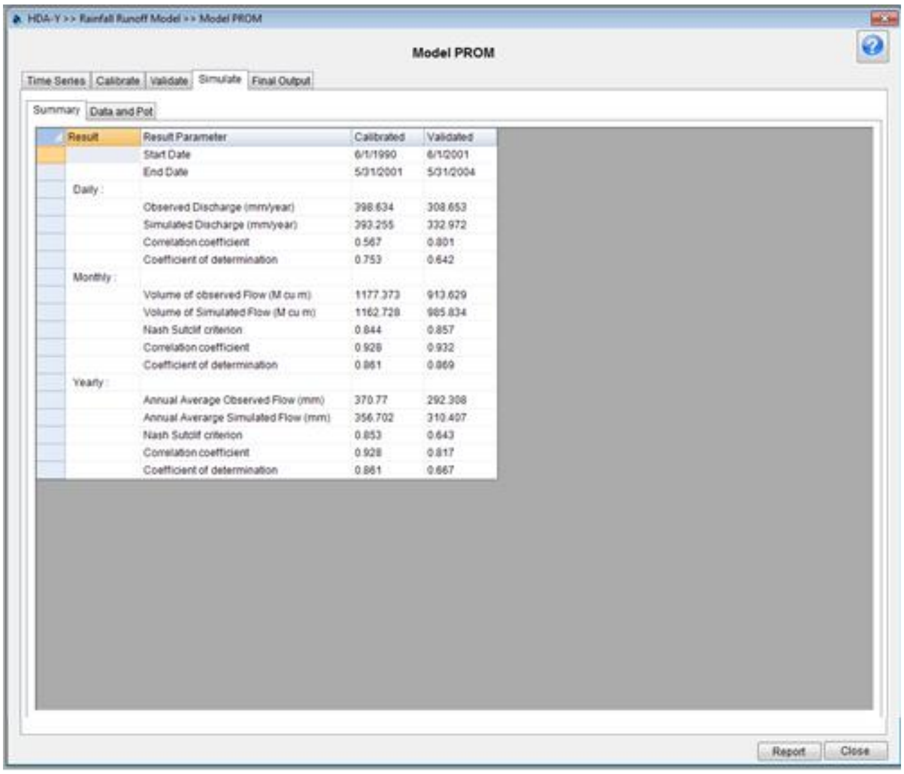
○ Scatter plot

Start date 6/ 1/2004 End date 12/31/2005

Time Period: Daily

	Date	Precipitation (mm)	Temperature (degree celcius)	Potential Evaporation (mm)	Observed Discharge (cumecs)	Simulated Discharge (cum
1	6/1/2004	0	70.9	5.983	0	
2	6/2/2004	0	72	6.058	0	
3	6/3/2004	0	70	5.919	0	
4	6/4/2004	0	70.1	5.899	0	
5	6/5/2004	0	68.6	5.79	0	
6	6/6/2004	0	67.5	5.715	7.412	7
7	6/7/2004	0.5	62.4	5.392	3.919	3
8	6/8/2004	4.1	62.4	5.354	3.054	3
9	6/9/2004	14.1	61.3	5.295	2.827	2
10	6/10/2004	0	60.1	5.169	2.767	2
11	6/11/2004	22.5	58.5	5.055	2.73	
12	6/12/2004	27.7	58	5.013	4.06	
13	6/13/2004	1.2	57.3	4.934	3.092	3
14	6/14/2004	5.6	55.6	4.822	3.086	3
15	6/15/2004	106.8	53.1	4.629	14.504	14
16	6/16/2004	44.9	49.6	4.385	41.456	4
17	6/17/2004	1.4	49.9	4.406	19.297	19
18	6/18/2004	16.5	48.8	4.331	12.303	12
19	6/19/2004	20.3	50.4	4.464	38.257	38

Figure 6.7 Simulation Tabular output



Result	Result Parameter	Calibrated	Validated
	Start Date	6/1/1990	6/1/2001
	End Date	5/31/2001	5/31/2004
Daily :			
	Observed Discharge (mm/year)	398.634	308.653
	Simulated Discharge (mm/year)	393.255	332.972
	Correlation coefficient	0.567	0.801
	Coefficient of determination	0.753	0.642
Monthly :			
	Volume of observed Flow (M cu m)	1177.373	913.629
	Volume of Simulated Flow (M cu m)	1162.728	985.834
	Nash Sutclif criterion	0.844	0.857
	Correlation coefficient	0.928	0.932
	Coefficient of determination	0.861	0.869
Yearly :			
	Annual Average Observed Flow (mm)	370.77	292.308
	Annual Averarge Simulated Flow (mm)	356.702	310.407
	Nash Sutclif criterion	0.853	0.643
	Correlation coefficient	0.928	0.817
	Coefficient of determination	0.861	0.667

Figure 6.8 : Results summary report - Model PROM

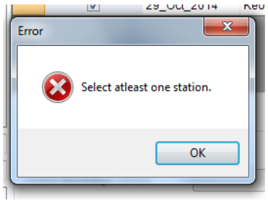
Test Example – 6.2

MODEL E

The test Example data for Model E is same as considered in Example 6.1.
Monthly data set of observed flow of Keolari in Pranhita sub-basin of Godavari, with catchment area 2970 sq km for a length of 15 years is used for rainfall-runoff analysis. From the land use map of the area, it has been derived that 86 % of the catchment is non-irrigated. Since MODEL E is designed for monthly simulation, data preparation will involve aggregation sub-module of Data Completion under selected dataset available on daily time period. The steps of aggregation have been described in sec 3.1 of Technical Manual 1.

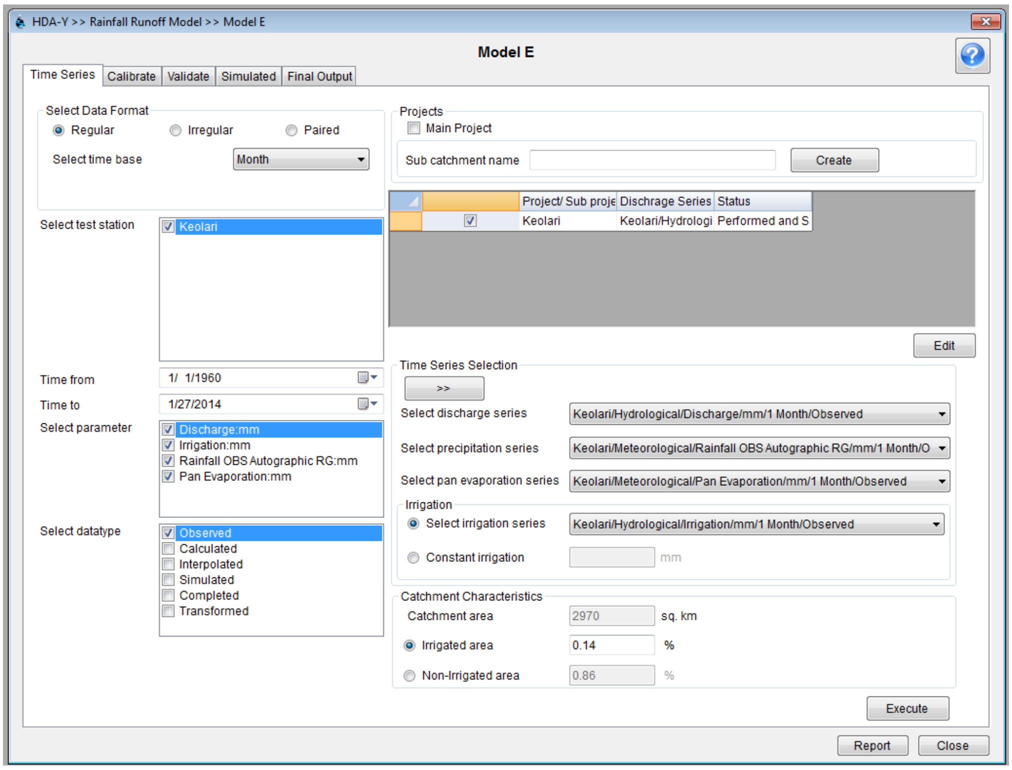
Selection of Project specifications and Time series

First step towards developing the model scenario is to decide on the catchment and sub-catchments for running the module. A selection dataset comprises of discharge series, precipitation, pan evaporation and field irrigation depth series, taken from the Global selection specified in the left panel. The project representing basin for rainfall-runoff simulation is created with an identification name, usually taken as the name of the gauging station to be used for calibration. It may be a single sub-basin or a network of multiple sub-basins in series or parallel. The catchment area of the basin/sub-basins are provided at this stage as can be seen from the model main Dialogue Box shown in **Figure 6.9.** In case of Keolari rainfall-runoff modeling, a single catchment is created with Keolari G&D station as the outlet point. In the absence of flow selected, the model asks to include the relevant reference flow series


Error

Select atleast one station.

In case of multiple sub-basins, the selected flow series can be further allocated to each lumped unit of simulation through the dropdown in the time series selection panel. In the catchment characteristics panel, the drainage area (sq km) and % irrigation area is provided corresponding to each sub-catchment.



Select Data Format: ● Regular ○ Irregular ○ Paired

Select time base: Month

Projects: ☐ Main Project

Sub catchment name:

	Project/ Sub proje	Dischrage Series	Status
☑	Keolari	Keolari/Hydrologi	Performed and S

Select test station: ☑ Keolari

Time from: 1/ 1/1960

Time to: 1/27/2014

Select parameter:
☑ Discharge:mm
☑ Irrigation:mm
☑ Rainfall OBS Autographic RG:mm
☑ Pan Evaporation:mm

Select datatype:
☑ Observed
☐ Calculated
☐ Interpolated
☐ Simulated
☐ Completed
☐ Transformed

Time Series Selection

Select discharge series: Keolari/Hydrological/Discharge/mm/1 Month/Observed

Select precipitation series: Keolari/Meteorological/Rainfall OBS Autographic RG/mm/1 Month/O

Select pan evaporation series: Keolari/Meteorological/Pan Evaporation/mm/1 Month/Observed

Irrigation
● Select irrigation series: Keolari/Hydrological/Irrigation/mm/1 Month/Observed
○ Constant irrigation: mm

Catchment Characteristics
Catchment area: 2970 sq. km
● Irrigated area: 0.14 %
○ Non-Irrigated area: 0.86 %

Figure 6.9 : Main Dialog box for providing input for Model E

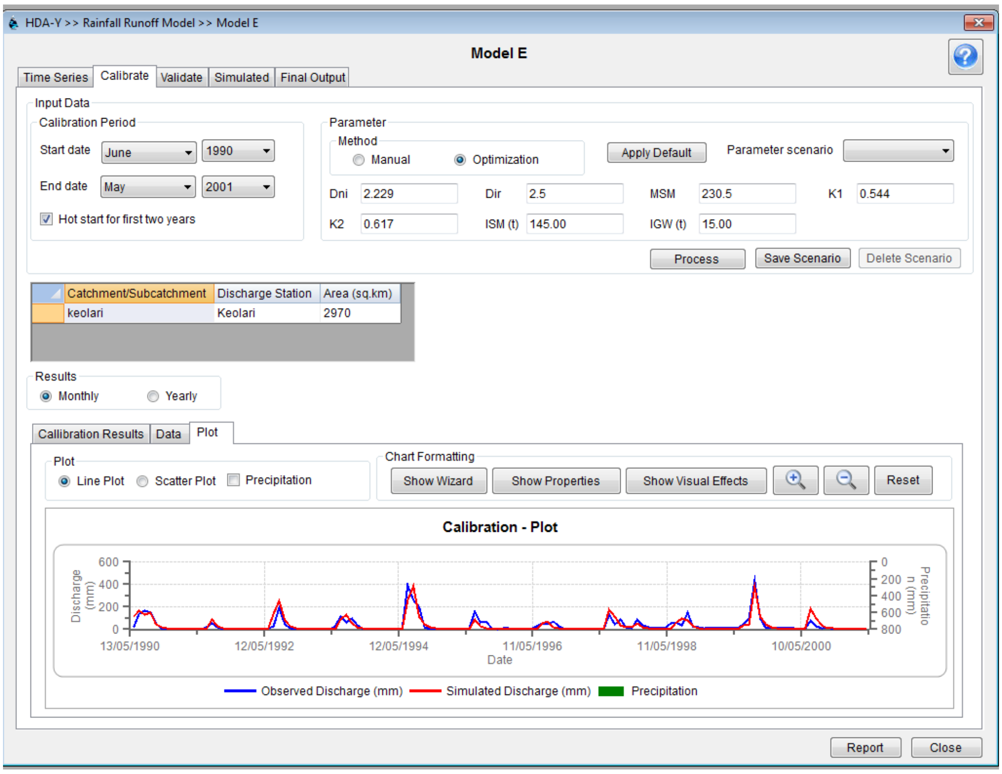
Calibration of MODEL E

According to the available records for the selected data-set, the start time for calibration is automatically selected. The user can change the time at this stage if he chooses. For Keolari, the model is calibrated for the period from June, 1990 to May, 2001. “hot start” check box enables the user to consider the option of warming up. Refer *Figure 6.10* for calibration specifications.

The calibration parameters are available to the user at this stage. The sequence to execute the model at this stage is described best as a) Setting default values to the input parameters b) perform manual calibration and c) perform auto calibration. The default and calibrated values for the parameters are given in Table 6.2.

Table 6.2 : Calibration parameters in Model E

Parameter		Default	Calibrated
Pan coefficient for un-irrigated area	D_{ni}	0.5	2.229
Pan coefficient for irrigated area	D_{ir}	0.5	2.5
Maximum soil moisture content	MSM	350	230.5
Coefficient for quick flow recession	K1	0.5	0.544
Coefficient for ground water component	K2	0.5	0.617
Initial soil moisture level	ISM (t)	145	145
Initial ground water storage	IGW (t)	15	15


HDA-Y >> Rainfall Runoff Model >> Model E

Model E

Input Data

Calibration Period

Start date: June 1990

End date: May 2001

☑ Hot start for first two years

Parameter

Method: ○ Manual ● Optimization

Parameter scenario:

Dni 2.229 Dir 2.5 MSM 230.5 K1 0.544

K2 0.617 ISM (t) 145.00 IGW (t) 15.00

Catchment/Subcatchment	Discharge Station	Area (sq.km)
keolari	Keolari	2970

Results: ● Monthly ○ Yearly

Plot: ● Line Plot ○ Scatter Plot ☐ Precipitation

Figure 6.10 Main Dialog box for providing input in Model E

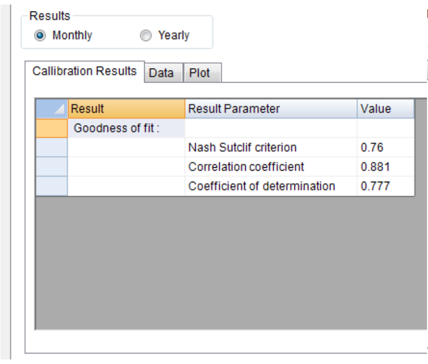
Figure 6.11 shows the output of MODEL E in the form of Statistical Summary, Tabular output and Plot on monthly and annual time scale.

Validation in Model E

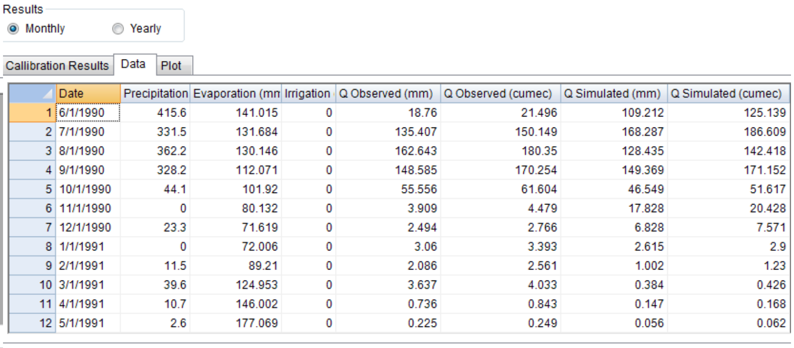
The Model is validated for the period from June, 2001 to May, 2004. Refer *Figure 6.12* for the output of MODEL E in the form of Statistical Summary, Tabular output and Plot on monthly and annual time scale.

Simulation in Model E

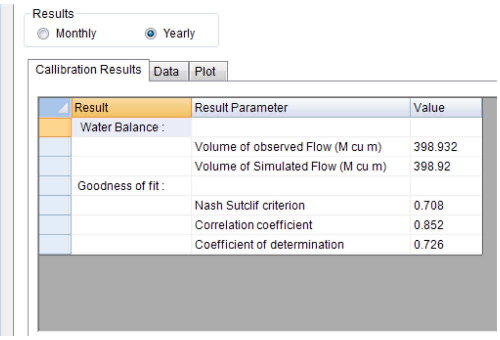
Model is simulated for the period from June, 2004 to December, 2005. *Figure 6.13* gives the Statistical Summary of MODEL E results.



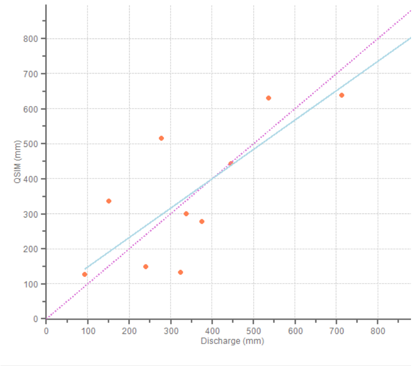
Result	Result Parameter	Value
Goodness of fit :		
	Nash Sutclif criterion	0.76
	Correlation coefficient	0.881
	Coefficient of determination	0.777



	Date	Precipitation	Evaporation (mm	Irrigation	Q Observed (mm)	Q Observed (cumec)	Q Simulated (mm)	Q Simulated (cumec)
1	6/1/1990	415.6	141.015	0	18.76	21.496	109.212	125.139
2	7/1/1990	331.5	131.684	0	135.407	150.149	168.287	186.609
3	8/1/1990	362.2	130.146	0	162.643	180.35	128.435	142.418
4	9/1/1990	328.2	112.071	0	148.585	170.254	149.369	171.152
5	10/1/1990	44.1	101.92	0	55.556	61.604	46.549	51.617
6	11/1/1990	0	80.132	0	3.909	4.479	17.828	20.428
7	12/1/1990	23.3	71.619	0	2.494	2.766	6.828	7.571
8	1/1/1991	0	72.006	0	3.06	3.393	2.615	2.9
9	2/1/1991	11.5	89.21	0	2.086	2.561	1.002	1.23
10	3/1/1991	39.6	124.953	0	3.637	4.033	0.384	0.426
11	4/1/1991	10.7	146.002	0	0.736	0.843	0.147	0.168
12	5/1/1991	2.6	177.069	0	0.225	0.249	0.056	0.062



Result	Result Parameter	Value
Water Balance :		
	Volume of observed Flow (M cu m)	398.932
	Volume of Simulated Flow (M cu m)	398.92
Goodness of fit :		
	Nash Sutclif criterion	0.708
	Correlation coefficient	0.852
	Coefficient of determination	0.726



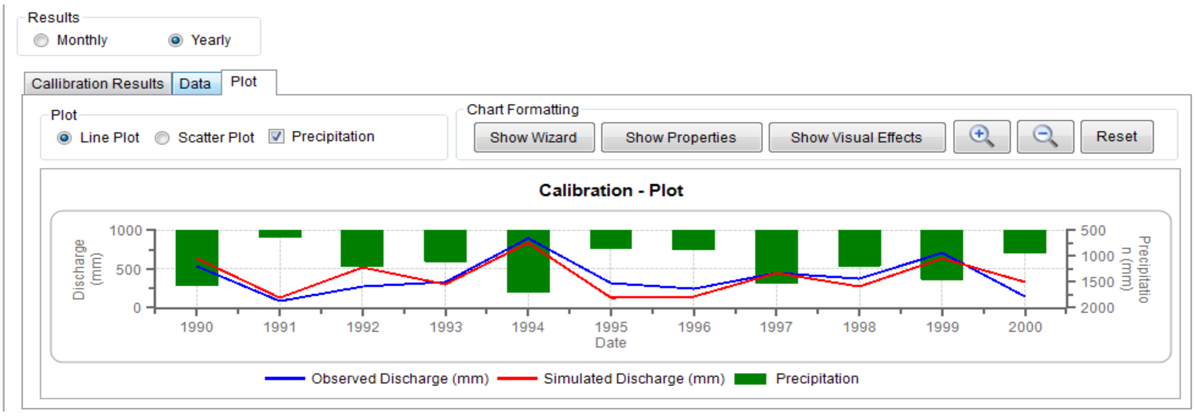
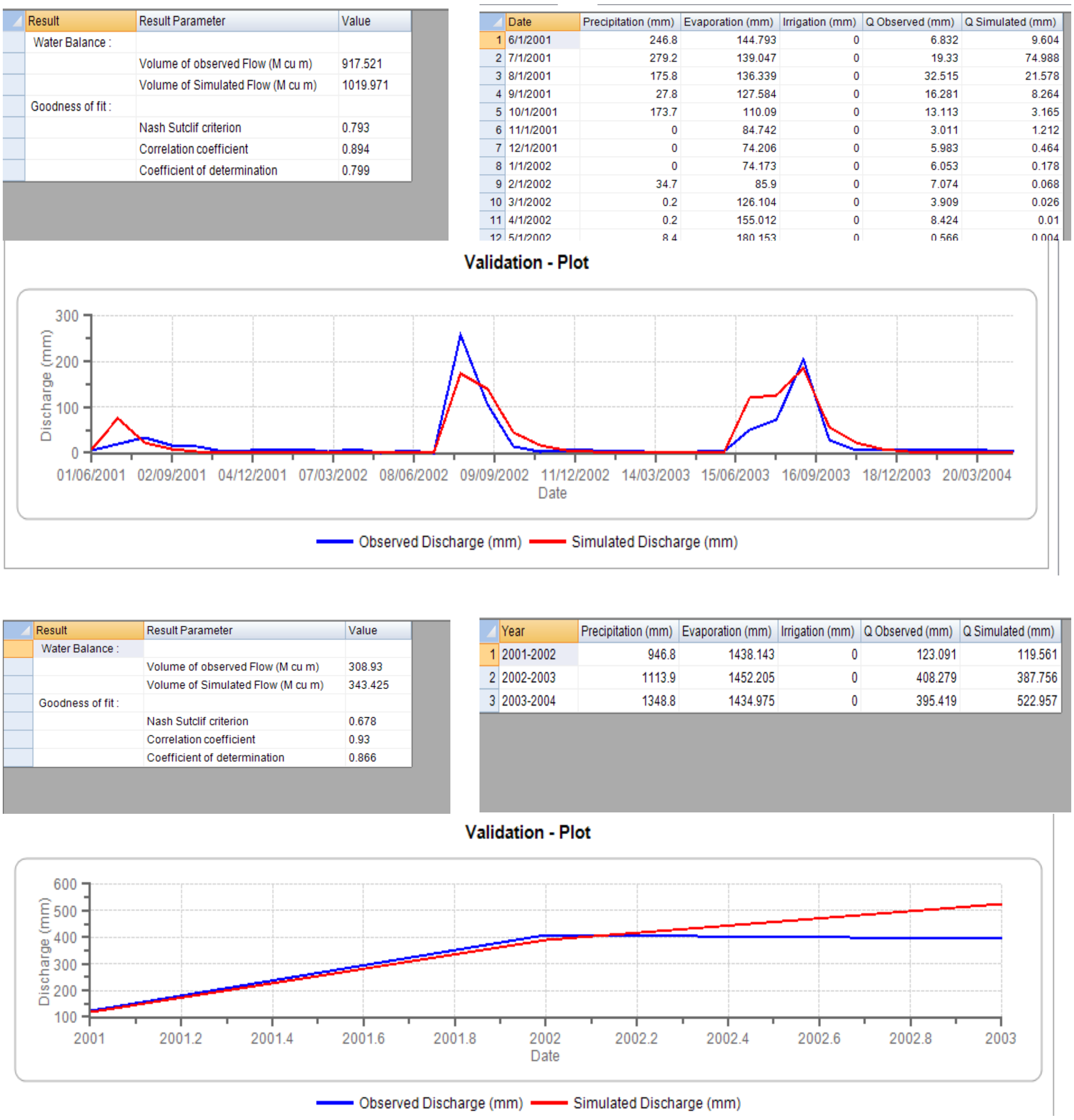


Figure 6.11 Calibration results in Model E– Monthly and Annual time scale output



Result	Result Parameter	Value
Water Balance :		
	Volume of observed Flow (M cu m)	917.521
	Volume of Simulated Flow (M cu m)	1019.971
Goodness of fit :		
	Nash Sutclif criterion	0.793
	Correlation coefficient	0.894
	Coefficient of determination	0.799

	Date	Precipitation (mm)	Evaporation (mm)	Irrigation (mm)	Q Observed (mm)	Q Simulated (mm)
1	6/1/2001	246.8	144.793	0	6.832	9.604
2	7/1/2001	279.2	139.047	0	19.33	74.988
3	8/1/2001	175.8	136.339	0	32.515	21.578
4	9/1/2001	27.8	127.584	0	16.281	8.264
5	10/1/2001	173.7	110.09	0	13.113	3.165
6	11/1/2001	0	84.742	0	3.011	1.212
7	12/1/2001	0	74.206	0	5.983	0.464
8	1/1/2002	0	74.173	0	6.053	0.178
9	2/1/2002	34.7	85.9	0	7.074	0.068
10	3/1/2002	0.2	126.104	0	3.909	0.026
11	4/1/2002	0.2	155.012	0	8.424	0.01
12	5/1/2002	8.4	180.153	0	0.566	0.004

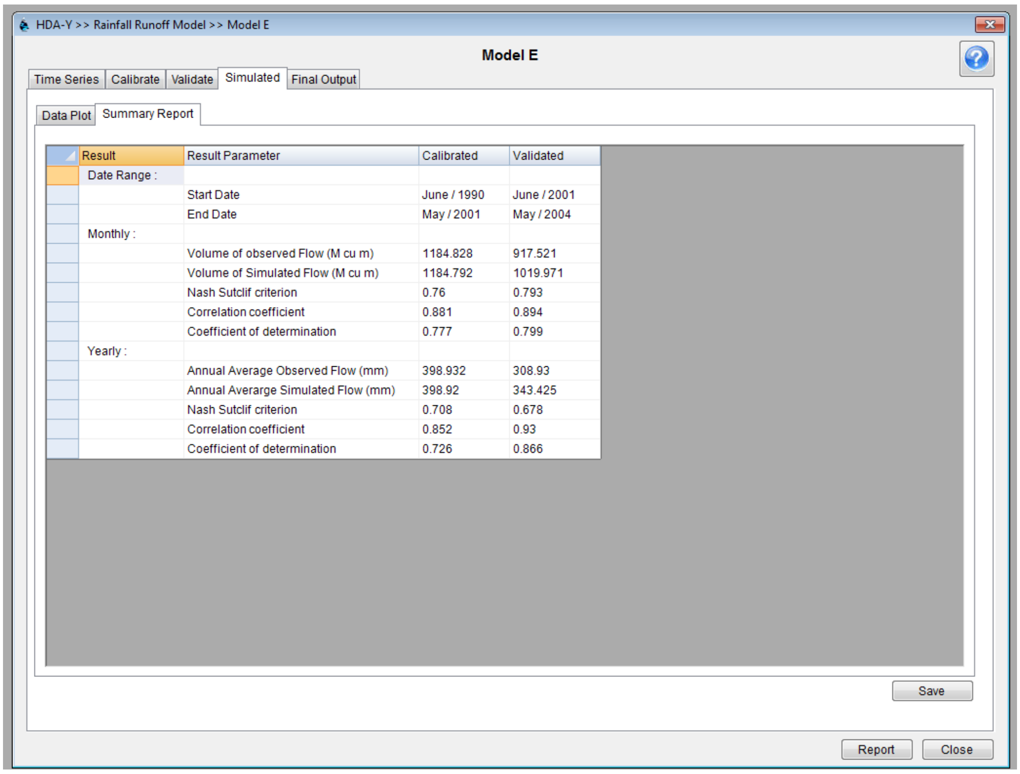
Validation - Plot

Result	Result Parameter	Value
Water Balance :		
	Volume of observed Flow (M cu m)	308.93
	Volume of Simulated Flow (M cu m)	343.425
Goodness of fit :		
	Nash Sutclif criterion	0.678
	Correlation coefficient	0.93
	Coefficient of determination	0.866

	Year	Precipitation (mm)	Evaporation (mm)	Irrigation (mm)	Q Observed (mm)	Q Simulated (mm)
1	2001-2002	946.8	1438.143	0	123.091	119.561
2	2002-2003	1113.9	1452.205	0	408.279	387.756
3	2003-2004	1348.8	1434.975	0	395.419	522.957

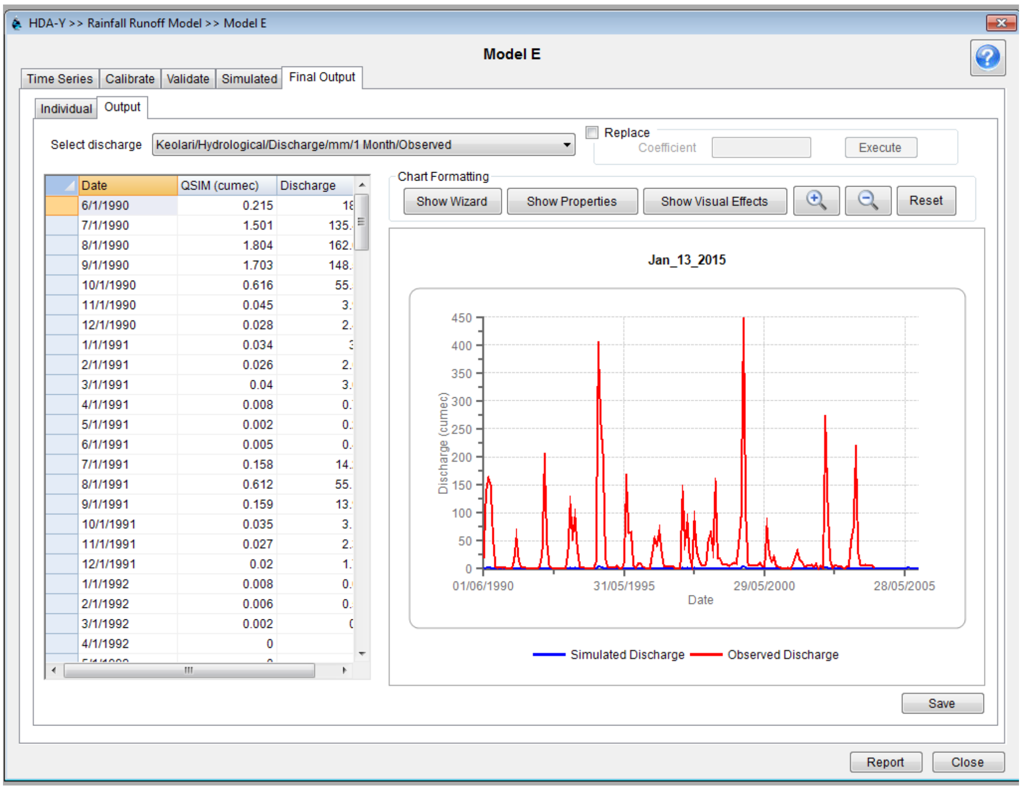
Validation - Plot

Figure 6.12 Validation results in Model E – Monthly and Annual time scale output



Result	Result Parameter	Calibrated	Validated
Date Range :			
	Start Date	June / 1990	June / 2001
	End Date	May / 2001	May / 2004
Monthly :			
	Volume of observed Flow (M cu m)	1184.828	917.521
	Volume of Simulated Flow (M cu m)	1184.792	1019.971
	Nash Sutclif criterion	0.76	0.793
	Correlation coefficient	0.881	0.894
	Coefficient of determination	0.777	0.799
Yearly :			
	Annual Average Observed Flow (mm)	398.932	308.93
	Annual Averarge Simulated Flow (mm)	398.92	343.425
	Nash Sutclif criterion	0.708	0.678
	Correlation coefficient	0.852	0.93
	Coefficient of determination	0.726	0.866

Figure 6.13 : Results summary report - Model E



Select discharge: Keolari/Hydrological/Discharge/mm/1 Month/Observed

☐ Replace

Date	QSIM (cumec)	Discharge
6/1/1990	0.215	18
7/1/1990	1.501	135.
8/1/1990	1.804	162.
9/1/1990	1.703	148.
10/1/1990	0.616	55.
11/1/1990	0.045	3.
12/1/1990	0.028	2.
1/1/1991	0.034	3
2/1/1991	0.026	2.
3/1/1991	0.04	3.
4/1/1991	0.008	0.
5/1/1991	0.002	0.
6/1/1991	0.005	0.
7/1/1991	0.158	14.
8/1/1991	0.612	55.
9/1/1991	0.159	13.
10/1/1991	0.035	3.
11/1/1991	0.027	2.
12/1/1991	0.02	1.
1/1/1992	0.008	0.
2/1/1992	0.006	0.
3/1/1992	0.002	0
4/1/1992	0	

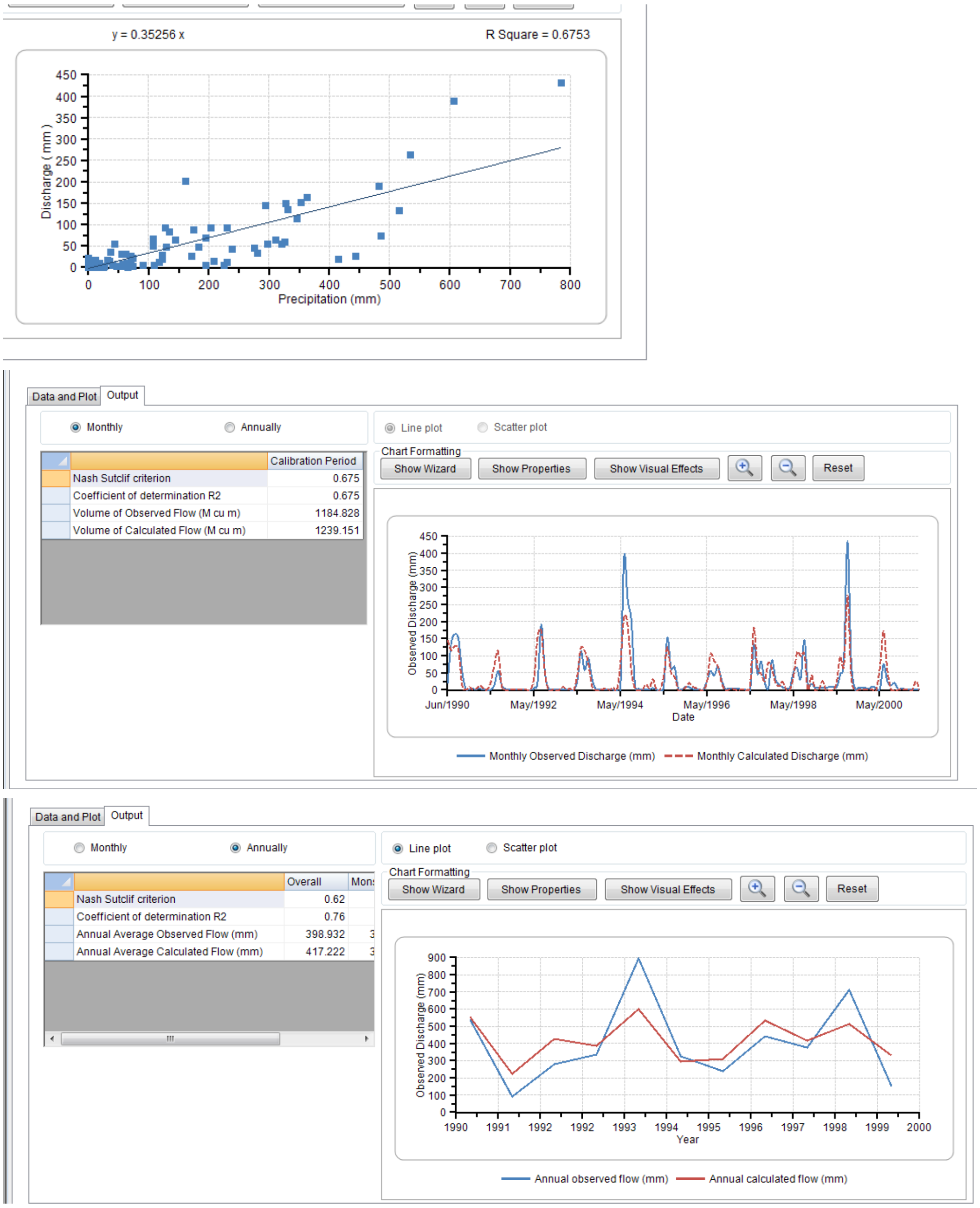
Figure 6.14 : Output in Model E – Tabular and Graphical

Test Example – 6.3

REGM

Considering the test data of Keolari in Wardha sub-basin of Godavari, as used in Examples 6.1 and 6.2, model simulation has been undertaken in REGM. The procedure of developing inputs for the model is same as in PROM and Model E. The current Example illustrates the outputs of various REGM sub-modules for a comparative understanding of the application. (From *Figure 6.15 to Figure 6.30)*

i) Runoff Coefficient Model (RCM)



● Monthly ○ Annually

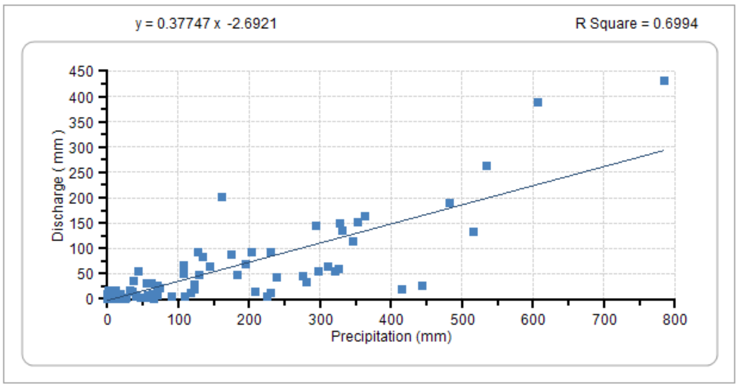
	Calibration Period
Nash Sutclif criterion	0.675
Coefficient of determination R2	0.675
Volume of Observed Flow (M cu m)	1184.828
Volume of Calculated Flow (M cu m)	1239.151

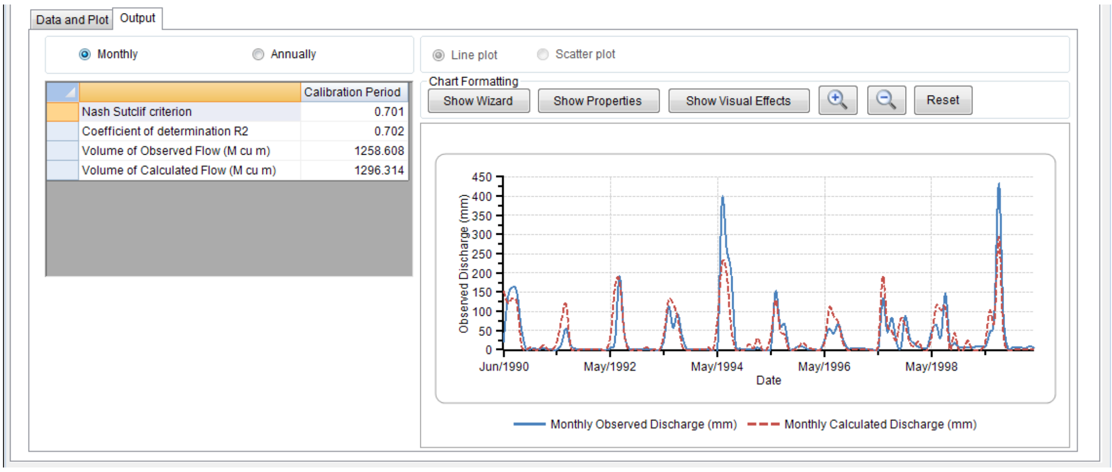
○ Monthly ● Annually

	Overall	Mon
Nash Sutclif criterion	0.62	
Coefficient of determination R2	0.76	
Annual Average Observed Flow (mm)	398.932	3
Annual Average Calculated Flow (mm)	417.222	3

Figure 6.15 : Calibration Output (Monthly and Annual) in RCM-REGM

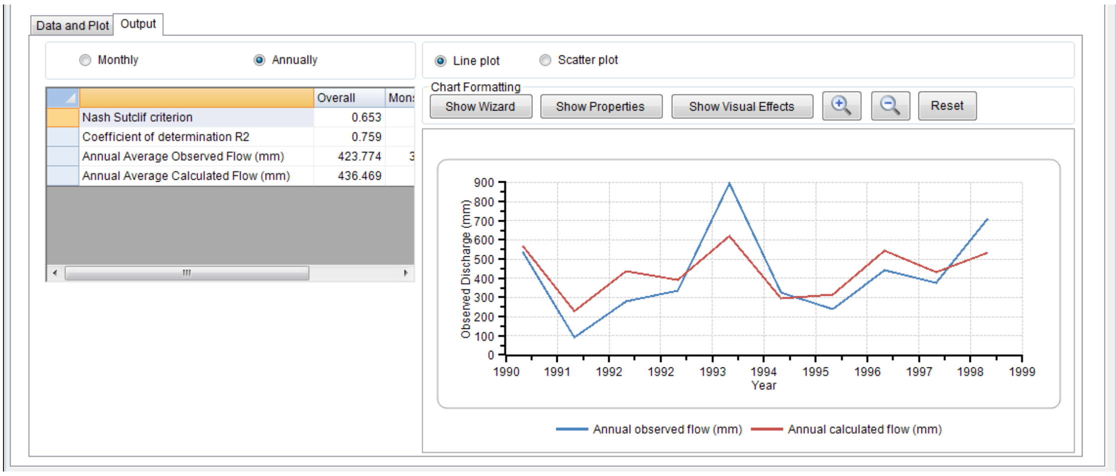
ii) Single Regression Model (SRM)





● Monthly ○ Annually

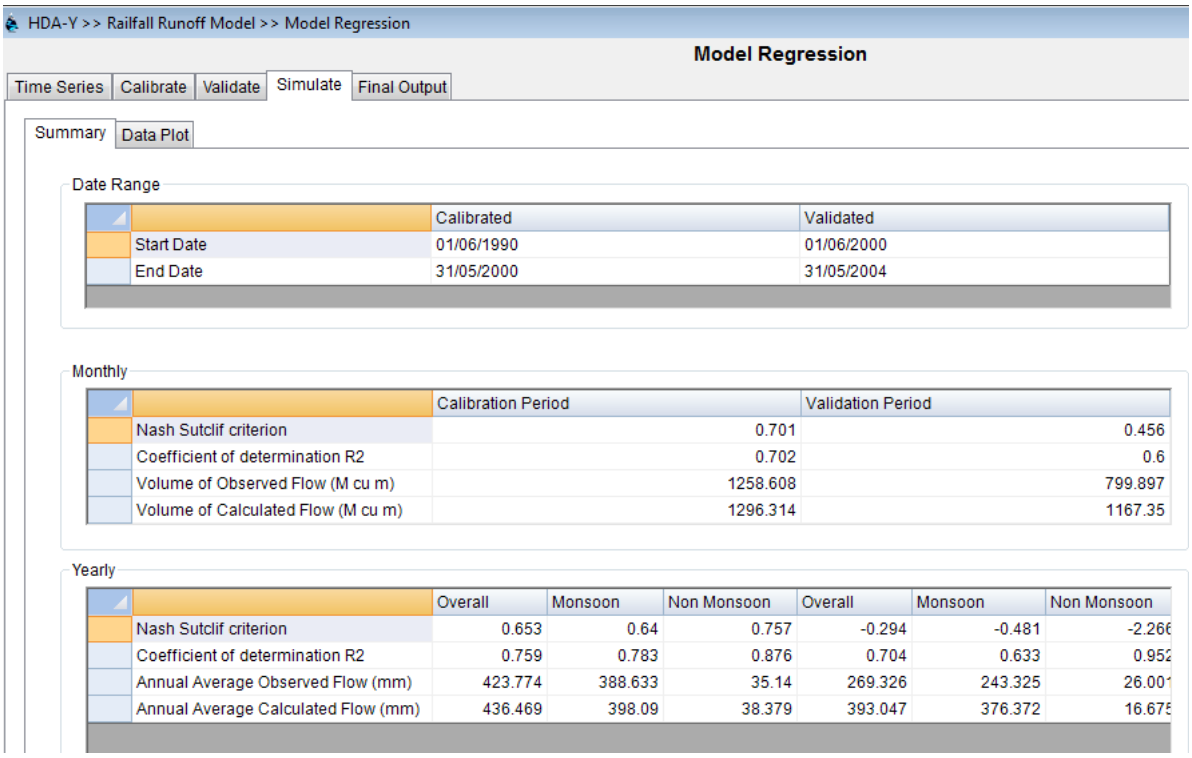
	Calibration Period
Nash Sutclif criterion	0.701
Coefficient of determination R2	0.702
Volume of Observed Flow (M cu m)	1258.608
Volume of Calculated Flow (M cu m)	1296.314



○ Monthly ● Annually

	Overall	Mon
Nash Sutclif criterion	0.653	
Coefficient of determination R2	0.759	
Annual Average Observed Flow (mm)	423.774	3
Annual Average Calculated Flow (mm)	436.469	

Figure 6.16 : Calibration Output (Monthly and Annual) in SRM-REGM



Date Range

	Calibrated	Validated
Start Date	01/06/1990	01/06/2000
End Date	31/05/2000	31/05/2004

Monthly

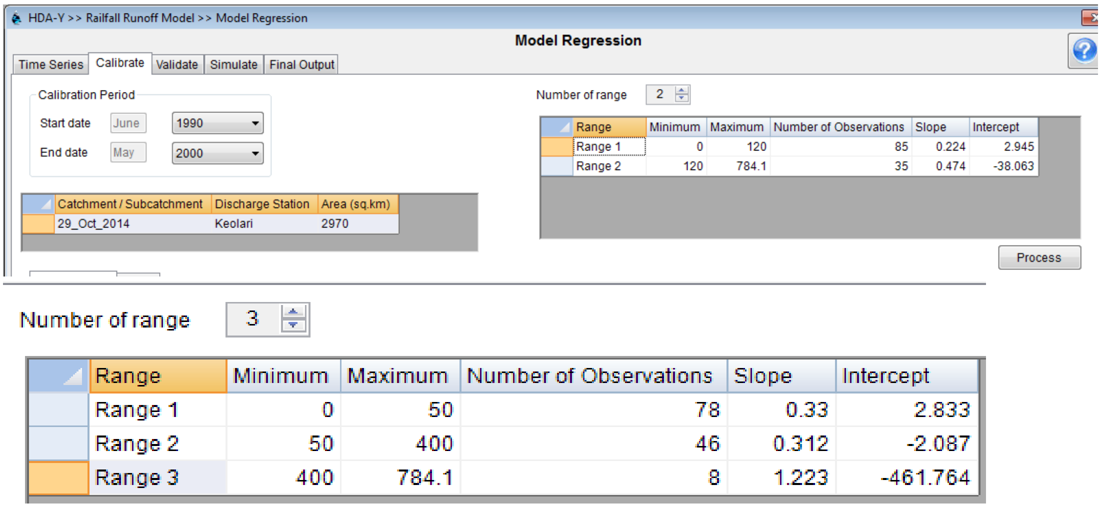
	Calibration Period	Validation Period
Nash Sutclif criterion	0.701	0.456
Coefficient of determination R2	0.702	0.6
Volume of Observed Flow (M cu m)	1258.608	799.897
Volume of Calculated Flow (M cu m)	1296.314	1167.35

Yearly

	Overall	Monsoon	Non Monsoon	Overall	Monsoon	Non Monsoon
Nash Sutclif criterion	0.653	0.64	0.757	-0.294	-0.481	-2.266
Coefficient of determination R2	0.759	0.783	0.876	0.704	0.633	0.952
Annual Average Observed Flow (mm)	423.774	388.633	35.14	269.326	243.325	26.001
Annual Average Calculated Flow (mm)	436.469	398.09	38.379	393.047	376.372	16.675

Figure 6.17 : Result Summary in SRM-REGM

iii) Range Dependant Single Regression Model (RRM)



Calibration Period
Start date June 1990
End date May 2000

Catchment / Subcatchment	Discharge Station	Area (sq.km)
29_Oct_2014	Keolari	2970

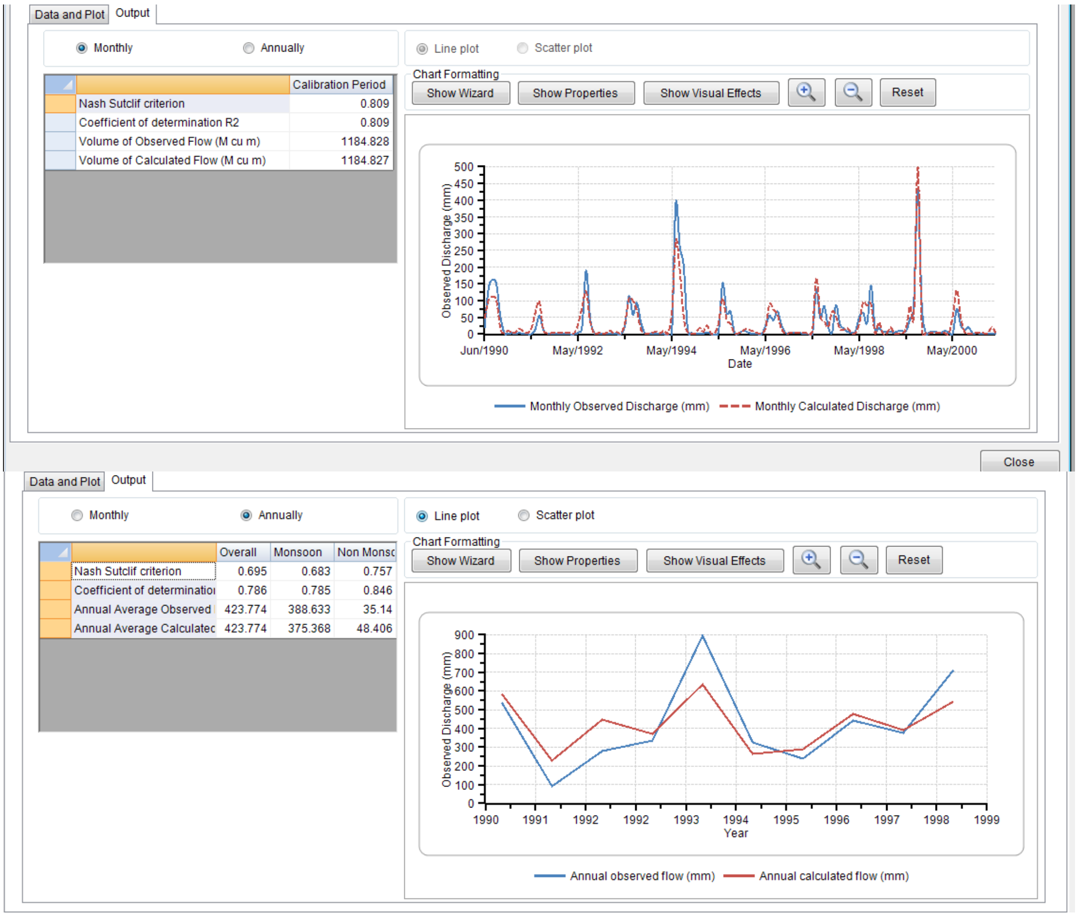
Number of range 2

Range	Minimum	Maximum	Number of Observations	Slope	Intercept
Range 1	0	120	85	0.224	2.945
Range 2	120	784.1	35	0.474	-38.063

Number of range 3

Range	Minimum	Maximum	Number of Observations	Slope	Intercept
Range 1	0	50	78	0.33	2.833
Range 2	50	400	46	0.312	-2.087
Range 3	400	784.1	8	1.223	-461.764

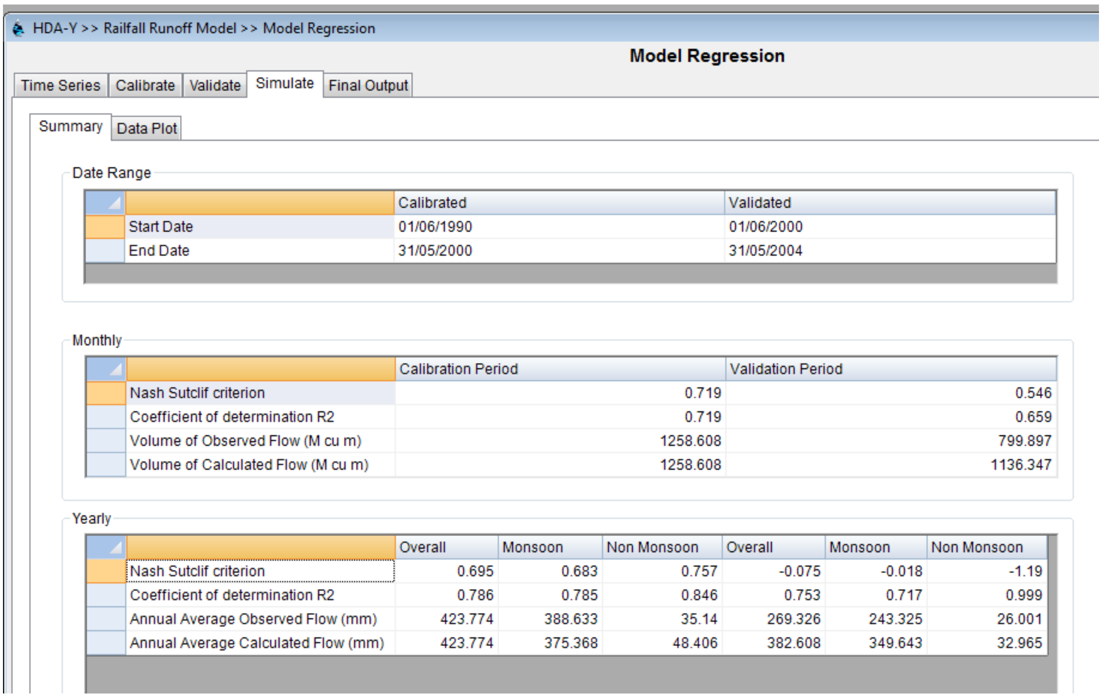
Figure 6.18 : Dialog box showing range selection in RRM-REGM



	Calibration Period
Nash Sutclif criterion	0.809
Coefficient of determination R2	0.809
Volume of Observed Flow (M cu m)	1184.828
Volume of Calculated Flow (M cu m)	1184.827

	Overall	Monsoon	Non Monsc
Nash Sutclif criterion	0.695	0.683	0.757
Coefficient of determinatio	0.786	0.785	0.846
Annual Average Observed	423.774	388.633	35.14
Annual Average Calculatec	423.774	375.368	48.406

Figure 6.19 : Calibration Output (Monthly and Annual) in RRM-REGM



Date Range

	Calibrated	Validated
Start Date	01/06/1990	01/06/2000
End Date	31/05/2000	31/05/2004

Monthly

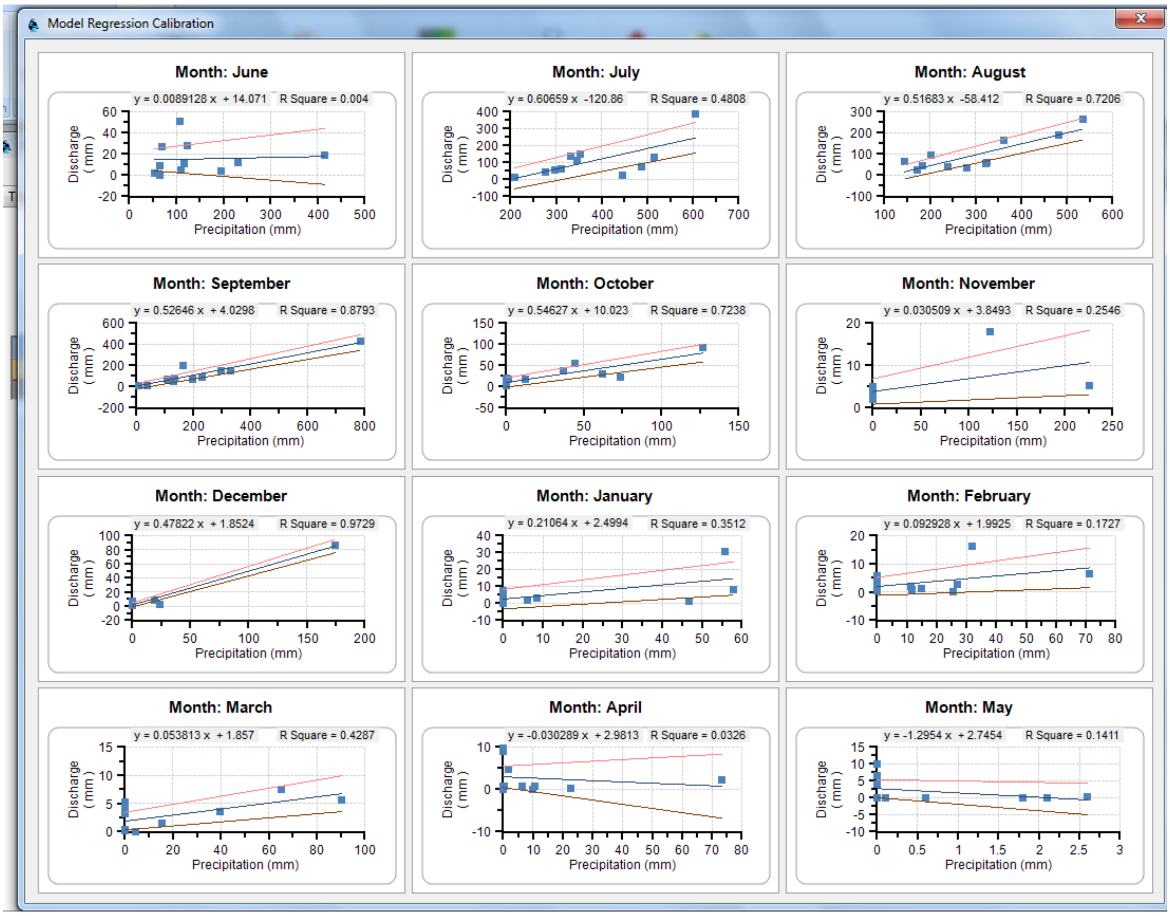
	Calibration Period	Validation Period
Nash Sutclif criterion	0.719	0.546
Coefficient of determination R2	0.719	0.659
Volume of Observed Flow (M cu m)	1258.608	799.897
Volume of Calculated Flow (M cu m)	1258.608	1136.347

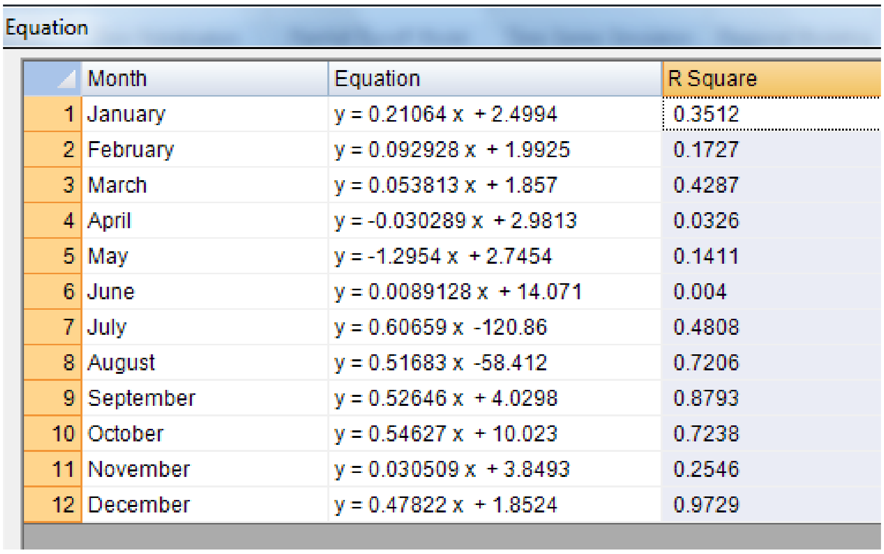
Yearly

	Overall	Monsoon	Non Monsoon	Overall	Monsoon	Non Monsoon
Nash Sutclif criterion	0.695	0.683	0.757	-0.075	-0.018	-1.19
Coefficient of determination R2	0.786	0.785	0.846	0.753	0.717	0.999
Annual Average Observed Flow (mm)	423.774	388.633	35.14	269.326	243.325	26.001
Annual Average Calculated Flow (mm)	423.774	375.368	48.406	382.608	349.643	32.965

Figure 6.20 : Result Summary in RRM-REGM

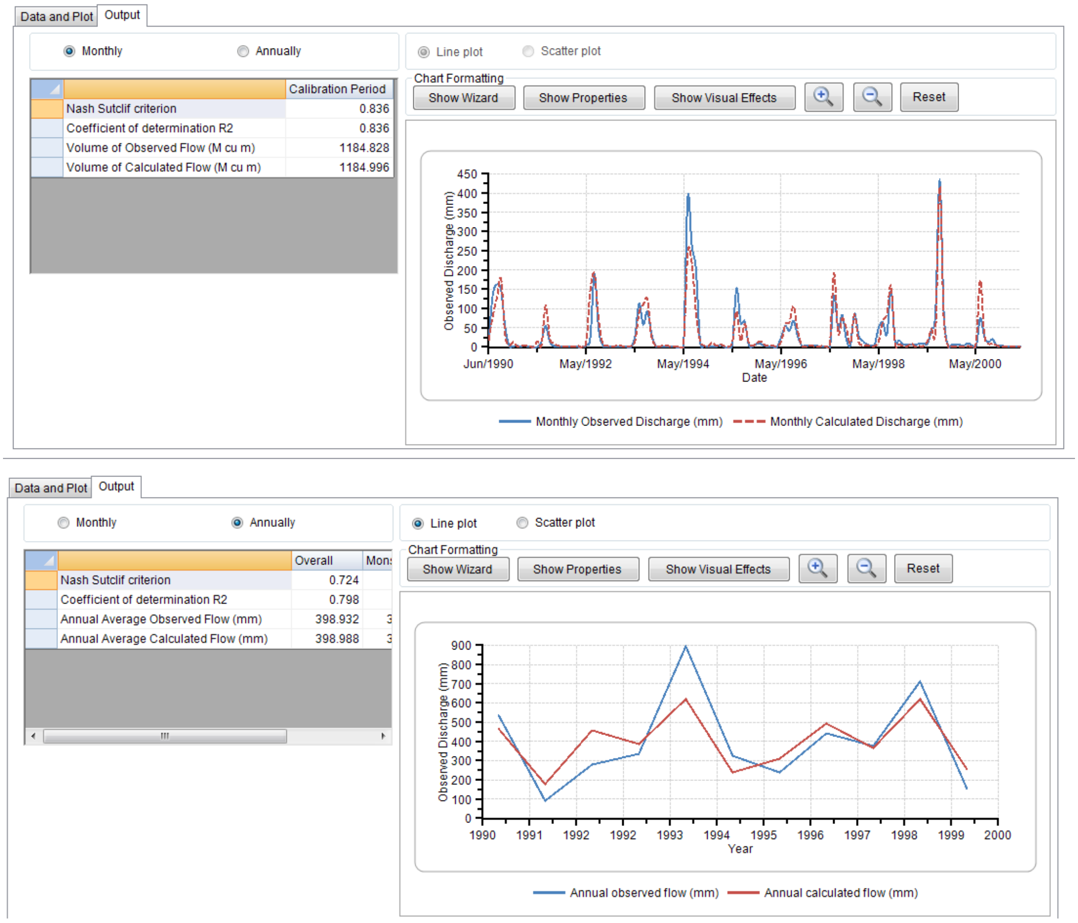
iv) Monthly Linear Regression Model (MLM)




Equation

	Month	Equation	R Square
1	January	y = 0.21064 x + 2.4994	0.3512
2	February	y = 0.092928 x + 1.9925	0.1727
3	March	y = 0.053813 x + 1.857	0.4287
4	April	y = -0.030289 x + 2.9813	0.0326
5	May	y = -1.2954 x + 2.7454	0.1411
6	June	y = 0.0089128 x + 14.071	0.004
7	July	y = 0.60659 x -120.86	0.4808
8	August	y = 0.51683 x -58.412	0.7206
9	September	y = 0.52646 x + 4.0298	0.8793
10	October	y = 0.54627 x + 10.023	0.7238
11	November	y = 0.030509 x + 3.8493	0.2546
12	December	y = 0.47822 x + 1.8524	0.9729

Figure 6.21 : Monthly Linear Equations derived in MLM-REGM



● Monthly ○ Annually

○ Line plot ○ Scatter plot

Chart Formatting

	Calibration Period
Nash Sutclif criterion	0.836
Coefficient of determination R2	0.836
Volume of Observed Flow (M cu m)	1184.828
Volume of Calculated Flow (M cu m)	1184.996

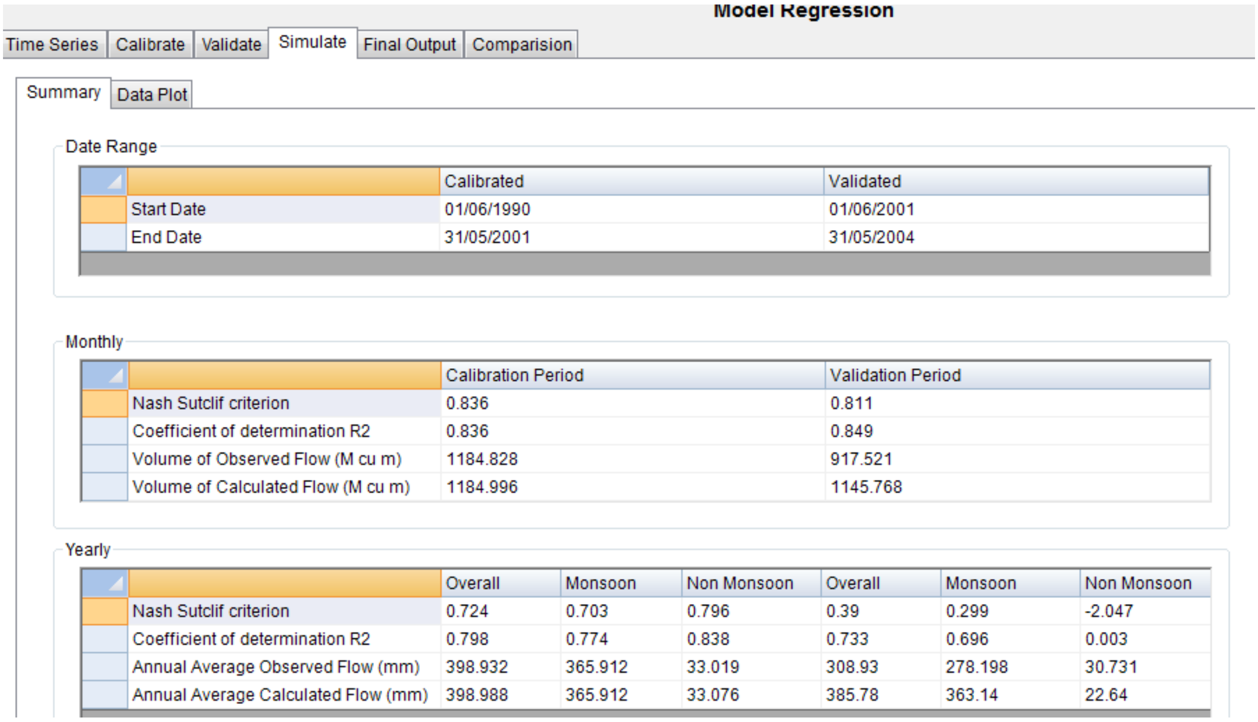
○ Monthly ● Annually

● Line plot ○ Scatter plot

Chart Formatting

	Overall	Mon:
Nash Sutclif criterion	0.724	
Coefficient of determination R2	0.798	
Annual Average Observed Flow (mm)	398.932	3
Annual Average Calculated Flow (mm)	398.988	3

Figure 6.22 : Calibration Output (Monthly and Annual) in MLM-REGM



Date Range

	Calibrated	Validated
Start Date	01/06/1990	01/06/2001
End Date	31/05/2001	31/05/2004

Monthly

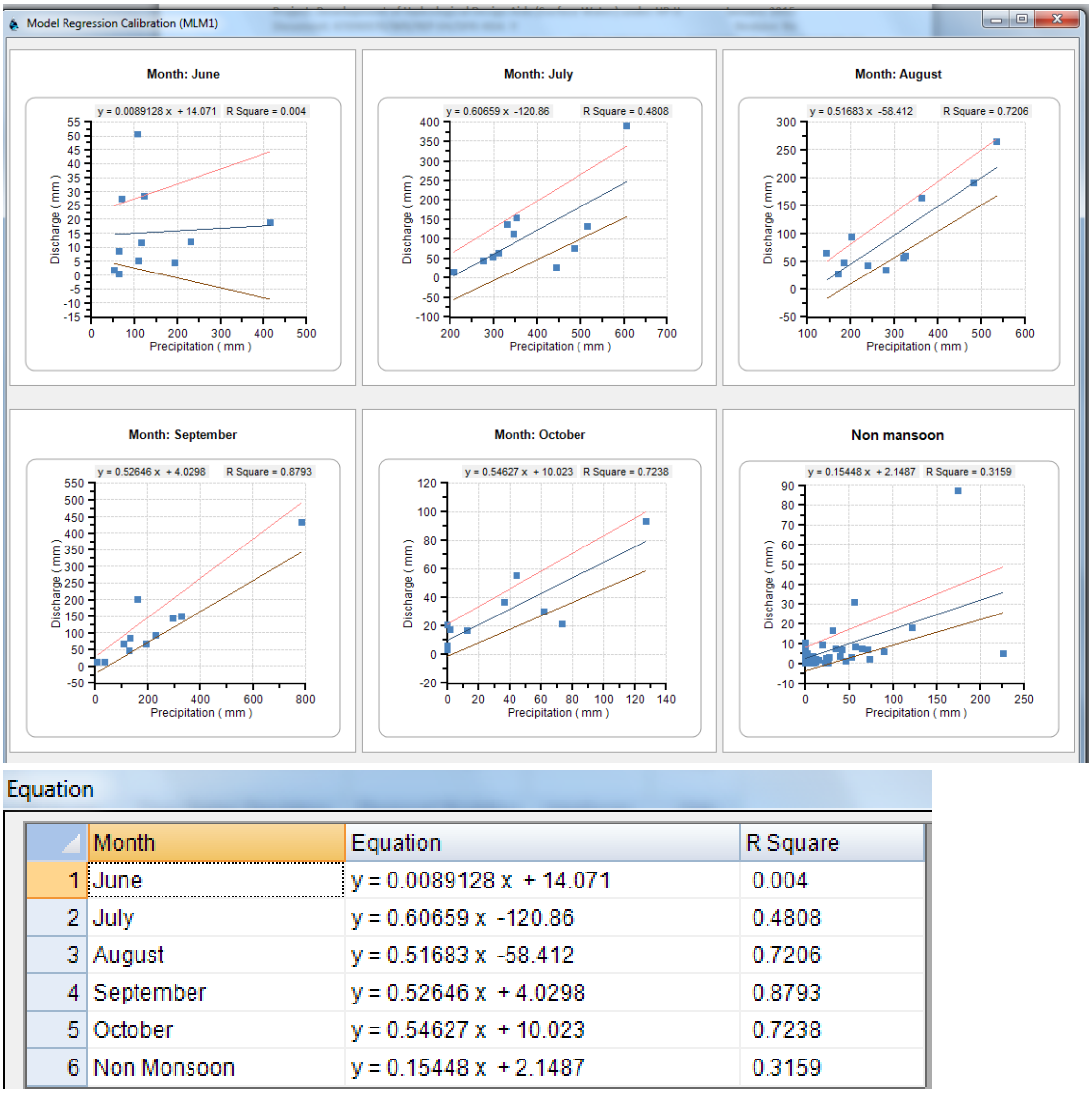
	Calibration Period	Validation Period
Nash Sutclif criterion	0.836	0.811
Coefficient of determination R2	0.836	0.849
Volume of Observed Flow (M cu m)	1184.828	917.521
Volume of Calculated Flow (M cu m)	1184.996	1145.768

Yearly

	Overall	Monsoon	Non Monsoon	Overall	Monsoon	Non Monsoon
Nash Sutclif criterion	0.724	0.703	0.796	0.39	0.299	-2.047
Coefficient of determination R2	0.798	0.774	0.838	0.733	0.696	0.003
Annual Average Observed Flow (mm)	398.932	365.912	33.019	308.93	278.198	30.731
Annual Average Calculated Flow (mm)	398.988	365.912	33.076	385.78	363.14	22.64

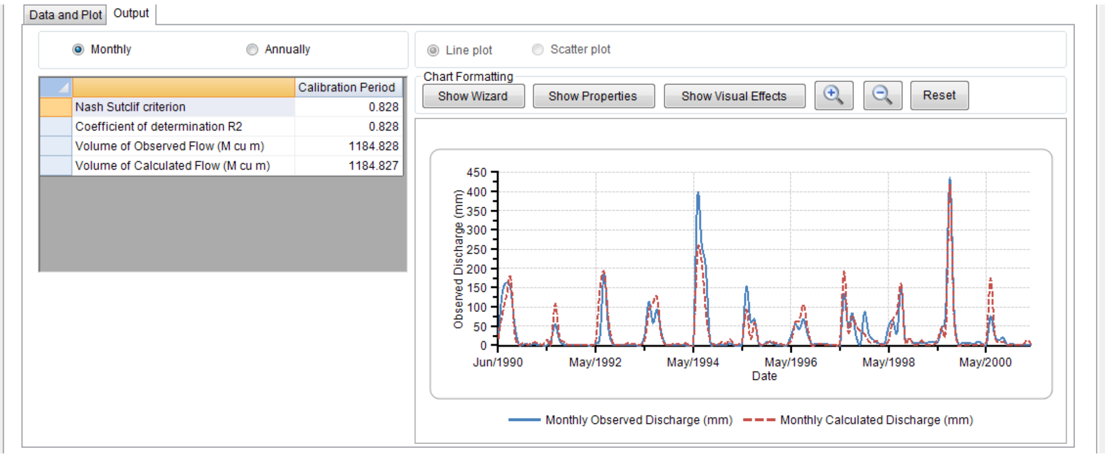
Figure 6.23 : Result Summary in MLM – REGM

v) Monthly Linear Regression Model for Monsoon season (MLM1)



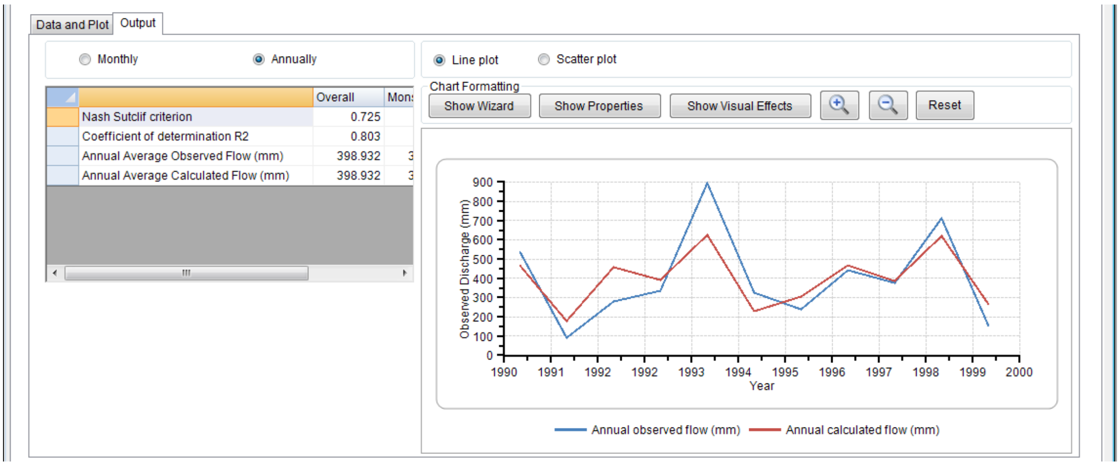
	Month	Equation	R Square
1	June	y = 0.0089128 x + 14.071	0.004
2	July	y = 0.60659 x -120.86	0.4808
3	August	y = 0.51683 x -58.412	0.7206
4	September	y = 0.52646 x + 4.0298	0.8793
5	October	y = 0.54627 x + 10.023	0.7238
6	Non Monsoon	y = 0.15448 x + 2.1487	0.3159

Figure 6.24 : Monthly Linear Equations derived in MLM1-REGM



● Monthly ○ Annually

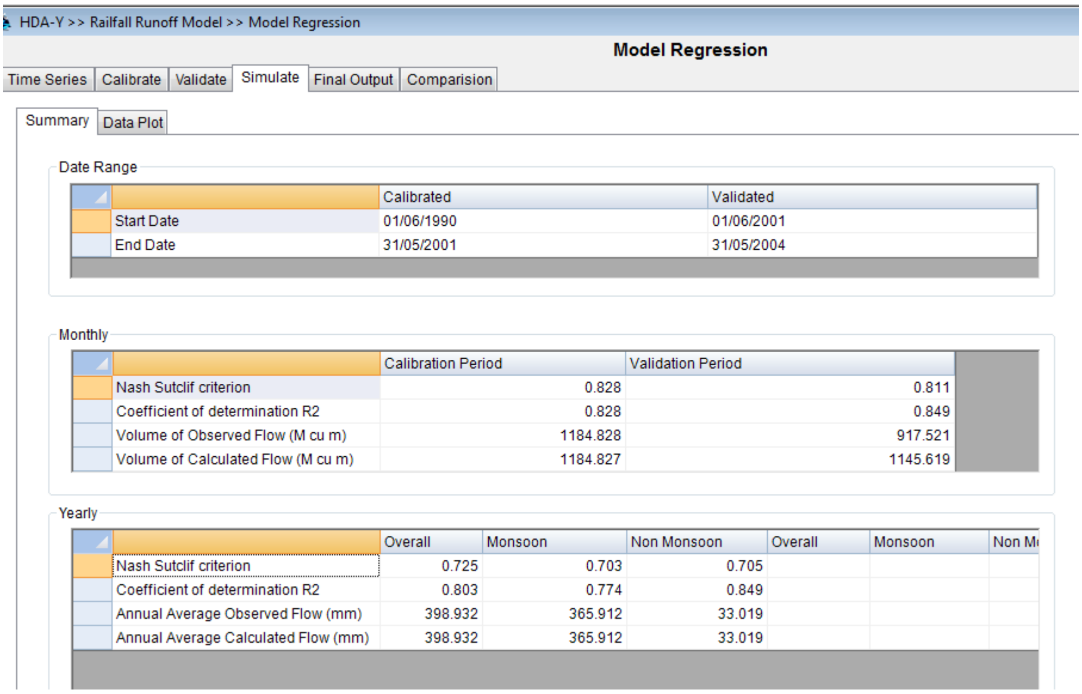
	Calibration Period
Nash Sutclif criterion	0.828
Coefficient of determination R2	0.828
Volume of Observed Flow (M cu m)	1184.828
Volume of Calculated Flow (M cu m)	1184.827



○ Monthly ● Annually

	Overall	Mon
Nash Sutclif criterion	0.725	
Coefficient of determination R2	0.803	
Annual Average Observed Flow (mm)	398.932	3
Annual Average Calculated Flow (mm)	398.932	3

Figure 6.25 : Calibration Output (Monthly and Annual) in MLM1-REGM



Model Regression

Date Range

	Calibrated	Validated
Start Date	01/06/1990	01/06/2001
End Date	31/05/2001	31/05/2004

Monthly

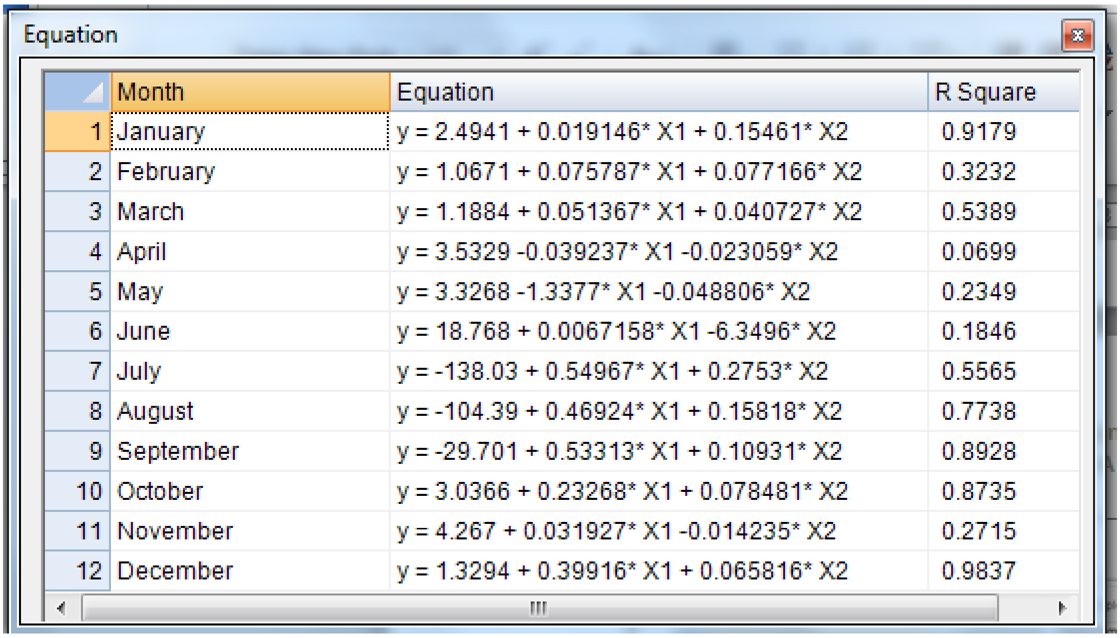
	Calibration Period	Validation Period
Nash Sutclif criterion	0.828	0.811
Coefficient of determination R2	0.828	0.849
Volume of Observed Flow (M cu m)	1184.828	917.521
Volume of Calculated Flow (M cu m)	1184.827	1145.619

Yearly

	Overall	Monsoon	Non Monsoon	Overall	Monsoon	Non Mo
Nash Sutclif criterion	0.725	0.703	0.705			
Coefficient of determination R2	0.803	0.774	0.849			
Annual Average Observed Flow (mm)	398.932	365.912	33.019			
Annual Average Calculated Flow (mm)	398.932	365.912	33.019			

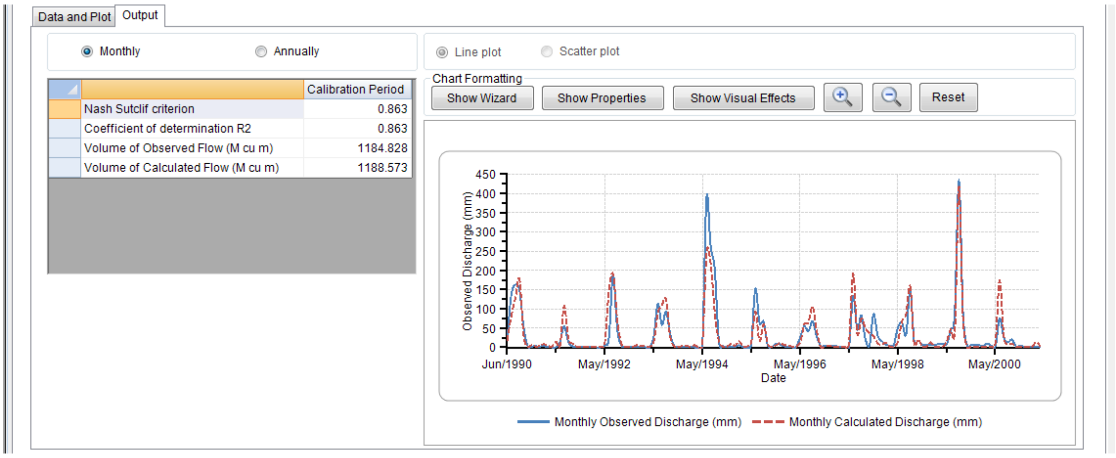
Figure 6.26 : Result Summary in MLM1 – REGM

vi) Multiple Regression Model Monsoon season (MRM)



	Month	Equation	R Square
1	January	y = 2.4941 + 0.019146* X1 + 0.15461* X2	0.9179
2	February	y = 1.0671 + 0.075787* X1 + 0.077166* X2	0.3232
3	March	y = 1.1884 + 0.051367* X1 + 0.040727* X2	0.5389
4	April	y = 3.5329 -0.039237* X1 -0.023059* X2	0.0699
5	May	y = 3.3268 -1.3377* X1 -0.048806* X2	0.2349
6	June	y = 18.768 + 0.0067158* X1 -6.3496* X2	0.1846
7	July	y = -138.03 + 0.54967* X1 + 0.2753* X2	0.5565
8	August	y = -104.39 + 0.46924* X1 + 0.15818* X2	0.7738
9	September	y = -29.701 + 0.53313* X1 + 0.10931* X2	0.8928
10	October	y = 3.0366 + 0.23268* X1 + 0.078481* X2	0.8735
11	November	y = 4.267 + 0.031927* X1 -0.014235* X2	0.2715
12	December	y = 1.3294 + 0.39916* X1 + 0.065816* X2	0.9837

Figure 6.27 : Monthly Multi-Linear Equations derived in MRM-REGM

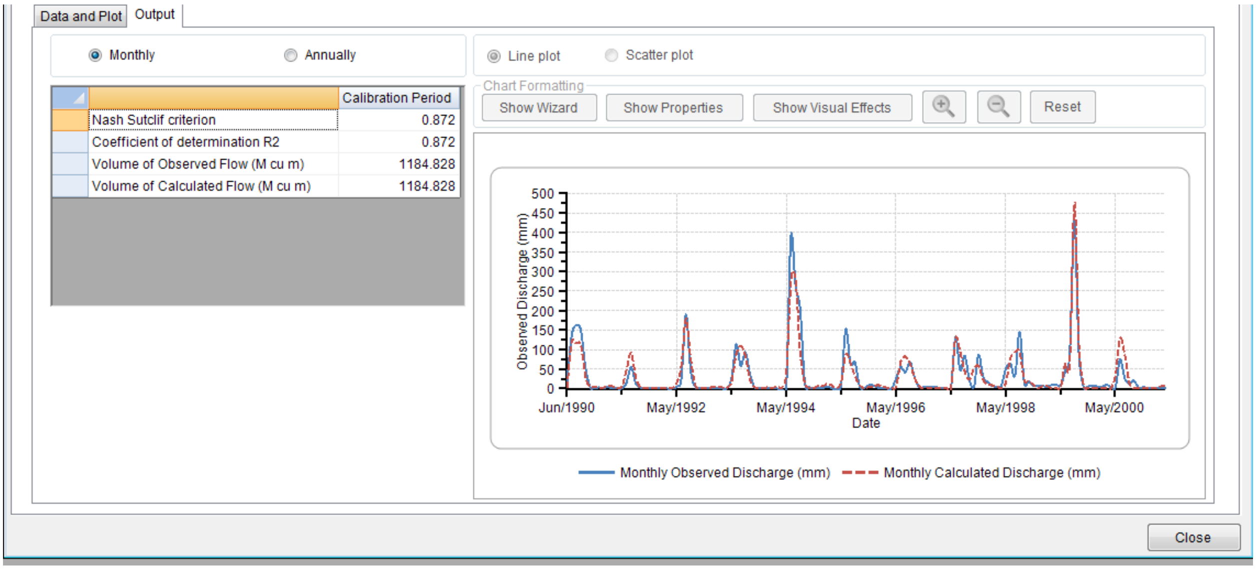


● Monthly ○ Annually

	Calibration Period
Nash Sutclif criterion	0.863
Coefficient of determination R2	0.863
Volume of Observed Flow (M cu m)	1184.828
Volume of Calculated Flow (M cu m)	1188.573

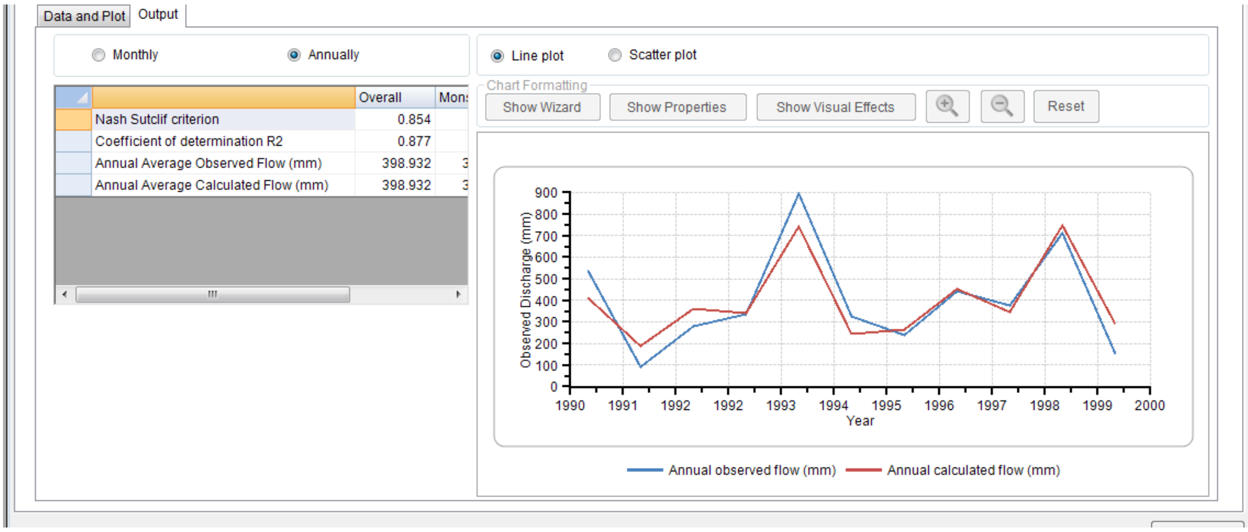
Figure 6.28 : Calibration Output (Monthly) in MRM-REGM

vii) Range Based Multiple Regression Model RRM1



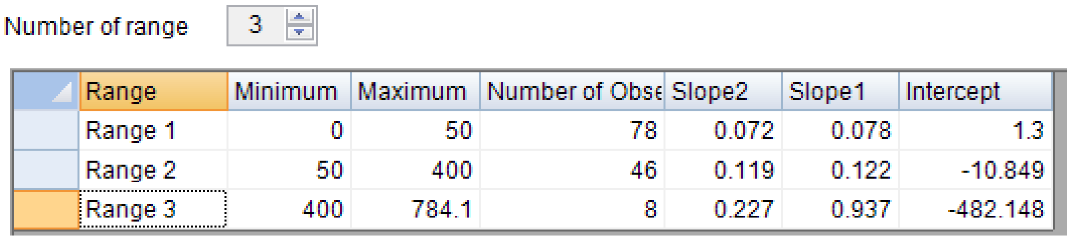
● Monthly ○ Annually

	Calibration Period
Nash Sutclif criterion	0.872
Coefficient of determination R2	0.872
Volume of Observed Flow (M cu m)	1184.828
Volume of Calculated Flow (M cu m)	1184.828



○ Monthly ● Annually

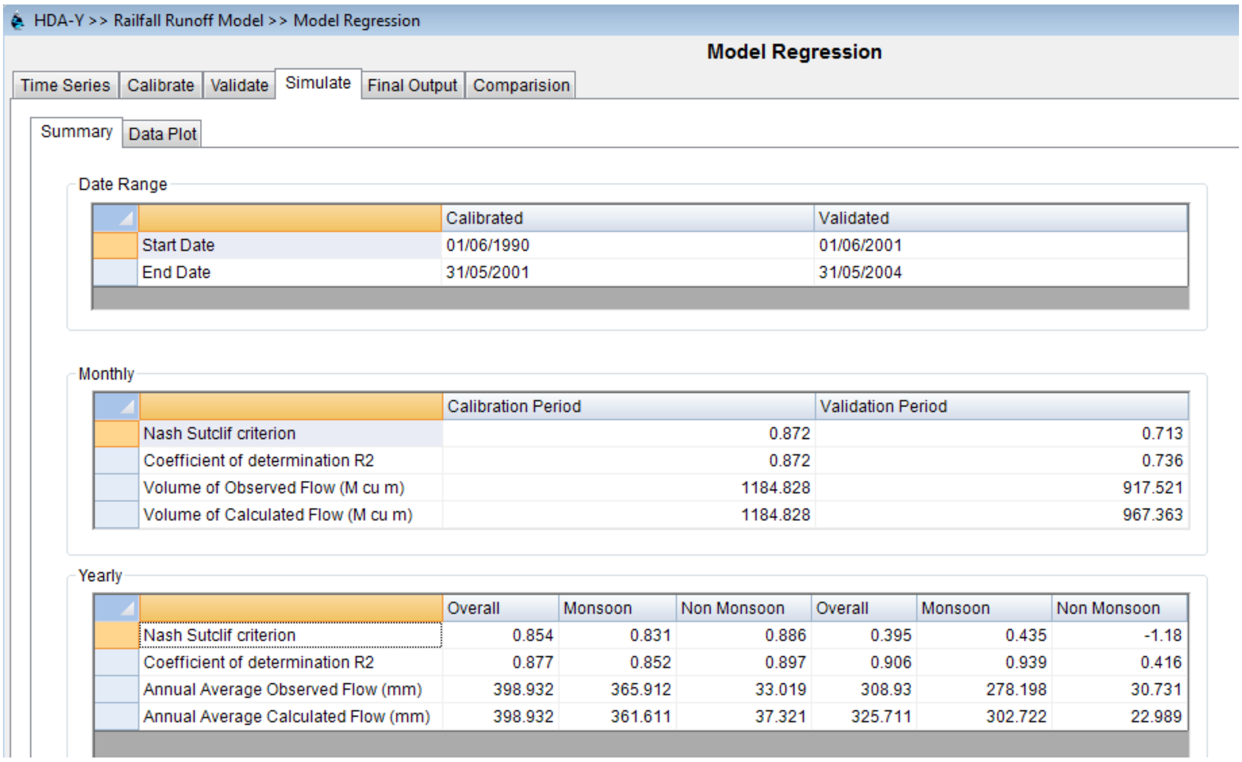
	Overall	Mon
Nash Sutclif criterion	0.854	
Coefficient of determination R2	0.877	
Annual Average Observed Flow (mm)	398.932	3
Annual Average Calculated Flow (mm)	398.932	3



Number of range 3

Range	Minimum	Maximum	Number of Obse	Slope2	Slope1	Intercept
Range 1	0	50	78	0.072	0.078	1.3
Range 2	50	400	46	0.119	0.122	-10.849
Range 3	400	784.1	8	0.227	0.937	-482.148

Figure 6.29 : Calibration Output (Monthly and Annual) in RRM1-REGM



Date Range

	Calibrated	Validated
Start Date	01/06/1990	01/06/2001
End Date	31/05/2001	31/05/2004

Monthly

	Calibration Period	Validation Period
Nash Sutclif criterion	0.872	0.713
Coefficient of determination R2	0.872	0.736
Volume of Observed Flow (M cu m)	1184.828	917.521
Volume of Calculated Flow (M cu m)	1184.828	967.363

Yearly

	Overall	Monsoon	Non Monsoon	Overall	Monsoon	Non Monsoon
Nash Sutclif criterion	0.854	0.831	0.886	0.395	0.435	-1.18
Coefficient of determination R2	0.877	0.852	0.897	0.906	0.939	0.416
Annual Average Observed Flow (mm)	398.932	365.912	33.019	308.93	278.198	30.731
Annual Average Calculated Flow (mm)	398.932	361.611	37.321	325.711	302.722	22.989

Figure 6.30 : Result Summary in RRM1 - REGM

Contents

7 DATA VALIDATION MODEL – FLOW MEASUREMENT 1
7.1 STAGE DISCHARGE RELATIONS 1
7.2 FITTING RATING CURVE 3
7.3 RATING CURVE WITH BACKWATER CORRECTION 5
7.4 RATING CURVE WITH UNSTEADY FLOW CORRECTION 7
7.5 UNCERTAINTY IN STAGE-DISCHARGE RELATIONSHIP 8
7.6 VALIDATION OF RATING CURVE 9
7.7 EXTRAPOLATION OF STAGE-DISCHARGE RELATIONSHIP 11
7.8 STAGE-DISCHARGE TRANSFORMATION 12
7.9 MEASURING STRUCTURES 13

List of Figures

Figure 7. 1 : Rating Curve : log-log plot for range identification 2
Figure 7.2 : Rating Curve for Backwater 6
Figure 7.3 : Dialogue Box for Backwater Rating Curve 7
Figure 7.4 : Coefficient of discharge C_e as a function of notch angle for fully contracted V-notch weirs.... 16
Figure 7.5 : C_e as a function of h_1/p_1 and p_1/B_1 for 90 degree V-notch sharp crested weir (From British Standard 3680 : Part 4 A and ISO/TC 113/GT 2 (France – 10) 1971).... 17
Figure 7.6 : WES Spillway section 17
Figure 7.7 : Section of Cylindrical Crested weir 19
Figure 7.8 : Rectangular Throated Flume dimensions.... 21
Figure 7.9 : Trapezoidal Throated Flume dimensions 22
Figure 7.10 : Triangular Flume dimensions 23
Figure 7.11 : Truncated Triangular Flume dimensions.... 24
Figure 7.12 : Circular Flume dimensions 25
Figure 7.13 : U Throated Flume dimensions 26
Figure 7.14 : Parshall Flume dimensions.... 27
Figure 7.15 : H-Flume dimensions.... 29

List of Tables

Table 7.1 : Backwater Rating Curve....6
Table 7.2 : Methods of Rating curve extrapolation 11
Table 7.3 : Value of Ce as a function of ratios bc / B1 and h1 / p1 (from Georgia Institute of Technology) 16
Table 7.4 : Parameters of the discharge equation of Parshall-flumes....27
Table 7.5 : Parameters of the discharge equation of H-flumes 29

7 DATA VALIDATION MODEL – FLOW MEASUREMENT

7.1 STAGE DISCHARGE RELATIONS

In order to model the streams and rivers for any hydro-meterogical analysis, a continuous stream flow data is needed. Whereas stage can be observed at regular time interval with a reasonable effort, continuous measurement of flow across a river section is not practical. The discharge rating curve transforms the continuous stage data to a continuous record of stream discharge. A rating table or curve is a relationship between stage and discharge at a cross section of a river which is established by making concurrent observations of stage and discharge over a period of time. A stage-discharge curve or rating curve is a graph of water surface elevation versus flow rate in a channel which is set up for a pre-selected cross-section referred to as 'control'. The control is governed by the geometry of the section and the shape of river downstream of a section. Two types of control can exist, Section control and Channel control.

The governing hydraulic equation for section control[1] in general and basic form are expressed as :

$$Q = C_D BH^{\beta}$$

Where,

Q = stream discharge (cumec)

H = Hydraulic head (m)

B = Cross-sectional width (m)

C_D = Coefficient of discharge and includes several parameters

β = Power law exponent dependant on the cross-sectional shape of the control section

Stage discharge relationship for channel controls with uniform flow are governed by the Manning or Chezy equation, as it applies to the reach of the controlling channel downstream from the gauge. The Mannings equation is given by :

$$Q = \frac{1}{n} A R^{0.67} S_f^{0.5}$$

Where,

A = Cross-sectional area in sq. m

R = Hydraulic Radius in m

S_f = friction slope in m

N = channel roughness

The Chezy equation is

$$Q = C A R^{0.5} S_f^{0.5}$$

Where,

C = Chezy form of roughness

In many situations, the cross-section is a combination of controls. During low discharge, the section is a section control or a structure control. During peak flow, the section becomes a channel control. The above equations are applicable for steady or quasi-steady flow.

7.1.1 Fitting of rating curves

When a number of discharge measurements for a particular cross-section are plotted on a logarithmic scale, it is useful to ascertain the type of relationship. Refer ***Figure 7.1***. The scatter in the plot gives a fairly good assessment of the type of stage-discharge relationship required for the cross section.

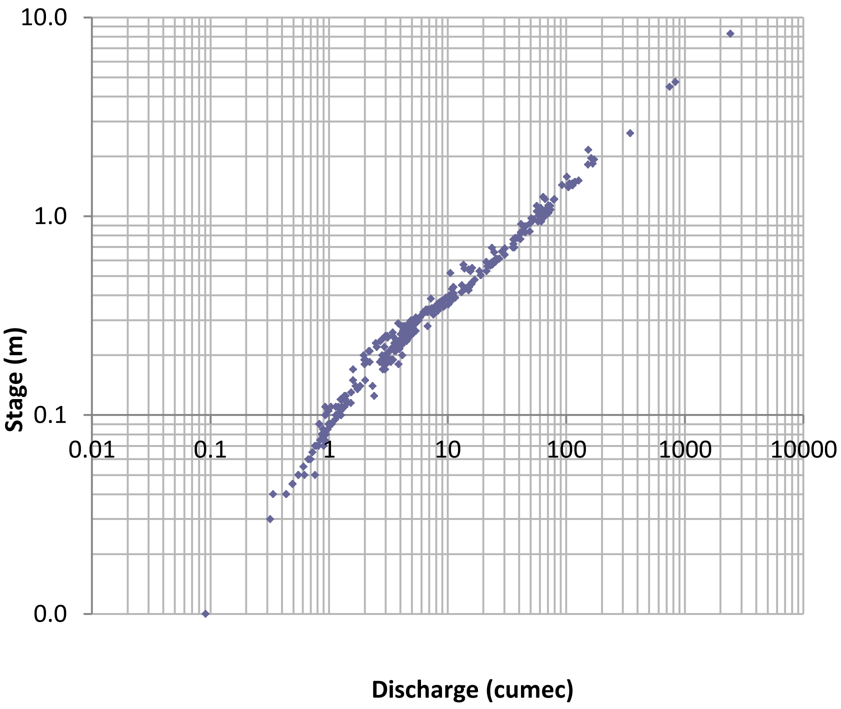


Figure 7. 1 : Rating Curve : log-log plot for range identification

If there is negligible scatter in the plotted points and it is possible to draw a smooth single valued curve through the plotted points, a simple rating curve is required. In some cases, due to varying natural conditions, it is obvious that the plotted points are not located on one smooth curve. A Compound rating curve is developed for which different equations for different ranges of water levels are required. However, if scatter is not negligible then it requires further probing to determine the cause of such higher scatter. There are three distinct possibilities:

- The station is affected by the variable backwater conditions arising due for example to tidal influences or to high flows in a tributary joining downstream. A Rating curve incorporating the backwater corrections are required to be established. An additional information on fall of stage with respect to an auxiliary stage gauging station is needed.
- The stage discharge rating is affected by variation in the local acceleration due to unsteady flow. Rate of change of stage with respect to time is additional information to be used in establishing the corrected Rating relation.

- The stage discharge rating is affected by scouring of the bed or changes in vegetation characteristics. A shifting bed results in a wide scatter of points on the graph. The changes are erratic and may be progressive or may fluctuate from scour in one event and deposition in another. A shift adjustment is made to account for these changes.

7.2 FITTING RATING CURVE

7.2.1 *Simple Rating Curve*

This is described by a three parameter power type equation described by :

$$Q = C_r\,(H\text{-}a)^{\beta}$$

Where, Q = stream discharge (cumec)

H = Gauge Elevation (m)

a = gauge reading corresponding to zero discharge / zero gauge level (m)

C_r and β are rating curve coefficients. (H-a) is the effective depth of water on the control. C_r is a scale factor which is numerically equal to the discharge when effective depth of water is equal to 1.

7.2.2 *Compound rating curve*

If flood plain carries flow over the full cross-section, the discharge consists of two parts – flow through the river and flow through the flood plain. Compound Channel is a channel having flood plain section to accommodate flood wave. The rating curve changes significantly as soon as the flood plain at level (H-a1) is flooded. The rating curve for this situation of a compound channel is determined by considering the flow through the floodplain portion separately.

$$Q = C_r\,(H\text{-}a)^{\beta} + C_f\,(H\text{-}a1)^{\beta 1}$$

Where, Q = stream discharge (cumec)

H = Gauge Elevation (m)

a = gauge reading corresponding to zero discharge / zero gauge level (m)

a1 = Flood Plain level (m)

C_r and β are rating curve coefficients for river section ; C_{r1} and β1 are rating curve coefficients for flood plain section.

7.2.3 *Steps for developing the Rating Curve in DVM-FM*

i) Determination of datum (a)

The datum (a) is defined as the water level corresponding to which, flow is zero. Optimisation procedure is used to fix the datum elevation. First trial value of ‘a’ is provided by the user. It is varied within a range of 2 m with the objective of minimizing the standard error. The datum value can be lower than the lowest of the observed reading or the level of deepest point opposite the channel controlled gauging station. This is an initial user defined value. The final ‘a’ value is derived by iteration under minimum standard error criterion in DVM.

ii) Identification of stage range for developing the rating curve / type of rating curve.

Rating curves usually have a break point, which is around the stage at which the river spreads out of its banks, or it could be at a lower stage if the river bed cross section changes dramatically. Above that stage, the river does not rise as fast, given that other conditions remain constant. This is illustrated by a change in slope in the rating curve. DVM facilitates the user to identify the segments for developing the Rating Curve. The 'h-a' and discharge data are plotted on a log-log scale as a scatter plot. The plot is inspected by the user for breaking points. The value of h at breaking point indicates a change in the nature of rating curve. Through user defined stage elevation, equation for each of the segments is then established. The simple scatter plot between concurrent observations of stage and discharge over a period of time covering the defined range of stages can be used to ascertain the type of stage discharge relationship.

DVM allows the user to select or exclude the water level values to be fitted and select and test the number of segments to be used. A rating curve is established between concurrent observations of stage and discharge over a period of time covering the defined range of stages. The type of rating curve is ascertained by plotting the observed stage and discharge data on a simple plot. The scatter of the plot will give the type of stage discharge relationship. If it is possible to draw a smooth curve through the plotted points and the scatter is little, a simple rating curve is fitted.

iii) Determination of rating curve coefficients

A least squares procedure is used to fit the rating equation and an error of fit statistic is calculated for the overall fit and for individual ranges.

The Error of estimate (S) is a measure of the square of difference of observations with respect to the calculated value given by :

$$S = [\frac{\sum^{1}(Q-Q_c)^2}{N-p}]^{0.5}$$

With first estimate of parameters by Least Square, the final equation is derived by optimisation considering minimum error as the objective function.

7.2.4 Input parameter

The inputs required to develop the rating curves are :

Paired Data - Stage Level (m) and corresponding discharge (cumec) field observed data

Zero gauge level = **'a** '(m).

Flood plain level= **'a1' (**m).

Range of stage levels for developing rating curve i.e. Lower range (m) and Upper range (m)

7.2.5 Limitations of Simple and Compound Rating Curve

To develop a rating curve, a series of streamflow measurements (current meter readings) are plotted versus the accompanying stage, and a smooth curve is drawn through the points. There can be significant scatter around this curve. Therefore, it is expressed that the discharge read from the rating curve is the most likely value, but it could be a little different from the measured value. Also, since rating curves are developed with few stage/discharge measurements, and measurements of high flows are rare, there can be significant errors in rating curves at high levels, especially around record level flows.

Stage discharge relation for unstable controls poses problems when segments of a stage-discharge relationship can change position occasionally.

Variable backwater caused mainly by downstream reservoirs, dams, dense vegetation, tides influence the flow at gauging-station control affect the stage-discharge relation.

When rivers are in flood, a complexity exists in defining the flood plain storage. The flow interactions between main channel and flood plain often results in flow pattern difficult to define at the gauging section.

When water surface slope changes either due to rapidly rising or rapidly falling water levels in a channel control reach causing hysteresis in the rating curve, adds to complexities.

Reference: Test Example 7.1

7.3 RATING CURVE WITH BACKWATER CORRECTION

At times it becomes essential to select the the gauging station with is subject to backwater effects such as regulated water courses, confluences, variable water of a downstream reservoir, downstream constriction with a variable capacity such as weed, river with return of overbank flow etc. The presence of backwater does not allow the use of unique simple rating curve. It causes variable energy slope at a given stage and is therefore, a function of stage and slope. This requires a stage to be measured continuously at both base gauge and auxiliary gauge set at the same datum located some distance downstream.

Constant/ Unit fall rating method has been provided in DVM which is recommended when backwater is always present.

This is used with the assumption that the relation between the discharge ratio and the fall ratio is given by

$$\frac{Q}{Q_n} = \sqrt{\frac{F}{F_n}}$$

Where,
Q = measured discharge
F = Measured fall
Q_n = Discharge from the rating curve corresponding to base gauge water level
F_n = the constant fall
In the unit fall method, F_n = 1.0 m. Equation becomes,
$Q_n = Q / \sqrt{F}$
The rating curve is developed by plotting the measured = Q / $\sqrt{F}$ values against the corresponding measured water level h from the base gauge. The rating curve is fitted to the plotted points.

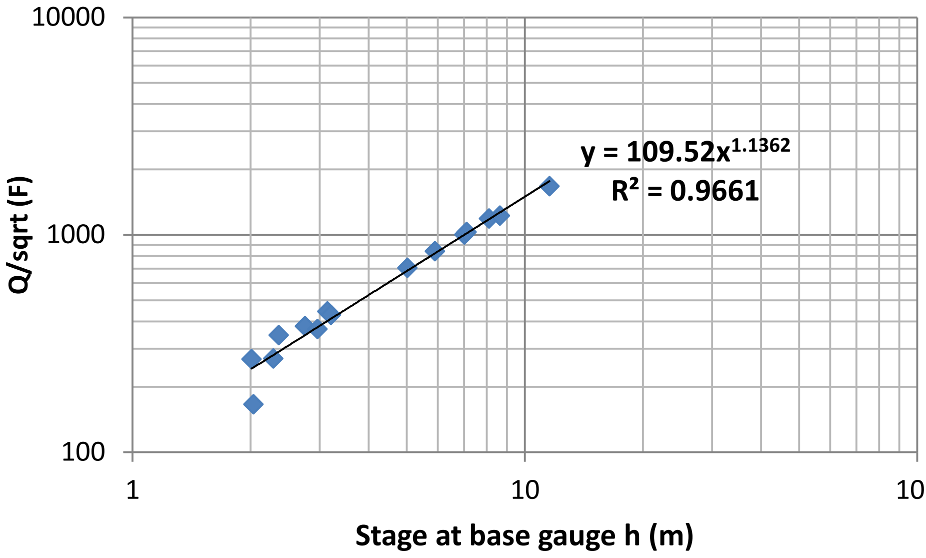


Figure 7.2 : Rating Curve for Backwater

The resulting rating curve is $Q_n = 109.52\ h^{1.1362}$

Table 7.1 shows an example of a unit fall rating for a site with high backwater from a power dam where backwater exists at all stages and at all time.

Table 7.1 : Backwater Rating Curve

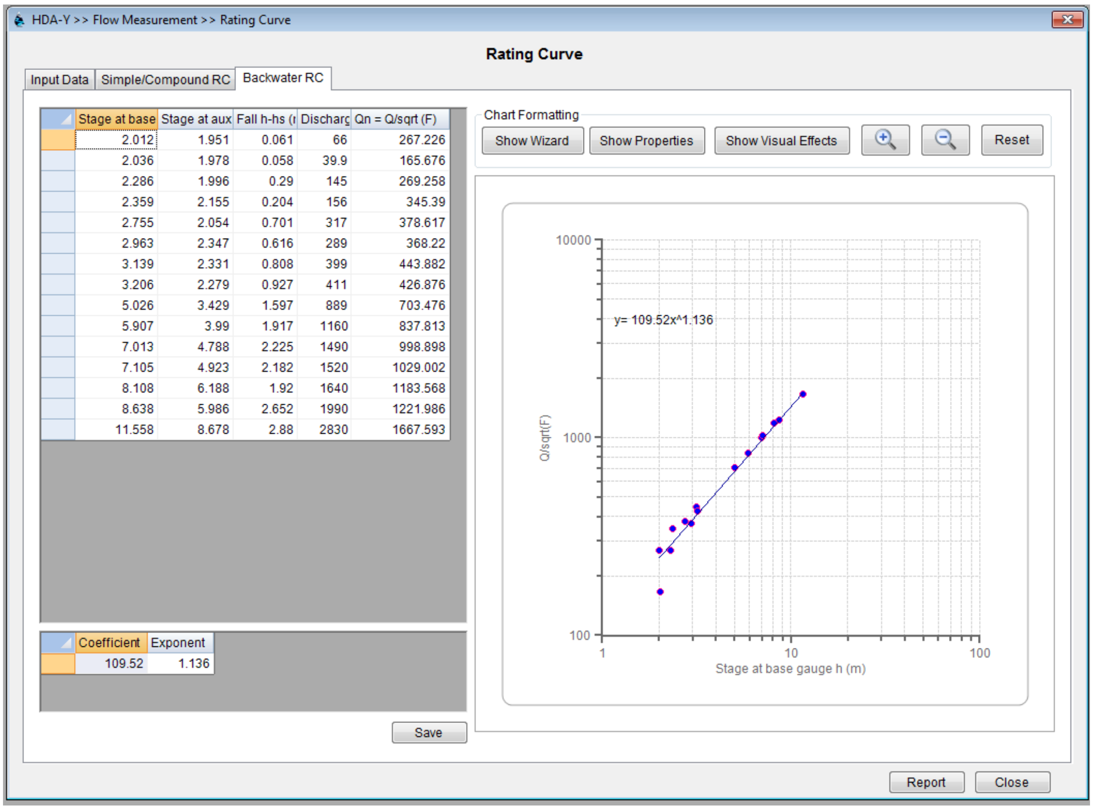
Measu-rement No.	Stage at base gauge h	Stage at auxiliary gauge h_s	Fall = $h-h_s$	Discharge Q	Q_n = Q/√ (F)	$Q_n = 109.4\ h^{1.137}$
	M	m	m	cumec	cumec	cumec
1	2.012	1.951	0.061	66	267.2	242.4
2	2.036	1.978	0.058	39.9	165.7	245.7
3	2.286	1.996	0.29	145	269.3	280.2
4	2.359	2.155	0.204	156	345.4	290.4
5	2.755	2.054	0.701	317	378.6	346.4
6	2.963	2.347	0.616	289	368.2	376.2
7	3.139	2.331	0.808	399	443.9	401.7
8	3.206	2.279	0.927	411	426.9	411.5
9	5.026	3.429	1.597	889	703.5	685.8
10	5.907	3.99	1.917	1160	837.8	824.0
11	7.013	4.788	2.225	1490	998.9	1001.4
12	7.105	4.923	2.182	1520	1029.0	1016.3
13	8.108	6.188	1.92	1640	1183.6	1180.9
14	8.638	5.986	2.652	1990	1222.0	1269.0
15	11.558	8.678	2.88	2830	1667.6	1.0

From this curve, the discharge is computed as :

For stage h = 2.5 m, Fall F = 0.44 m,

⇒ $Q_n = 109.4 * 2.5^{1.137} = 310.1$ cumec

⇒ $Q = 310.1 * \sqrt{0.44} = 206$ cumec



Stage at base	Stage at aux	Fall h-hs (r	Discharg	Qn = Q/sqrt (F)
2.012	1.951	0.061	66	267.226
2.036	1.978	0.058	39.9	165.676
2.286	1.996	0.29	145	269.258
2.359	2.155	0.204	156	345.39
2.755	2.054	0.701	317	378.617
2.963	2.347	0.616	289	368.22
3.139	2.331	0.808	399	443.882
3.206	2.279	0.927	411	426.876
5.026	3.429	1.597	889	703.476
5.907	3.99	1.917	1160	837.813
7.013	4.788	2.225	1490	998.898
7.105	4.923	2.182	1520	1029.002
8.108	6.188	1.92	1640	1183.568
8.638	5.986	2.652	1990	1221.986
11.558	8.678	2.88	2830	1667.593

Coefficient	Exponent
109.52	1.136

Figure 7.3 : Dialogue Box for Backwater Rating Curve

7.4 RATING CURVE WITH UNSTEADY FLOW CORRECTION

The stage-discharge relationship for a gauging station gives the value of steady flow discharge for a given stage. For rivers where dynamic flow conditions are characterised by passing flood wave, most pronounced in mildly sloped rivers, the instantaneous value of discharge determined from steady state rating curve can be significantly different from the true discharge called Hysteresis.

Omitting the acceleration terms in the dynamic flow equation, the relation between the steady and unsteady discharge is expressed as :

$$Q_m = Q_r \sqrt{1 + \frac{1}{C\,S_0}\frac{dh}{dt}}$$

Where,

Q_m = measured discharge

Q_r = estimated steady state discharge from the rating curve

C = wave velocity (celerity)

S_0 = energy slope for steady state flow dh/dt = rate of change of stage derived from the difference in gauge height at the beginning and end of a gauging (= for rising ; - for falling)

Q_r is the steady state discharge and is obtained by establishing a rating curve as a median curve through the uncorrected stage discharge observations or using those observations for which the rate of change of stage is negligible.

Reartranging the above equations gives :

$$\frac{1}{C\,S_0} = \frac{(Qm/Qr)^2 - 1}{dh/dt}$$

The quantity (dh/dt) is obtained by knowing the stage at the beginning and end of the stage discharge observation or from the continuous stage record. Thus the value of factor ($1/cS_0$) can be obtained by the above relationship for every observed stage. The factor ($1/cS_0$) varies with stage and a parabola is fitted to its estimated values and stage as :

$$\frac{1}{C\,S_0} = a + b\,h + ch^2$$

A minimum stage h_{min} is specified beyond which the above relation is valid. A maximum value of factor ($1/cS_0$) is also specified so that acceptably high value can be avoided from taking part in the fitting of the parabola.

HDA does not include unsteady flow correction method as the supporting data is rarely observed in practical application scenario.

7.5 UNCERTAINTY IN STAGE-DISCHARGE RELATIONSHIP

The uncertainty in stage-discharge is derived by statistical analysis of the scatter of the measurements around the rating curve. It is similar in concept to the standard error derived in regression analysis. However, unlike regression curve fitting, stage discharge curve are derived commonly using hydraulic reasoning as well as mathematical fitting. Therefore, uncertainty is used in preference to the more restrictively defined statistical standard error. (***Reference : ISO 1100-2:2010(E) pp. 71***)

The uncertainty of a rating curve relationship is characterized by the standard error of estimate S, calculated from the dispersion of the stage-discharge data around the rating curve given by :

$$S = [\frac{\sum^{1} (\ln Q - \ln Q_c)^2}{N - p}]^{0.5}$$

Where,

Q = Measured discharge

Q_c = Corresponding discharge calculated from rating curve equation

N = Number of gaugings in rating curve segment

p = Number of rating curve parameters estimated from N gaugings

The uncertainty of the discharge value is computed from the rating curve for any particular value of the stage is given by u(Qc(h)).

The standard uncertainty is the value ln Qc at gauge height h. This is given by :

$$\text{u (ln Qc (h)) =S} \left\{ \frac{1}{N} + \frac{\left[\ln(h-e) - \overline{\ln(h-e\ \ )}\right]^2}{\sum\left[\ln(h-e) - \overline{\ln(h-e\ \ )}\right]^2} \right\}^{0.5}$$

An expanded uncertainty is derived by multiplying the standard uncertainty by a coverage factor k is given by :

U (ln Q_c (h)) = k u (ln Q_c (h))

Where, k is the coverage factor which provides a specified level of confidence. If the distribution is assumed to be approximately normal (Gaussian), the coverage factors k of 1, 2 and 3 correspond to levels of confidence of about 68%, 95% and 99.8% respectively.

The expanded uncertainty defines the uncertainty interval around the computed value lnQc(h) which is expected to encompass the specified fraction of the distribution of values that could reasonably be attributed to the discharge. The interval is thus expressed as

ln Q_c (h) $\pm$ U ln Q_c (h) . The corresponding uncertainty interval for discharges is found by taking anti-logarithm.

(*Note ; The 'expanded uncertainty' and 'level of confidence' are not to be confused with the statistical quantities 'confidence interval' and 'confidence level'.*)

The expanded uncertainty U(lnQc(h) with coverage factor k=2 and the corresponding uncertainty limits on lnQc(h) shouls be calculated for each observation of (h-e) related to the corresponding gauging. The limits will therefore take the form of curved lines on each side of the stage-discharge relationship and exhibit a minimum at the mean value of ln(h - e)

7.6 VALIDATION OF RATING CURVE

Validation of Rating Curve is performed to assess the reliability of the Rating Curve. Graphical and Numerical Tests are conducted to show whether the gaugings fit the current relationship equally and without bias over the full range of flow and over the full time period to which it has been applied.

Under the DVM, Graphical Validation Test, stage/discharge plot with new gaugings has been provided. In this method, new check gaugings are plotted on the rating curve with 95% confidence limits. It needs to be checked if gauging; i.e. inside the confidence limits and whether they can be judged acceptable with respect to deviation. Considering the standard error at 5% significance level, it is expected that 19 out of 20 observations will lie inside the limits.

Under Numerical Validation Tests, three procedures have been included :

7.6.1 *Student's 'T' Test to check gaugings*

In this test, the 't' statistic is calculated as the ratio of the mean deviation and the standard error of the difference of the means as :

T = d_1/ S

Where, d_1 = mean deviation of the new gaugings used to derive the existing rating

S = standard error of the difference of the means expressed as $S = a\sqrt{\frac{N+N_1}{N\,N_1}}$

N = Number of gaugings used to derive the existing rating
N_1 = Number of new gaugings

$$a = \sqrt{\frac{\sum d^2 + \sum (d_1 - \overline{d_1})^2}{N+N_1-2}}$$

$\sum d^2$ = Sum of the square of the percent differences for the old gaugings from the existing rating.

If the computed value of 't' = $\frac{\overline{d}}{S}$ is greater than the critical value of 't' for (N + N1 -2) degrees of freedom at 95% probability level, new rating needs to be developed.

7.6.2 *Test for absence from bias in signs*

A well balanced rating curve must ideally have even distribution of number of positive and negative deviations of the observed values from the Rating curve. The test is performed by counting observed points falling on either side of the curve. If Qi is the observed value and Qc the estimated value, the expression Qi and Qc should have an equal chance of being positive or negative. The sequence of the differences is considered according to the Binomial law (p+q) N .

Where,

N = Number of observations

p , q = probabilities of occurrence of positive and negative values \

Np = Expected number of positive signs

The 't' statistic is given by :

$$t = \frac{|N_1 - N_p| - 0.5}{\sqrt{Npq}}$$

The resulting value is compared with the critical value of 't' statistic at 5% significance level degree of freedom equal to the total number of stage discharge data. If critical 't' > t, it can be considered that the data does not show any bias with respect to sign of the deviations between observed and computed discharge.

7.6.3 *Test for absence from bias in values*

The test checks if a particular stage discharge curve yields significant underestimates or overestimates as compared to the actual observations, on which it is based. The percent difference is worked out as :

P = 100 (Qi – Qc) / Qc

If there are N observations and P1, P2, ……., PN are the percentage differences and Pav is the average differences, the standard error of Pav is given by :

t = (Pav – 0) / Se

If the critical value of 't' statistic for 5% significance level and N degrees of freedom is greater than the value computed above, then it may be considered that there is no statistical bias in the observed values with respect to their magnitudes as compared to that obtained by the rating curve.

7.7 EXTRAPOLATION OF STAGE-DISCHARGE RELATIONSHIP

In accordance with the ISO 1100-2:2010(E), the stage discharge relationship should not be applied outside the range of discharge measurements upon which it is based. However, if estimates are necessary beyond the range, the, channel and control should be examined carefully for some distance downstream and upstream of the gauge before making an extrapolation. It should be checked for flow obstructions, contractions, expansions, debris, channel shape changes. In presence of these channel conditions, extrapolation is not proposed.

The methods that can be applied for extrapolation are :

1. Logarithmic plotting
2. Mannings or Chezy equation
3. Velocity area method
4. One dimensional flow model

The above procedure are discussed in ***Table 7.2.***

Table 7.2 : Methods of Rating curve extrapolation

	Methods	Description	Limitations
1	Logarithmic plotting	If the control shape does not change significantly and the channel roughness remains fairly constant	Suited to channel control conditions for medium and high flow. Should not be used to extrapolate more than 1.5 times the highest measured discharge.
2	Manning's or Chezy's equation	Special care needed if shape of the cross-section changes appreciably because friction slope can also change significantly.	Friction slope of bankful and within banks may be significantly different.
3	Velocity Area method	Dependant on stage-velocity relationship which is accurate in the range where discharge measurements are available but	Accuracy is questionable in the range above highest measurements.
4	One-dimensional flow model	Have limitations on hydraulic equations when cross-section shape	Have limitations on hydraulic equations when cross-section shape changes.

	Methods	Description	Limitations
		changes.	

In view of limitations of various procedures and ease of application, extrapolation by logarithmic plotting is provided under DVM, which facilitates straight line extrapolation. For low flows when section control exists, arithmetic plotting can be done so that the rating curve can be extrapolated to zero discharge.

7.8 STAGE-DISCHARGE TRANSFORMATION

Water level series can be transformed in discharge series by use of stage-discharge relation in one of the following forms:

1. Single channel rating curve
2. Compound channel rating curve
3. Rating curve with backwater correction
4. User structure equation
5. Measuring structure relations

For a particular transformation, the combination of water level and discharge series, cross-sections and structure parameters required to transform stages into discharges is stored in the database to facilitate the transformation at subsequent occasions.

7.8.1 Single channel rating curve

When unsteady flow and backwater effects are negligible, the stage discharge data are fitted by a single channel relationship, valid for a given time period and water level range. For a single channel rating curve, the stage-discharge transformation reads :

$$Q_t = c_{1,t}(h_t + a_{1,t})^{b_{1,i}}$$

Where,

Q_t = discharge at time t (m^3/s)

h_t = measured water level at time t (m)

i = index for water level interval for which the parameters are valid

a_1, b_1, c_1 are parameters of the power equation.

7.8.2 Compound Channel rating curve

The compound channel rating curve is used to avoid large values of the parameter b and low values of c-parameter in the power equation at levels where the river begins to spill over from its channel to the floodplain.

When a compound channel rating has been applied, the discharge for the flood plain interval will be computed by adding the discharge computed for the river section upto the maximum flood plain level using the parameters for the one but last interval, and the discharge computed for the flood plain section for the last interval :

$$Q = Q_r + Q_{fp}$$

Where,

Q_r = discharge flowing through the main river section upto the maximum water level

Q_{fp} = discharge flowing through the flood plain section

7.8.3 *Rating curve with Backwater correction*

Where the station is affected by backwater and the rating curve with backwater correction has been established, the stage-discharge transformation by Unit Fall Rating method is carried out using following equation :

$$Q = Q_n\sqrt{F}$$

Where,

Q_n = Reference discharge computed using the established rating curve

F = Reference fall in the equation, available as parameters of the established rating curve

$F_t = h_{1t} - h_{2t}$ = measured fall between the stages at the station under consideration (h_{1t}) and the reference station (h_{2t}). The stages used for calculating the fall have to be synchronized in time.

7.9 MEASURING STRUCTURES

Flow measurement structures are applied in several fields. For irrigation and drainage projects, all types of weirs, flumes and gates are applied.

Broadly, the functions of irrigation structure are tabulated below :

Structures	**Function**			
	Level control	Flow regulation	Flow measurement	Flow removal
Headworks	M	M	M	
Cross-regulators and check structures (Full supply)	M		A	
Cross-regulators and check structures (less than Full supply)	M	M	M	
Tail and Emergency structure	M		O	
Structures in secondary and tertiary canal	M	M	M	
Small farm intakes	M		M	
Division structures	M	M	M	
Drop structures	M		O	

M = Main function, O = Additional function

(Reference ; Hydrometry : W. Boiten)

The measurement structures considered for flow measurement are :

i) Broad Crested weir

ii) Sharp Crested weir

iii) Short crested weir
  (a) WES Spillway
  (b) Cylindrical crested weir
iv) Flumes
  (a) Rectangular throated flume
  (b) Trapezoidal throated flume
  (c) Rectangular/Triangular/Trapezoidal flume
  (d) Truncated Triangular flume
  (e) Circular flume
  (f) U-throated flume
  (g) Parshall flume
  (h) H-flumes
v) Gates
  (a) Free flow
  (b) Submerged flow

7.9.1 Broad crested weir

A broad-crested weir is an overflow structure with a horizontal crest above which the deviation from a hydrostatic pressure distribution because of centripetal acceleration may be neglected. In other words, the streamlines are practically straight and parallel. To obtain this situation the length of the weir crest in the direction of flow (L) should be related to the total energy head over the weir crest as 0.08 <= H1/L <= 0.50. H1/L >= 0.08 because otherwise the energy losses above the weir crest cannot be neglected, and undulations may occur on the crest. H1/L <= 0.50, so that only slight curvature of streamlines occurs above the crest and a hydrostatic pressure distribution may be assumed. The general equation for calculating discharges over a broad crested weir is:

$$Q= A_c[\ 2g\ (H_1 - y_c)]^{\ 0.5}$$

The symbols used are explained as follows :

- h_r = reference level
- Q= discharge
- g = acceleration due to gravity g = 9.81 m/s^2
- P = height of weir
- L = length of weir
- b = crest width of weir
- h_1 = upstream water level (measured head)
- α = bottom angle V shape
- H_1 = upstream energy level
- H_2 = downstream energy level

For Rectangular control section, the head discharge equation for free flow is given by :

$Q = C_g \cdot C_d \cdot b \cdot C_v \cdot h_1^{3/2}$

$C_g = (2/3)^{3/2} \sqrt{g}$

C_d = Coefficient of Discharge derived based on ISO 4374 as a function of h1/ L and b/L depending on the roughness of the crest (after : Boiten, 1987)

C_v = Characteristic discharge coefficient expressed as a function of area ratio $C_d A/A_1$ where A = imaginary wetted area at the control section if it is assumed that the water depth y = h1 ; A_1 is the wetted area at the head measurement station.

For a **Parabolic section** with a focus distance f,

$Q = C_g \cdot C_d \cdot C_v \cdot h_1^{2}$

$C_g = (3/4)1^{/2} \sqrt{fg}$

For a **V shaped control section** with α bottom angle ,

$Q = C_g \cdot C_d \cdot b \cdot C_v \cdot h_1^{5/2}$

$C_g = (4/5)^{5/2} \sqrt{g}/2 \tan(\alpha/2)$

Reference : Test Example 7.2

7.9.2 *Sharp crested weir*

'Sharp crested' or 'thin plate' weirs are those overflow structures whose length of crest in the direction of flow is equal to or less than 2 mm. The symbols used in defining head-discharge equation in free flow are explained as follows :

hr = reference level

Q= discharge

g = acceleration due to gravity g = 9.81 m/s2

B = width of the approach channel

b = crest width of weir

p = height of crest

h1 = upstream water level (measured head)

α = bottom angle V shape

A rectangular notch symmetrically located is a vertically thin plate which is placed perpendicular to the sides and bottom of a straight channel, defined as a rectangular sharp crested weir . The basic equation for a rectangular sharp crested weir is given by:

$Q = C_e \cdot (2/3) \sqrt{2g} \cdot b \cdot h_1^{1.5}$

C_e is the effective discharge coefficient (refer ***Table 7.3***) which is a function of b/**B** and h_1/p.

Table 7.3 : Value of C_e as a function of ratios b_c / B_1 and h_1 / p_1 (from Georgia Institute of Technology)

b_c / B_1	C_e	b_c / B_1	C_e
1.0	$0.602 + 0.075\ h_1 / p_1$	0.5	$0.592 + 0.011\ h_1 / p_1$
0.9	$0.599 + 0.064\ h_1 / p_1$	0.4	$0.591 + 0.0058\ h_1 / p_1$
0.8	$0.597 + 0.045\ h_1 / p_1$	0.3	$0.59 + 0.002\ h_1 / p_1$
0.7	$0.595 + 0.03\ h_1 / p_1$	0.2	$0.589 - 0.0018\ h_1 / p_1$
0.6	$0.593 + 0.018\ h_1 / p_1$	0.1	$0.588 - 0.0021\ h_1 / p_1$
		0.	$0.587 - 0.0023\ h_1 / p_1$

The V-shaped notch of a sharp crested weir frequently referred as 'Thomson Weir' is a vertical thin plate placed perpendicular to the sides and bottom of a straight channel. It is one of the most precise discharge measuring device suitable for a wide range of flow. The basic equation for a triangular V-shaped sharp crested weir

$$Q = C_e\ .\ (8/15)\ \sqrt{2g}\ .\ \tan(\alpha/2).\ h_1^{\ 2.5}$$

$$C_e = f(\ h1/p1,\ p1/B1,\ \alpha\ )$$

If the ratio $h1/p1 \leq 0.4$ and $h1/B1 \leq 0.2$, the V-notch weir is fully contracted and the C_e become a function of only the notch angle α (Refer ***Figure 7.4***). If the contraction of the nappe is not fully developed, the effective discharge coefficient can be read from ***Figure7.5***

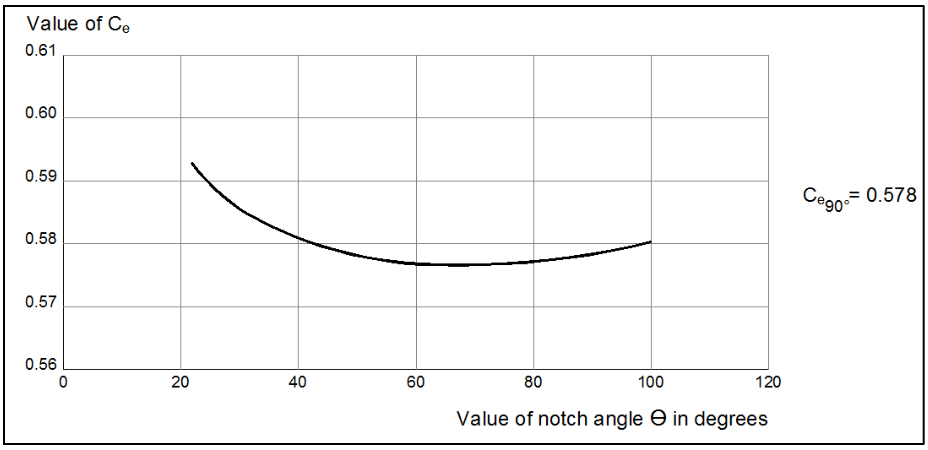
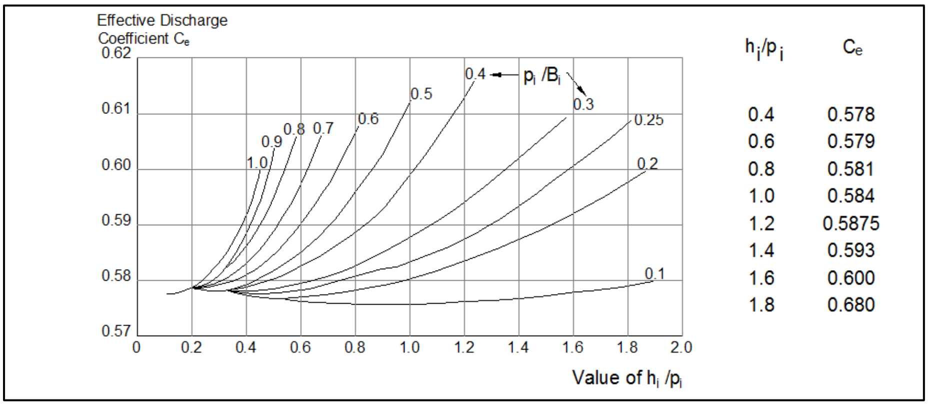


Figure 7.4 : Coefficient of discharge C_e as a function of notch angle for fully contracted V-notch weirs



h_i/p_i	C_e
0.4	0.578
0.6	0.579
0.8	0.581
1.0	0.584
1.2	0.5875
1.4	0.593
1.6	0.600
1.8	0.680

Figure 7.5 : C_e as a function of h_1/p_1 and p_1/B_1 for 90 degree V-notch sharp crested weir (From British Standard 3680 : Part 4 A and ISO/TC 113/GT 2 (France – 10) 1971)

Reference : Test Example 7.3 and 7.4

7.9.3 Short Crested Weir

In a short-crested weir, the curvature of the streamline above the crest cannot be neglected. The same measuring structure can act as a broad-crested weir for low heads (H1/L < 0.5) while with an increase of head, the influence of streamline curvature becomes significant and the structure acts as a short-crested weir. Due to the pressure and velocity distributions above the weir crest, the discharge coefficient (Cd) of a short-crested weir is higher than that of a broad-crested weir.

7.9.3.1 WES Spillway

WES Spillway is shaped according to the lower nappe surface of an aerated sharp-crested weir and the triangular profile weir whose control section is situated above a separation bubble downstream of a sharp weir crest.

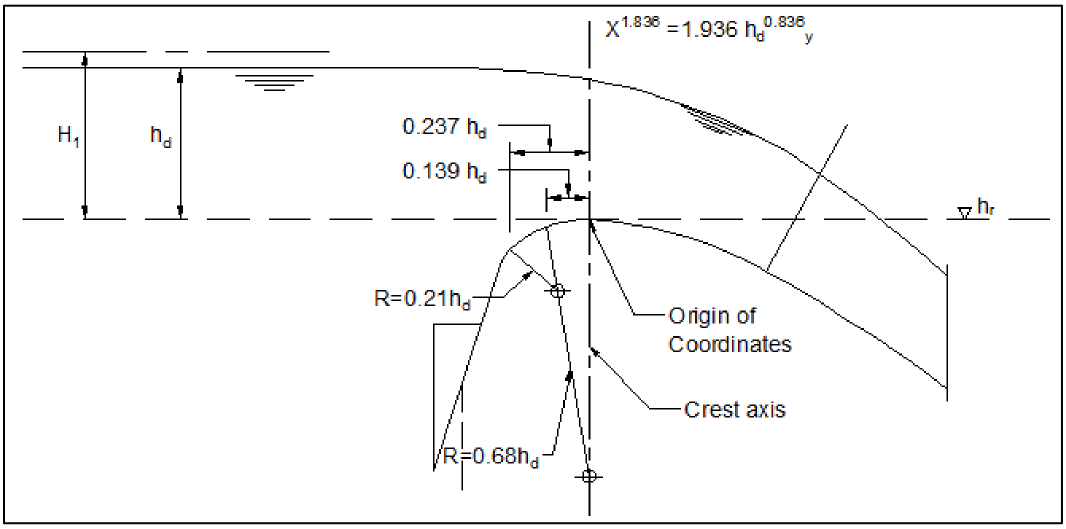


Figure 7.6 : WES Spillway section

Referring to ***Figure 7.6,*** the dimensions are :

hr = Reference level

P = height of spillway

b = width of spillway

x = slope parameter

h1 = upstream water level

H1 = upstream energy head

H2 = downstream energy level

$Q = C_g \, Ce \, b \, H_1{}^{3/2}$

$C_g = (2/3)^{3/2} \sqrt{g}$

$C_e = C_0 \, C_1 . \, C_2$

$C_0 = 1.3$

$C_1 = 0.693 + 0.516\,(H_1/h_1) - 0.438\,(H_1/h_1)^2 + 0.089\,(H_1/h_1)^3$ $P/h_1 \leq 0.2$

$C_1 = 0.692 + 0.521\,(H_1/h_1) - 0.311\,(H_1/h_1)^2 + 0.063\,(H_1/h_1)^3$ $P/h_1 = 0.33$

$C_1 = 0.6907 + 0.544\,(H_1/h_1) - 0.313\,(H_1/h_1)^2 + 0.056\,(H_1/h_1)^3$ $P/h_1 = 0.67$

$C_1 = 0.6906 + 0.544\,(H_1/h_1) - 0.309\,(H_1/h_1)^2 + 0.063\,(H_1/h_1)^3$ $P/h_1 = 1.00$

$C_1 = 0.6896 + 0.553\,(H_1/h_1) - 0.307\,(H_1/h_1)^2 + 0.061\,(H_1/h_1)^3$ $P/h_1 \geq 1.33$

For values of P/h_1 between 0.2 and 0.33, interpolation between the above formula is applied.

$C_2 = 1.00$ for $x = 0$

$C_2 = 1.012 - 0.0136\,(P/H_1) + 0.0038\,(P/H_1)^2$ for $x = 1$

$C_2 = 1.033 - 0.0379\,(P/H_1) + 0.0139\,(P/H_1)^2$ for $x = 2$

$C_2 = 1.050 - 0.0861\,(P/H_1) + 0.0333\,(P/H_1)^2$ for $x = 3$

The modular limit $H_2/H_1 = 0.3$. If this value is exceeded, the discharge is reduced by a factor f :

$f = 1.097 - 0.6796\,(H_2/H_1) + 1.438\,(H_2/H_1)^2 - 1.159\,(H_2/H_1)^3$ for $0.3 < H_2/H_1 \leq 0.8$

$f = 20.327 - 78.274\,(H_2/H_1) + 105.57\,(H_2/H_1)^2 - 47.63\,(H_2/H_1)^3$ for $H_2/H_1 > 0.8$

Reference : Test Example 7.5

7.9.3.2 Cylindrical Crested Weir

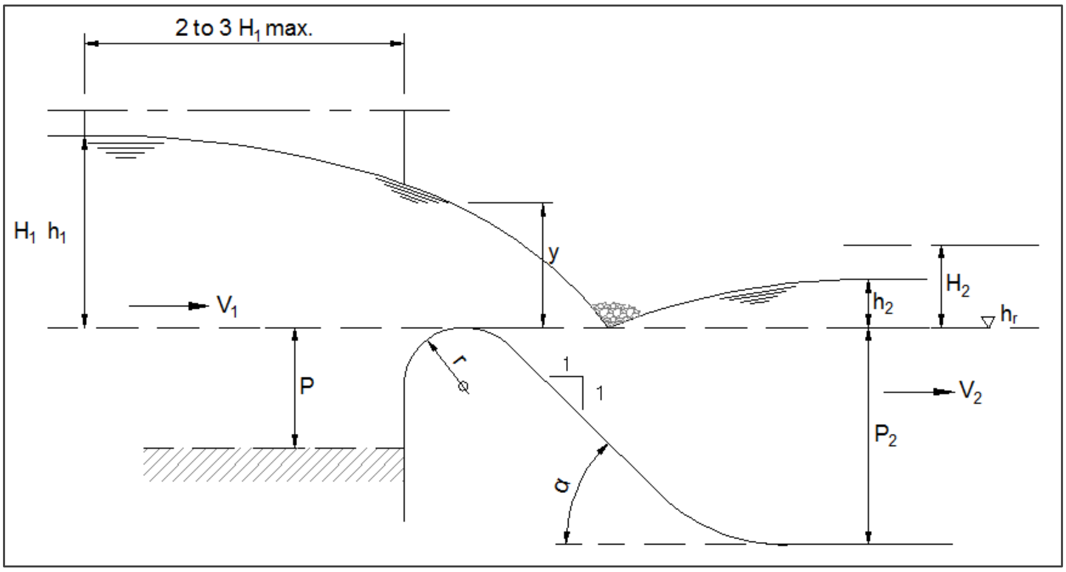


Figure 7.7 : Section of Cylindrical Crested weir

Referring to ***Figure 7.7,*** the dimensions are :

h_r = reference level

P = height of weir

b = width of weir

x = slope parameter

r = radius of weir sill

H1 = upstream energy level

H2 = downstream energy level

$Q = C_g \, Ce \, b \, H_1^{\,3/2}$

$C_g = (2/3)^{3/2} \sqrt{g}$

$C_e = C_0 \, C_1 . \, C_2$

$C_0 = 1.1846 + 0.1318 \ln (H_1/r)$ for $H_1/r < 0.88$
$C_0 = 1.1922 + 0.1915 \ln (H_1/r)$ for $0.88 \leq H_1/r < 4.8$
$C_0 = 1.49$ for $H_1/r \geq 4.8$

$C_1 = 0.9764 + 0.0914 \ln (P/H_1)$ for $P/H_1 < 1.0$
$C_1 = 0.9352 + 0.0494 (P/H_1) + 0.00927 (P/H_1)^2$ for $1 \leq P/H_1 < 2.4$
$C_1 = 1.00$ for $P/H_1 > 2.4$

C_2 is given by the equations for the Wess Spillway.

The modular limit $H_2/H_1 = 0.33$. For higher values of H_2/H_1, the discharge according to the first equation is reduced by a factor f

$f = 1.224 - 1.671 (H_2/H_1) + 3.605 (H_2/H_1)^2 - 2.829 (H_2/H_1)^3$ for $0.33 < H_2/H_1 < 0.85$

$f = 5.361 - 20.649\,(H_2/H_1) + 32.105\,(H_2/H_1)^2 - 16.789\,(H_2/H_1)^3$ for $H_2/H_1 \geq 0.85$

Reference : Test Example 7.6

7.9.4 Flumes

A critical depth flume is essentially a geometrically specified constriction built in an open channel where sufficient fall is available for critical flow to occur in the throat of the flume. Flumes are 'in-line' structure i.e. their centre-line coincides with the centre-line of the undivided channel in which the flow is to be measured.

7.9.4.1 *Rectangular Throated Flume*

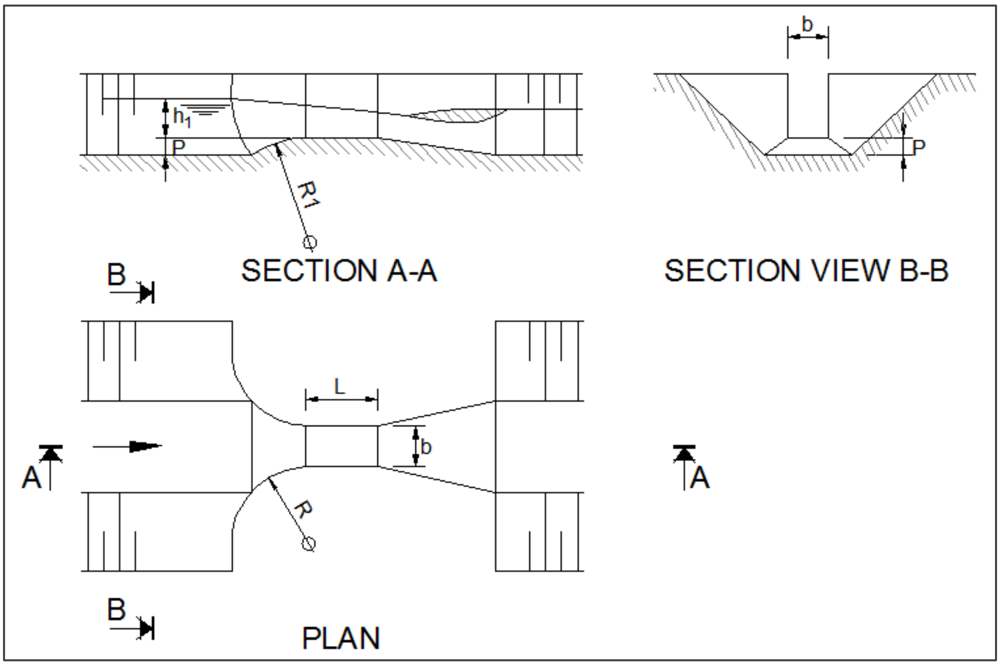


Figure 7.8 : Rectangular Throated Flume dimensions

Referring to *Figure 7.8,* the dimensions are :

h_r = reference level

L = Length of flume

b = width of flume throat

m_1 = modular limit

h_1 = upstream water level

H_1 = upstream energy level

$Q = C_g\, C_d\, b\, H_1^{\,3/2}$

$C_g = (2/3)^{3/2}\sqrt{g}$

$C_d = (1\text{-}0.006\ L/b)\ (1\text{-}0.003\ L/h_1)^{\,3/2}$

The modular limit is in the order 0.85 – 0.95. If the modular limit is exceeded, a missing value is entered for discharge.

Reference : Test Example 7.7

7.9.4.2 Trapezoidal Throated Flume

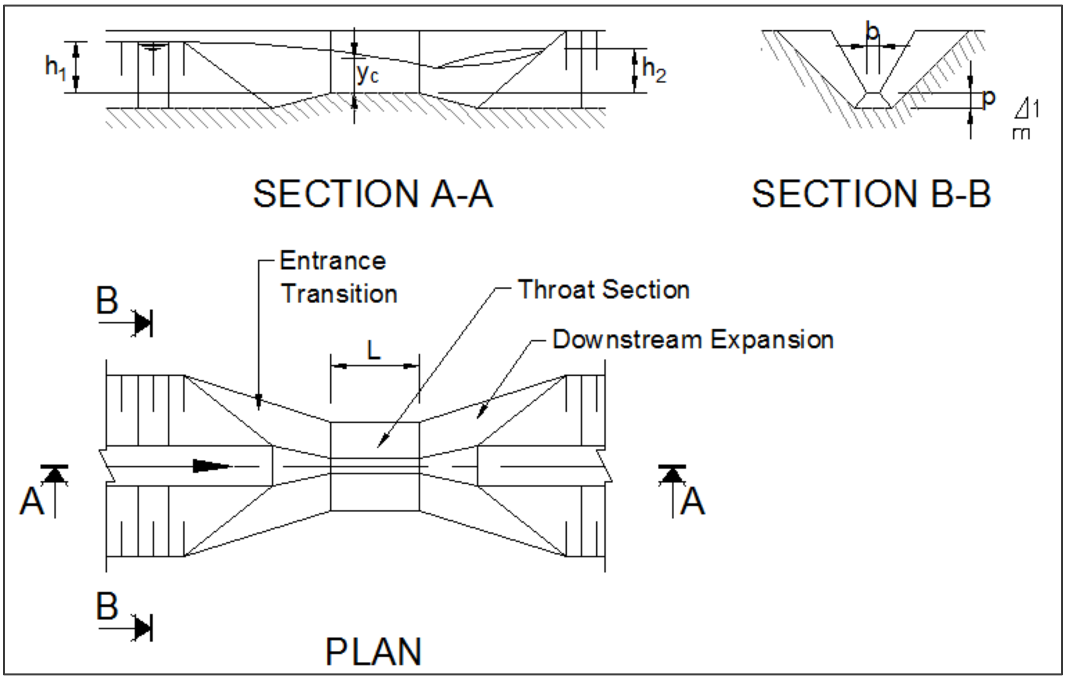


Figure 7.9 : Trapezoidal Throated Flume dimensions

Referring to ***Figure 7.9***, the dimensions are :

L = Length of flume

b = width of flume throat bottom

m = side slope

m_1 = modular limit

h_1 = upstream water level

H_1 = upstream energy level

$Q = C_g\, C_d\, C_s\, b\, H_1{}^{3/2}$

$C_g = (2/3)^{3/2} \sqrt{g}$

$C_d = (1-0.006\, L/b)\ (1-0.003\, L/h_1)^{3/2}$

Where,

$x = 0.972 - 0.878\, m + 0.366\, m^2 - 0.0543\, m^3$ for $m \le 2$

$x = 0.438 - 0.127\, m + 0.015\, m^2 - 0.5976\, m^3$ for $m > 2$

$C_s = 1.002 + 0.678\, y + 0.0327\, y^2 - 0.065\, y^3$ for $y \le 3$

$C_s = 0.088 + 1.144\, y - 0.0488\, y^2 - 0.0016\, y^3$ for $y > 3$

With $y = mh_1/b$

The modular limit is in the order 0.85 – 0.95. If the modular limit is exceeded, a missing value is entered for discharge.

Reference : Test Example 7.8

7.9.4.3 *Rectangular/Triangular/Trapezoidal flume*

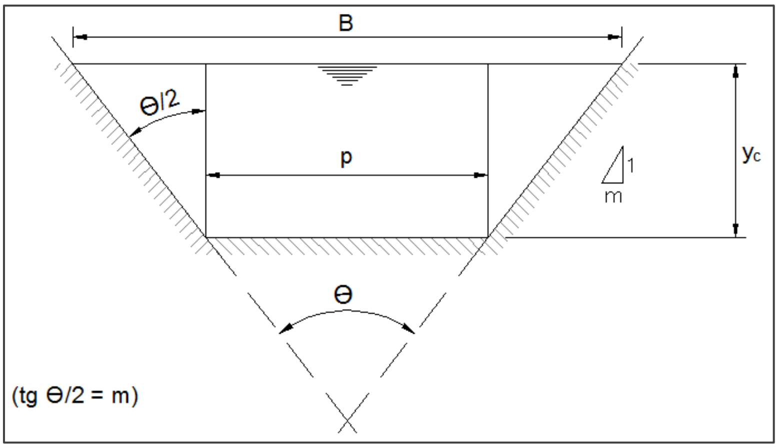


Figure 7.10 : Triangular Flume dimensions

Referring to ***Figure 7.10***, the dimensions are :

h_r = reference level

L = Length of flume

b = width of flume throat bottom

m = side slope

m_1 = modular limit

h_1 = upstream water level

H_1 = upstream energy level

$Q = C_g\, C_d\, (b\, y_c + m\, y_c{}^2)(H_1 - y_c)^{1/2}$

$C_g = \sqrt{2g}$

$C_d = 0.845 + 0.726\,(H_1/L) - 1.563\,(H_1/L)^2 + 1.156\,(H_1/L)^3$ for $H_1/L \leq 0.5$

$C_d = 0.957 - 0.017\,(H_1/L) + 0.046\,(H_1/L)^2 + 0.017\,(H_1/L)^3$ for $H_1/L > 0.5$

$Y_c = 2/3\ H1$ for $m = 0$

$Y_c = [\,b_1 + (b_1{}^2 + 40\, m\, b\, H_1)^{1/2}\,]/\,10m$ for $m > 0$

Following profiles can be covered

b > 0 and m = 0	rectangular flume
b = 0 and m > 0	triangular flume

$b > 0$ and $m > 0$ trapezoidal flume

The modular limit is in the order 0.85 – 0.95. If the modular limit is exceeded, a missing value is entered for discharge.

Reference : Test Example 7.9

7.9.4.4 Truncated Triangular Flume

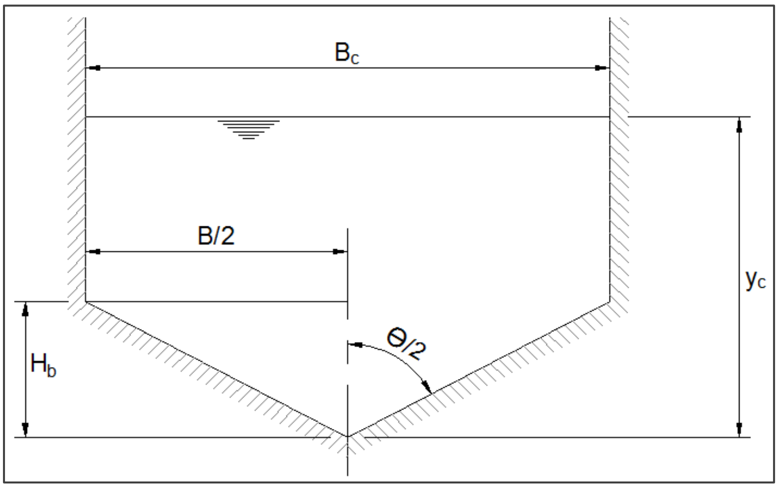


Figure 7.11 : Truncated Triangular Flume dimensions

Referring to *Figure 7.11*, the dimensions are :

h_r = reference level

L = Length of flume

b = width of flume

h_{tr} = height of triangle

m_1 = modular limit

H_1 = upstream energy level

$Q = C_g\, C_d\, m\, H_1^{\,5/2}$ for $H_1 \le \frac{5}{4} h_{tr}$

$C_g = 16/25 \sqrt{\frac{2}{5} g}$

C_d is given by rectangular flume equations

$m = b\ /\ 2\ h_{tr}$

$Q = C_g\, C_d\, b\, (H_1 - h_{tr})^{3/2}$ for $H_1 > \frac{5}{4} h_{tr}$

$C_g = (2/3)^{3/2} \sqrt{g}$

C_d is given by the Rectangular Flume equations

Reference : Test Example 7.10

7.9.4.5 Circular Flume

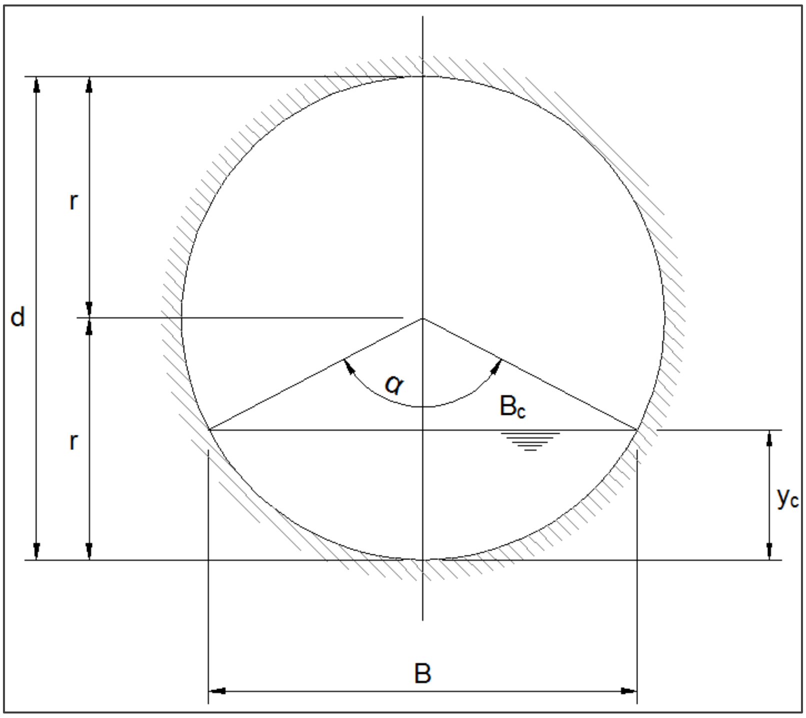


Figure 7.12 : Circular Flume dimensions

Referring to ***Figure 7.12***, the dimensions are :

h_r = reference level

L = Length of flume

d = Diameter of flume

m_1 = modular limit

H_1 = upstream energy level

$Q = C_g\, C_d\, Ac\, (H_1 - y_c)^{1/2}$

$C_g = \sqrt{2g}$

C_d is given by rectangular flume equations

$Y_c = H_1 \{0.75183 - 0.04410 (\frac{H_1}{d}) + 0.02578 (\frac{H_1}{d})^2 - 0.04568 (\frac{H_1}{d})^3\}$ for $(\frac{H_1}{d}) \leq 1$

$Y_c = H_1 \{0.52496 + 0.53698 (\frac{H_1}{d}) - 0.46709 (\frac{H_1}{d})^2 - 0.09393 (\frac{H_1}{d})^3\}$ for $1 < (\frac{H_1}{d}) \leq 1.8$

$Y_c = H_1 \{01.0505 - 0.34016 (\frac{H_1}{d}) + 0.01743 (\frac{H_1}{d})^2 - 0.005307 (\frac{H_1}{d})^3\}$ for $(\frac{H_1}{d}) > 1.8$

$A_c = \frac{1}{8} d^2 (\alpha - \sin \alpha)$

$\alpha = 2.\, \text{Arc cos} (1 - 2\, y_c / d)$

If the modular limit (user input)is exceeded, a missing value is entered for discharge.

Reference : Test Example 7.11

7.9.4.6 U-throated Flume

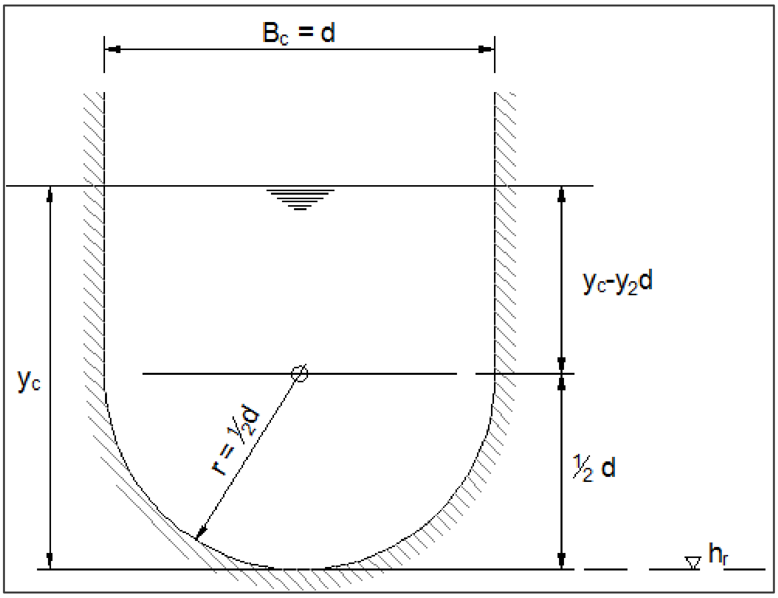


Figure 7.13 : U Throated Flume dimensions

Referring to ***Figure 7.13***, the dimensions are :

h_r = reference level

L = Length of flume

d = b = width of flume

m_1 = modular limit

H_1 = upstream energy level

For $H_1 < 0.7$ d, the formula of circular flume apply.

For $H_1 \geq 0.7$ d, the discharge is computed by :

$Q = C_g C_d b (H_1/3 - 0.0358 b)^{3/2}$

$C_g = 2\sqrt{2g}$

C_d is given by the Rectangular Flume.

Reference : Test Example 7.12

7.9.4.7 Parshall Flume

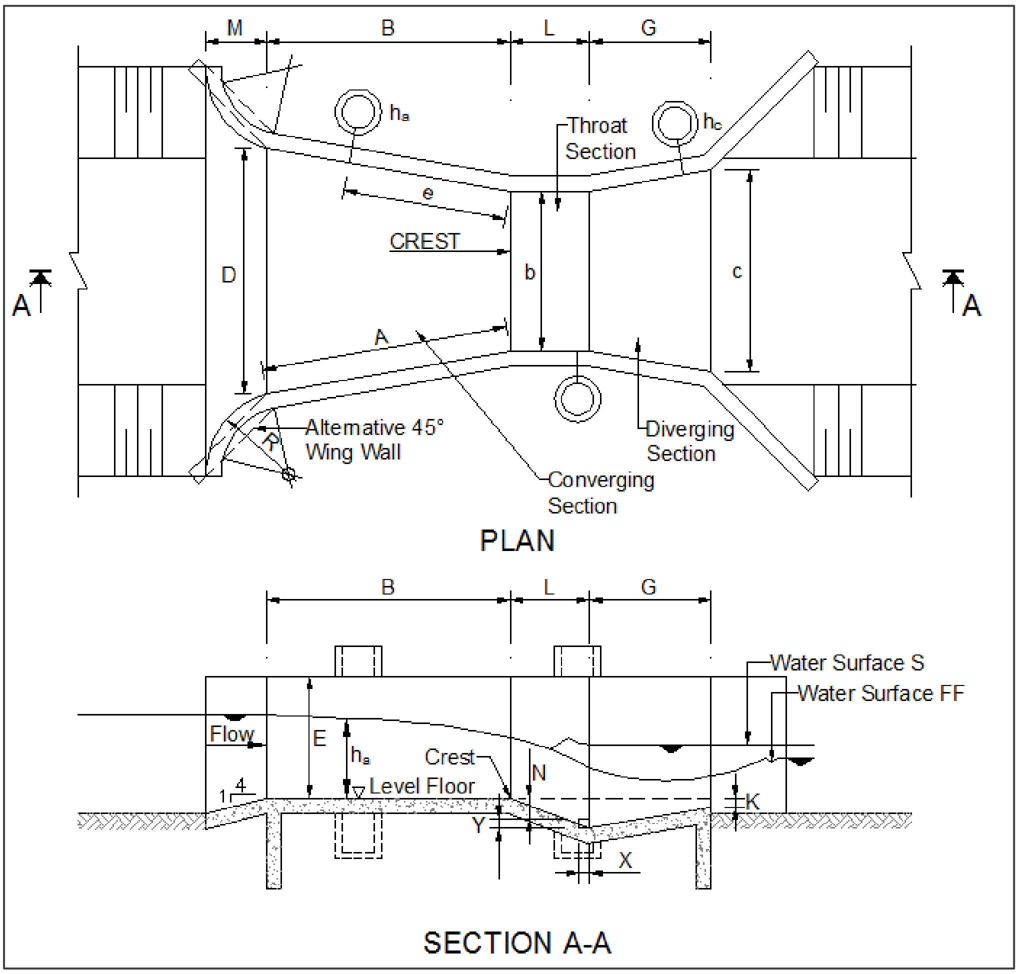


Figure 7.14 : Parshall Flume dimensions

Referring to ***Figure 7.14***, the dimensions are :

h_r = reference level

n_{pf} = throat width number

h_1 = upstream water level

h_2 = downstream water level

The general equation is of the form

$Q = K h_1^u$

K and u follow according to ***Table7.4***

Table 7.4 : Parameters of the discharge equation of Parshall-flumes

width	n_{pf}	K	u	m_l	p	a	b	c	m_f
1“	1	0.0604	1.55	0.5	1.64	-4.5837	11.118	-4.8464	$1.0*10^{-3}$
2”	2	0.1207	1.55	0.5	1.48	-5.2025	12.141	-5.1189	$1.0*10^{-3}$

width	n_{pf}	K	u	m_l	p	a	b	c	m_f
3“	3	0.1771	1.55	0.5	1.65	-5.3387	12.834	-5.3693	$1.0*10^{-3}$
6”	4	0.3812	1.58	0.6	1.57	-1.6117	5.3856	-1.3952	$1.0*10^{-3}$
9“	5	0.5354	1.53	0.6	1.5	-4.2328	10.747	-4.0566	$1.0*10^{-3}$
1'	6	0.6909	1.522	0.7	1.54	-5.0446	5.5661	-0.80775	$1.0*10^{-3}$
1'6”	7	1.506	1.538	0.7	1.54	-5.0446	5.5661	-0.80775	$1.4*10^{-3}$
2'	8	1.428	1.55	0.7	1.54	-5.0446	5.5661	-0.80775	$1.8*10^{-3}$
3'	9	2.184	1.566	0.7	1.54	-5.0446	5.5661	-0.80775	$2.4*10^{-3}$
4'	10	2.953	1.578	0.7	1.54	-5.0446	5.5661	-0.80775	$3.1*10^{-3}$
5'	11	3.732	1.587	0.7	1.54	-5.0446	5.5661	-0.80775	$3.7*10^{-3}$
6'	12	4.519	1.595	0.7	1.54	-5.0446	5.5661	-0.80775	$4.3*10^{-3}$
7'	13	5.312	1.601	0.7	1.54	-5.0446	5.5661	-0.80775	$4.9*10^{-3}$
8'	14	6.112	1.607	0.7	1.54	-5.0446	5.5661	-0.80775	$5.4*10^{-3}$
10'	15	7.463	1.6	0.8	2.00	-26.086	49.689	-23.103	1.0
12'	16	8.859	1.6	0.8	2.00	-26.086	49.689	-23.103	1.2
15'	17	10.96	1.6	0.8	2.00	-26.086	49.689	-23.103	1.5
20'	18	14.45	1.6	0.8	2.00	-26.086	49.689	-23.103	2.0
25'	19	17.94	1.6	0.8	2.00	-26.086	49.689	-23.103	2.5
30'	20	21.44	1.6	0.8	2.00	-26.086	49.689	-23.103	3.0
40'	21	28.43	1.6	0.8	2.00	-26.086	49.689	-23.103	4.0
50'	22	35.41	1.6	0.8	2.00	-26.086	49.689	-23.103	5.0

The modular limit mf varies from 0.5 to 0.8. In case this limit is exceeded, the discharge is reduced with the quantity Q_e, where :

$Q_e = m_f\, q\, h_1^{p}$

$q = 10^{(a\, +\, bS\, +\, c\, S\text{^}2)}$ with $S = h_2 / h_1$

The parameters m1, mf, a, b are presented in Table 7.4. The corrected discharge then follows from :

$Q_c = Q - Q_e$

Reference : Test Example 7.13

7.9.4.8 *H-flumes*

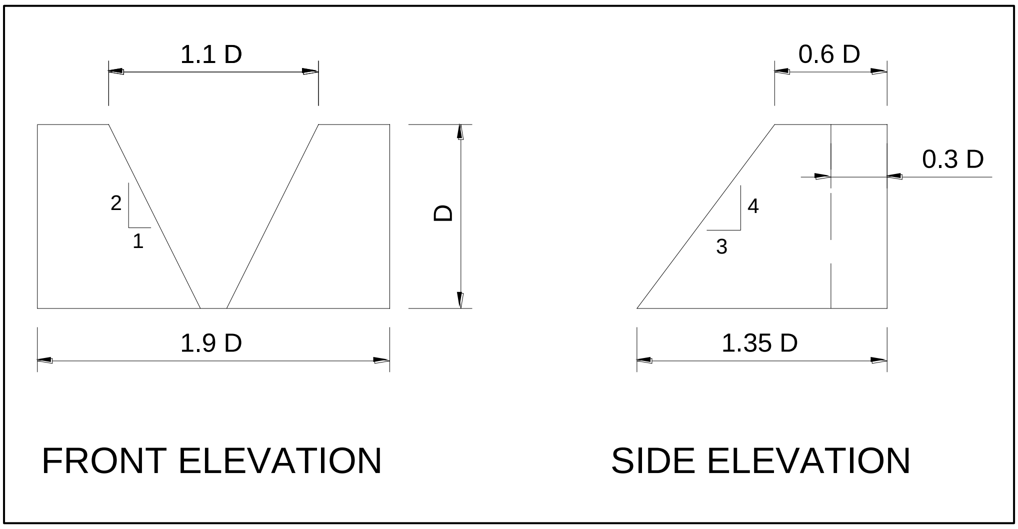


Figure 7.15 : H-Flume dimensions

Referring to *Figure 7.15*, the dimensions are:

hr = reference level

nH = flume depth number

h1 = upstream water level

h2 = downstream water level

$Q = 10 (a + b \log h1 + (c \log h1)^2$

The parameters a, b and c follow from Table 7.5.

Table 7.5 : Parameters of the discharge equation of H-flumes

Type	Depth	n_H	a	b	c	m_l
HS	0.4'	1	-0.4361	2.5151	0.1379	0.25
HS	0.6'	2	-0.4430	2.4908	0.1657	0.25
HS	0.8'	3	-0.4410	2.4571	0.1762	0.25
HS	1.0'	4	-0.4382	2.4193	0.179	0.25
H	0.5'	5	0.0372	2.6629	0.1954	0.25
H	0.75'	6	0.0351	2.6434	0.2243	0.25
H	1.0'	7	0.0206	2.5902	0.2281	0.25
H	1.5'	8	0.0238	2.5473	0.254	0.25
H	2.0'	9	0.0237	2.4918	0.2605	0.25
H	2.5'	10	0.0268	2.4402	0.26	0.25
H	3.0'	11	0.0329	2.3977	0.2588	0.25
H	4.5'	12	0.0588	2.3032	0.2547	0.25
HL	3.5'	13	0.3081	2.3935	0.2911	0.30
HL	4.0'	14	0.3160	2.3466	0.2794	0.30

Reference : Test Example 7.14

7.9.5 Gates

Flow through the gates is called underflow and in some cases 'sluice gate flow'. The head-discharge equations are:

Free flow:

Q= C1 . b. a. $\sqrt{2gh_1}$

Where,

a = gate opening

C1 = characteristic discharge coefficient for free flow. C1 is a function of the parameter h1/a and the bottom shape of the gate.

Submerged flow:

Q= C2 . b. a. $\sqrt{2g(h_1 - h_2)}$

Where,

h2 = downstream head

C2 = Coefficient for submerged flow. C2 is a function of the parameter h2/h1 and the bottom shape of the gate.

DEFINITIONS

1. Section control – A specific cross-section of a stream channel located downstream from a water-level gauge that controls the relationship between gauge height and discharge at the gauge. A section control can be a natural feature such as a rock ledge, gravel bar, a severe constriction in the channel or natural accumulation of debris. Low flows are controlled by a section control.
2. Channel control – It consists of a combination of features throughout a reach at and downstream from a gauge such as channel size, shape, curvature, slope and roughness. The length of channel reach depends on the slope of channel and magnitude of flow. High flows are usually controlled by a channel control.
3. Hysteresis – The discharge for a particular stage is greater than the normal discharge during rising stages and less than normal during falling stages. This effect is called hysteresis or a loop rating curve. This is due to the fact that the approaching velocities in the advancing portion of the wave are larger than a steady uniform flow. In the receding phase of the flood wave, it is reduced as approach velocity gives lower discharge than the equivalent steady state condition.
4. Modular limit - Each structure has an equation which is applicable as long as the downstream water level is below a certain limiting water level known as the modular limit.
5. Uncertainty – The uncertainty of the rating-curve relationship is characterised by the standard error of estimate calculated from he dispersion of stage-discharge data around the rating curve. Defined as a parameter associated with the result of a measurement, that

characterizes the dispersion of the values that could reasonably be attributed to the measurand.

6. Standard uncertainty – It is ddefined as uncertainty expressed as standard deviation.
7. Expanded uncertainty – Defined as a quantitity defining an interval about the result of a measurement that can be expected to encompass a large fraction of values that could reasonably be attributed to the measurand.
8. Level of confidence – The fraction of distribution expected to be encompassed by the expanded uncertainty interval is called the level of confidence.

REFERENCES

Boiten W., Hydrometry 3rd edition A comprehensive introduction to the measurement of flow in open channels, CRC Press

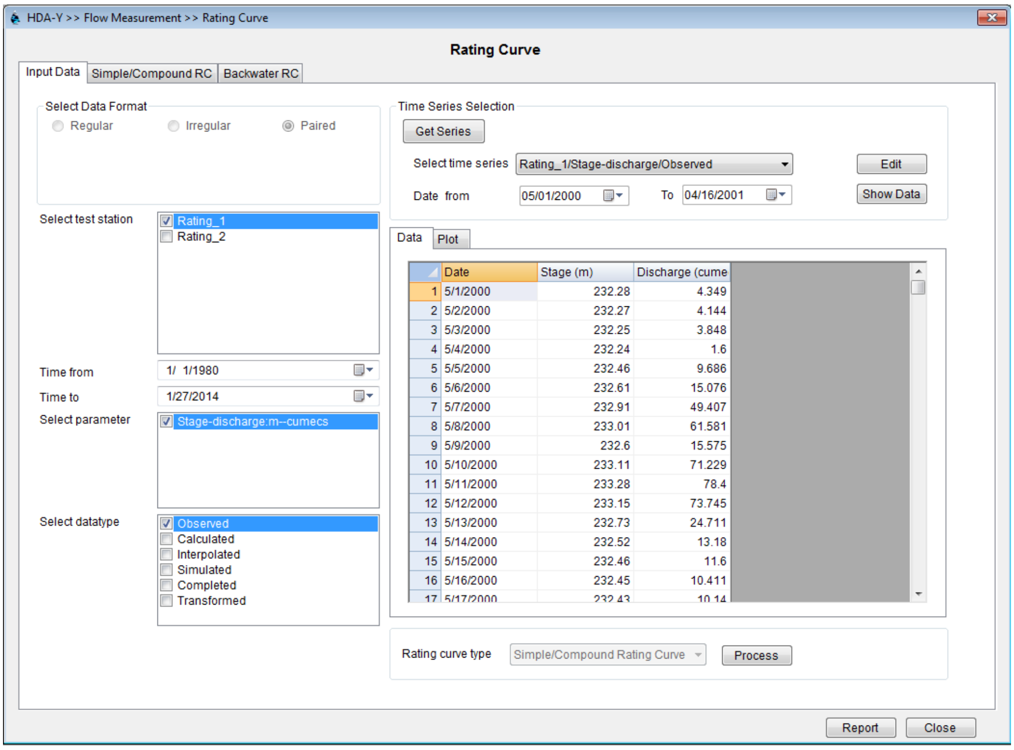
HYMOS 4.0, Technical Manual, June, 2001, Streamflow Measurements, delft hydraulics.

ISO 1088:2007(E), Hydrometry – Velocity Area Methods using current-meters – Collection and processing of data for determination of uncertainties in flow measurement

Operation Manual – Data Processing and Analysis Volume 888 – Part II, January 2003, Hydrology Project.

Test Example – 7.1

Input Data Tab enables selection of field measurement stage-discharge Data for developing the Rating curves which can be Simple, Compound or Backwater Rating Curve (Refer *Figure- 7.1*).



Select Data Format: ○ Regular ○ Irregular ● Paired

Select test station: ☑ Rating_1 ☐ Rating_2

Time from: 1/ 1/1980

Time to: 1/27/2014

Select parameter: ☑ Stage-discharge:m--cumecs

Select datatype: ☑ Observed ☐ Calculated ☐ Interpolated ☐ Simulated ☐ Completed ☐ Transformed

Select time series: Rating_1/Stage-discharge/Observed

Date from: 05/01/2000 To: 04/16/2001

	Date	Stage (m)	Discharge (cume
1	5/1/2000	232.28	4.349
2	5/2/2000	232.27	4.144
3	5/3/2000	232.25	3.848
4	5/4/2000	232.24	1.6
5	5/5/2000	232.46	9.686
6	5/6/2000	232.61	15.076
7	5/7/2000	232.91	49.407
8	5/8/2000	233.01	61.581
9	5/9/2000	232.6	15.575
10	5/10/2000	233.11	71.229
11	5/11/2000	233.28	78.4
12	5/12/2000	233.15	73.745
13	5/13/2000	232.73	24.711
14	5/14/2000	232.52	13.18
15	5/15/2000	232.46	11.6
16	5/16/2000	232.45	10.411
17	5/17/2000	232.43	10.14

Rating curve type: Simple/Compound Rating Curve

Figure 7. 1 : Data Selection for developing the Rating Curves

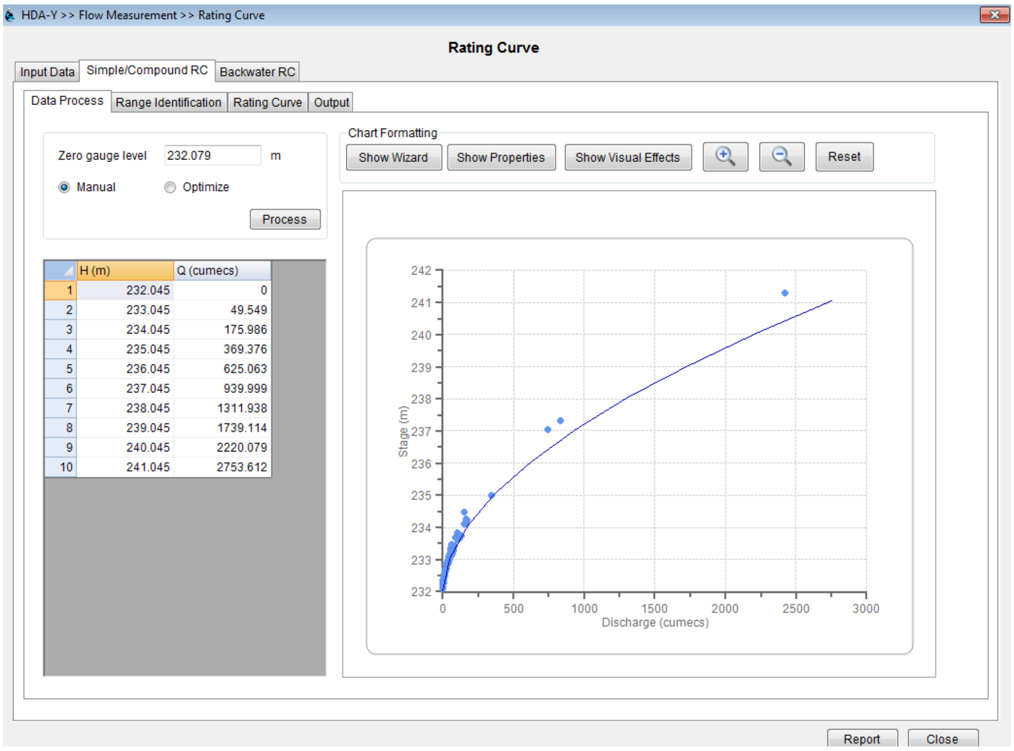
Simple/Compound RC Tab enables development of Simple and Compound Rating curve. The process is executed in four steps :

Data process – Supports selection of data for plotting as Q vs head for viewing and identification of data error / outlie (Refer *Figure 7.2*).

Range identification – Setting range in the data-set for developing the Rating Curve. The Compound Rating curve can also be specified at this stage after defining the flood plain details (Refer *Figure 7.3*).

Rating curve – Development of Rating curve for all segments with uncertainty analysis (Refer *Figure 7.4, 7.5, 7.6* and *7.7.*)

Output – Comprises of output data table and plot (Refer *Figure 7.8*).

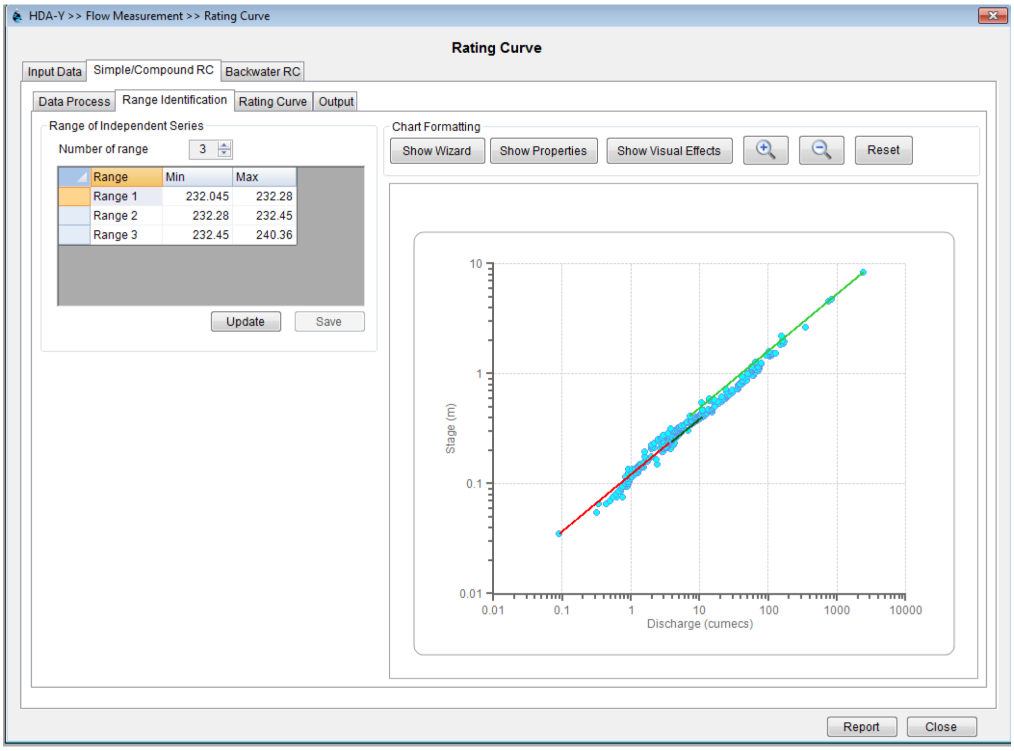


Zero gauge level 232.079 m

● Manual ○ Optimize

	H (m)	Q (cumecs)
1	232.045	0
2	233.045	49.549
3	234.045	175.986
4	235.045	369.376
5	236.045	625.063
6	237.045	939.999
7	238.045	1311.938
8	239.045	1739.114
9	240.045	2220.079
10	241.045	2753.612

Figure 7. 2 : Rating Curve view with complete data set.

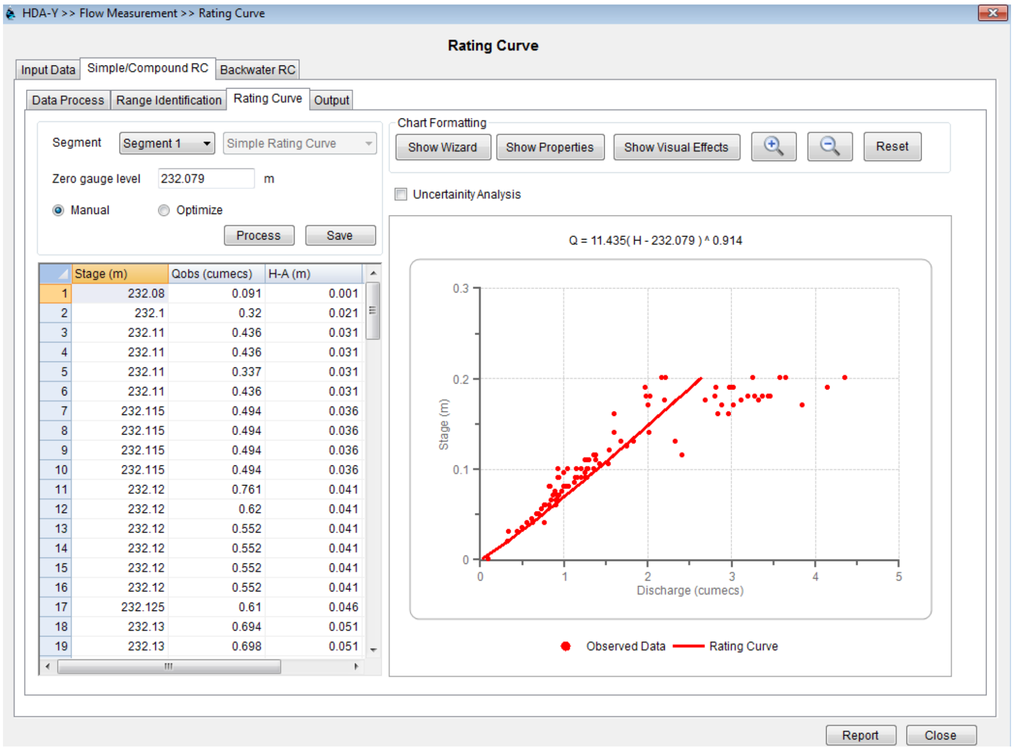


Range of Independent Series

Number of range 3

Range	Min	Max
Range 1	232.045	232.28
Range 2	232.28	232.45
Range 3	232.45	240.36

Figure 7. 3 :Range identification for the Rating Curves



Segment: Segment 1; Simple Rating Curve

Zero gauge level: 232.079 m

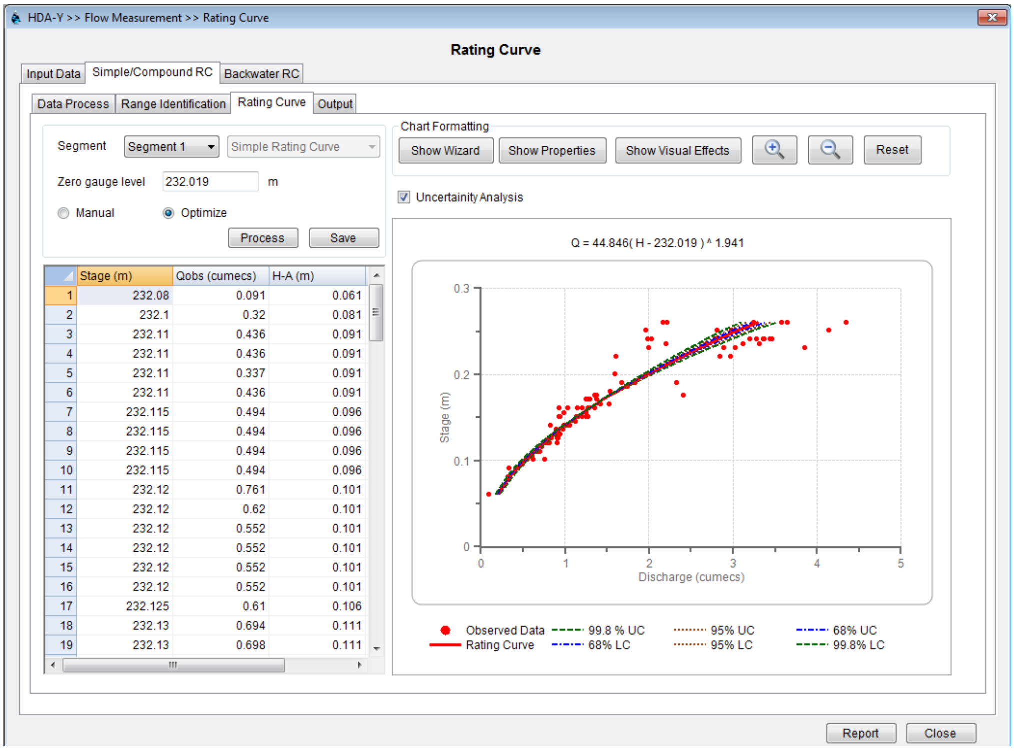
● Manual ○ Optimize

☐ Uncertainity Analysis

Q = 11.435(H - 232.079) ^ 0.914

	Stage (m)	Qobs (cumecs)	H-A (m)
1	232.08	0.091	0.001
2	232.1	0.32	0.021
3	232.11	0.436	0.031
4	232.11	0.436	0.031
5	232.11	0.337	0.031
6	232.11	0.436	0.031
7	232.115	0.494	0.036
8	232.115	0.494	0.036
9	232.115	0.494	0.036
10	232.115	0.494	0.036
11	232.12	0.761	0.041
12	232.12	0.62	0.041
13	232.12	0.552	0.041
14	232.12	0.552	0.041
15	232.12	0.552	0.041
16	232.12	0.552	0.041
17	232.125	0.61	0.046
18	232.13	0.694	0.051
19	232.13	0.698	0.051

Figure 7. 4 :Rating Curves of Segment 1 developed by Least Square



Segment: Segment 1; Simple Rating Curve

Zero gauge level: 232.019 m

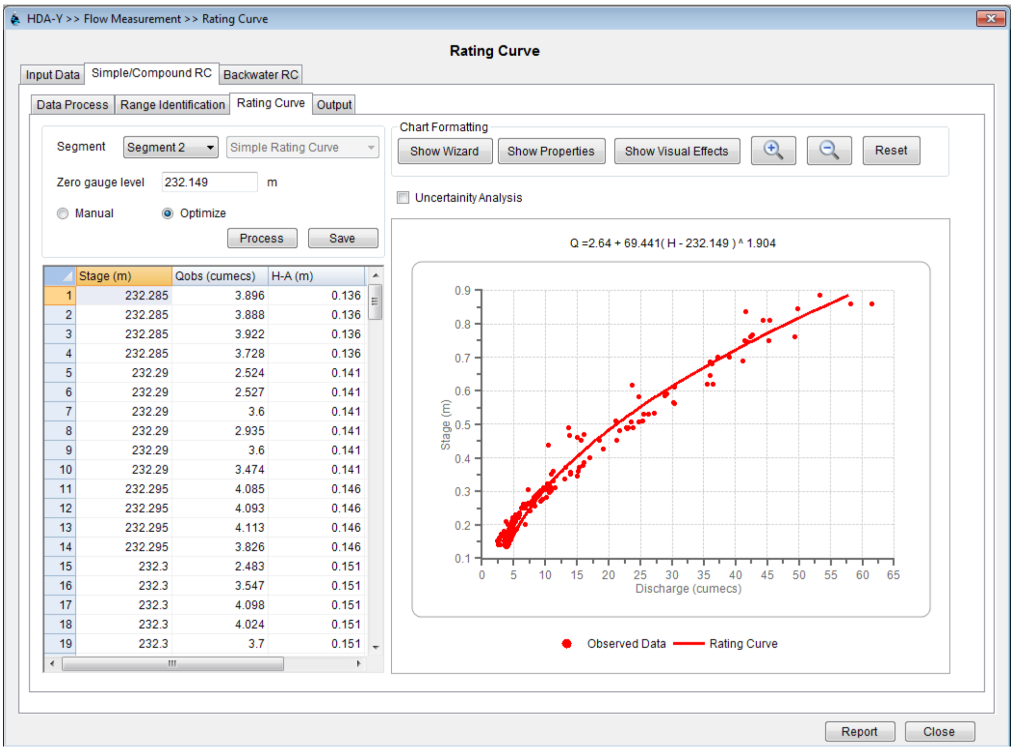
○ Manual ● Optimize

☑ Uncertainity Analysis

Q = 44.846(H - 232.019) ^ 1.941

	Stage (m)	Qobs (cumecs)	H-A (m)
1	232.08	0.091	0.061
2	232.1	0.32	0.081
3	232.11	0.436	0.091
4	232.11	0.436	0.091
5	232.11	0.337	0.091
6	232.11	0.436	0.091
7	232.115	0.494	0.096
8	232.115	0.494	0.096
9	232.115	0.494	0.096
10	232.115	0.494	0.096
11	232.12	0.761	0.101
12	232.12	0.62	0.101
13	232.12	0.552	0.101
14	232.12	0.552	0.101
15	232.12	0.552	0.101
16	232.12	0.552	0.101
17	232.125	0.61	0.106
18	232.13	0.694	0.111
19	232.13	0.698	0.111

Figure 7. 5 :Rating Curves of Segment 1 developed by optimization



Segment: Segment 2 | Simple Rating Curve

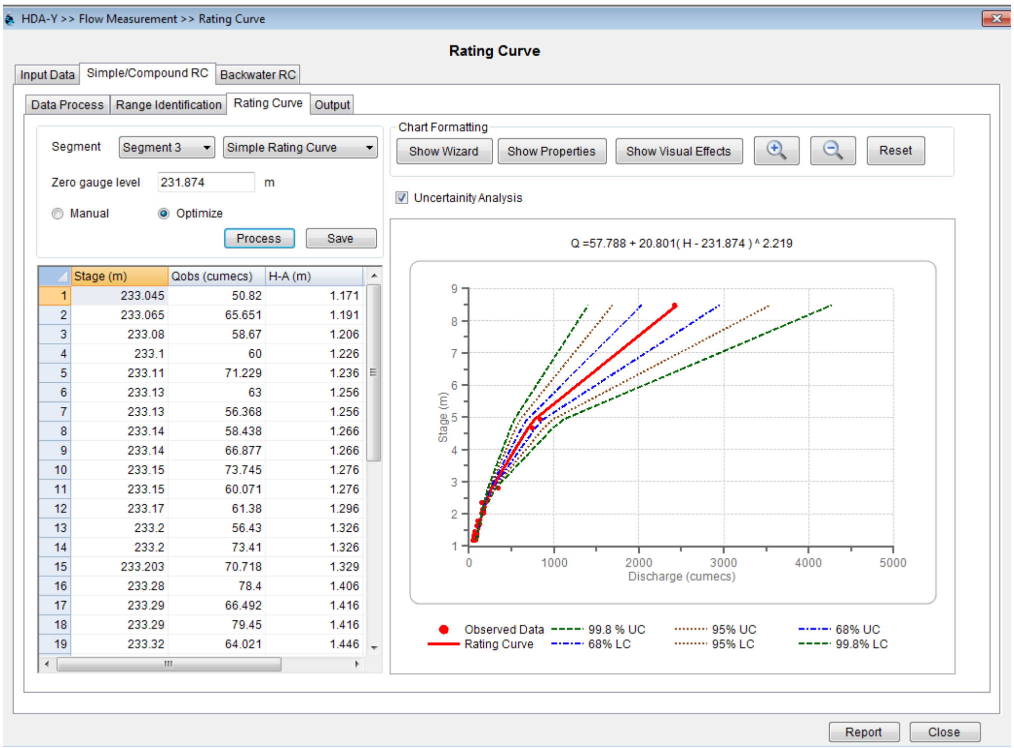
Zero gauge level 232.149 m

○ Manual ● Optimize

☐ Uncertainity Analysis

	Stage (m)	Qobs (cumecs)	H-A (m)
1	232.285	3.896	0.136
2	232.285	3.888	0.136
3	232.285	3.922	0.136
4	232.285	3.728	0.136
5	232.29	2.524	0.141
6	232.29	2.527	0.141
7	232.29	3.6	0.141
8	232.29	2.935	0.141
9	232.29	3.6	0.141
10	232.29	3.474	0.141
11	232.295	4.085	0.146
12	232.295	4.093	0.146
13	232.295	4.113	0.146
14	232.295	3.826	0.146
15	232.3	2.483	0.151
16	232.3	3.547	0.151
17	232.3	4.098	0.151
18	232.3	4.024	0.151
19	232.3	3.7	0.151

Figure 7. 6 :Rating Curves of Segment 2



Segment: Segment 3 | Simple Rating Curve

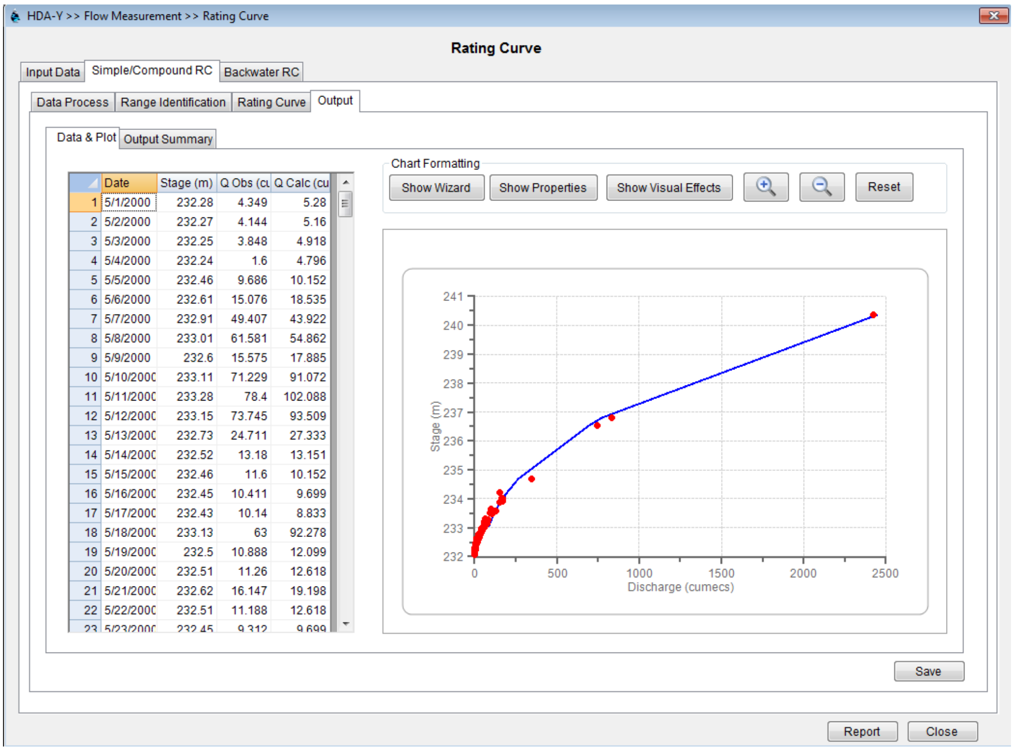
Zero gauge level 231.874 m

○ Manual ● Optimize

☑ Uncertainity Analysis

	Stage (m)	Qobs (cumecs)	H-A (m)
1	233.045	50.82	1.171
2	233.065	65.651	1.191
3	233.08	58.67	1.206
4	233.1	60	1.226
5	233.11	71.229	1.236
6	233.13	63	1.256
7	233.13	56.368	1.256
8	233.14	58.438	1.266
9	233.14	66.877	1.266
10	233.15	73.745	1.276
11	233.15	60.071	1.276
12	233.17	61.38	1.296
13	233.2	56.43	1.326
14	233.2	73.41	1.326
15	233.203	70.718	1.329
16	233.28	78.4	1.406
17	233.29	66.492	1.416
18	233.29	79.45	1.416
19	233.32	64.021	1.446

Figure 7. 7 : Rating Curves of Segment 3

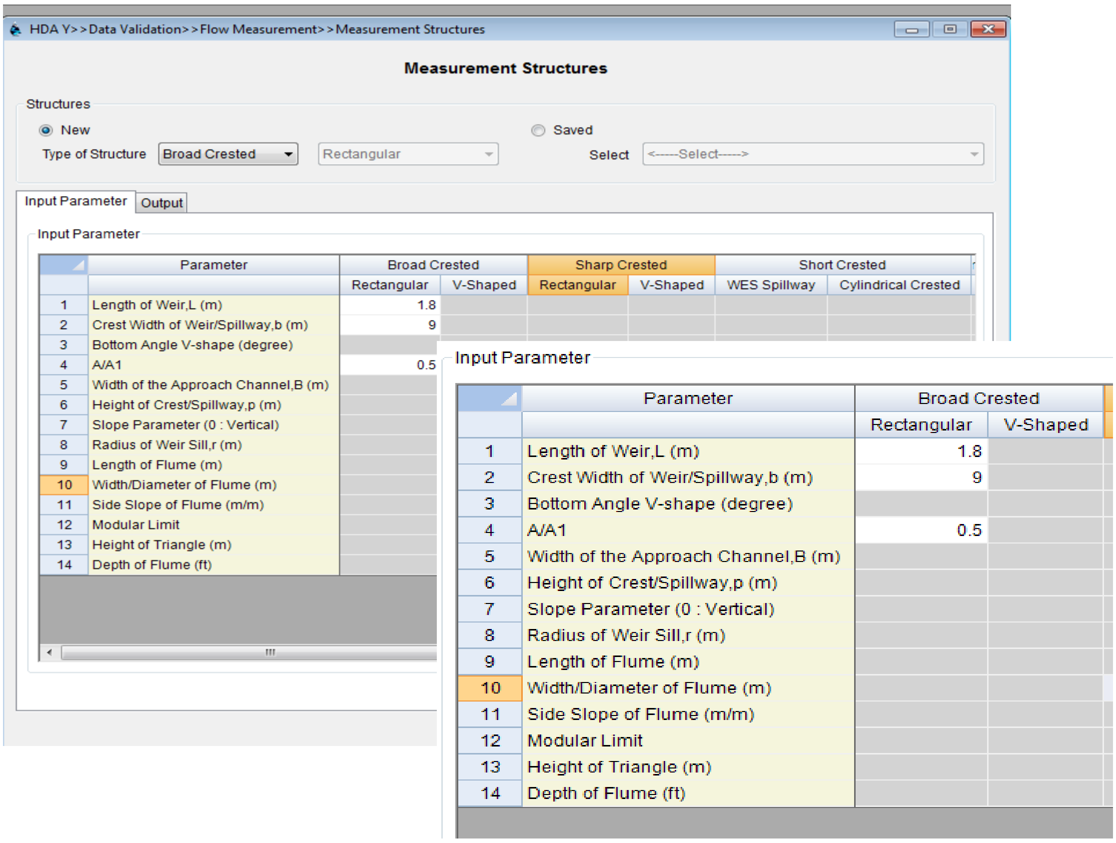


	Date	Stage (m)	Q Obs (cu	Q Calc (cu
1	5/1/2000	232.28	4.349	5.28
2	5/2/2000	232.27	4.144	5.16
3	5/3/2000	232.25	3.848	4.918
4	5/4/2000	232.24	1.6	4.796
5	5/5/2000	232.46	9.686	10.152
6	5/6/2000	232.61	15.076	18.535
7	5/7/2000	232.91	49.407	43.922
8	5/8/2000	233.01	61.581	54.862
9	5/9/2000	232.6	15.575	17.885
10	5/10/200	233.11	71.229	91.072
11	5/11/200	233.28	78.4	102.088
12	5/12/200	233.15	73.745	93.509
13	5/13/200	232.73	24.711	27.333
14	5/14/200	232.52	13.18	13.151
15	5/15/200	232.46	11.6	10.152
16	5/16/200	232.45	10.411	9.699
17	5/17/200	232.43	10.14	8.833
18	5/18/200	233.13	63	92.278
19	5/19/200	232.5	10.888	12.099
20	5/20/200	232.51	11.26	12.618
21	5/21/200	232.62	16.147	19.198
22	5/22/200	232.51	11.188	12.618
23	5/23/200	232.45	9.312	9.699

Figure 7. 8 :Data Output and plot of Rating Curve

Test Example – 7.2

Broad Crested Rectangular Weir



Measurement Structures

Structures

● New ○ Saved

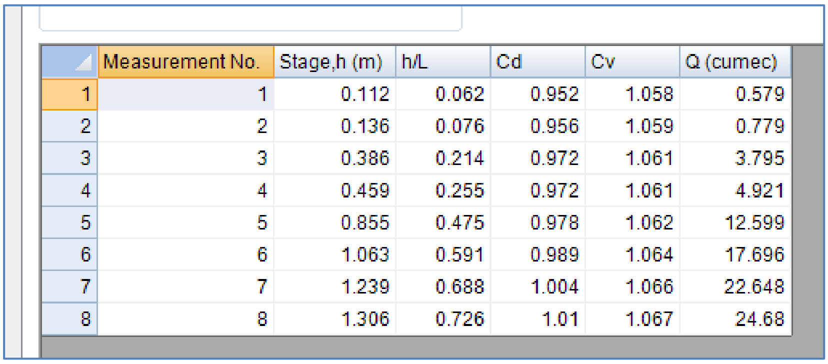
Type of Structure: Broad Crested | Rectangular

Select: <-----Select----->

Input Parameter

	Parameter	Broad Crested		Sharp Crested		Short Crested	
		Rectangular	V-Shaped	Rectangular	V-Shaped	WES Spillway	Cylindrical Crested
1	Length of Weir,L (m)	1.8					
2	Crest Width of Weir/Spillway,b (m)	9					
3	Bottom Angle V-shape (degree)						
4	A/A1	0.5					
5	Width of the Approach Channel,B (m)						
6	Height of Crest/Spillway,p (m)						
7	Slope Parameter (0 : Vertical)						
8	Radius of Weir Sill,r (m)						
9	Length of Flume (m)						
10	Width/Diameter of Flume (m)						
11	Side Slope of Flume (m/m)						
12	Modular Limit						
13	Height of Triangle (m)						
14	Depth of Flume (ft)						

Output

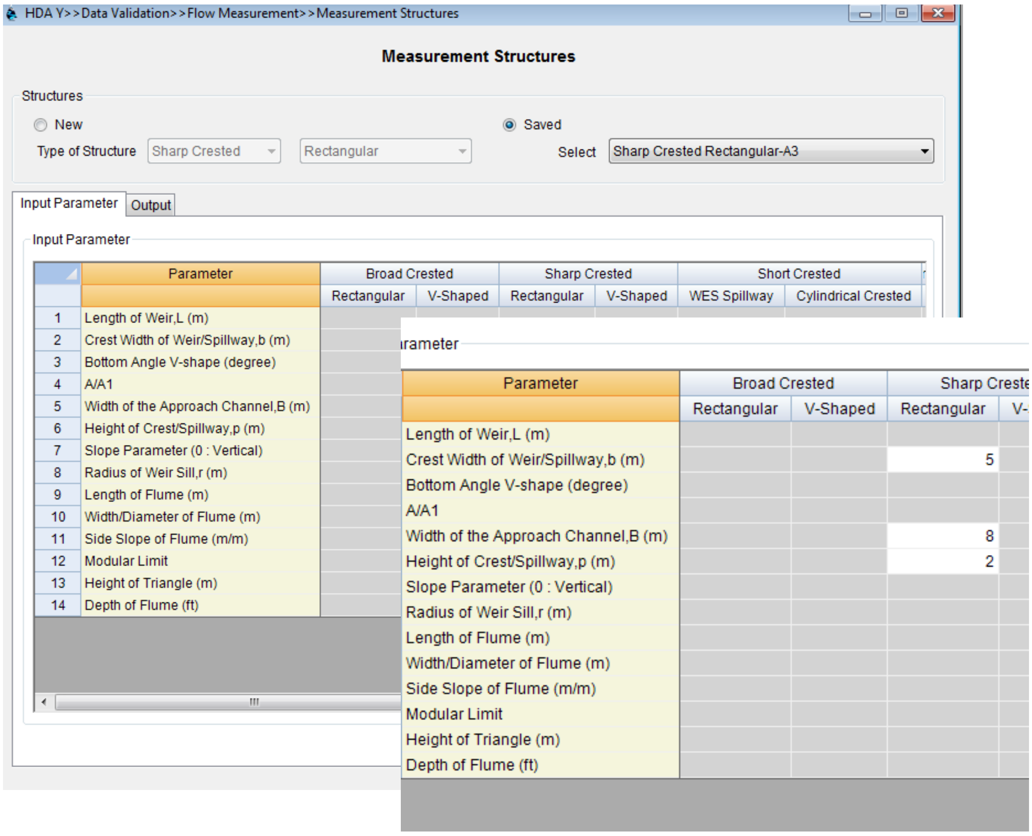


	Measurement No.	Stage,h (m)	h/L	Cd	Cv	Q (cumec)
1	1	0.112	0.062	0.952	1.058	0.579
2	2	0.136	0.076	0.956	1.059	0.779
3	3	0.386	0.214	0.972	1.061	3.795
4	4	0.459	0.255	0.972	1.061	4.921
5	5	0.855	0.475	0.978	1.062	12.599
6	6	1.063	0.591	0.989	1.064	17.696
7	7	1.239	0.688	1.004	1.066	22.648
8	8	1.306	0.726	1.01	1.067	24.68

Figure 7. 9 : Input and Output of Broad-crested Rectangular weir

Test Example – 7.3

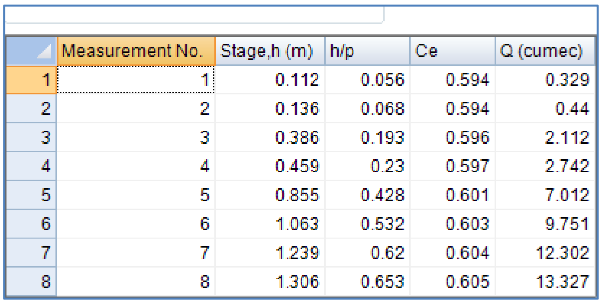
Sharp Crested Rectangular Weir



○ New
Type of Structure: Sharp Crested | Rectangular
● Saved
Select: Sharp Crested Rectangular-A3

Input Parameter

	Parameter	Broad Crested		Sharp Crested		Short Crested	
		Rectangular	V-Shaped	Rectangular	V-Shaped	WES Spillway	Cylindrical Crested
1	Length of Weir,L (m)						
2	Crest Width of Weir/Spillway,b (m)			5			
3	Bottom Angle V-shape (degree)						
4	A/A1						
5	Width of the Approach Channel,B (m)			8			
6	Height of Crest/Spillway,p (m)			2			
7	Slope Parameter (0 : Vertical)						
8	Radius of Weir Sill,r (m)						
9	Length of Flume (m)						
10	Width/Diameter of Flume (m)						
11	Side Slope of Flume (m/m)						
12	Modular Limit						
13	Height of Triangle (m)						
14	Depth of Flume (ft)						

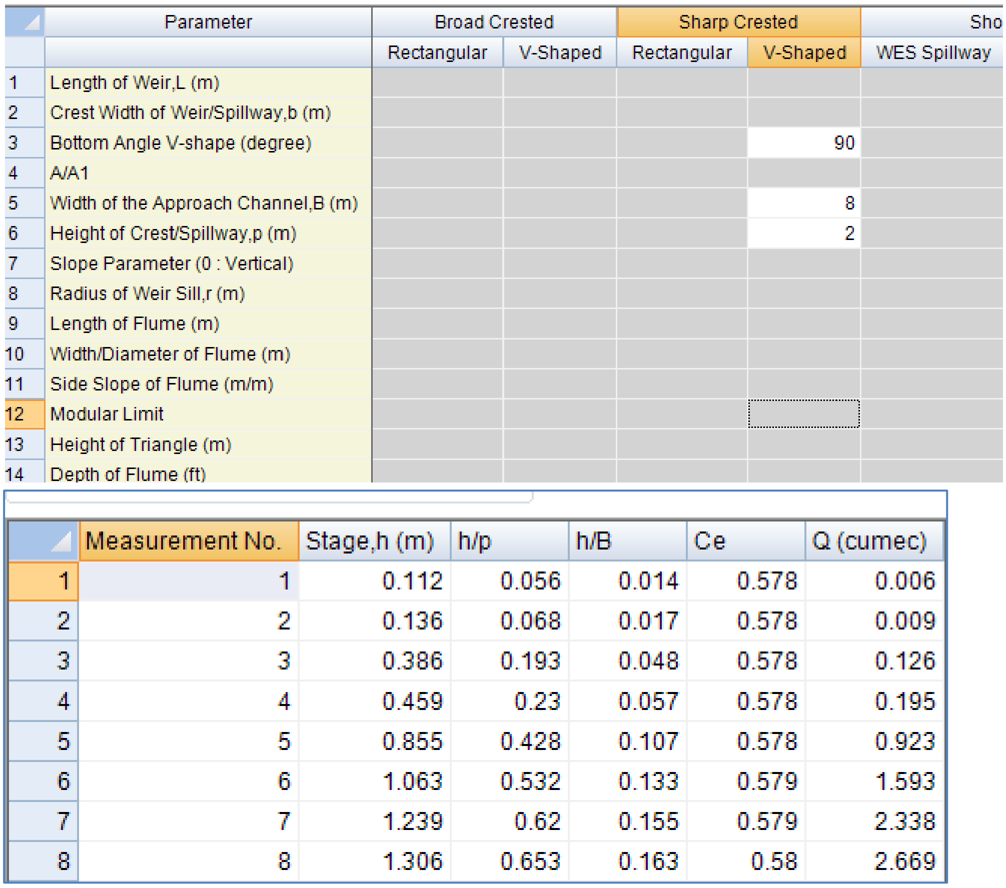


	Measurement No.	Stage,h (m)	h/p	Ce	Q (cumec)
1	1	0.112	0.056	0.594	0.329
2	2	0.136	0.068	0.594	0.44
3	3	0.386	0.193	0.596	2.112
4	4	0.459	0.23	0.597	2.742
5	5	0.855	0.428	0.601	7.012
6	6	1.063	0.532	0.603	9.751
7	7	1.239	0.62	0.604	12.302
8	8	1.306	0.653	0.605	13.327

Figure 7. 10 : Input and Output of Sharp-crested Rectangular weir

Test Example – 7.4

Sharp Crested V-Shaped Weir



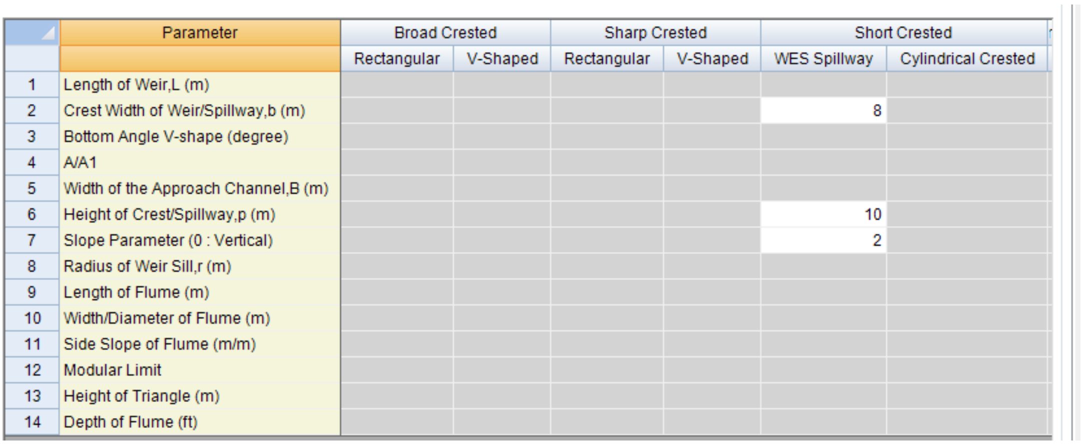
	Parameter	Broad Crested		Sharp Crested		Sho
		Rectangular	V-Shaped	Rectangular	V-Shaped	WES Spillway
1	Length of Weir,L (m)					
2	Crest Width of Weir/Spillway,b (m)					
3	Bottom Angle V-shape (degree)				90	
4	A/A1					
5	Width of the Approach Channel,B (m)				8	
6	Height of Crest/Spillway,p (m)				2	
7	Slope Parameter (0 : Vertical)					
8	Radius of Weir Sill,r (m)					
9	Length of Flume (m)					
10	Width/Diameter of Flume (m)					
11	Side Slope of Flume (m/m)					
12	Modular Limit					
13	Height of Triangle (m)					
14	Depth of Flume (ft)					

	Measurement No.	Stage,h (m)	h/p	h/B	Ce	Q (cumec)
1	1	0.112	0.056	0.014	0.578	0.006
2	2	0.136	0.068	0.017	0.578	0.009
3	3	0.386	0.193	0.048	0.578	0.126
4	4	0.459	0.23	0.057	0.578	0.195
5	5	0.855	0.428	0.107	0.578	0.923
6	6	1.063	0.532	0.133	0.579	1.593
7	7	1.239	0.62	0.155	0.579	2.338
8	8	1.306	0.653	0.163	0.58	2.669

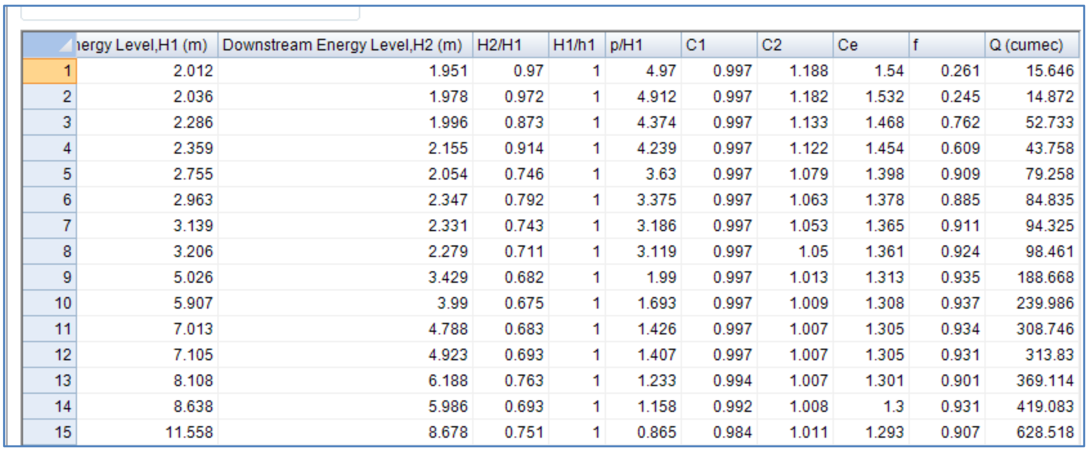
Figure 7. 11 : Input and Output of Sharp-crested V-shaped weir

Test Example – 7.5

Short Crested WES Spillway



	Parameter	Broad Crested		Sharp Crested		Short Crested	
		Rectangular	V-Shaped	Rectangular	V-Shaped	WES Spillway	Cylindrical Crested
1	Length of Weir,L (m)						
2	Crest Width of Weir/Spillway,b (m)					8	
3	Bottom Angle V-shape (degree)						
4	A/A1						
5	Width of the Approach Channel,B (m)						
6	Height of Crest/Spillway,p (m)					10	
7	Slope Parameter (0 : Vertical)					2	
8	Radius of Weir Sill,r (m)						
9	Length of Flume (m)						
10	Width/Diameter of Flume (m)						
11	Side Slope of Flume (m/m)						
12	Modular Limit						
13	Height of Triangle (m)						
14	Depth of Flume (ft)						

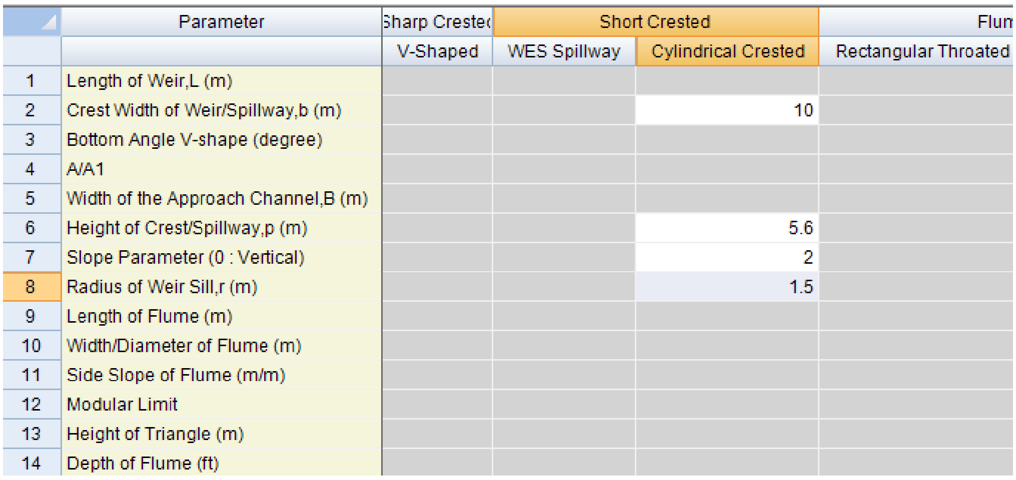


	nergy Level,H1 (m)	Downstream Energy Level,H2 (m)	H2/H1	H1/h1	p/H1	C1	C2	Ce	f	Q (cumec)
1	2.012	1.951	0.97	1	4.97	0.997	1.188	1.54	0.261	15.646
2	2.036	1.978	0.972	1	4.912	0.997	1.182	1.532	0.245	14.872
3	2.286	1.996	0.873	1	4.374	0.997	1.133	1.468	0.762	52.733
4	2.359	2.155	0.914	1	4.239	0.997	1.122	1.454	0.609	43.758
5	2.755	2.054	0.746	1	3.63	0.997	1.079	1.398	0.909	79.258
6	2.963	2.347	0.792	1	3.375	0.997	1.063	1.378	0.885	84.835
7	3.139	2.331	0.743	1	3.186	0.997	1.053	1.365	0.911	94.325
8	3.206	2.279	0.711	1	3.119	0.997	1.05	1.361	0.924	98.461
9	5.026	3.429	0.682	1	1.99	0.997	1.013	1.313	0.935	188.668
10	5.907	3.99	0.675	1	1.693	0.997	1.009	1.308	0.937	239.986
11	7.013	4.788	0.683	1	1.426	0.997	1.007	1.305	0.934	308.746
12	7.105	4.923	0.693	1	1.407	0.997	1.007	1.305	0.931	313.83
13	8.108	6.188	0.763	1	1.233	0.994	1.007	1.301	0.901	369.114
14	8.638	5.986	0.693	1	1.158	0.992	1.008	1.3	0.931	419.083
15	11.558	8.678	0.751	1	0.865	0.984	1.011	1.293	0.907	628.518

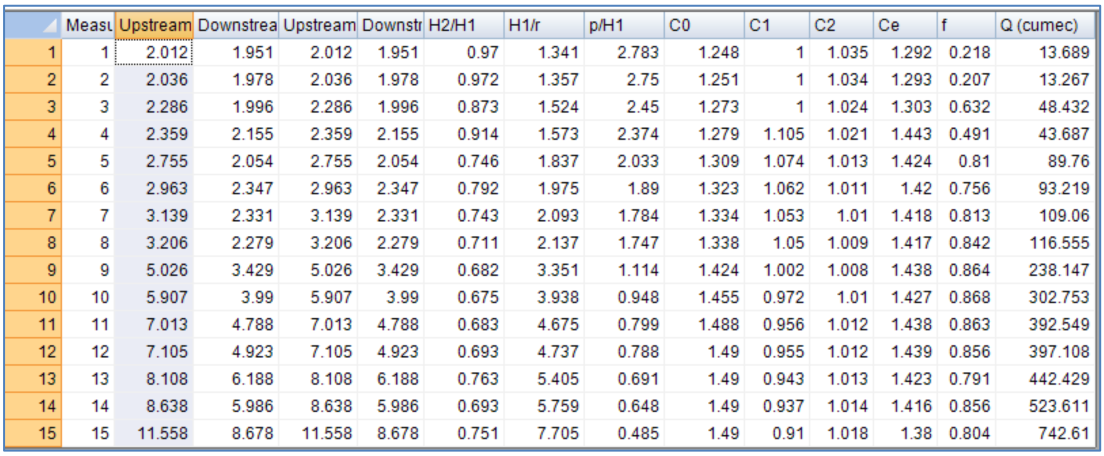
Figure 7. 12 : Input and Output of Sharp-crested Rectangular weir

Test Example – 7.6

Short Crested Cylindrical Weir



	Parameter	Sharp Creste	Short Crested		Flum
		V-Shaped	WES Spillway	Cylindrical Crested	Rectangular Throated
1	Length of Weir,L (m)				
2	Crest Width of Weir/Spillway,b (m)			10	
3	Bottom Angle V-shape (degree)				
4	A/A1				
5	Width of the Approach Channel,B (m)				
6	Height of Crest/Spillway,p (m)			5.6	
7	Slope Parameter (0 : Vertical)			2	
8	Radius of Weir Sill,r (m)			1.5	
9	Length of Flume (m)				
10	Width/Diameter of Flume (m)				
11	Side Slope of Flume (m/m)				
12	Modular Limit				
13	Height of Triangle (m)				
14	Depth of Flume (ft)				

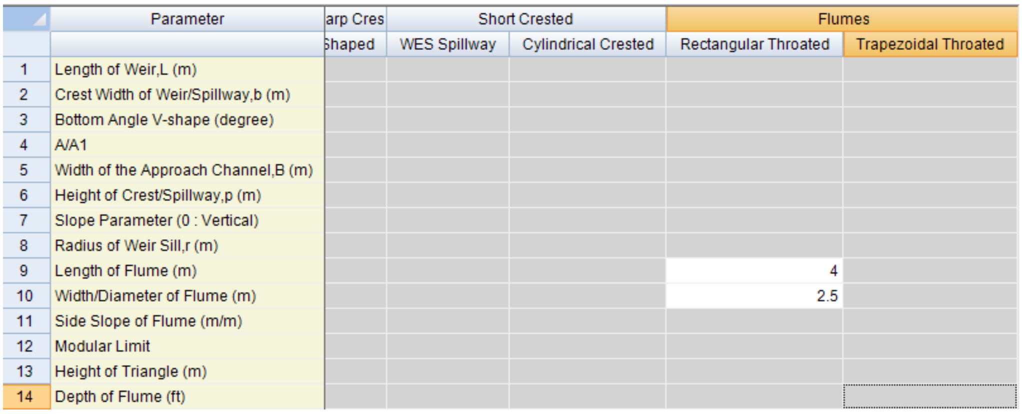


	Measu	Upstream	Downstrea	Upstream	Downstr	H2/H1	H1/r	p/H1	C0	C1	C2	Ce	f	Q (cumec)
1	1	2.012	1.951	2.012	1.951	0.97	1.341	2.783	1.248	1	1.035	1.292	0.218	13.689
2	2	2.036	1.978	2.036	1.978	0.972	1.357	2.75	1.251	1	1.034	1.293	0.207	13.267
3	3	2.286	1.996	2.286	1.996	0.873	1.524	2.45	1.273	1	1.024	1.303	0.632	48.432
4	4	2.359	2.155	2.359	2.155	0.914	1.573	2.374	1.279	1.105	1.021	1.443	0.491	43.687
5	5	2.755	2.054	2.755	2.054	0.746	1.837	2.033	1.309	1.074	1.013	1.424	0.81	89.76
6	6	2.963	2.347	2.963	2.347	0.792	1.975	1.89	1.323	1.062	1.011	1.42	0.756	93.219
7	7	3.139	2.331	3.139	2.331	0.743	2.093	1.784	1.334	1.053	1.01	1.418	0.813	109.06
8	8	3.206	2.279	3.206	2.279	0.711	2.137	1.747	1.338	1.05	1.009	1.417	0.842	116.555
9	9	5.026	3.429	5.026	3.429	0.682	3.351	1.114	1.424	1.002	1.008	1.438	0.864	238.147
10	10	5.907	3.99	5.907	3.99	0.675	3.938	0.948	1.455	0.972	1.01	1.427	0.868	302.753
11	11	7.013	4.788	7.013	4.788	0.683	4.675	0.799	1.488	0.956	1.012	1.438	0.863	392.549
12	12	7.105	4.923	7.105	4.923	0.693	4.737	0.788	1.49	0.955	1.012	1.439	0.856	397.108
13	13	8.108	6.188	8.108	6.188	0.763	5.405	0.691	1.49	0.943	1.013	1.423	0.791	442.429
14	14	8.638	5.986	8.638	5.986	0.693	5.759	0.648	1.49	0.937	1.014	1.416	0.856	523.611
15	15	11.558	8.678	11.558	8.678	0.751	7.705	0.485	1.49	0.91	1.018	1.38	0.804	742.61

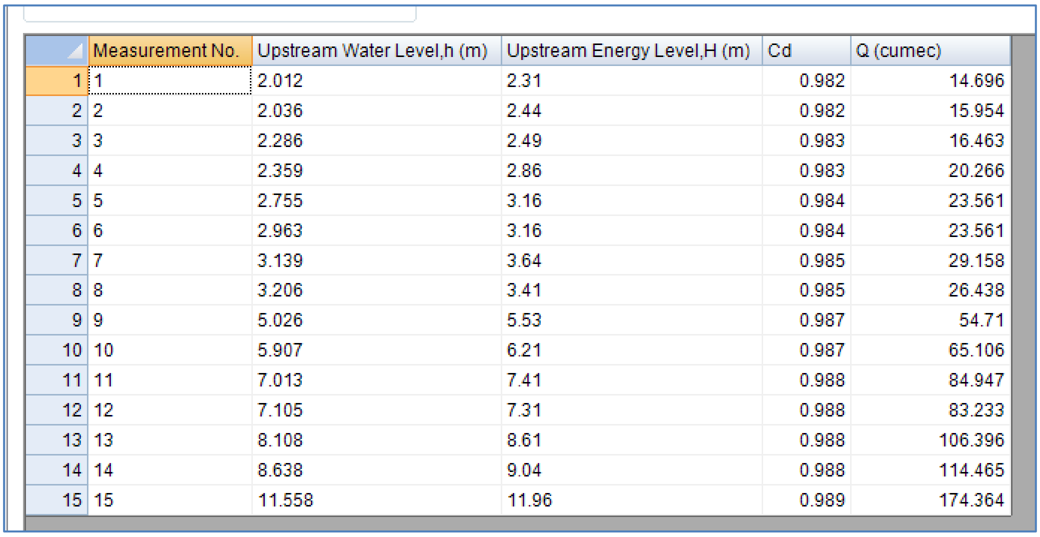
Figure 7. 13 : Input and Output of Sharp-crested Cylindrical weir

Test Example – 7.7

Rectangular Throated Flumes



	Parameter	arp Cres	Short Crested		Flumes	
		haped	WES Spillway	Cylindrical Crested	Rectangular Throated	Trapezoidal Throated
1	Length of Weir,L (m)					
2	Crest Width of Weir/Spillway,b (m)					
3	Bottom Angle V-shape (degree)					
4	A/A1					
5	Width of the Approach Channel,B (m)					
6	Height of Crest/Spillway,p (m)					
7	Slope Parameter (0 : Vertical)					
8	Radius of Weir Sill,r (m)					
9	Length of Flume (m)				4	
10	Width/Diameter of Flume (m)				2.5	
11	Side Slope of Flume (m/m)					
12	Modular Limit					
13	Height of Triangle (m)					
14	Depth of Flume (ft)					

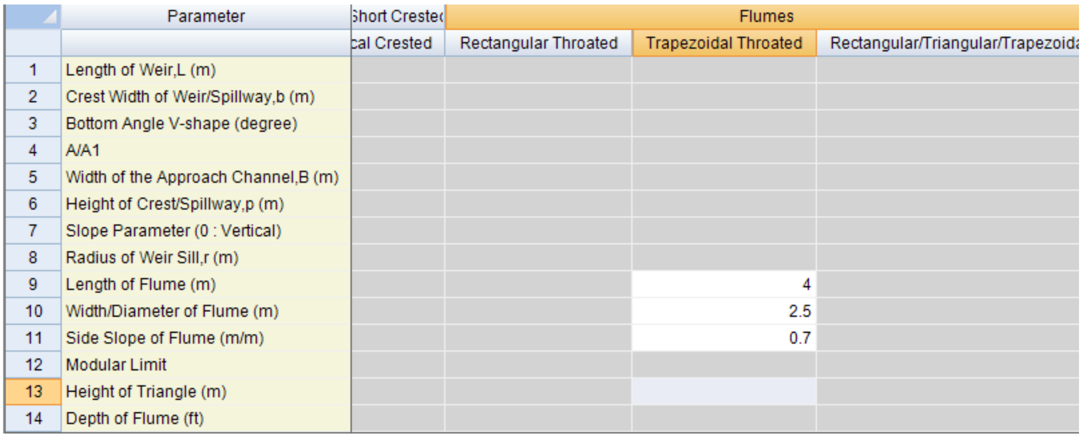


	Measurement No.	Upstream Water Level,h (m)	Upstream Energy Level,H (m)	Cd	Q (cumec)
1	1	2.012	2.31	0.982	14.696
2	2	2.036	2.44	0.982	15.954
3	3	2.286	2.49	0.983	16.463
4	4	2.359	2.86	0.983	20.266
5	5	2.755	3.16	0.984	23.561
6	6	2.963	3.16	0.984	23.561
7	7	3.139	3.64	0.985	29.158
8	8	3.206	3.41	0.985	26.438
9	9	5.026	5.53	0.987	54.71
10	10	5.907	6.21	0.987	65.106
11	11	7.013	7.41	0.988	84.947
12	12	7.105	7.31	0.988	83.233
13	13	8.108	8.61	0.988	106.396
14	14	8.638	9.04	0.988	114.465
15	15	11.558	11.96	0.989	174.364

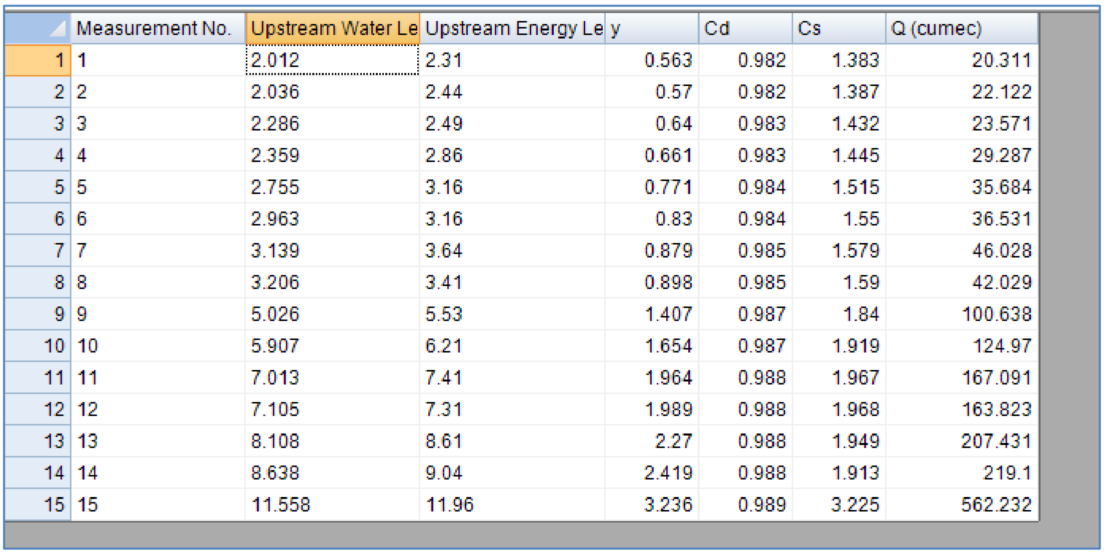
Figure 7. 14 : Input and Output of Rectangular throated Flume

Test Example – 7.8

Trapezoidal Throated Flumes



	Parameter	Short Creste	Flumes		
		cal Crested	Rectangular Throated	Trapezoidal Throated	Rectangular/Triangular/Trapezoida
1	Length of Weir,L (m)				
2	Crest Width of Weir/Spillway,b (m)				
3	Bottom Angle V-shape (degree)				
4	A/A1				
5	Width of the Approach Channel,B (m)				
6	Height of Crest/Spillway,p (m)				
7	Slope Parameter (0 : Vertical)				
8	Radius of Weir Sill,r (m)				
9	Length of Flume (m)			4	
10	Width/Diameter of Flume (m)			2.5	
11	Side Slope of Flume (m/m)			0.7	
12	Modular Limit				
13	Height of Triangle (m)				
14	Depth of Flume (ft)				

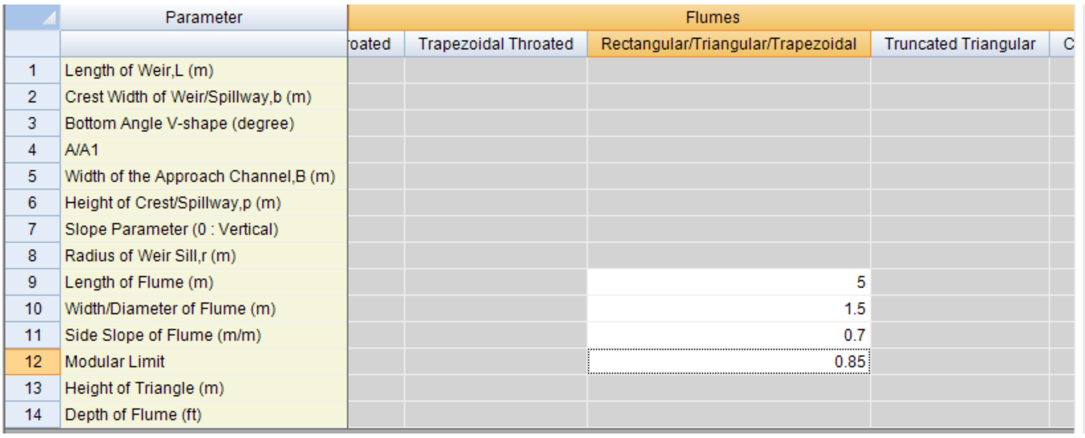


	Measurement No.	Upstream Water Le	Upstream Energy Le	y	Cd	Cs	Q (cumec)
1	1	2.012	2.31	0.563	0.982	1.383	20.311
2	2	2.036	2.44	0.57	0.982	1.387	22.122
3	3	2.286	2.49	0.64	0.983	1.432	23.571
4	4	2.359	2.86	0.661	0.983	1.445	29.287
5	5	2.755	3.16	0.771	0.984	1.515	35.684
6	6	2.963	3.16	0.83	0.984	1.55	36.531
7	7	3.139	3.64	0.879	0.985	1.579	46.028
8	8	3.206	3.41	0.898	0.985	1.59	42.029
9	9	5.026	5.53	1.407	0.987	1.84	100.638
10	10	5.907	6.21	1.654	0.987	1.919	124.97
11	11	7.013	7.41	1.964	0.988	1.967	167.091
12	12	7.105	7.31	1.989	0.988	1.968	163.823
13	13	8.108	8.61	2.27	0.988	1.949	207.431
14	14	8.638	9.04	2.419	0.988	1.913	219.1
15	15	11.558	11.96	3.236	0.989	3.225	562.232

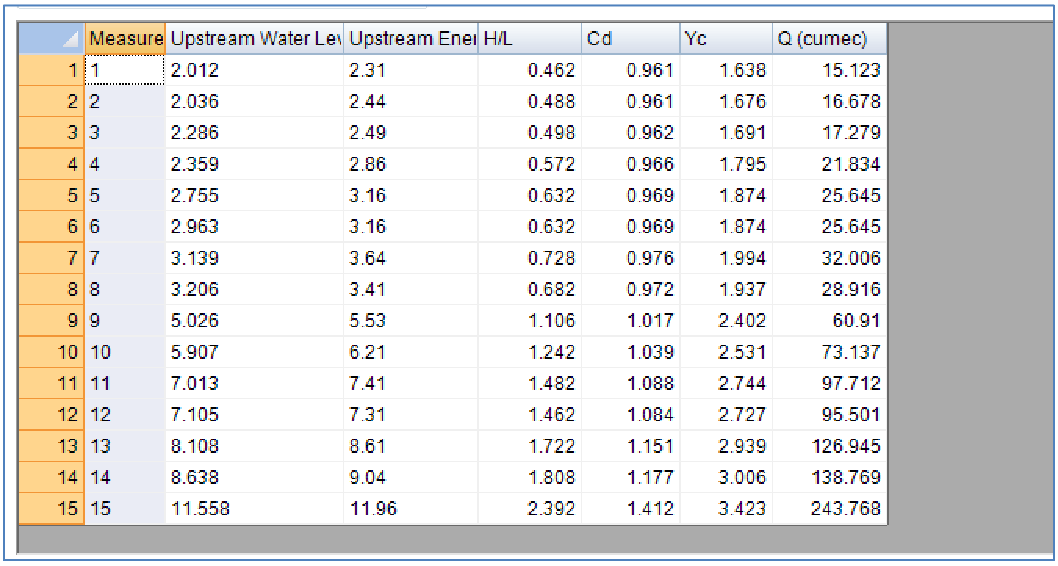
Figure 7. 15 : Input and Output of Trapezoidal Throated Flume

Test Example – 7.9

Rectangular/Triangular/Trapezoidal Flumes



	Parameter	Flumes				
		roated	Trapezoidal Throated	Rectangular/Triangular/Trapezoidal	Truncated Triangular	C
1	Length of Weir,L (m)					
2	Crest Width of Weir/Spillway,b (m)					
3	Bottom Angle V-shape (degree)					
4	A/A1					
5	Width of the Approach Channel,B (m)					
6	Height of Crest/Spillway,p (m)					
7	Slope Parameter (0 : Vertical)					
8	Radius of Weir Sill,r (m)					
9	Length of Flume (m)			5		
10	Width/Diameter of Flume (m)			1.5		
11	Side Slope of Flume (m/m)			0.7		
12	Modular Limit			0.85		
13	Height of Triangle (m)					
14	Depth of Flume (ft)					

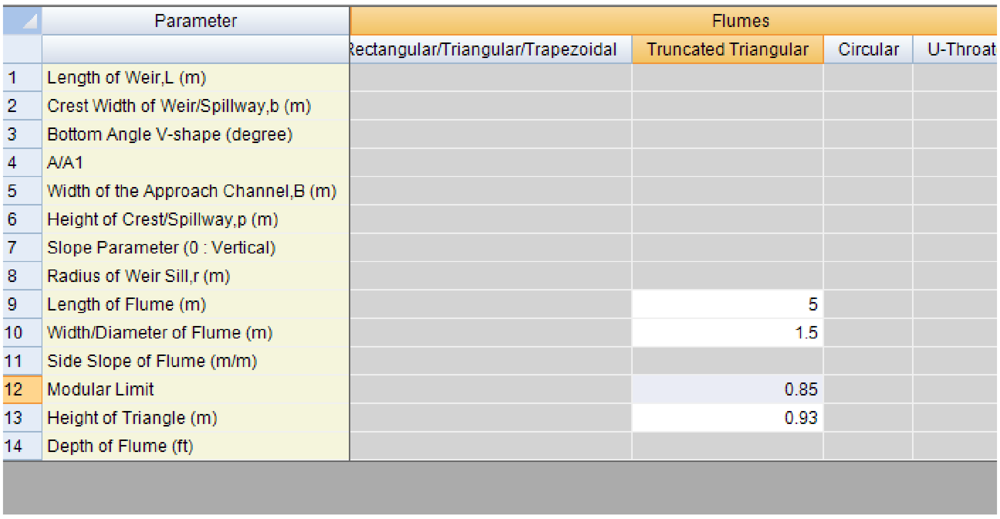


	Measure	Upstream Water Le	Upstream Ener	H/L	Cd	Yc	Q (cumec)
1	1	2.012	2.31	0.462	0.961	1.638	15.123
2	2	2.036	2.44	0.488	0.961	1.676	16.678
3	3	2.286	2.49	0.498	0.962	1.691	17.279
4	4	2.359	2.86	0.572	0.966	1.795	21.834
5	5	2.755	3.16	0.632	0.969	1.874	25.645
6	6	2.963	3.16	0.632	0.969	1.874	25.645
7	7	3.139	3.64	0.728	0.976	1.994	32.006
8	8	3.206	3.41	0.682	0.972	1.937	28.916
9	9	5.026	5.53	1.106	1.017	2.402	60.91
10	10	5.907	6.21	1.242	1.039	2.531	73.137
11	11	7.013	7.41	1.482	1.088	2.744	97.712
12	12	7.105	7.31	1.462	1.084	2.727	95.501
13	13	8.108	8.61	1.722	1.151	2.939	126.945
14	14	8.638	9.04	1.808	1.177	3.006	138.769
15	15	11.558	11.96	2.392	1.412	3.423	243.768

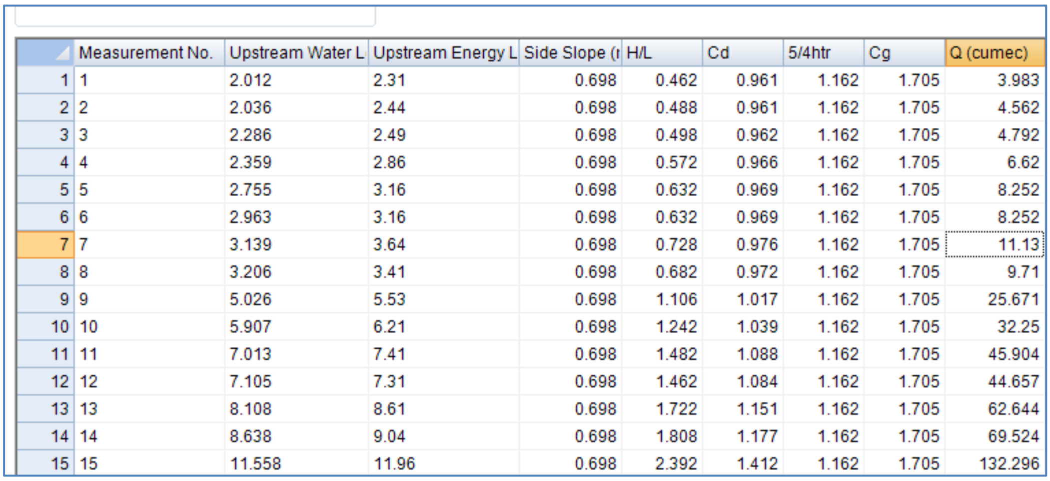
Figure 7. 16 : Input and Output of Rectangular/Triangular/Trapezoidal Flume

Test Example – 7.10

Truncated Triangular Flumes



	Parameter	Flumes			
		ectangular/Triangular/Trapezoidal	Truncated Triangular	Circular	U-Throat
1	Length of Weir,L (m)				
2	Crest Width of Weir/Spillway,b (m)				
3	Bottom Angle V-shape (degree)				
4	A/A1				
5	Width of the Approach Channel,B (m)				
6	Height of Crest/Spillway,p (m)				
7	Slope Parameter (0 : Vertical)				
8	Radius of Weir Sill,r (m)				
9	Length of Flume (m)		5		
10	Width/Diameter of Flume (m)		1.5		
11	Side Slope of Flume (m/m)				
12	Modular Limit		0.85		
13	Height of Triangle (m)		0.93		
14	Depth of Flume (ft)				

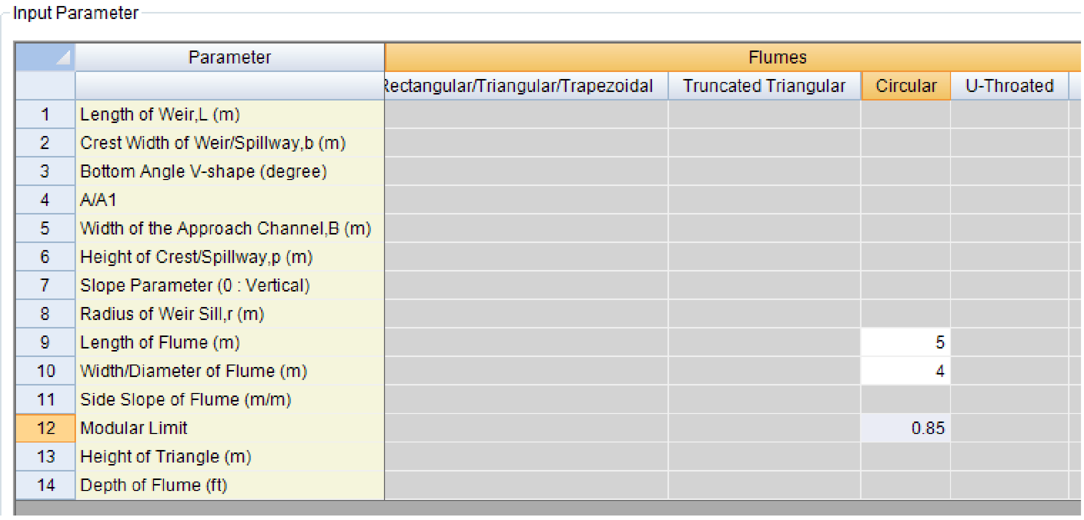


	Measurement No.	Upstream Water L	Upstream Energy L	Side Slope (	H/L	Cd	5/4htr	Cg	Q (cumec)
1	1	2.012	2.31	0.698	0.462	0.961	1.162	1.705	3.983
2	2	2.036	2.44	0.698	0.488	0.961	1.162	1.705	4.562
3	3	2.286	2.49	0.698	0.498	0.962	1.162	1.705	4.792
4	4	2.359	2.86	0.698	0.572	0.966	1.162	1.705	6.62
5	5	2.755	3.16	0.698	0.632	0.969	1.162	1.705	8.252
6	6	2.963	3.16	0.698	0.632	0.969	1.162	1.705	8.252
7	7	3.139	3.64	0.698	0.728	0.976	1.162	1.705	11.13
8	8	3.206	3.41	0.698	0.682	0.972	1.162	1.705	9.71
9	9	5.026	5.53	0.698	1.106	1.017	1.162	1.705	25.671
10	10	5.907	6.21	0.698	1.242	1.039	1.162	1.705	32.25
11	11	7.013	7.41	0.698	1.482	1.088	1.162	1.705	45.904
12	12	7.105	7.31	0.698	1.462	1.084	1.162	1.705	44.657
13	13	8.108	8.61	0.698	1.722	1.151	1.162	1.705	62.644
14	14	8.638	9.04	0.698	1.808	1.177	1.162	1.705	69.524
15	15	11.558	11.96	0.698	2.392	1.412	1.162	1.705	132.296

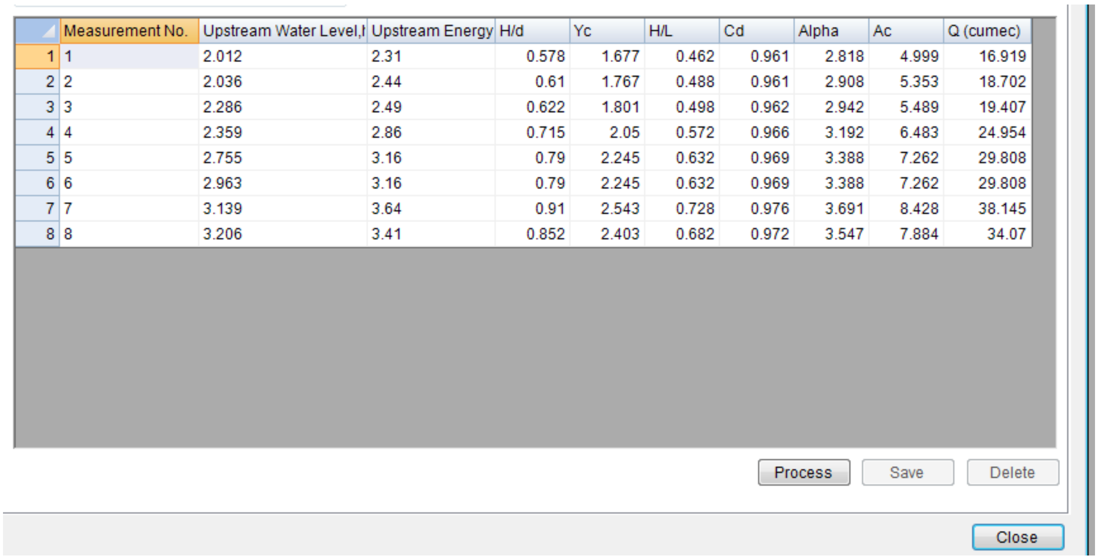
Figure 7. 17 : Input and Output of Truncated Triangular Flume

Test Example – 7.11

Circular Flumes


Input Parameter

	Parameter	Flumes			
		ectangular/Triangular/Trapezoidal	Truncated Triangular	Circular	U-Throated
1	Length of Weir,L (m)				
2	Crest Width of Weir/Spillway,b (m)				
3	Bottom Angle V-shape (degree)				
4	A/A1				
5	Width of the Approach Channel,B (m)				
6	Height of Crest/Spillway,p (m)				
7	Slope Parameter (0 : Vertical)				
8	Radius of Weir Sill,r (m)				
9	Length of Flume (m)			5	
10	Width/Diameter of Flume (m)			4	
11	Side Slope of Flume (m/m)				
12	Modular Limit			0.85	
13	Height of Triangle (m)				
14	Depth of Flume (ft)				

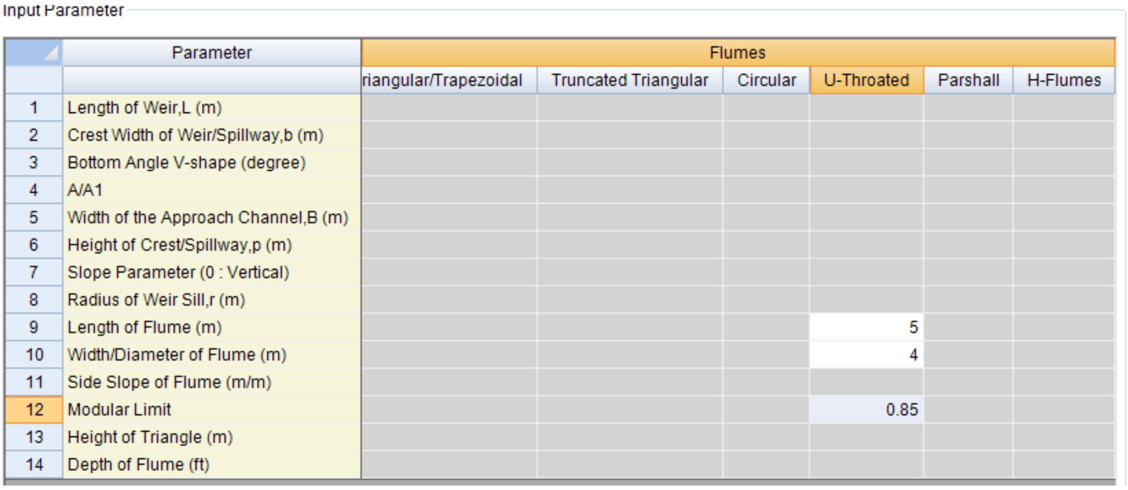


	Measurement No.	Upstream Water Level,I	Upstream Energy	H/d	Yc	H/L	Cd	Alpha	Ac	Q (cumec)
1	1	2.012	2.31	0.578	1.677	0.462	0.961	2.818	4.999	16.919
2	2	2.036	2.44	0.61	1.767	0.488	0.961	2.908	5.353	18.702
3	3	2.286	2.49	0.622	1.801	0.498	0.962	2.942	5.489	19.407
4	4	2.359	2.86	0.715	2.05	0.572	0.966	3.192	6.483	24.954
5	5	2.755	3.16	0.79	2.245	0.632	0.969	3.388	7.262	29.808
6	6	2.963	3.16	0.79	2.245	0.632	0.969	3.388	7.262	29.808
7	7	3.139	3.64	0.91	2.543	0.728	0.976	3.691	8.428	38.145
8	8	3.206	3.41	0.852	2.403	0.682	0.972	3.547	7.884	34.07

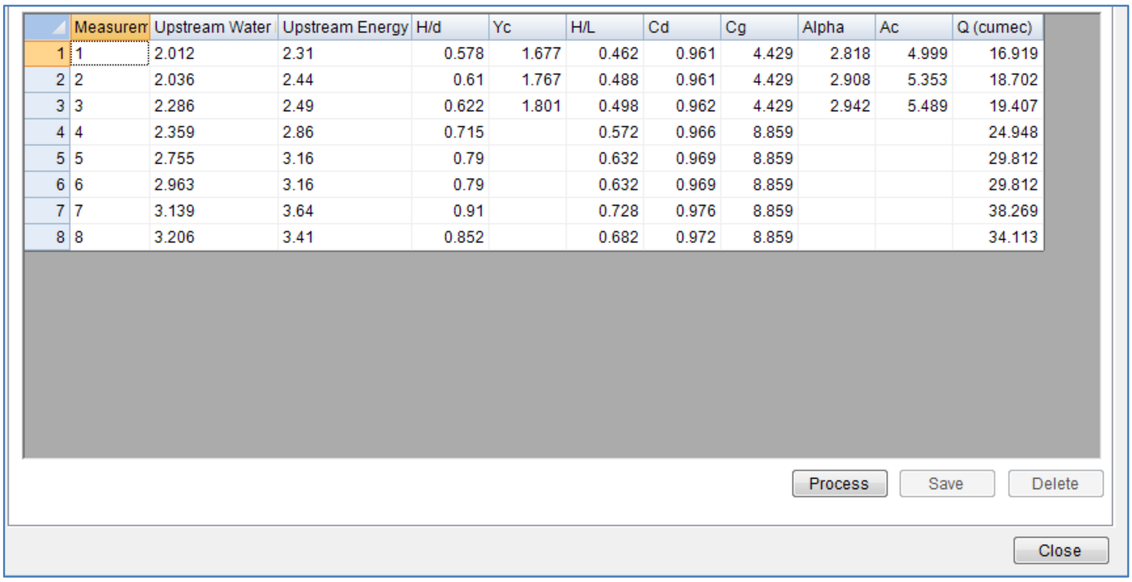
Figure 7. 18 : Input and Output of Circular Flumes

Test Example – 7.12

U-Throated Flumes


Input Parameter

	Parameter	Flumes					
		riangular/Trapezoidal	Truncated Triangular	Circular	U-Throated	Parshall	H-Flumes
1	Length of Weir,L (m)						
2	Crest Width of Weir/Spillway,b (m)						
3	Bottom Angle V-shape (degree)						
4	A/A1						
5	Width of the Approach Channel,B (m)						
6	Height of Crest/Spillway,p (m)						
7	Slope Parameter (0 : Vertical)						
8	Radius of Weir Sill,r (m)						
9	Length of Flume (m)				5		
10	Width/Diameter of Flume (m)				4		
11	Side Slope of Flume (m/m)						
12	Modular Limit				0.85		
13	Height of Triangle (m)						
14	Depth of Flume (ft)						

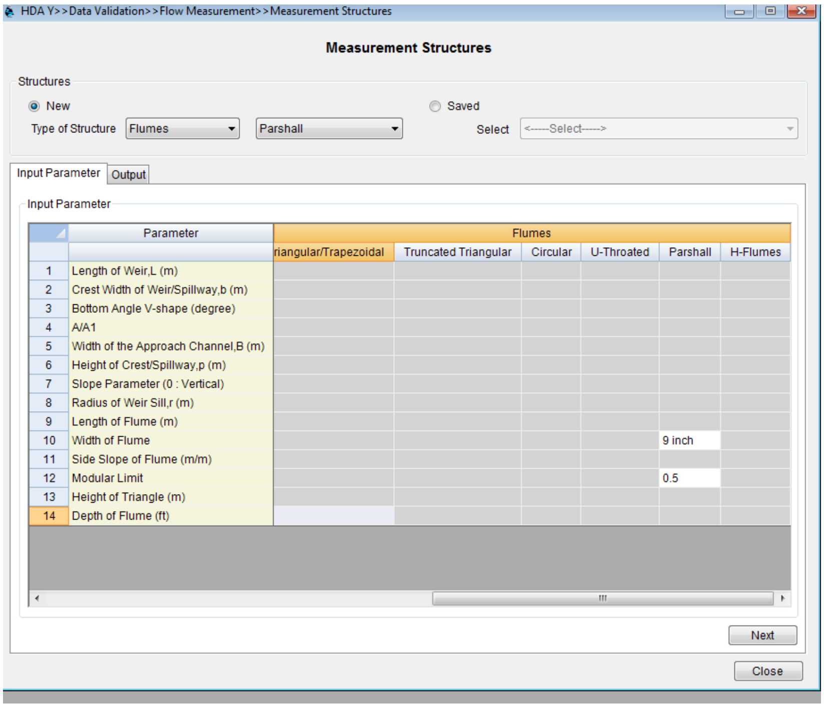


	Measurem	Upstream Water	Upstream Energy	H/d	Yc	H/L	Cd	Cg	Alpha	Ac	Q (cumec)
1	1	2.012	2.31	0.578	1.677	0.462	0.961	4.429	2.818	4.999	16.919
2	2	2.036	2.44	0.61	1.767	0.488	0.961	4.429	2.908	5.353	18.702
3	3	2.286	2.49	0.622	1.801	0.498	0.962	4.429	2.942	5.489	19.407
4	4	2.359	2.86	0.715		0.572	0.966	8.859			24.948
5	5	2.755	3.16	0.79		0.632	0.969	8.859			29.812
6	6	2.963	3.16	0.79		0.632	0.969	8.859			29.812
7	7	3.139	3.64	0.91		0.728	0.976	8.859			38.269
8	8	3.206	3.41	0.852		0.682	0.972	8.859			34.113

Figure 7. 19 : Input and Output of U-Throated Flumes

Test Example – 7.13

Parshall Flumes



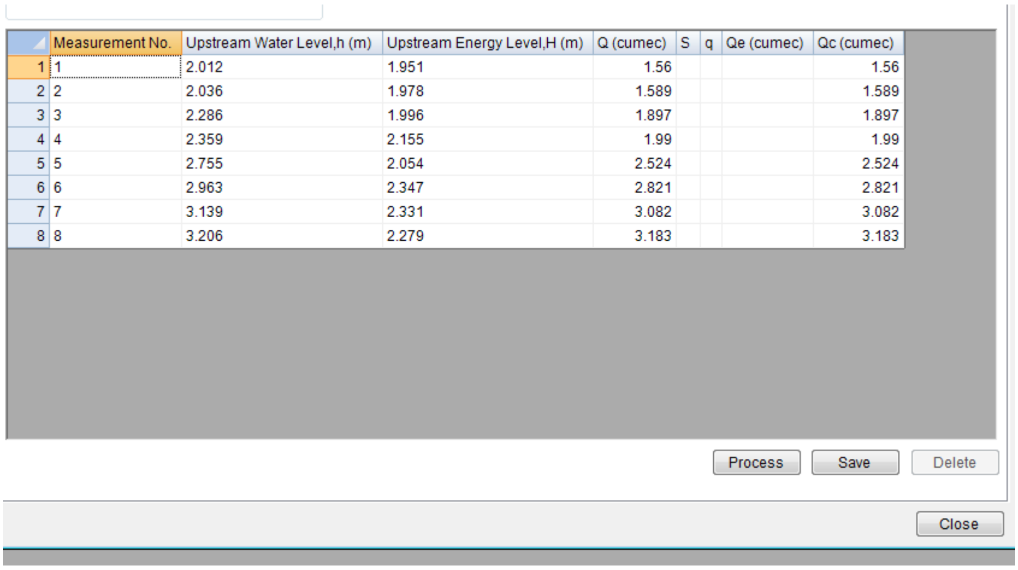
● New ○ Saved

Type of Structure: Flumes, Parshall

Select: <-----Select----->

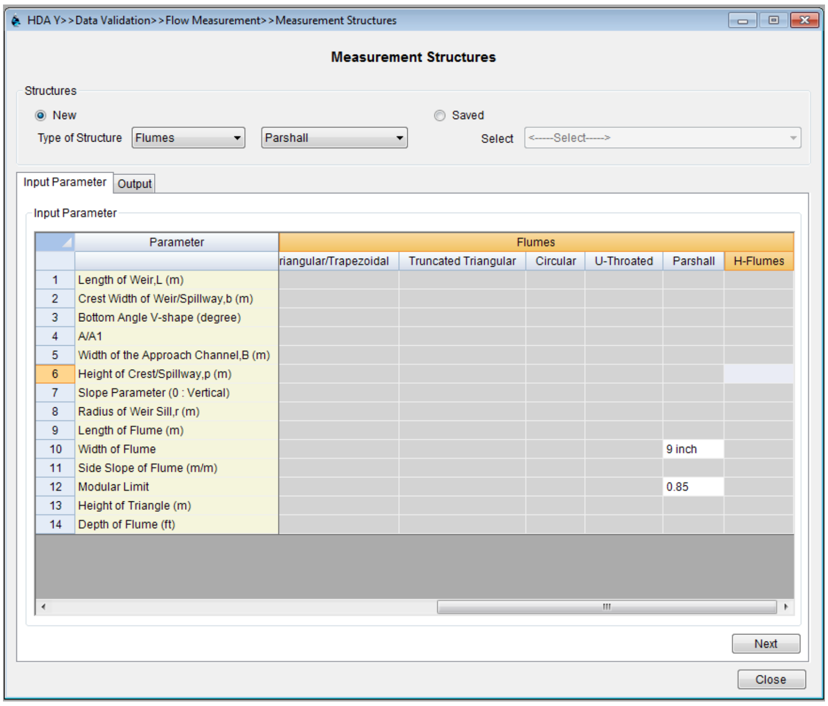
Input Parameter

	Parameter	Flumes					
		riangular/Trapezoidal	Truncated Triangular	Circular	U-Throated	Parshall	H-Flumes
1	Length of Weir,L (m)						
2	Crest Width of Weir/Spillway,b (m)						
3	Bottom Angle V-shape (degree)						
4	A/A1						
5	Width of the Approach Channel,B (m)						
6	Height of Crest/Spillway,p (m)						
7	Slope Parameter (0 : Vertical)						
8	Radius of Weir Sill,r (m)						
9	Length of Flume (m)						
10	Width of Flume					9 inch	
11	Side Slope of Flume (m/m)						
12	Modular Limit					0.5	
13	Height of Triangle (m)						
14	Depth of Flume (ft)						



	Measurement No.	Upstream Water Level,h (m)	Upstream Energy Level,H (m)	Q (cumec)	S	q	Qe (cumec)	Qc (cumec)
1	1	2.012	1.951	1.56				1.56
2	2	2.036	1.978	1.589				1.589
3	3	2.286	1.996	1.897				1.897
4	4	2.359	2.155	1.99				1.99
5	5	2.755	2.054	2.524				2.524
6	6	2.963	2.347	2.821				2.821
7	7	3.139	2.331	3.082				3.082
8	8	3.206	2.279	3.183				3.183

Figure 7. 20 : Input and Output of Parshall Flumes



Measurement Structures

Structures

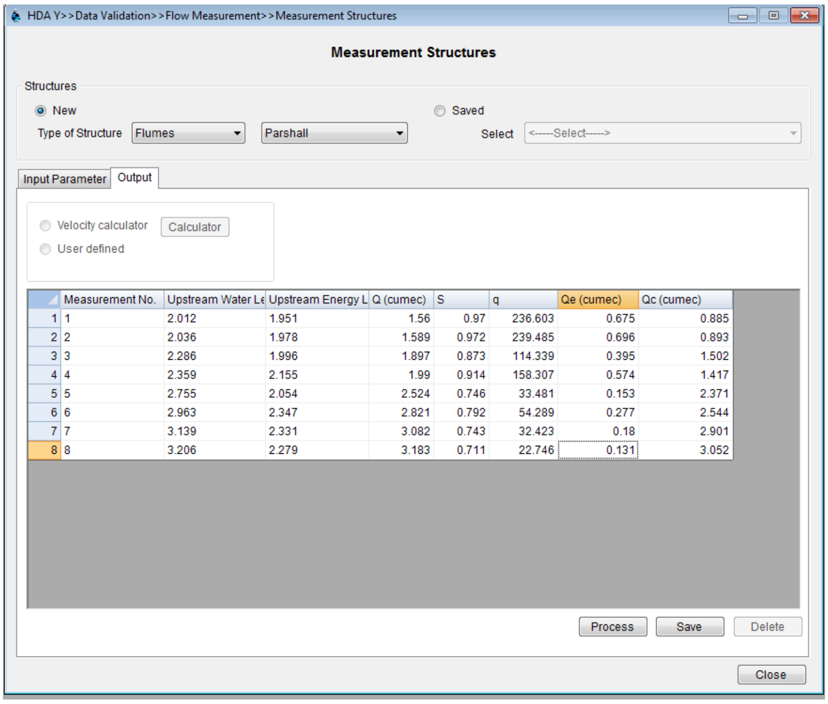
● New ○ Saved

Type of Structure: Flumes | Parshall

Select: <-----Select----->

Input Parameter

	Parameter	Flumes					
		riangular/Trapezoidal	Truncated Triangular	Circular	U-Throated	Parshall	H-Flumes
1	Length of Weir,L (m)						
2	Crest Width of Weir/Spillway,b (m)						
3	Bottom Angle V-shape (degree)						
4	A/A1						
5	Width of the Approach Channel,B (m)						
6	Height of Crest/Spillway,p (m)						
7	Slope Parameter (0 : Vertical)						
8	Radius of Weir Sill,r (m)						
9	Length of Flume (m)						
10	Width of Flume					9 inch	
11	Side Slope of Flume (m/m)						
12	Modular Limit					0.85	
13	Height of Triangle (m)						
14	Depth of Flume (ft)						



Measurement Structures

Structures

● New ○ Saved

Type of Structure: Flumes | Parshall

Select: <-----Select----->

○ Velocity calculator

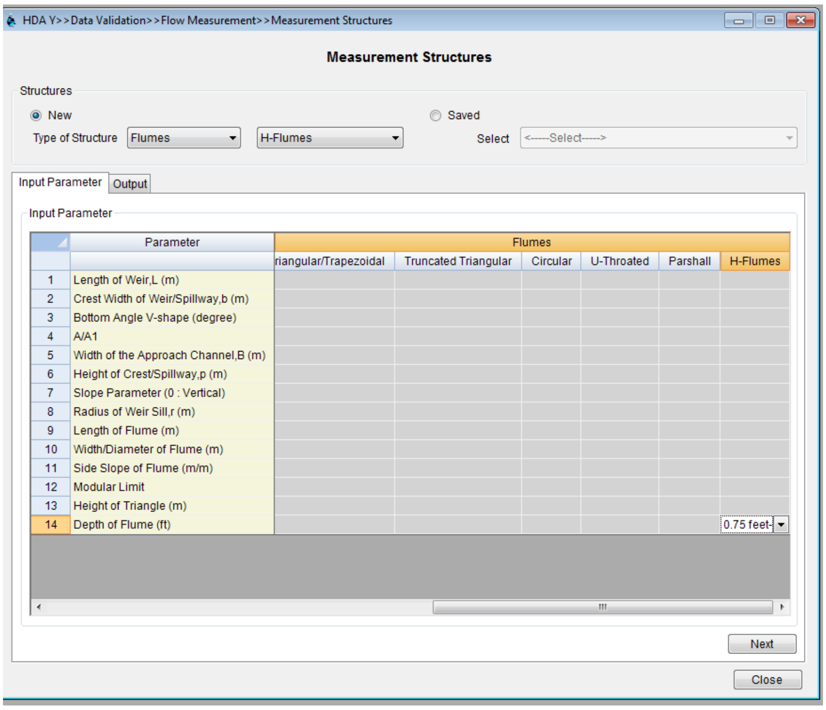
○ User defined

	Measurement No.	Upstream Water Le	Upstream Energy L	Q (cumec)	S	q	Qe (cumec)	Qc (cumec)
1	1	2.012	1.951	1.56	0.97	236.603	0.675	0.885
2	2	2.036	1.978	1.589	0.972	239.485	0.696	0.893
3	3	2.286	1.996	1.897	0.873	114.339	0.395	1.502
4	4	2.359	2.155	1.99	0.914	158.307	0.574	1.417
5	5	2.755	2.054	2.524	0.746	33.481	0.153	2.371
6	6	2.963	2.347	2.821	0.792	54.289	0.277	2.544
7	7	3.139	2.331	3.082	0.743	32.423	0.18	2.901
8	8	3.206	2.279	3.183	0.711	22.746	0.131	3.052

Figure 7. 21 : Input and Output of Parshall Flumes

Test Example – 7.14

H- Flumes



Measurement Structures

Structures

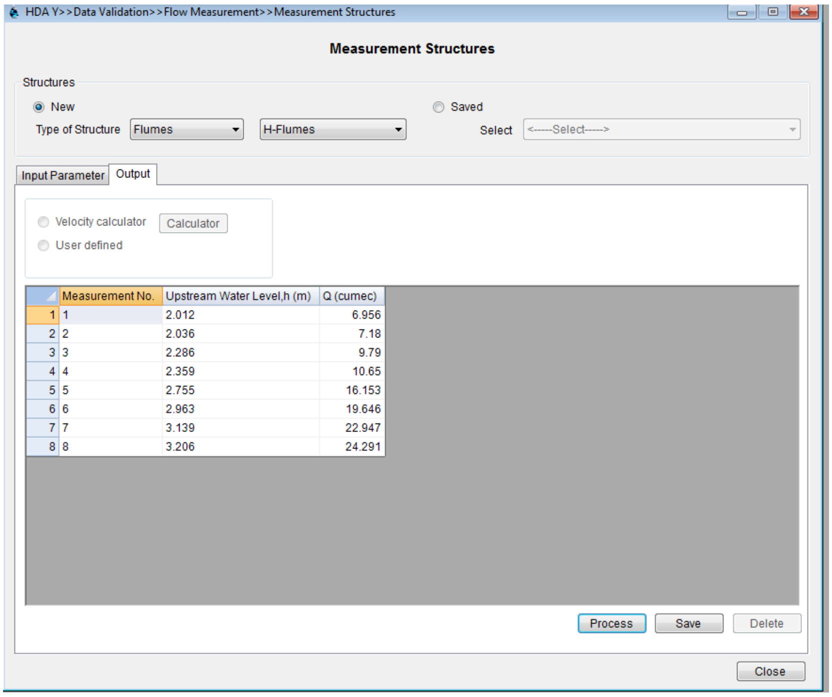
● New ○ Saved

Type of Structure: Flumes | H-Flumes

Select: <-----Select----->

Input Parameter

	Parameter	Flumes					
		riangular/Trapezoidal	Truncated Triangular	Circular	U-Throated	Parshall	H-Flumes
1	Length of Weir,L (m)						
2	Crest Width of Weir/Spillway,b (m)						
3	Bottom Angle V-shape (degree)						
4	A/A1						
5	Width of the Approach Channel,B (m)						
6	Height of Crest/Spillway,p (m)						
7	Slope Parameter (0 : Vertical)						
8	Radius of Weir Sill,r (m)						
9	Length of Flume (m)						
10	Width/Diameter of Flume (m)						
11	Side Slope of Flume (m/m)						
12	Modular Limit						
13	Height of Triangle (m)						
14	Depth of Flume (ft)						0.75 feet-



Measurement Structures

Structures

● New ○ Saved

Type of Structure: Flumes | H-Flumes

Select: <-----Select----->

○ Velocity calculator

○ User defined

	Measurement No.	Upstream Water Level,h (m)	Q (cumec)
1	1	2.012	6.956
2	2	2.036	7.18
3	3	2.286	9.79
4	4	2.359	10.65
5	5	2.755	16.153
6	6	2.963	19.646
7	7	3.139	22.947
8	8	3.206	24.291

Figure 7. 22 : Input and Output of H- Flumes

Contents

8 TIME SERIES MODEL 1
8.1. INTRODUCTION 1
8.2. SELECTION OF MODEL TYPE 1
8.3. IDENTIFICATION OF MODEL FORM 5
8.4. PARAMETER ESTIMATION 8
8.5. GOODNESS OF FIT FOR ARMA MODELS 9
8.6. GENERATION OF SYNTHETIC SERIES 9

8 TIME SERIES MODEL

8.1. INTRODUCTION

The objective of the stochastic streamflow generation is to develop sound historical naturalised streamflow dataset that is derived to represent the most relevant statistical characteristics of the historic series. A mathematical model representing stochastic process has been provided in HDA-Y as 'Time series model (TSM)". An important characteristic of a time series is 'stationarity'. A stochastic process is stationary in the mean or first order stationary if the expected values do not vary with time i.e. $E(X_1) = E(X_2) = E(X_3)$------$E(X_t) = \mu$, t=1,2,-----. A process is second order stationary when it is second order stationary in the mean and covariance. The modelling involves converting non-stationary time series into stationary time series. This is done by successively removing trend and periodicity from the observed series.

A time series can be divided into deterministic and stochastic components. While the deterministic component can be further decomposed into trend and periodicity, the stochastic component comprises of sequentially dependant and random parts. The sequentially dependant part of time series can be modelled as

a. Autoregressive (AR) process
b. Moving Average (MA) process
c. Autoregressive Moving Average (ARMA) process

The modelling involves converting non-stationary time series to a stationary time series. The essential step in this process is to capture the various statistical properties inherent to the natural historical streamflow sequence. This is achieved in TSM by selecting the appropriate statistical distribution models and parameter sets that can best be described in four steps as below:

- Selection of model type
- Identification of model form
- Estimation of model parameters
- Testing goodness of fit of the model

8.2. SELECTION OF MODEL TYPE

The statistical characteristics of the samples of hydrological series are important deciding factors in the selection of the type of model.

Some salient statistical functions are defined by :

Mean

$$M_X = \frac{1}{N}\sum_{1}^{N} X_i$$

Standard Deviation

$$S_X = \sqrt{\frac{\sum (X_i - M_X)^2}{N-1}}$$

Skewness

$$C_{SX} = \frac{N}{(N-1)(N-2)} \sum_{1}^{N} \frac{(X_i - M_x)^3}{S_X^3}$$

Where,

X_i = Time Series
M_x = Mean of Time Series
S_x = Standard Deviation of the Series
N = Total No. of years

The p^{th} order linear AR model of z_t is represented by

$z_t = \Phi_1 z_{t-1} + \Phi_2 z_{t-2} + \ldots\ldots\ldots + \Phi_p z_{t-p} + R_t$

The q^{th} order linear MA model of z_t is represented by

$z_t = R_t + \theta_1 R_{t-1} + \theta_2 R_{t-2} + \ldots\ldots\ldots + \theta_q R_{t-q}$

The $(p,q)^{th}$ order linear ARMA model of z_t is represented by

$z_t = \Phi_1 z_{t-1} + \Phi_2 z_{t-2} + \ldots\ldots\ldots + \Phi_p z_{t-p} + R_t - \theta_1 R_{t-1} - \theta_2 R_{t-2} \ldots\ldots\ldots - \theta_q R_{t-q}$

There are two important functions at the model identification stage.

8.2.1. Autocorrelation function ACF

The autocovariance function measures the degree of linear dependence of a time series. The autocovariance C_k between x_t and x_{t+k} is determined by

$$C_k = \frac{1}{(N)} \sum_{t=1}^{N} (X_t - \overline{X})(X_{t+k} - \overline{X})$$

Where k represents the time lag between the correlated pairs X_t and X_{t+k}. For k=0, Co becomes the Variance. A dimensionless measure of linear dependence is obtained by dividing Ck by Co .

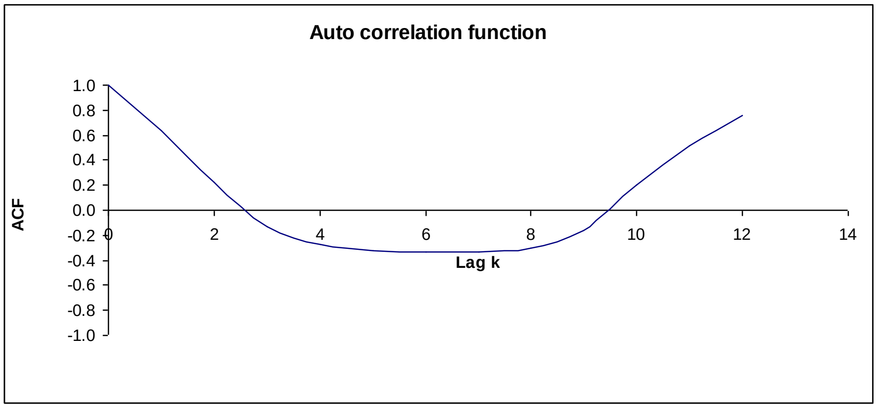
$$r_k = \frac{C_k}{C_0} = \frac{\sum_{t=1}^{N-K} (X_t - \overline{X})(X_{t+k} - \overline{X})}{\sum_{t=1}^{N} (X_t - \overline{X})^2}$$

Wkere rk is called Autocorrelation Coefficient or ACF.. Because the ordered pairs are drawn from the same time series, r_k is also called serial or autocorrelation co-efficient.

An alternate estimate of ACF is

$$r_k = \frac{\sum_{t=1}^{N-K} (X_t - \overline{X})(X_{t+k} - \overline{X})}{\left[\sum_{t=1}^{N-K} (X_t - \overline{X}_t)^2 (X_{t+k} - \overline{X}_{t+k})^2 \right]^{\frac{1}{2}}}$$

The plot of r_k vs. k is defined as a correlogram. A correlogram always starts with unity at the origin.



8.2.2. Partial Autocorrelation function PACF

The partial autocorrelation coefficient PACF in an AR process of order k is a measure of the linear association between z_t and z_{t+k} for $t \leq k$ .This relationship can be represented by :

$z_{t+k} = \varphi_1 z_{t+k-1} + \varphi_2 z_{t+k-2} + \ldots\ldots\ldots + \varphi_k z_t + R(t)$

Therefore, φ_k is a measure of relationship between z_t and z_{t+k} in the k-th order autoregressive process after accounting for the terms z_{t+k-1} to z_{t+1} .

A computationally efficient menthod for estimation of φ_k is Yule Walker equation. The Yule Walker (or difference) equation for an AR(k) model is :
$\rho_k = \varphi_1 \rho_{k-1} + \varphi_2 \rho_{k-2} + \varphi_3 \rho_{k-3} + \ldots\ldots\ldots + \varphi_p \rho_{k-p}$, k=1,……,p (1)

The above constitutes the set of linear equations :
$\varphi_1(k) \rho_0$ e+ $\varphi_2(k) \rho_1 + \ldots\ldots\ldots + \varphi_k(k) \rho_{k-1} = \rho_1$
$\varphi_1(k) \rho_0 + \varphi_2(k) \rho_1 + \ldots\ldots\ldots + \varphi_k(k) \rho_{k-1} = \rho_1$
$\varphi_1(k) \rho_0 + \varphi_2(k) \rho_1 + \ldots\ldots\ldots + \varphi_k(k) \rho_{k-1} = \rho_1$
. . . .
. . . .
. . . .
. . . .
$\varphi_1(k) \rho_{k-1} + \varphi_2(k) \rho_{k-2} + \ldots\ldots\ldots + \varphi_k(k) \rho_0 = \rho_k$

which may be written as :

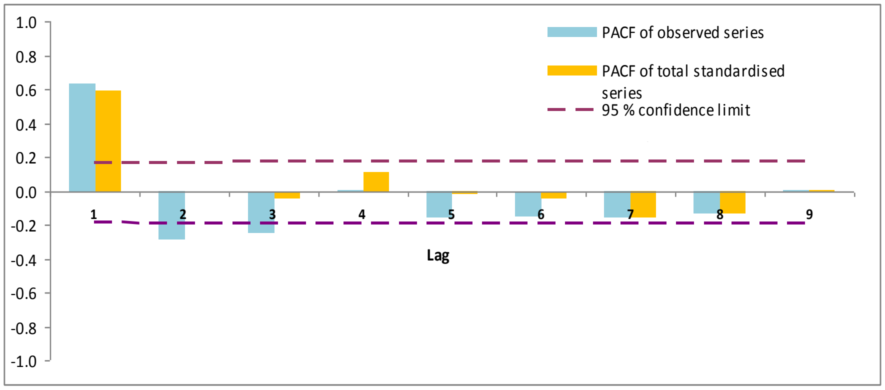
$$\begin{array}{cccccccc}
1 & \rho_1 & \rho_2 & \cdots & \rho_{k-1} & \varphi_1 & & \rho_1 \\
\rho_1 & 1 & \rho & \cdots & \rho_{k-2} & \varphi_2 & & \rho_2 \\
\rho_2 & \rho_1 & 1 & \cdots & \rho_{k-3} & \varphi_3 & & \rho_3 \\
. & . & . & & . & . & = & . \\
. & . & . & & . & . & & . \\
. & . & . & & . & . & & . \\
\rho_{k-1} & \rho_{k-2} & \rho_{k-3} & \cdots & 1 & \varphi_k & & \rho_k
\end{array}$$

or,

$$P_k \varphi_k = \rho_k$$

$$\varphi_k = P_k^{-1} \rho_k$$

Thus the partial autocorrelation function φ_k is determined by successively applying eqn 1 .



The low flow of the dry season mainly result from groundwater effluence. They have relatively small variation which may be represented by an autoregressive (AR) process . The high flows are formed mainly by large rainfall or snowmelts or both. This mixed behaviour could be modelled by adding a moving average (MA) component to the autoregressive (AR) component. The principle tool for model identification are Visual display of the original series and behaviour of the auto correlation function coupled with that of the partial autocorrelation function. For an AR process, the ACF tails off exponentially or damped sine wave where as the PACF cuts off to zero. In MA, it is the reverse i.e. ACF cuts off while PACF tails exponentially or shows damped sine wave. Series with low decaying correlogram (long memory) can be modelled by ARMA rather than AR model as ARMA may come out with a smaller number of parameters to estimate than the auto regressive model of higher order.

ARMA modelling procedure has been developed in TSM of HDA.

8.3. IDENTIFICATION OF MODEL FORM

A visual inspection of a display of the original series may reveal the presence of a trend, persistence, long term cycle or outliers.

8.3.1. Testing and removal of Trend

Inconsistency (systematic errors) and non-homogeneity (natural disruptive or human induced changes) are mainly responsible for the over year trends or for sudden changes. It is important to identify and remove them before determining the series characteristics. In TSM, the trend component of the observed series is estimated by developing linear regression. A t-test of the slope of regression line establishes the presence of non-homogeneity.

The trend free series is obtained as X_t = Qt-(Q_0 –at) at t=1,12N

Where, Q_t = Time series, N=Number of year, Q_0 and a are coefficients of linear regression line.

Subsequent modeling of the time series is performed using X_t

8.3.2. Transformation to Normality

Several tests are available for testing the hypothesis that a given series is normal. Among statistical tests, Skewness test of normality is a simple and sufficiently accurate test. It is based on the fact that skewness coefficient for a normal variable is zero.

Table of Skewness Test of Normality (After Snedecor and Cochran , 1967, pp552) has been used to identify the skewness in the series for sample size less than 150. If skewness of a time series $\hat{g} < g_\alpha(N)$, the hypothesis of normality is established.

Table of Skewness Test for Normality

	Significance level α			Significance level α	
N	.02	.1	N	0.02	0.1
25	1.061	0.711	70	0.673	0.459
30	0.986	0.662	80	0.631	0.432
35	0.923	0.621	90	0.596	0.409
40	0.870	0.587	100	0.567	0.389
45	0.825	0.558	125	0.508	0.350
50	0.787	0.534	150	0.464	0.321
60	0.723	0.492	175	0.430	0.298

If a time series is skewed then a transformation function Box-Cox transformation is to be used to transform into normal series. Let us consider the original periodic series $x_{v,\tau}$ where v denotes the year, τ = 1,2…, ω and ω (number of time interval in the year) = 12. Then transformed normal series $y_{v,\tau}$ can be obtained as

$$y_{v,\tau} = {(x_{v,\tau}^{\lambda_\tau} - 1)}/{\lambda_\tau} \qquad \lambda_\tau \neq 0$$

$$y_{v,\tau} = \log x_{v,\tau} \qquad \lambda_\tau = 0$$

where,

$y_{v,\tau}$ = transformed normal series

λ = transformation constant

8.3.3. Removal Of Within Year Periodicity

The presence of cycles in a simple plot of data Xt or Qt is usually an adequate indicator of periodicity. However, hydrologic series are mostly periodic

The estimates of the periodic mean $\bar{y}_\tau$ and periodic standard deviation S_τ can be determined in the following way :

$$\bar{y}_\tau = \frac{1}{N}\sum_{v=1}^{N} y_{v,\tau}$$

$$S_\tau = \sqrt{\frac{1}{N-1}\sum_{v=1}^{N}(y_{v,\tau} - \bar{y}_\tau)^2}$$

$y_{v,\tau}$ = transformed normal series.

$\bar{y}_\tau$ = Mean of normal series

S_τ = Standard deviation of normal series

N = Total No. of years

v = year 1,2,3….N

8.3.4. Standardisation

From the sample estimates, standardisation $Z_{v,\tau}$ and total standardisation is carried out to develop the series $z_{v,\tau}$ by

$$Z_{v,\tau} = \frac{y_{v,\tau} - \bar{y}_\tau}{S_\tau}$$

$$z_{v,\tau} = \frac{Z_{v,\tau} - M}{S}$$

$Z_{v,\tau}$ = Standardised series

$z_{v,\tau}$ = Total Standardised series

M = Mean of Standardised series $Z_{v,\tau}$

S = Standard Deviation of Standardised series $Z_{v,\tau}$

$y_{v,\tau}$ = Transformed normal series.

By removing the periodicity in the mean and in the standard deviation the series $\mathbf{z_{v,\tau}}$ becomes stationary provided the autocorrelation function is approximately stationary. $\mathbf{z_{v,\tau}}$ series may be represented by an ARMA model with either constant or time varying (periodic) coefficient.

Periodic hydrologic series have periodicity in the mean and standard deviation. They may be symmetric or skewed with either constant or periodic skewness, and may have autoregressive time dependence structure with either constant or periodic autoregression coefficients.

Lag k correlation coefficient and lag k Auto covariance (C_0, C_1, C_2, C_3……C_{12}) are derived for the total standardised series as shown in Figure.

$$r_k(z) = \frac{\sum_{t=1}^{N} [\![(z]\!]_t - \bar{z}_t) * (z_{t+k} - \bar{z}_{t+k})}{\sqrt{\sum_{t=1}^{N} [\![(z]\!]_t - \bar{z}_t)^2 * \sum_{t=1}^{N} [\![(z]\!]_{t+k} - \bar{z}_{t+k})^2}}$$

$\bar{z}_t$ = Mean of total Standardised series

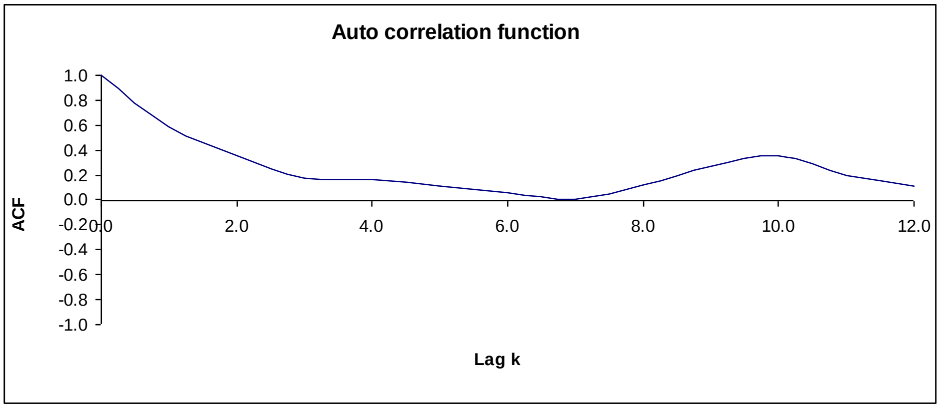
$\bar{z}_{t+k}$ = Mean of total Standardised series for $(t+k)$

k = Lag

$r_k(z)$ = Lag k auto correlation coefficient of total Standardised series

t $= 1,2,3 \ldots\ldots N$

N = Total no. of observations



$$C_k = \frac{\sum_{t=1}^{N} (z_t * z_{t+k})}{N-k}$$

C_k = **Lag k auto covariance of total Standardised series** .

ARMA(p, q) model with constant coefficient

$$z_t = \sum_{j=1}^{p} \emptyset_j * z_{t-j} - \sum_{i=1}^{q} \theta_i * \varepsilon_{t-i} + \varepsilon_t$$

Where,

$\emptyset \text{ and } \theta$ are the coefficients of the model and ε_t is the independent normal variable.

The ARMA (1,1) model has been used extensively in hydrology

$z_t = (\emptyset_1 * z_{t-1}) + \varepsilon_t - (\theta_1 * \varepsilon_{t-1})$

8.4. PARAMETER ESTIMATION

The parameters are, estimated at two levels of increasing accuracy: a preliminary estimate followed by a likelihood method.

Preliminary estimate

Autoregression AR coefficients $\llbracket(\emptyset\rrbracket_{1})$

$$\emptyset_1 = \frac{r_2}{r_1}$$

$r_1 and\ r_2$ = Lag 1 and 2 auto correlation of total standardised series.

Moving Average MA coefficient $\llbracket(\theta\rrbracket_{1})$

$$C_0' = (1 + \emptyset_1^2)C_0 - 2\emptyset_1 C_1$$

$$C_1' = (1 + \emptyset_1^2\ )C_1 - \emptyset_1(C_2 + C_0)$$

$$\theta_1 = \frac{-C_1'}{\sigma_\varepsilon^2}$$

$$\sigma_\varepsilon^2 = \frac{C_0'}{1 + \emptyset_1^2}$$

$C_0, C_1 and\ C_2$ = Lag 0,1 and 2 auto covariance of total standardised series.

θ_1 = MA coefficient.

σ_ε^2 = Residual variance

Maximum Likelihood estimates

Having obtained preliminary estimates of parameters of tentative model, efficient estimates of the parameters are needed that take into account all the information contained in the data.

For judiciously selected values of $\llbracket(\emptyset\rrbracket_{1})$ and $\llbracket(\theta\rrbracket_{1})$ in the neighbourhood of the initial estimates calculate the residuals and the sum of square of residual series. The maximum likelihood corresponds to the minimum of the sum of the squares of residual.

$\varepsilon_t = z_t - (\emptyset_1 * z_{t-1}) + (\theta_1 * \varepsilon_{t-1})$

$S(\theta, \emptyset) = \sum_{t=1}^{N} (\varepsilon_t)^2$

$\sigma_\varepsilon^2 = \frac{1}{N} S(\theta, \emptyset)$

ε_t = Residual series

$S(\theta,\emptyset)$ = Sum of square of residuals.
σ_ε^2 = Final estimate of Residual variance

8.5. GOODNESS OF FIT FOR ARMA MODELS

Once the parameters of the identified model have been estimated, the next phase is to verify the validity of the model. For most of the hydrologic time series, for example for flow series, the underlying physics involves many phenomena and their interactions, such as rainfall, interception, detention, infiltration, snowmelt, groundwater flow, evapotranspiration, etc. Most of these phenomena have variations in time and space, and their representation by stochastic process is too complex to be expressed in simple lumped models. As a result, there is a need of non subjective criteria for the selection between competing models for the same phenomena. A common rule for choosing between models is the principle of parsimony of parameters, which requires a model with the smallest number of parameters. One criteria for selecting among competing ARMA (p,q) models is the Akaike information criteria. The Akaike information criterion is a measure of the relative goodness of fit of a statistical model considering the principle of parsimony in model building, proposed by Hirotsugu Akaike (1974). For comparing among competing ARMA (p,q) models he used

$$AIC\ (p,q) = N\ ln(\sigma_\varepsilon^2) + 2(p+q)$$

N = sample size
σ_ε^2 = Maximum likelihood estimate of the residual variance.
Under this criterion the preferred model is the one with the minimum AIC value.

8.6. GENERATION OF SYNTHETIC SERIES

Once the ARMA model has been selected it may be used for generation of synthetic data. The series is generated by the formula

ARMA (p,q)

$$z_t = \sum_{j=1}^{p} \emptyset_j * z_{t-j} - \sum_{i=1}^{q} \theta_i * \varepsilon_{t-i} + \varepsilon_t$$

ARMA (1,1)

$$z_t = (\emptyset_1 * z_{t-1}) + \varepsilon_t - (\theta_1 * \varepsilon_{t-1})$$

After synthetic series generation, an Inverse Standardization is needed to produce the normalised series $y_{v,\tau}$. Likewise , if a transformation such as logarithmic transformation has been used to obtain the $y_{v,\tau}$ series, an inverse transformation , i.e. exponentiation, is necessary to obtain the desired series $X_{v,\tau}$

$$Z_{v,\tau} = \frac{z_{v,\tau} * S}{M}$$

$$y_{v,\tau} = \frac{Z_{v,\tau} * S_\tau}{\bar{y}_\tau}$$

$$X_{v,\tau} = [(y_{v,\tau} * \lambda_\tau) + 1]^{1/\lambda_\tau}$$