CHAPTER 6

WATER RESOURCES SYSTEMS MODELING – STATUS AND FUTURE DIRECTIONS

6.1 Introduction

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

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

6.2 What is a Water Resources System?

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

6.2.1 Classification

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

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

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

6.2.2 Approaches for WRS modeling

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

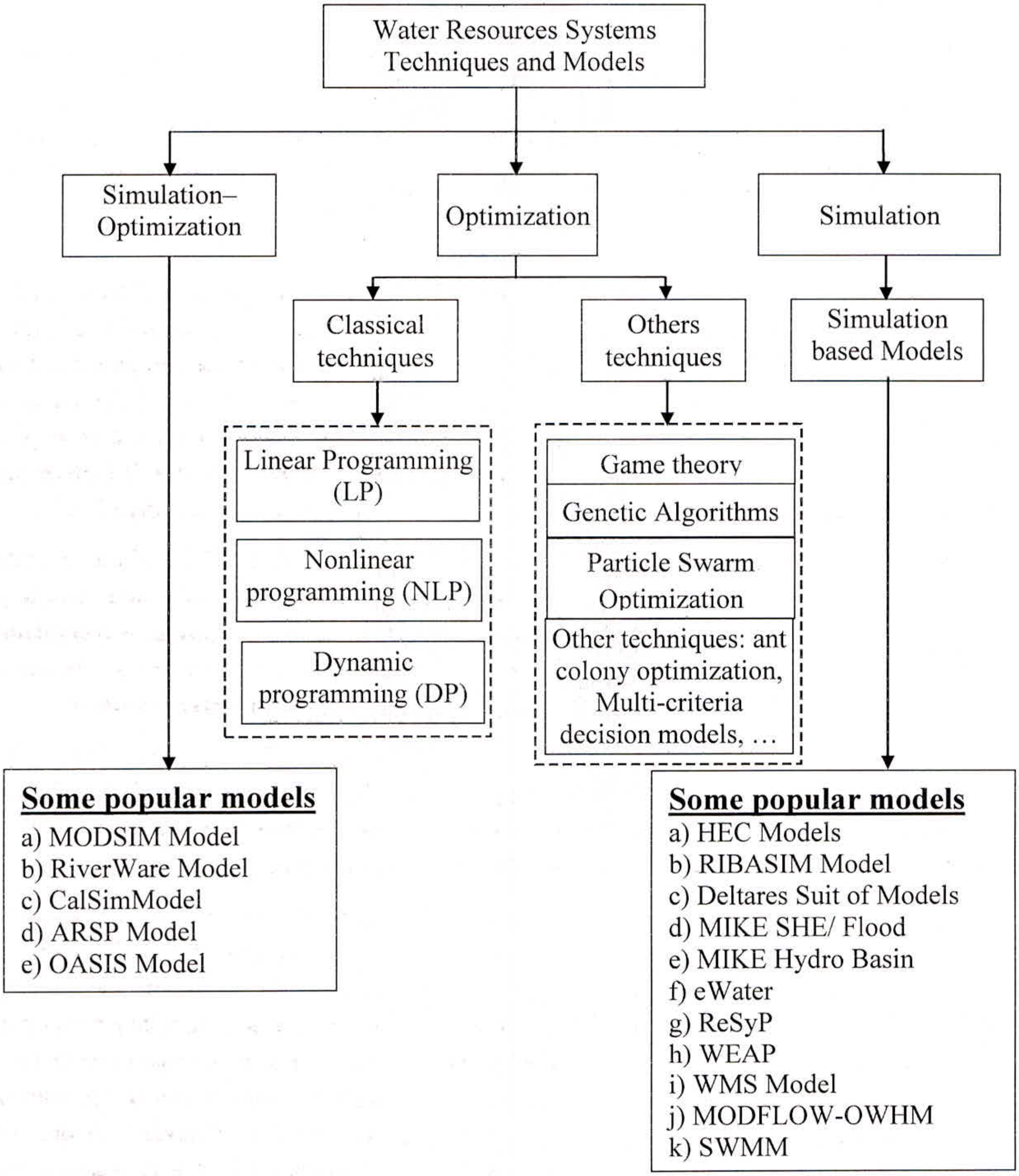


Figure 6.1: Classification of WRS models

6.3 Simulation

Normally, the structure or behavior of the system being studied is so complex that its analytical solution is not possible. Simulation is the process of duplicating the behavior of an existing or proposed system. It consists of designing a model of the system and conducting experiments with this model either for better understanding of the functioning of the system or for evaluating various strategies for its management.

The essence of simulation is to reproduce the behavior of the system in every important aspect to learn how the system will respond to conditions that may be imposed on it or may occur in the future. The main advantage of simulation models lies in their capacity to accurately describe the reality. The proposed configurations of projects can be assessed to judge whether their performance would be adequate or not before investments are made. Likewise, operating policies can be tested before they are implemented in actual situations.

A simulation model of a water resource system simulates its operation with a defined operation policy, using the parameters of physical and control structures, time series of flows, demands, and the variables describing water quality, etc. The evaluation of the design parameters or operation policy is through the objective function (flow or demand related measures or economic indices) or some measure of reliability. Since simulation models do not use an explicit analytical procedure to determine the best combination of the controlling variables, it is necessary to proceed by trial and error or follow a strategy of parameter sampling (Jain and Singh 2003).

Simulation models may be categorized as: a) physical (a scale model of a spillway operated in a hydraulics laboratory), b) analog (a system of electrical components, resistors and capacitors, arranged to act as analog of pipe resistances and storage elements), c) mathematical (a compilation of equations and logical statements that represent the actions of a system's elements). Mathematical simulation models are very useful and popular in the field of water resources.

Simulation models can also be classified as static or dynamic. Dynamic models take into account the changing parameters of the system (structures and facilities) and the variations in their operation. These are assumed as fixed in static models. The development and application of dynamic models is a more involved exercise and often static models give acceptable results.

Many hydrological variables are stochastic in character. Deterministic and stochastic simulation models are distinguished by the way this stochasticity is accounted for. A time-series of gauged flows represents a sample of the stochastic process. Under certain conditions, deterministic simulation models can be used with confidence. For example, if measured monthly flows for a period of 40 years are used as input in simulation and the system has not undergone large changes, a deterministic model may be adequate. If the process is stationary, the sample can be considered a reasonably good characterization of the stochastic process. But a number of model's results with synthetically generated sequences of inflows give a very good indication of the expected system performance.

Simplification in system representation can also be achieved by neglecting variables that do not impart a decisive impact on the system behavior. If the output is not sensitive to the variation of certain variables, these can be considered as constants.

The modeling of a continuous process by a discrete model involves the assumption that the continuous changes during a defined period take place instantly at the end or at the beginning of the period. The decision-making process in water resource systems is discrete; simulation models are also discrete models. The real-life process, however, is continuous. Therefore, the time step size is an important aspect of the model and should be chosen carefully. This choice depends on the degree of aggregation and the time variability of inputs.

Event scanning and periodic scanning are two common ways of time management in simulation models. In the event scan approach, the clock is advanced by the amount necessary to trigger the occurrence of the next, most imminent event, not by some fixed, predetermined interval. The time step size also depends on the water uses. For example, operation of irrigation systems may be simulated with 10-day to 15-day time intervals whereas hydropower systems typically use a daily interval. Flood control systems are simulated with sub-daily intervals such as 3-hour or even smaller. This approach requires some scheme for determining when events are to occur. The periodic scan technique adjusts the simulation clock by one predetermined uniform unit and then examines the system to determine whether any event occurred during that interval. If any occurred, the event or events are simulated; otherwise no action is taken. The simulation clock is then advanced another unit, and the process is repeated. However, it requires some scheme to determine the time when the events take place (Pooch and Wall 1992).

Following are the steps in development and application of a simulation model: a) Define the problem, b) Describe the water resource system and its hydrological relationships, c) Decide the model structure, input, and output, d) Test the model; if it is not suitable, go to step 'c', and then e) Apply the model to the problem. If an existing model is being used, then steps 'c' to 'e' can be skipped. After the model of a system is developed and tested, experiments are conducted with it to investigate various scenarios or answer the question "WHAT IF?". The simulation models are much helpful in understanding the consequences or implications of changing one or more of the decision variables.

A detailed multi-reservoir simulation was executed by Jain et al. (2005) for analysis and design of a large inter-basin water transfer system in India. The authors presented the complexities involved in planning a large inter-basin water transfer scheme and demonstrated the efficacy of simulation modeling approach in finding acceptable and efficient solutions.

Lee et al. (2011) applied a simulation-operation method for finding a trade-off between flood control and reservoir filling objectives under a climatic change scenario in the Columbia River basin. Yang et al. (2015) have analyzed and identified the water-related issues including population, economy, land change, water demand, water supply, wastewater, and water quality. Relationships among and within these issues were formulated based on mathematical models as well as equations of water resource used for effective solution. Calibrated and validated model was used to investigate optimum water-use strategy in Laoshan District of China.

A simulation-based optimization model was proposed to maximize multiple benefits, such as flood control, hydropower generation and navigation by Liu et al. (2015). Using the data of the China's Three Gorges Reservoir (TGR), the proposed method was demonstrated to provide an effective design for the seasonal flood limited water level (FLWL).

6.4 Optimization

Optimization is a popular subject in water resources studies. It has been widely applied as a solution tool for water resources systems planning and management. The term "optimization" is often used synonymously with mathematical programming to refer to a mathematical expression in which a standard algorithm is applied to calculate a set of decision variables that minimize or maximize an objective function subject to the constraints. Optimization techniques are covered in numerous books (Loucks et al. 1981; Jain and Singh 2003). Although optimization and simulation are alternative modeling approaches with different characteristics, the distinction is somewhat obscured by the fact that most models contain elements of both approaches. All optimization models also simulate some important features of the system. Simulation models are advantageous precisely because optimization models cannot handle all complexities of a system whereas simulation models can, to a great extent. An optimization approach may involve numerous iterative executions of a simulation model, possibly with the iterations being automated to various degrees. Mathematical programming algorithms are embedded within many simulation models to perform certain computations.

The objective function of an optimization model may be a penalty or utility function used to define operating rules based on relative priorities or may be a mathematical expression of a planning or operational objective. The following water management objectives are commonly of interest in WRS optimization: a) minimizing difference between water demand and release, b) reliability of the system, c) maximization the hydroelectric power generation, d) maximum reduction of flood peak, and e) maximization of benefits or minimization of costs.

6.4.1. Optimization techniques

Many optimization techniques have been used to solve problems of water resources systems. Linear programming (LP), nonlinear programming (NLP), dynamic programming (DP) and genetic algorithms are the techniques of optimization which have been commonly used in water resources system studies. Besides these, other optimization techniques such as Ant Colony Optimization, Particle Swarm Optimization, Multi-criteria Decision Models, etc. are also used in WRS studies.

6.4.1.1 Linear Programming (LP)

Linear programming is concerned with maximization or minimization of a linear objective function subject to linear equality or inequality constraints. Although the objective function and the constraints in many real-life water problems are not linearly related, these can be approximately linearized and the LP technique can be used to obtain the solution. LP models have been widely used to solve a variety of industrial, economic, engineering and hydrological problems. More details of LP can be found in Loucks et al. (1981). Many efficient public domain/commercial packages to solve LP problems have been developed, e.g., LINDO (http://www.lindo.com/).

LP technique has been extensively applied in water resources sector. Barlow et al. (2003) presented an LP based conjunctive management model to evaluate the tradeoffs between groundwater withdrawal and stream flow depletion in United States. Khare et al. (2007) used a LP model for investigating the scope of conjunctive use of surface water and groundwater for a link canal command in Andhra Pradesh, India. Li et al. (2010) used an inexact two-stage water management model for irrigation planning. Lu et al. (2011) developed and applied an inexact rough interval fuzzy LP model to generate conjunctive water allocation strategies. Gaur et al. (2011) used similar models for management and planning of surface water and groundwater resources. Sun et al. (2011) reported that irrigation water productivity for the double cropping system can be improved under optimized water management. Singh (2014) formulated linear programming (LP) model with groundwater for the annual farm income maximization in Rohtak district of Haryana, India.

6.4.1.2 Nonlinear programming (NLP)

In Nonlinear Programming (NLP) problems, either the objective function and/or one or more constraints are nonlinear functions of decision variables. Similar to LP, efficient codes to solve NLP problems have been developed. Shuffled Complex Evolution (SCE_UA) algorithm (Duan et al. 1993) is generalized algorithm to solve a NLP problem. It has been widely used in hydrology for tasks such as calibration of hydrologic models.

Benli and Kodal (2003) formulated a crop water benefit function-based NLP model for the determination of irrigation water needs and farm income under adequate and limited water supply conditions in southeast Anatolian Region of Turkey. Ghahraman and Sepaskhah (2004) used LP and NLP models for exploring the irrigation optimization. A similar approach was adopted by Shang and Mao (2006). For the efficient utilization of water resources in a coastal groundwater basin of Orissa in India, NLP and LP models were developed and applied by Rejani et al. (2009). A conjunctive use planning model was formulated by Chiu et al. (2010), considering optimal pumping and recharge strategy. Montazar et al. (2010) developed an integrated soil water balance algorithm and coupled it to an NLP model for carrying out water allocation planning in complex deficit agricultural water resources systems. Huang et al. (2012) developed an integrated two-stage interval quadratic programming model for water resources planning and management in China.

6.4.1.3 Dynamic programming (DP)

Dynamic Programming (DP) is an enumerative technique developed by Richard Bellman in 1953. This technique is used to get the optimum solution to a problem which can be represented as a multistage decision process. DP formulation is based on the Bellman principle of optimality which states that an optimal policy has the property that whatever the initial state and decisions are, the remaining decisions must constitute an optimal policy with respect to the state resulting from first decision. DP is not a class of optimization techniques, but is a powerful procedure to solve sequential decision problems. Many problems in water resources involve a sequence of decisions from one period to the next. Such problems can be decomposed into a series of smaller problems that can be conveniently handled by DP. Unlike LP and NLP, there is no generalized software for DP (except a few attempts).

Use of DP technique is common in irrigation planning and management (Yakowitz 1982) and has been widely used by various researchers worldwide (Shangguan et al. 2002; Tran et al. 2011). Several improvements of DP have been suggested: incremental DP with successive approximation (IDPSA) by Shim et al. (2002); state increment DP (SIDP) by Yurtal et al. (2005); folded DP (FDP) by Kumar and Baliarsingh (2003). Yi et al. (2003) also used modified DP to maximize hydropower generation. Li et al. (2011) have developed and used a robust multistage interval-stochastic programming method and applied it in the regional water management systems planning.

6.4.1.4 Genetic Algorithms (GA)

Genetic algorithms belong to the larger class of evolutionary algorithms (EA) which generate solutions to optimization problems by using techniques inspired by natural evolution, such as inheritance, mutation, selection and crossover. Though GA has been widely used for many water resources optimization problems (Nicklow 2010), its application for irrigation planning is relatively new (Kumar et al. 2006). A GA model was used by Karamouz et al. (2009) to optimize a water allocation scheme considering the conjunctive use of surface water and groundwater resources.

6.4.1.5 Ant Colony Optimization (ACO)

ACO is a discrete combinatorial optimization algorithm based on the collective behavior of ants in their search for food. It is noticed that a colony of ants is able to find the shortest route from their nest to a food source via an indirect form of communication that involves deposition of a chemical substance, called pheromone, on the paths as they travel. Over time, shorter and more desirable paths are reinforced with greater amounts of pheromone thus becoming the dominant path for the colony (Afshar et al. 2015). ACO algorithm has been applied in various fields of water resources, such as(1) reservoir operation and surface water management, (2) water distribution systems, (3) drainage and wastewater engineering, (4) groundwater systems including remediation, monitoring, and management, (5) Environmental and Watershed Management Problems etc (Afshar et al. 2015).

6.4.1.6 Particle Swarm Optimization (PSO)

Particle swarm optimization (PSO) is a swarm intelligence based stochastic optimization technique. It is an efficient approach to optimize a function by using a population-based search method. A population of particles that contains possible solutions evolve in a dynamical way. These particles are initially generated at random and freely fly through the multi-dimensional search space (Kennedy and Eberhart, 1995). This method has been applied in many water resources management studies (Baltar and Fontane 2007; Chang et al. 2013).

6.4.1.7 Multi Criteria Decision Making (MCDM)

MCDM is concerned with structuring and solving decision and planning problems involving multiple criteria. The purpose is to support decision makers facing such problems. Typically, a unique optimal solution does not exist for many problems and it is necessary to use decision maker's preferences to differentiate between solutions (Majumder 2015). MCDM has been successfully used in various WRS studies such as urban water supply, catchment management, ground water management, water allocation, water policy and supply planning, and water quality management (Hajkowicz and Collins 2007).

6.5 Simulation-Optimization Techniques

Combined use of simulation and optimization models allows us to use the strength of these two techniques. For instance, an optimization can be employed to screen a large number of alternatives and choose a few which can undergo detailed investigation by simulation model.

Wurbs (2005) reviewed generalized river/reservoir simulation and optimization models and concluded: a) The generalized ResSim, RiverWare, MODSIM and WRAP modeling systems are representative of current endeavors of water management community in the United States to improve decision support for a broad spectrum of river basin management activities; and b) Simulation and optimization modeling strategies, measures of system performance, computational methods, time step length, hydrologic period of analysis, and data management schemes vary with the different types of applications. In general, developing and applying a reservoir/river system model involves significant time, effort, and expertise. The worth of a reservoir/river system management modeling system depends upon its capabilities to contribute to actual water management decision-making processes.

An assessment of integrated water resources optimization model by Mayer and Muñoz–Hernandez (2009) compares optimization model applications in various river basins around the world. Rani and Moreira (2010) have surveyed simulation–optimization models as applied to reservoir system operation problems; many models have (simulation–optimization) capability such as MODSIM-DSS (Labadie et al. 2000), CALSIM (Draper et al. 2004 and ARSP (http://www.bossintl.com/html/arsp_details.html).

6.6 Game Theory

Game theory is mainly used in economics, political science, and psychology, as well as logic, computer science, biology and poker. Many researchers have attempted water conflict resolution studies in a game-theoretic framework. Carraro et al. (2005) and Zara et al. (2006) reviewed game theoretic water conflict resolution studies. Game theory has been mainly applied for: (1) water or cost/benefit allocation among users (Lippai and Heaney 2000; Wang et al. 2008); (2) groundwater management (Loaiciga 2004; Raquel et al. 2007); (3) water allocation among trans-boundary users (Madani and Hipel 2007; Elimam et al. 2008); (4) water quality management (Sauer et al. 2003; Schreider et al. 2007).

6.7 Review of selected WRS models

A number of public-domain and commercial software packages are readily available for a broad range of water resources systems analysis and applications. The generalized models discussed here are categorized into pure simulation and simulation-optimization models. Recently, Carter (2015) has compiled the information about hydrologic models.

6.7.1 Generalized pure simulation based models

This section reviews selected pure simulation models.

6.7.1.1 HEC Models

A variety of models and decision support tools have been developed at Hydrologic Engineering Centre (HEC), U.S. Army Corps of Engineers (USACE), Davis, California (link:http://www.hec.usace.army.mil/). The relevant models are Hydrologic Modeling System

(HEC-HMS), River Analysis System (HEC-RAS), Prescriptive Reservoir Model program, HEC-ResPRM, Reservoir System Simulation (HEC-ResSim), Flood Damage Reduction Analysis (HEC-FDA) etc. Spatial database for these models are to be prepared by GIS platform (ArcGIS software). All models can be used for simulation though HEC-ResPRM and HEC-HMS also have optimization function. Software of these models along with user manuals are freely available.

The HEC-HMS software simulates many hydrologic processes such as infiltration, evapo-transpiration, snowmelt, soil moisture accounting etc. for continuous simulation and procedures such as unit hydrograph and hydrologic routing. Advanced capabilities are also provided for gridded runoff simulation using the linear quasi-distributed runoff transform (ModClark). Supplemental analysis tools are provided for model optimization, forecasting streamflow, depth-area reduction, assessing model uncertainty, erosion and sediment transport, and water quality. HEC-RAS allows the user to perform computations for one-dimensional steady flow, one and two-dimensional unsteady flow, sediment transport/mobile bed, and water quality/ temperature modeling. Graphical interface of HEC RAS model displaying some of its capabilities is shown in the Fig. 6.2. Weaver (2016) has reanalyzed records of flood using HEC-2, HEC-RAS, and USGS Gauge Data of the Conestoga River and they have carried out corrections to 2013 HEC-RAS (river analysis system) for simulation.

Applications of HEC's software for reservoir systems operation simulation are widely reported in literature (Draper et al. 2004; Jenkins et al. 2004; Watkins and Moser 2006). HEC-ResSim is used to model reservoir operations at one or more reservoirs for a different type of operational goals and constraints. The software simulates reservoir operations for flood risk management, low flow augmentation and water supply planning, detailed reservoir regulation plan investigations, and real-time decision support. HEC-ResSim package contains a graphical user interface (GUI) and a computational program for simulation of reservoir operation. The software also has included the capacity of data storage and management capabilities and graphics and reporting facilities (Klipsch and Hurst 2007), see Fig.6.3. Trinh et al (2016) have used HEC-ResSim to reconstruct the historical data on water supply from Shasta Dam to its supply region. HEC-FDA provides the capability to perform an integrated hydrologic engineering and economic analysis during the formulation and evaluation of flood risk management plans.

The Data Storage System, HEC-DSS (HEC, 1995 and HEC, 2009) can be used for storage and retrieval of input and output time-series data.

6.7.1.2 RIBASIM Model

River Basin Simulation Model, RIBASIM is a generic model package for simulating the behavior of river basins under various hydrological conditions. The model package is a comprehensive and flexible tool which links the hydrological water inputs at various locations with the specific water users in the basin. RIBASIM enables the user to evaluate a variety of measures related to infrastructure, operational and demand management and to see the results in terms of water quantity, water quality and flow composition. RIBASIM can also generate flow patterns which provide a basis for detailed water quality and sedimentation analyses in river reaches and reservoirs. RIBASIM can be applied to a river basin, a part of a river basin or a combination of river basins. Detailed documents of RIBASIM model is available in the site https://www.deltares.nl/en/software/ribasim/.

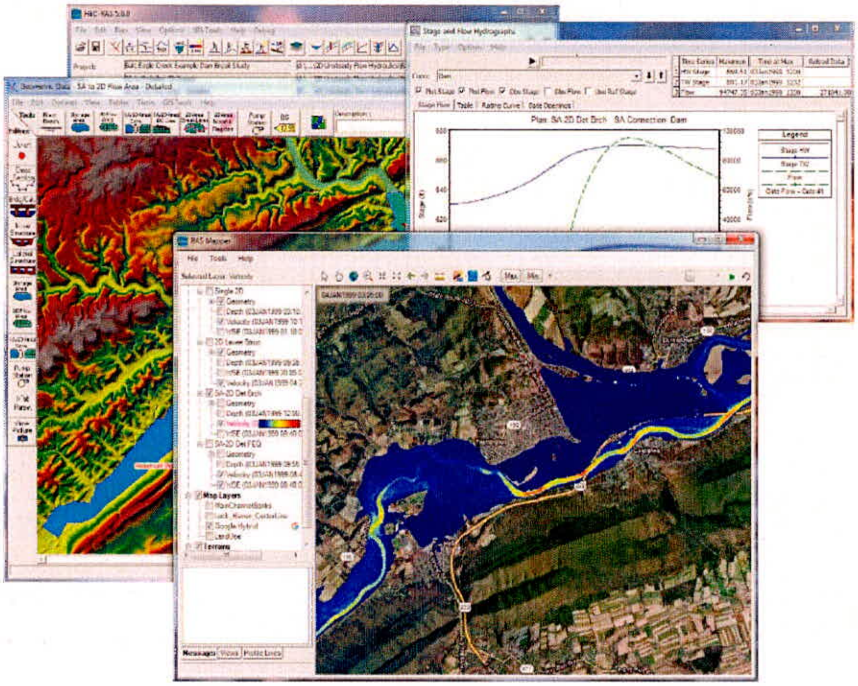


Figure 6.2: HEC RAS model

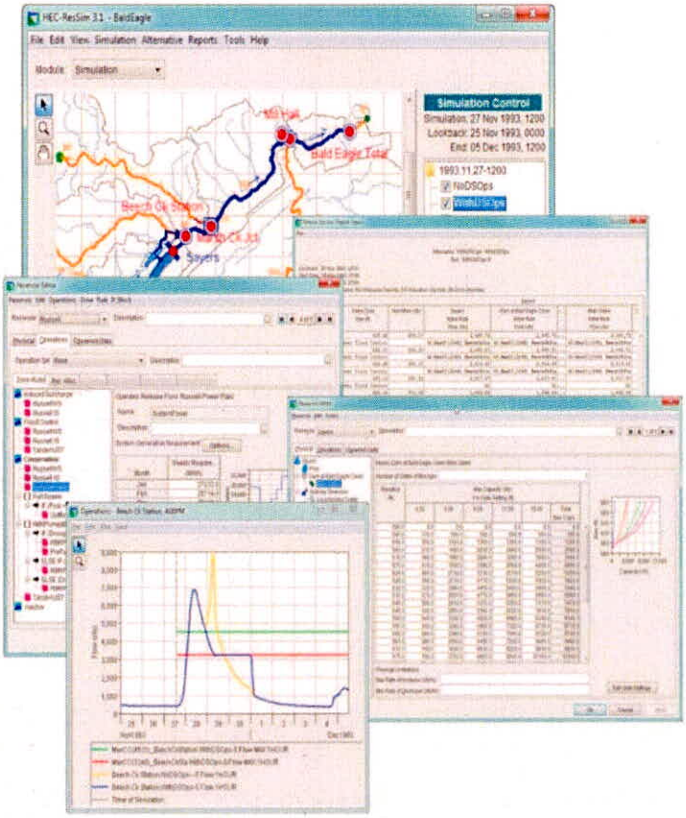


Figure 6.3: HEC-ResSim Modeling System

Tzoraki et al. (2015) have calculated the potential water allocation, the planning of new water infrastructures and the demand management considering different hydrological conditions (normal, dry, and very dry) using the RIBASIM model in the island of Crete, Greece. They concluded that increasing water scarcity impacts on available water resources due to climate change. Water pricing should be reformed in critical climatic condition.

6.7.1.3 Deltares Models

Deltares (https://www.deltares.nl/en/) has developed simulation software products, such as the Delft3D Flexible Mesh Suite (Delft3D FM) for modeling of coastal waters, estuaries, rivers, lakes, rural and urban areas. SOBEK suite of models has been developed by Deltares for flood forecasting, optimization of drainage systems, control of irrigation systems, sewer overflow design, river morphology, salt water intrusion and surface water quality. The modules within the SOBEK modeling suite simulate the complex flows and the water related processes in almost any system. The modules represent phenomena and physical processes in an accurate way in one-dimensional (1D) network systems and on two-dimensional (2D) horizontal grids. It is the ideal tool for guiding the designer in making optimum use of resources. A policy related long-term fresh water supply and flood risk management has been launched by the government of the Netherlands using Delta models (Prinsen et al. 2015). They have used the Delta models to compute demand in present situation, future scenarios (2050 and 2100) and possible adaptation measurements in national and regional level.

6.7.1.4 MIKE SHE

MIKE SHE is an integrated system to model groundwater, surface water, recharge and evapo-transpiration. MIKE SHE includes all important aspects of hydrology and is a fully integrated model (https://www.mikepoweredbydhi.com/products/mike-she). MIKE SHE can solve the problems related to: a) integrated catchment hydrology, b) conjunctive use and management of surface water and groundwater, c) irrigation and drought management, d) wetland management and restoration, e) environmental river flows, f) floodplain management, g) groundwater-induced flooding, h) land use and climate change impacts on groundwater and surface water, i) nutrient fate and management, and j) integrated mine water management. Sandu & Virsta (2015) have used the MIKE SHE to simulate surface flow as runoff and subsurface flow drainage routed through tile drainage infrastructure within the Argesel River watershed. They have concluded that the structural parameters of the model like grid size significantly influenced the simulation time and the simulated outflow hydrograph while the time step parameters had a moderate influence on river discharge.

6.7.1.5 MIKE HYDRO Basin

MIKE HYDRO Basin is a multipurpose, map-based decision support tool for planning and management of river basins. MIKE HYDRO Basin is designed for analyzing water sharing issues at international, national or local river basin scale. Developed by DHI technologies (https://www.mikepoweredbydhi.com/products/mike-hydro-basin), MIKE HYDRO Basin software can be used for: a) Multi sector solution alternatives to water allocation and water shortage problems; b) Climate change impact assessments on water resources availability and quality; c) Exploration of conjunctive use of groundwater and surface water; d) Optimization of reservoir and hydropower operations; e) Evaluation and improvement of irrigation scheme performance; and f) Integrated water resources management (IWRM) studies. Some of the features available in the software include: rainfall runoff modeling, hydraulic routing, global ranking, water quality, reservoirs, hydropower, reservoir sedimentation, data assimilation, scripting and programming.

MIKE FLOOD

MIKE FLOOD is the unique toolbox for professional flood modelers and information regarding model can be found at https://www.mikepoweredbydhi.com/products/mike-flood. It includes a wide selection of specialized 1D and 2D flood simulation engines, enabling you to model any flood problem - whether it involves rivers, floodplains, flooding in streets, drainage networks, coastal areas, dams, levee and dike breaches, or any combination of these. MIKE FLOOD is applicable at any scale from a single parking lot to regional models offering multiple options for speeding up computation performance through parallelised simulation engines. Applications range from classical flood extent and risk mapping to environmental impact assessments of severe flood events.

MIKE URBAN

MIKE URBAN is the urban water modeling software which can cover all water networks in a city including water distribution systems, storm water drainage systems, and sewer collection in separate and combined systems. For many applications of drinking water, storm water and waste water networks, MIKE URBAN has been successfully used. More information about this software is available at https://www.mikepoweredbydhi.com/products/mike-urban.

6.7.1.6 eWater Source

Australia's National Hydrological Modeling Platform (NHMP) has designed the eWater Source software to simulate all aspects of water resource systems to support integrated planning operations and governance from urban catchment to river basin scales including human and ecological influences (http://ewater.org.au/products/ewater-source/). The software can be used as rainfall-runoff model, groundwater interaction model, nutrient and sediment generation and transport model, crop water use model, etc. It can provide the application of water management rule such as the water sharing rules, resource allocation and environmental flow requirements.

6.7.1.7 NIH_ReSyP Model

National Institute of Hydrology has developed a software package known as NIH_ReSyP (NIH_*Re*servoir *Sy*stems *P*ackage). The package includes modules for reservoir capacity computation using sequent peak analysis, storage-yield-reliability analysis, determination of dependable flows, derivation of trial rule curve levels, simulation of operation of a multipurpose multi-reservoir system for conservation and flood control purposes, hydropower analysis, reservoir routing, and distribution of sediments in reservoir. NIH has developed NIH_ReSyP specifically for deriving operation policies for Indian reservoirs by using the practices being followed in India. The software is free and it has been used in many studies.

6.7.1.8 WEAP Model

Water Evaluation and Planning (WEAP) is a user-friendly software tool that provides an integrated approach to water resources planning (http://www.weap21.org/). WEAP has been developed by the Stockholm Environment Institute's U.S. Center. The software has wide range applications such as rainfall-runoff, groundwater recharge, hydropower generation, water rights and allocation priorities, pollution tracking and water quality, vulnerability assessments, cost-benefit analysis, etc. Mourad and Alshihabi (2015) have used the WEAP model to assess present and future water demand and supply in Syria till 2050. The results have shown that climate change might reduce the inflow from Euphrates, Tigris, and Orontes and water resources will also be affected due to reduced rainfall and increasing evaporation.

6.7.1.9. WMS Model

The Watershed Modeling System (WMS) is a watershed hydrology and hydraulics based graphical interface software. It has been developed by the Environmental Modeling Research Laboratory of Brigham Young University. The main components of WMS include: snowfall accumulation and melting, precipitation and interception, infiltration, evapo-transpiration, surface water retention, surface runoff and flow routing, and groundwater flow (saturated and unsaturated conditions). This software supports other hydrological software such as HEC-RAS, HEC-HMS, TR-20, TR-55, MODRAT, HSPF, Rational Method, and NFF. All these models along with a GIS framework make the task of watershed modeling and mapping easier. Detailed information of WMS is available at http://www.aquaveo.com/software/wms-watershed-modeling-system-introduction.

6.7.1.10 MODFLOW-OWHM

The One-Water Hydrologic Flow Model (MF-OWHM) is a MODFLOW based integrated hydrologic flow model (IHM).The software has been designed by United States Geological Survey (USGS) for analysis of conjunctive-use problems. Detailed information is available at http://water.usgs.gov/ogw/modflow-owhm/.The MODFLOW-OWHM provides the tools for simulating evapo-transpiration (ET), surface water routing (SWR), recharge (RCH), irrigation (FMP), drain and return flow (DRT), unsaturated zone (UZF), and seawater intrusion (SWI). Coupling MODFLOW-OWHM with MODFLOW-LGR (a package for using locally refined grid to simulate groundwater) provides an effective tool for measuring the local influence of tanks and check dams in increasing groundwater levels. This model has been used in many Indian commands for allocating reservoir water through canal systems (Carter, 2015).

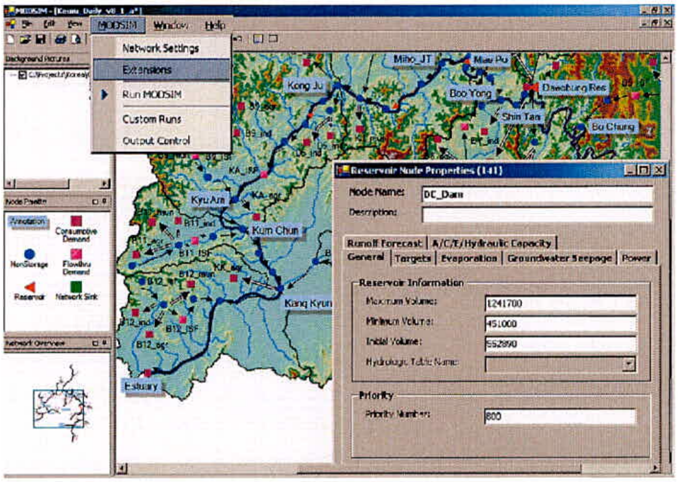
6.7.1.11 SWMM

Storm Water Management Model (SWMM) is a dynamic rainfall-runoff simulation model which is used for single event or long-term (continuous) simulation of runoff quantity and quality. The runoff component of SWMM operates on a collection of sub-catchment areas that receive precipitation and estimate runoff and pollutant loads. The routing portion of SWMM transports this runoff through a system of pipes, channels, storage/treatment devices, pumps, and regulators. SWMM tracks the quantity and quality of runoff generated within each sub-catchment and the flow rate, flow depth, and quality of water in each pipe and channel during a simulation period comprised of multiple time steps. The reference manual for SWMM describes the SWMM's hydrologic models, its hydraulic models, and its water quality and low impact development models. Detailed information of SWMM is available at https://www.epa.gov/water-research/storm-water-management-model-swmm.

6.7.2 Generalized simulation–optimization models

6.7.2.1 MODSIM Model

MODSIM is a simulation-optimization model which has been developed jointly by the Colorado State University (CSU) and the Bureau of Reclamation's Pacific North West Region (BRPNWR). The software (MODSIM version 8.5) along with user's manual can be downloaded from (http://modsim.engr.colostate.edu/). The model uses network flow programming (NFP) which employ an efficient Lagrangian relaxation algorithm (RELAX-IV) (Bertsekas and Tseng 1994). MODSIM can be used for developing basin-wide schemes for short-term water management, long-term operational planning, drought contingency planning, water right analysis and environmental concerns. The model has GUI and allows users to create and link reservoirs in network objects (Figure 6.4). Shourian et al. (2008) have used the PSO-MODSIM model to optimize water allocation at basin scale.



Node Name: DC_Dam
Description:
Maximum Volume: 1241700
Minimum Volume: 451000
Initial Volume: 552890
Hydrologic Table Name:
Priority Number: 800

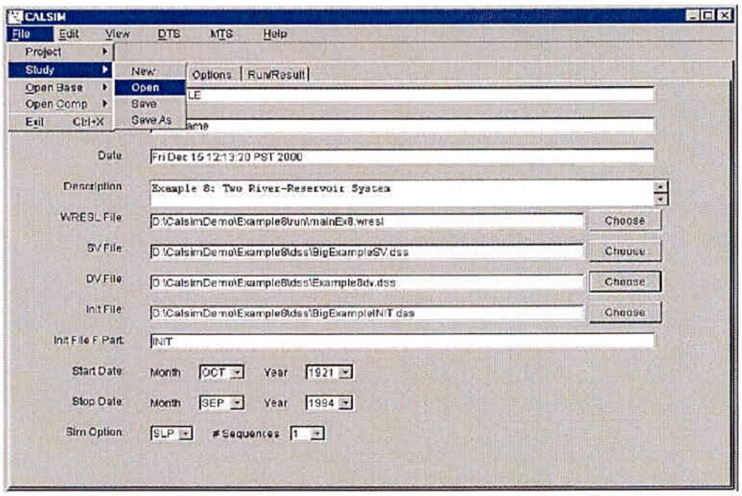
Figure 6.4: MODSIM Model

6.7.2.2 RiverWare Model

RiverWare is a multi-objective river basin modeling tool which has been developed at the Center for Advanced Decision Support for Water and Environmental Systems (CADSWES) of the University of Colorado (http://cadswes.colorado.edu/).The model uses goal programming (GP) with linear programming (LP) as an engine to optimize each of a set of prioritized policy goals, input by the user (Zagona et al. 2001). Management of daily scheduling, mid-term forecasting and long-range planning can be done by this software. A study on water supply has been carried out in the Tarrant Regional Water District (TRWD), Texas in the United States using RiverWare Model (Smith et al. (2015).

6.7.2.3 WRIMS (CalSim Model)

The Water Resource Integrated Modeling System (WRIMS), formally named CALSIM is a graphical based generalized water resources modeling system for measuring operational alternatives of large, complex river basins (Fig. 6.5). The model has been developed by the California State Department of Water Resources (CSDWR) and the U.S.Bureau of Reclamation (USBR) (Draper et al. 2003). Detailed information regarding CalSim model is available at http://baydeltaoffice.water.ca.gov/modeling/hydrology/CalSim/index.cfm. The CalSim utilizes LP/MILP to determine an optimal set of decisions for user defined weights and constraints. The model can also play a flexible foundation for potential future analyses including ensemble forecasting, evaluation of climate change scenarios, assistance with weekly operations forecasts, simulation of water transfers and hydropower operations, etc. A daily time-step planning and operations model is being developed using CalSim-II (Van Lienden et al. 2006). Georgakakos et al. (2012) have used the CalSim model to assess the value of adaptive reservoir management versus traditional operation practices in the context of climatic change in Northern California.



LE
ame
Date: Fri Dec 15 12:13:20 PST 2000
Description: Example 8: Two River-Reservoir System
WRESL File: D:\CalsimDemo\Example8\run\mainEx8.wresl
SV File: D:\CalsimDemo\Example8\dss\BigExampleSV.dss
DV File: D:\CalsimDemo\Example8\dss\Example8dv.dss
Init File: D:\CalsimDemo\Example8\dss\BigExampleINIT.dss
Init File F Part: INIT
Start Date: Month OCT Year 1921
Stop Date: Month SEP Year 1994
Sim Option: SLP #Sequences 1

Figure 6.5: CalSim Model

6.7.2.4 ARSP Model

The Acres Reservoir Simulation Program (ARSP) was developed by Acres International Corporation (AIC) and is commercialized and supported by BOSS International. Information regarding model can be found at http://www.bossintl.com/html/arsp_details.html. The ARSP is a Network flow programming (NFP) based model which simulates multi-purpose, multi-reservoir systems. The software can be used in any water resource system incorporating natural inflows, precipitation, evaporation, and evapo-transpiration as input data. The operational features that can be evaluated include storage and release of water by reservoirs, physical discharge controls at reservoir outlets, water flow in channels and consumptive demands. These operational features can be defined as steady-state or time-varying. The reservoir operation policy has been specified using ARSP by prioritizing water requirements (Richter and Barnard 2004; Taghian et al. 2013).

6.7.2.5 OASIS Model

The Operational Analysis and Simulation of Integrated Systems (OASIS) model is a generalized LP-simulation model developed by Hydrologics (http://www.hydrologics.net/). The software has an innovative feature; it simulates the routing of water by solving a linear program. Apart from that, the software can be used to facilitate associations to other simulation models and multi-objective analysis of a water resources system. A drought related problem (McCrodden et al. 2010) and reservoir operations modeling (Rivera et al. 2016) have been studied by this model.

6.8 Evaluation of Models

For this report, detailed information has been collected from various software developers such as Deltares, DHI Water Environment Health (DHI), eWater, India's National Institute of Hydrology (NIH), Stockholm Environmental Institute (SEI), U.S. Army Corps of Engineers (USACE), U.S. Department of Agriculture (USDA), and U.S. Geological Survey (USGS).

The models were assessed on the basis of computational functionality, user interface and capabilities, licensing requirements and software support. Different issues that have been investigated include: water allocation and planning, flood management, groundwater management, conjunctive use, water quality, and sediment transport. This review has been prepared based on a desktop, and is based on review of technical reports, user manuals of the models, tutorials, personal experience with some models, and published studies. However, testing could not be performed on WRS software for validating performance as demonstrated in the literature. Table 6.1 shows the comparative overview of issues addressed by various software's for water resources systems analysis. Carter (2015) carried out a review of currently available hydrological software to identify the packages that can help water resources management in India. Since applications of WRS software are unique in hydrologic setting, institutional setting, and intended use, a detailed review of WRS functionality is recommended before their acquisition for determining suitability in managing the concerned issue of water resources.

6.9 Way Forward

Water resource issues keep changing as growing awareness and exposure uncover unforeseen problems, changes in preferences of society generate new challenges, and new studies may reveal issues that were not important in past. Periodic reviews and updates are necessary to direct research towards emerging issues and problems. The studies need to emphasize on development of models and methods of prediction as well as data collection and monitoring systems. Improvement in the availability of data in terms of the type, coverage and quality may reduce the cost of many water resources projects. Proper management of the constructed projects is essential and is possible by following a scientifically developed operational plan.

Table- 6.1 WRS models evaluated and their relevance to water resources management in India [Adapted from Carter (2015)]

Software Developer	Software Package	Water Allocation	Reservoir Operations	Irrigation Demand Estimation	Flood Mapping and Warning	Conjunctive Use	Water Quality	Simulation	Simulation-Optimization
USACE	HEC-RAS, HEC-HMS	-	-	-	X	-	X	X	-
Deltares	RIBASIM	X	X	X	-	-	X	X	-
Deltares	SOBEK v2.14	X	X	-	X	-	X	X	-
DHI	MIKE SHE	X	X	X	X	X	X	X	-
DHI	MIKE HYDRO Basin	X	X	X	-	-	X	X	-
DHI	MIKE FLOOD	-	-	-	X	-	-	X	-
DHI	MIKE URBAN	-	-	-	X	-	X	X	-
eWater	Source	X	X	X	-	X	X	X	-
NIH	NIH_ReSyP	-	X	-	-	-	-	X	-
SEI	WEAP	X	X	X	-	-	X	X	-
USACE	GSSHA (WMS)	X	X	X	X	X	X	X	-
USGS	MODFLOW-OWHM	X	-	X	-	X	X	X	-
EPA	SWMM	-	-	-	X	-	X	X	-
CSU and BRPNWR	MODSIM Model	X	-	-	-	-	-	-	X
CADSWES	RiverWare Model	X	X	-	-	-	-	-	X
CSDWR and USBR	WRIMS (CalSimModel)	X	X	-	-	X	-	-	X
AIC	ARSP	X	X	-	-	-	-	-	X
Hydrologics	OASIS	-	X	-	-	-	-	-	X

There are many challenges in planning and management of a WRS. A large amount of data needs to be handled and the chosen model/software should be able to work with large dataset. A systematic comparison among possible development and management options is also essential. The models should also be able to interact with other models for the sake of integrated management of WRS.

A challenge with WRS management is to adopt a methodology which can incorporate all the information available to planners and managers into a quantitative framework so as to simulate and predict the outcome of alternative approaches and policies. The modeling framework should be flexible enough to accurately represent the systems; it should be easy to explain it to the decision-makers. Moreover, it should be able to represent the variability and uncertainties inherent in such systems explicitly. For example, the changing climate presents significant challenges to water managers as application of traditional water resources management approaches become questionable due to growing uncertainty and water managers need to adapt or mitigate to these uncertainties. The challenge of climate change is a priority concern for WRS management, where the main issue is to provide better projections of how climate might change water availability and demands in future and then, in accordance, update the operation policies.

A number of generalized models have been developed to study different aspects of WRS. Details of the selected WRS models and their applications are given in the Table 6.1. Some models are open source while others are not available free. Some open source models/software are SWMM, SEAWAT, models from the HEC-family (HEC-HMS, HEC-RAS, HEC-ResSim, HEC-FDA, HEC-DSS etc.), etc. Some of these open source models are very robust and have been tested widely. Generally, open source software has limited manuals, guidelines and test data, user interface, algorithm, upgradation, etc. Due to long history and strong institutional support, HEC group of models do not have these issues and users can easily implement HEC software as per their requirement. Geographical information systems (GISs) are increasingly being included in planning and management models, and hydrologic models can be directly linked to GIS databases. Most of the HEC models have been linked with GIS database.

Based on our experience, it appears that simulation technique is best suited for planning and management of real-life WRSs. For some problems, combined use of simulation and optimization can help in quickly converging to the best solution.

For wider application in India, the WRS models need to have the following features: a) these should preferably be available in public domain; b) adequate documentation (Users' manual, etc.) should be easily available; c) the model/software should be backed up by an active institution or group; and d) there should be adequate expertise in the country to gainfully apply the model.Based on these yardsticks, the models from HEC, USGS, Deltares, and NIH can be picked up for wider application in India. Under NHP, we need to strive to develop expertise in the country, particularly in the State Government organizations, to beneficially use these models. At the same time, indigenous model/software tailored to Indian conditions also needs to be developed.

WRS planning studies need to consider changes in climatic variable since these changes have important implication on fresh water arability of India. Management of floods and droughts is also important in India because different regions of India are routinely affected by floods and droughts every year. Many regions in India have inadequate freshwater resources to meet domestic, economic development and environmental needs. Lack of adequate clean water to meet human drinking water and sanitation needs is indeed a constraint on human health, productivity, and on economic development as well as on the maintenance of a clean environment and healthy ecosystems. Irrigation efficiency needs to be increased by the use of advanced instrumentation and better agricultural water management to save water. Water quality of many rivers in India has degraded substantially and necessary action should be taken to improve quality of water flowing in these rivers.

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