SEPIC

Support to Enhance Privatization, Investment, and Competitiveness in the Water Sector of the Romanian Economy

INTERNATIONAL SURVEY OF DECISION SUPPORT SYSTEMS FOR INTEGRATED WATER MANAGEMENT

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Contents

Acronyms

BASINS	Better Assessment Science Integrating Point and Nonpoint Sources
CALSIM	CALifornia Water Resources SImulation Model
CWMS	Corps Water management System (HEC)
DAEWPS	Danube Accident Emergency Warning and Prevention System
DBAM	Danube Basin Alarm Model
DEM	Digital Elevation Models
DSS	Decision Support Systems
DWR	California State Department of Water Resources
EMRL	Environmental Modeling Research Laboratory
EU	European Union
GIS	Geographic Information System
GOR	Government of Romania
GUI	Graphic User Interface
HEC	Hydrologic Engineering Center (USACE)
HMS	Hydrologic Modeling System (HEC)
ICPDR	International Commission for the Protection of the Danube River
PIAC	Principal International Alert Centres
RAS	River Analysis System (HEC)
ResSim	Reservoir Simulation System (HEC)
FIA	Flow Impact Analysis (HEC)
MAFWEP	Ministry of Agriculture Forestry Water and Environment Protection
OASIS	Operational Analysis and Simulation of Integrated Systems
OCL	Operational Control Language
SEPIC	Support to Enhance Privatization, Investment, and Competitiveness
SMS	Surface Water Modeling System
USAID	US Agency for International Development
USACE	U.S. Army Corps of Engineers
USFHWA	U.S. Federal Highway Administration
WATMAN	Water Management
WES	Waterways Experiment Station (USACE)
WMS	Watershed Modeling System
WRESL	Water Resources Engineering Simulation Language

1. Introduction

The USAID financed project Support to Enhance Privatization, Investment, and Competitiveness (SEPIC) in the Water Sector of the Romanian Economy was initiated by the Ministry of Agriculture Forestry Water and Environment Protection (MAFWEP) with the objectives of:

- Improving the management, quality, and sustainability of Romania's valuable water resources;
- Helping Romanian enterprises to become more profitable, competitive, and sustainable;
- Supporting MAFWEP's efforts in implementing the Government of Romania's (GOR's) National Strategy in terms of harmonization of the Romanian legal and regulatory framework with that of the EU; and
- Extending the GOR's capacity to make decisions on water allocation, manage floods, droughts, and accidental spills.

The SEPIC Project has three components, the third of which is Trade and Investment Initiatives for Modern Water and Disaster Management Systems. Under this component a system will be developed to integrate meteorological and hydrological data and enable use of the resultant information as a water management (WATMAN) tool. The WATMAN system will extend the government's capacity to make decisions on water allocation, manage floods, droughts, and accidental spills. The suite of decision support tools required for integrated management will include the aforementioned weather and flood forecasting models, linked to water allocation and accidental spill models.

One of the first tasks in developing the WATMAN system is to undertake an International survey of Decision Support Systems (DSSs) for Integrated Water Management describing individual models and their respective applications, data requirements (including topographical and cadastral information), use of Geographic Information System (GIS) platforms in data management, analysis or presentation. The report will also describe international applications of DSS models at the supra-basin (where there are inter-basins transfers), basin, and sub-basin levels.

The report draws heavily upon and updates the work in the author's previous reports on Decision Support Systems (Watkins and McKinney, 1995) and River Basin Modeling (McKinney et al., 1999).

2. Description of Decision Support Systems

2.1 Introduction to Decision Support Systems

What is a DSS? The classic definition of a DSS provided by Sprague and Carlson (1982) is "an interactive computer-based support system that helps decision makers utilize data and models to solve unstructured problems." Key terms in this definition are: interactive, data, and models, which are a recurring theme among developers of water management DSSs. Adelman (1992) defined decision support systems (DSSs) as "interactive computer programs that utilize analytical methods, such as decision analysis, optimization algorithms, program scheduling routines, and so on, for developing models to help decision makers formulate alternatives, analyze their impacts, and interpret and select appropriate options for implementation." Poch et al. (2003) define a DSS as "an intelligent information system that reduces the time in which decisions are made, and improves the consistency and quality of those decisions." Explicit in these definitions is that DSSs integrate various technologies and aid in option selection; whereas the implicit idea is that these are options for solving relatively large, unstructured problems. Thus, one may think of a Water Resources Management DSS as:

> *A Decision Support System (DSS) is an integrated, interactive computer system, consisting of analytical tools and information management capabilities, designed to aid decision makers in solving relatively large, unstructured water resource management problems.*

In the context of this report, decision makers are the planners and managers of water resource systems who are responsible for solving water-related problems or meeting water resource needs. The objective of these decision makers is, among other things, to provide the reliable supply of water with a quality appropriate for its use, production of hydropower, protection from floods, and protection of ecosystems.

Three main subsystems must be integrated in an interactive manner in a DSS (Orlob, 1992; Close et al., 2003): (1) a user-interface for dialog generation and managing the interface between the user and the system; (2) a model management subsystem; and (3) an information management subsystem. Considering this in more detail, DSS architecture consists of the following components (see Figure 1):

- *Data measurement* – the tasks involved in data gathering;
- *Data processing* – the tasks involved in registration of measurements into databases and their subsequent processing, retrieval, and storage;
- *Analysis* – the models used to infer the state of the system so that reasonable decision alternatives can be formulated;
- *Decision support* – the gathering and merging of conclusions from knowledge-based and numerical techniques and the interaction of users with the computer system through an interactive and graphical user interface.
- *Decision implementation* – the formulation of actions to be implemented in solving a specific problem.

The process begins with the collection and processing of data, followed by use of the data in the analysis of various water resources problems. Then the analysis is used in conjunction with expert advice and interpretation along with decision makers' inputs to support the taking of a decision or formulation of a plan. This process culminates in the implementation of the agreed upon plan or decision. In practice this is not a linear, step-by-step process, but a cyclical process with data entering the process, analysis being performed, and decisions being taken in an almost continuous fashion.

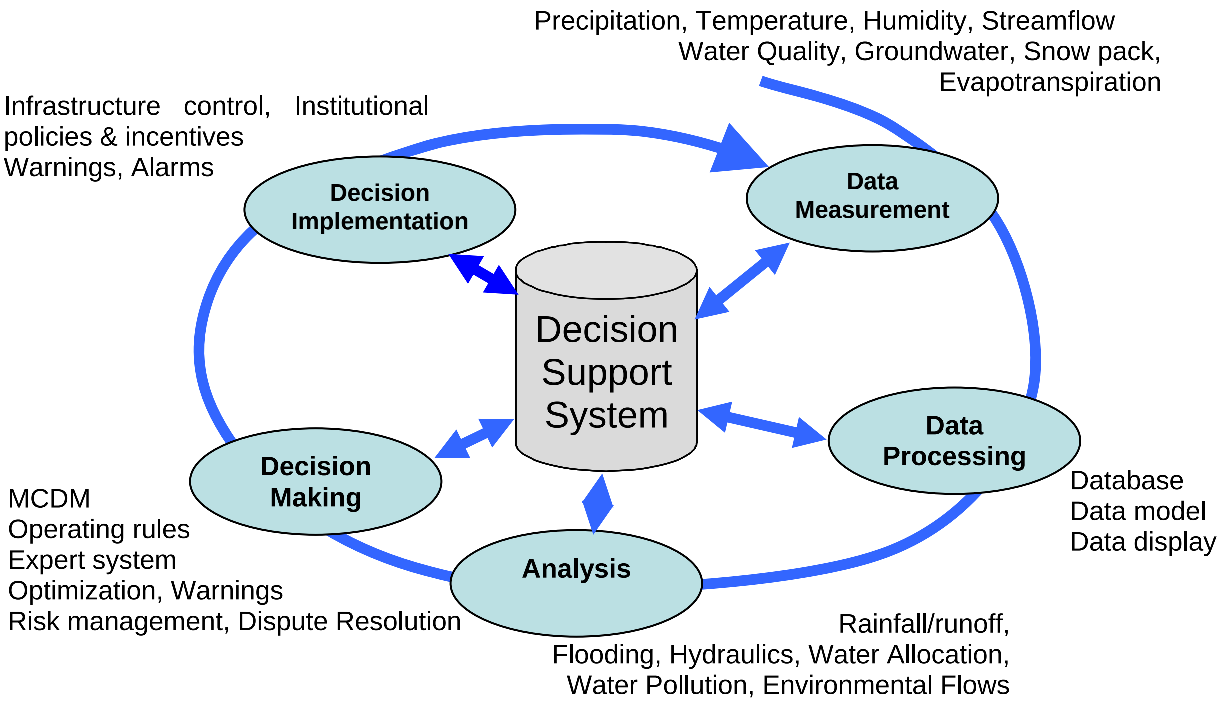

Figure 1. Diagram of a general framework for a water resources decision support system.

DSSs for water resources problems began to appear in the mid-1970s and have been discussed in the literature since the mid-1980s (Loucks et al., 1985a, 1985b; Labadie and Sullivan, 1986; Loucks and da Costa 1991; Fedra, 1992; Georgakakos, and Martin, 1996; Watkins and McKinney, 1995; Loucks, 1995; McKinney et al., 2000). Over the past decade, rapidly advancing computational ability, the development of user-friendly software and operating systems, and increased access to and familiarity with computers among decision makers has made the use of computer models in water resources management commonplace. As noted by Simonivic (1996) “The computer has moved out of data processing, through the user’s office into knowledge processing.” Given the increasing complexity and disciplinary breadth of water management problems, DSSs have become necessary to make models more useful. However, the development and application of DSSs to water resources management is far from a mature field for a number of reasons, including a lack of case studies in which the performance of DSSs has been evaluated in appropriate institutional settings; the multidisciplinary nature of DSSs and their theoretical underpinnings; and the lack of available methods to measure the effectiveness of them.

2.2 Important Decisions in Water Management

Integrated water resources management requires the consideration of a wide scope of social, economic and environmental aspects of resource use and protection. However, in the context of the type of decisions to be considered here, we choose to focus on two principal areas of decision making in water resources management:

- *Emergency water management* - involving floods or chemical spills; and

- *Water regulation and allocation* - involving water supply for municipalities, agriculture, industry, hydropower production, and environmental protection.

Decision making regimes tend to be different for these two areas due to the difference in time available for making decisions (hours in the first case and days to months in the second).

2.2.1 Emergency Water Management

Early Warning Systems - Early warning systems for floods or accidental chemical spills are information systems designed to send automated hydrologic and water quality data regarding water-related disasters to river basin planners, who combine them with meteorological data and river basin models to disseminate hazard forecasts and formulate strategies to mitigate economic damage and loss of human life. Early warning systems are typically comprised of the following subsystems:

- *Early warning subsystem* - including the hardware and software to monitor and forecast floods and accidental spills, and to collect, transmit, and disseminate data to disaster management agencies;
- *Risk information subsystem* - including data-processing tools and analysis models to assess the potential impact of impending hazardous events and facilitate the design of preemptive mitigation strategies;
- *Preparedness subsystem* - including institutions responsible for raising awareness about floods and chemical spills and for developing pre-disaster preparedness strategies; and
- *Communication subsystem* - including communication of timely information on impending hazardous events, potential risk scenarios, and preparedness strategies to vulnerable groups so that they may take appropriate mitigation measures.

Floods - Protection from flooding events requires higher dimension models and smaller time steps than for most other water resource management models, such as municipal or agricultural water supply, recreation, water quality, etc. Flood flows usually occur over short time intervals (hours to days or weeks) making it impractical to model such events in multipurpose water resource planning models using simple mass balances. Calculating flood inundation as a result of flood wave propagation in a catchment requires two-dimensional modeling, rather than one-dimensional modeling.

Structural measures (e.g., reservoirs, levees, flood proofing) and non-structural measures (e.g., land use controls and zoning, flood warning and evacuation plans) are used to protect against floods. Upstream reservoir operators must provide storage capacity for flood protection and emergency warning to populations living in downstream floodplains. These operators need to know how much water to release and when in order to minimize expected flood damage downstream. The flood flow and peak in a basin depend on flood storage capacity and flood flow release policies. These can be determined by simulating flood events entering basin reservoirs. Expected flood damage can be predicted if the distribution of peak flows and the relationships between flood stage and damage, and flood stage and peak flow are known.

Accidental Chemical Spills - Accidental chemical spills are a major concern for areas that have vulnerable riverine ecosystems and cities with vulnerable drinking-water supplies and weak spill response capabilities. In order to provide emergency response capability to protect against accidental spills, studies are performed to determine travel times in river reaches. The results of these studies can be used to plan emergency responses to chemical spills into rivers, including guiding decisions regarding closing and reopening of intakes to drinking-water systems. A system for supporting response to accidental spills should include a database of potential spill sites and locations of agricultural chemicals, oil tanks, pesticides, and hazardous wastes stored on or near a river. The database should also include the bridges and rail lines which cross rivers and often serve as transport for hazardous materials. From the use of such a DSS tool, spill responders can quickly find directions to spill sites, emergency contacts and details about chemicals and how they react with the river under various conditions. Spill responders can also run computer simulations of spills to practice their response and determine how long it takes for a spill to reach critical locations downstream. During a real spill, an emergency response team would use the data to make decisions about deploying people and equipment.

Emergency planning for spills in rivers and lakes entails having advective, nonreactive, nonmixing transport models capable of providing quick, worst-case scenarios of chemical concentrations at critical points downstream of spill sites. These allow for planning and deciding on alerts to be issued. More detailed, advective-dispersive, reactive modeling of the chemical fate and transport in the river system typically follow after the immediate response actions are taken.

2.2.2 Water Regulation, Allocation, and Quality

River Basin Management - In the area of general river basin management, DSSs help decision makers with a myriad of problems, including:

- Operation of reservoirs for supply of water for various purposes including recreation, municipal and industrial water use, instream flows, irrigation, and hydropower production;
- Examination of the effects of land-use and land-management policies on water quality;
- Assessment of eutrophication in surface water bodies;
- Development of pollution control plans for river basins and estuaries, including hydrodynamic and water quality impacts of alternative control strategies;
- Design and operation of wastewater treatment plants, i.e., what level of treatment is necessary to meet water quality goals under specific flow conditions; and
- Management of river basins, including the evaluation of the interrelationships between economic productivity and environmental degradation in a basin.

Lake and Reservoir Management - In the area of lake and reservoir management, support is needed to make decisions regarding pollution control, water supply, and hydropower operation, mitigation of climate change effects, reservoir eutrophication, phosphorus control strategies, and operation of multiple reservoir systems. Different types of models are required to provide support in this area, such as, water allocation models to determine the distribution of water for economic production and environmental protection in a basin; or two- and three- dimensional models to analyze water quality in lakes.

Non-Point Source Pollution – In this area decision support is needed to make plans for agricultural chemical use or protection of vulnerable water bodies, stream and aquifers. Modeling and managing agricultural non-point source pollution typically requires the use of a distributed parameter watershed model. The data management and visualization capabilities are needed to allowed decision makers to identify and analyze problem areas easily.

Groundwater and Conjunctive Use Management - Because decision makers are typically required to consider a multitude of social, legal, economic, and ecological factors, DSSs have great potential for improving the planning and management of conjunctive use (ground and surface water) systems. This can require the integration of a number of simulation and optimization models with graphic user interface capabilities to provide an adequate framework for the discussion of water allocation conflicts in a river basin. Conjunctive use models and multiobjective decision methods can be combined to provide decision support for inter-basin water transfer planning allowing decision makers to analyze the social, economic, and environmental impacts of water transfers. DSSs are valuable in facilitating the consideration of a wide range of impacts, allowing decision makers to incorporate technical information into the decision making process, and providing output which can be interpreted easily.

Water Treatment and Distribution Systems - The design and operation of water treatment and distribution systems are also complex tasks in which the experience of the designer or operator is critical. Typically, models of these systems have sacrificed physical accuracy so that solutions could be obtained in a timely manner. User evaluation of trade-offs between model solvability and accuracy in the design of water supply and distribution systems, evaluate investment options, and demonstrate interaction between water quantity and quality. General network simulation and optimization models can be used in scheduling and control methodology for water distribution systems in urban distribution systems to determine proper structural changes to the system that minimize disruption to existing customers. Recently, evolutionary methods, such as genetic algorithms, have been used to solve realistic models of large urban water distribution systems which are intractable with more traditional methods.

2.3 Technologies for Decision Making in Water Management

2.3.1 Simulation and Optimization Models

Basin-scale analyses are often undertaken using one of two types of models (McKinney et al., 1999): ones that *simulate* water resources behavior in accordance with a predefined set of rules governing water allocations and infrastructure operations, or ones that *optimize* and select allocations and infrastructure based on an objective function and accompanying constraints. Often the assessment of system performance can best be addressed with simulation models, whereas, optimization models tend to be more useful when system improvement is the main goal.

Basin-scale models that simulate the behavior of various hydrologic, water quality, economic, or other variables under fixed water allocation and infrastructure management policies are often used to assess the performance of water resources systems. A distinguishing feature of these simulation models, as opposed to optimization models, is their ability to assess performance over the long term. Consequently, simulation is the preferable technique to assess water resources system responses to extreme, nonequilibrium conditions, and thereby to identify the system components most prone to failure, or to evaluate system performance relative to a set of sustainability criteria that may span decades. However, sustainability analysis has been accomplished through optimization recently (Cai et al., 2002).

Models that optimize water resources based on an objective function and constraints must include a simulation component, however rudimentary, with which to calculate flows and mass balances. A distinct advantage of optimization models over simulation models is their ability to incorporate social value systems in the allocation of water resources. However, to be adopted by policy makers and system managers, optimal water allocations must agree with an infrastructure operator's perspective. This often requires that models be calibrated not only with respect to physical parameters of the system being modeled, but also with the respect to the system management, i.e., the operation and decision making process for the system. This later aspect is often overlooked in model development and application and leads to poor acceptance of models in practice.

In spite of the proliferation of computer technologies for decision support, classical simulation and optimization models remain at the heart of most water resources DSSs. For the most part, the models used in DSSs tend to have unwieldy input files and cryptic output files, making them useful only to technical specialists. Wide use of these models and the vastly expanded access to data have brought about the need for other technologies (e.g., databases and GUIs) to be integrated into DSSs in order to make data accessible to models and to make inputs and results understandable to analysts and decision makers. Unfortunately, except in a very few cases, most systems, both DSSs and stand alone models, have yet to utilize the capabilities of modern relational databases.

Simulation and optimization models used in water resources management have been reviewed by several authors (e.g., Yeh, 1985; Wurbs, 1993; Wurbs, 1994; Wurbs, 1998; Yeh, 1992; Wagner, 1995; and Labadie, 2004). Yeh (1985) provided a comprehensive state-of-the-art review of reservoir operation models with a strong emphasis on optimization methods. Wurbs (1993) provided a review of a wide array of reservoir simulation and optimization models and evaluated the usefulness of each approach for different decision-support situations. He hoped that his paper would help practitioners choose the appropriate model from the overwhelming number of models and modeling strategies which currently exist. Wurbs (1998) notes that common water resources models, such as those discussed below, are often used as components of DSSs. However, the models most frequently applied in water resources planning, design, and management do not exhibit the characteristics of DSSs. Labadie (2004) points out the need to improve the operational effectiveness and efficiency of water resource systems through the use of computer modeling tools. He notes that the demand for this is increasing as performance-based accountability in water management agencies increases and as operators and managers come to rely more on modeling tools to respond to new environmental and ecological constraints for which they have little experience to draw on.

Models used in decision support for integrated water management range from fully data oriented models to fully process oriented models. The choice depends on the quantity and quality of data available and the knowledge of important physical, chemical, biological, and economic processes affecting the system. Data oriented models are represented by regression models or neural networks (i.e., black box models). Process oriented models are represented by models which have detailed representations of processes, but require few site specific data (i.e., white box models).

Modeling projects tends to be complex and utilize a variety of data and analytical or computational tools from various sources. Proper and careful management of modeling projects can enhance the effectiveness with which models are developed, deployed, and used. The modeling process is an iterative procedure involving specific steps (Waveren et al., 1999):

- *Establish a project journal* – to allow developers and users to see what was changed or why a particular model run was made or what was learned. It allows third parties to continue from the point at which any previous project terminated;
- *Initiate the project* – so that the problem to be modeled and the objectives that are to be accomplished have clear definition;
- *Select a model to be used* – in light of the broader context in which the model will be used. Some situations require very detailed modeling of physical or chemical processes, while others require more attention to policy or economic aspects;
- *Analyze the model* – in light of the processes that will be modeled, the data available, and the data required by the model;
- *Test and evaluate the model* – to determine its strengths and limitations;
- *Interpret model results* – Develop a plan on how the model is to be used, identifying the input to be used, the time period(s) to be simulated, the quality of the results to be expected, and the methods to be used to interpret the results; and
- *Report the model results* – to the client recognizing that they may only be interested in some results and not the way they were obtained; and

2.3.2. Geographic Information Systems

Today's database systems provide comprehensive facilities for storing, retrieving, displaying and manipulating data essential to the decision-making process. Two common data manipulation and storage systems or tools are the relational database, which relates information in a tabular way so that the rules of relational algebra can be applied, and the geographic database (or geographic information system-GIS), which relates information pertaining to fundamental spatial features such as points, lines, and polygons. GIS not only brings spatial dimensions into the traditional water resources database, but also, more significantly, has the ability to better integrate the various social, economic, and environmental factors related to water resources planning and management for use in a decision-making process. GIS offers a spatial representation of water resources systems, but currently few predictive and related analytical capacities are available for solving complex water resources planning and management problems. In order to create a truly useful DSS for water management, a data model with geometric representations and spatial referencing is needed that has an open architecture to facilitate the integration of GIS and models.

There are several strategies for coupling an environmental model to a GIS (McKinney and Cai, 2002), ranging from a loose coupling where data are transferred between models and GIS, and each has separate database management capabilities and systems; to a tight coupling where data management in the GIS and model are integrated and they share the same database. The tightest coupling, and one which has yet to find efficient application in water resource modeling, is an embedded system, in which modeling and data are embedded in a single framework. One of the main reasons that embedded systems have yet to become useful is that many applications of modeling in water resources management tend to require the solution of large sets of simultaneous equations, something which GIS software, developed by geographers concerned with static map images, is not well suited to perform. Another reason for the lack of very tight coupling between GIS and models has been the lack of a data model that could easily represent a river basin in GIS. Lately, this issue has been resolved by the development of the ArcHydro data model (Maidment, 2002).

ArcHydro is a water resources data model that uses GIS to capture the essence of water resource systems in a manner that supports modeling. The ArcHydro data model defines a data structure of classes, such as watersheds, cross sections, monitoring points and time series in a manner that reflects the underlying physical watershed. Also defined in ArcHydro are relationships between the data, so that a river basin (catchment) may know which point represents its outlet, or a monitoring point may be aware of time series records for that location. ArcHydro also has a toolset to perform operations using the data, and visualize time series data.

ArcHydro is a data model for water resources which can facilitate tight coupling of water resource models and GIS. ArcHydro supports hydrologic simulation modeling by establishing connectivity between hydrologic features in the landscape which can be used to direct the flow of water between features in a model (Whitaker, 2004). The ArcHydro toolset can also calculate certain attributes useful in models, either through attribute accumulation routines, through relationships, network associations, or by direct calculation of parameters such as the length from a point on the network to the outlet of the river system. Water resource system modeling can be accomplished by exchanging data between ArcHydro and an independent model attached to ArcHydro using a dynamic linked library (Maidment, 2002). The Danish Hydraulics Institute has developed a time series manager that fits into the ArcHydro toolset and works with all of the feature classes defined in the ArcHydro data model (DHI, 2004). The ArcHydro data model is being used for water resources planning in the Rio Grande basin shared between the U.S. and Mexico (Patino et al., 2004) and the South Florida Water Management District for the basis of an enterprise GIS database to support flood control, natural system restoration, operations decision support, and regional modeling projects (PBS&J, 2004)

2.3.3 Expert Systems

Consisting of a set of rules and user-supplied data which interact through an inference engine, an expert or knowledge-based system is able to derive or deduce new facts or data from existing facts and conditions. Expert-system shells and programming languages have become widely available allowing users to define databases and rule sets. Some water resources DSS designers have though that expert systems would be a powerful complement to numerical and spatial analysis tools. This, however, has not turned out to be the case and few expert systems applications are in practical use today in the field of water resources management.

Fedra (1993a) reviewed the use of expert systems in water resources and identified three types of applications: purely knowledge driven systems, expert systems components in an intelligent front end, and fully embedded expert systems. Of these, intelligent front ends have been the most common. In general, they assist the user in selecting the appropriate numerical model or technique, specifying input parameter values, and interpreting model output. Lam and Swayne (1993) presented such an approach to the integration of virtually any computer technology useful to water resources planners. The role of the expert system is to provide an intelligent interface between the model and data, as well as descriptive dialogue between the user and machine. Palmer and Spence (1992) used the programming language PROLOG and natural language to represent knowledge about water resources management. Their purpose was to help users who were unfamiliar with formal database management or computer programming to access hydrologic and other data. Other examples of expert systems as intelligent front ends were given by Simonovic (1991) for open channel flow measurement, Simonovic (1992) for reservoir management, and Bender and Simonovic (1994) for long-range water supply forecast modeling.

Fully embedded or hybrid expert systems are typically problem-oriented rather than methodology-oriented. Whereas intelligent front ends enhance the use of models in a DSS, fully embedded expert systems enhance model results. McKinney, et al. (1993) proposed, and Burgin (1995) implemented, an expert information system for Texas water planning, in which expert systems and water resources planning models were used to enhance the modeling capacity of GIS. Hidden from the user, the rules invoked by the expert system eliminated planning options which did not meet certain qualitative constraints supplied by the user. Other embedded expert systems have been developed for irrigation systems planning (Nir, 1991) and for crop planning during droughts (Raman et al., 1992). Each of these agricultural expert systems was used to enhance simulation and optimization results.

Expert systems have found several applications in water supply and sewerage operating and maintenance. Mainly because solutions to these problems require gathering difficult information based on operator's experience, the variety of control mechanisms, and frequent changes in network topology (Leon et al., 2000). Shepherd and Ortolano (1996) describe an expert system for water-supply system operations decision support that evaluates operating plans and provides feedback, including suggestions for improvement, warnings, and alternatives. Leon et al. (2000) developed a hybrid expert system to minimize the pumping costs in the Seville City water-supply system. Hahn et al. (2002) describe the development of a knowledge base expert system for prioritizing sewer pipeline inspections used to target critical areas within a sewer drainage system.

Stanciulescu (1997) noted that the complex, non-linearity of environmental systems leads to uncertainty and difficulty in applying classical modeling methods. He presents a new approach to modeling and control of these systems, centered on a combination of mathematical model (written in Mathcad) and heuristic models (an expert system shell written in TurboProlog). The model was used to study the dynamics of bird populations in the Danube delta, including a knowledge base of behavioral, control and decision heuristic rules. Stanciulescu (1999) extended this system to include additional modeling capability and introduced the use of an expert system shell, written in the Clips language,

Expert systems have been applied to the problem of assessing watershed conditions considering numerous watershed functions, anthropogenic influences, and management concerns (Dai et al., 2004; Reynolds et al., 1996; Schmoldt and Rauscher, 1996; Reynolds, 1999). Representative of these applications is the Ecosystem Management Decision Support (EMDS) system (Reynolds, 2002; USDA, 2004) is an application framework for knowledge-based decision support of ecological assessments at any geographic scale. The system integrates a GIS as well as knowledge-based reasoning using the NetWeaver fuzzy logic engine (Saunders and Miller, 2004) and decision modeling technologies in the Windows environment to provide decision support for adaptive management of ecosystems. The majority of the applications reported are to landscape suitability and ecosystem restoration projects.

2.3.4 Multiobjective Analysis Tools

Water resources problems are inherently multifaceted with conflicting uses of water where tradeoffs must be made between stakeholders with differing goals. Multiobjective modeling methods have been used for several decades to determine the tradeoffs between various objectives in these problems. Several books devoted to the subject of multiobjective planning, many with applications to water resources problems, have been published over the past three decades, including Haimes, et al. (1975), Keeney and Raiffa (1976), Cohon (1978), Zeleny (1982), and Steuer (1986). Due to the conceptual difficulties involved in using multiobjective models (i.e., selecting criteria, specifying satisficing values, and evaluating trade-offs), several researchers have developed multiobjective decision support tools which meet two of the three requirements of a DSS. Namely, these tools provide analysis and interpretation capabilities, but not necessarily information management capabilities. Nonetheless, the potential of these tools in a fully developed DSS has become well known.

Examples of multiobjective decision support in water resources include Bogardi and Duckstein (1992), who presented an interactive multiobjective analysis method to embed the decision maker's implicit preference function; Ridgley and Rijsberman (1992), who employed multicriteria decision aid for a policy analysis of a Rhine estuary; and Theissen and Loucks (1992), who presented an interactive water resources negotiation support system. In these two examples, the authors concluded that the use of multicriteria evaluation effectively provided a group with decision support for the analysis.

Other work has focused on integrating technologies to support multiobjective analysis. Simonovic et al. (1992) presented a rule-based expert system to facilitate and improve the choice of multiobjective programming weights to be used in a reservoir operation model. Short- and long-term operating goals represented the trade-offs in the model. Lee et al. (1991) developed a DSS for dredge-fill management based on a modified fuzzy-composite programming method for multiobjective problems under uncertainty. Values of risk and cost were transformed into fuzzy numbers to incorporate uncertainties into the trade-off analysis.

Mahmoud and Garcia (2000) developed a multi-criteria evaluation system for evaluating an array of different management alternatives for anadromous fish migration along the Sacramento River in California. Several methods were compared and a “weighting approach” was found to be preferred. Mahmoud and Garcia (2000) point out that choosing among multi-criteria evaluation methods to rank multiple alternatives is critical not only because each method produces different rankings, but also choosing a methodology is subjective, based upon the predisposition of the decision maker.

2.4 Characteristics of a Water Management Decision Support System

2.4.1 Components of a Water Management DSS

Decision support systems (DSS) are customized software applications that add value to water resources models and help managers to make informed decisions using information generated by water resources models. As discussed earlier, a water management DSS would likely consist of the following components (see Fig. 1):

- *Data Measurement and Collection System* receiving various data (e.g., water level and temperature, precipitation, air temperature, concentrations, etc.) from stations throughout the river basins being managed, as well as weather data and forecasts;
- *Data Processing System* to store the data related to the processes of interest in the basins, both spatial and feature related as well as time series data;
- *Analytical System* of models and tools designed to predict watershed response and provide river forecasts, using data from the Data Collection System, and historical and river basin data needed to calibrate hydrologic models.
- *Decision Formulation and Selection System* for gathering and merging conclusions from knowledge-based and numerical techniques and the interaction of users with the computer system through an interactive and graphical user interface.
- *Decision implementation System* for disseminating decisions regarding water use under normal conditions, and flood warnings, river forecasts, and disaster response in affected areas.

All of these components are inextricably linked, such that the system’s effectiveness will be significantly diminished if one or more of the components is not designed and implemented to meet the overall demands of the DSS.

2.4.2 Issues to be Addressed in Constructing a Water Management DSS

There are a number of issues related to water management that must be considered when designing a DSS for effective decision making in this situation. First, water management takes place in a multidisciplinary and multi-jurisdictional environment and the problems must be approached from an integrated perspective (McKinney, 2003). Second, water management must be considered at the scale of the river basin in order to internalize the major, potential externalities between activities of users in different parts of a basin. Finally, the importance of scale effects in trying to model the integrated effects of water uses across an entire basin must be addressed.

Integrated Water Resources Management - Water resources management includes both structural interventions and nonstructural rules and policies. Structural interventions include the design and construction of physical works under criteria of safety, workability, durability, and economy, including short-term, operation and maintenance activities with existing structures and long-term investments in new structures. Nonstructural interventions combine optimal operating rules of hydrologic systems, economic optimization of water allocation, and understanding community behavior and institutional processes related to the formation and support of agencies making decisions about water management. These institutional directives, economic/financial incentives, and hydrologic system operating rules have greatly modified the traditional, structural approach to water management. The interdisciplinary nature of water problems requires the integration of technical, economic, environmental, social, and legal aspects into a coherent framework for decision making purposes. The requirements of users as well as those relating to the prevention and mitigation of water-related hazards should constitute an integral part of the integrated water management process.

Water allocation between competing uses is best addressed at the river basin scale through the use of combined economic and hydrological models. DSSs for integrated water management at the basin scale must adopt an interdisciplinary approach and a number of barriers must be overcome:

- Hydrological models often use *simulation techniques*, whereas most economic analyses are performed with *optimization procedures*;
- Political and administrative *boundaries* of economic systems are rarely the same as those of hydrological systems; and
- Different *spatial development scales*, and *time horizons* are frequently encountered in economic versus hydrologic models.

A DSS for water allocation at the basin scale should be designed to provide answers to water policy questions, including socio-economic issues, including:

- Transaction costs (e.g., information, monitoring, contracting and enforcement);
- Productivity of water and net benefits of different water users (e.g., agricultural, domestic and industrial use); and
- Demand for and economic value of water (e.g., production costs and willingness to pay).

River Basin Systems - Fig. 2 shows a schematic diagram of the components of a river basin system, including the sources of water supply (groundwater and surface water), the delivery system (river, canal and piping network), the water users (agricultural, municipal, and industrial), and the drainage collection system (surface and subsurface). The atmosphere forms the river basin's upper bound, and mass and energy exchange through this boundary determines the hydrologic characteristics of the basin. However, the state of the basin (e.g., reservoir and aquifer storage, and water quality) and the physical processes within the basin (e.g., stream flow, evapotranspiration, infiltration and percolation) are also affected by human actions, including impoundment, diversion, irrigation, drainage, and discharges from urban areas. Therefore, a DSS for water management in a river basin should include not only natural and physical processes, but artificial "hardware" (physical projects) and "software" (management policies) as well. An ideal DSS needs to model human behavior in response to policy initiatives. This may be as simple as a price elasticity of demand coefficient or something more complex (such as a model of farmers' simultaneous choice of optimal water use, crops, and water application technology). The essential relations within each component and the interrelations between these components in the river basin must be considered in DSSs.

The DSS needs to model the interactions between water allocation, agricultural productivity, non-agricultural water demand, and resource degradation to estimate the social and economic gains from improved water allocation and use efficiency. It should:

- Provide a description of the underlying *physical* processes,

- Provide a description of the *institutions* and rules that govern the flows of water and pollutants through the river basin,
- Depict the *water demand sites* along the river basin, including consumptive use locations for agricultural, municipal, industrial, and in-stream water uses (incorporating also reservoirs and aquifers); and
- Evaluate the *economic benefits* of water use by applying production and benefit functions with respect to water for the agricultural, environment, urban, and industrial sectors.

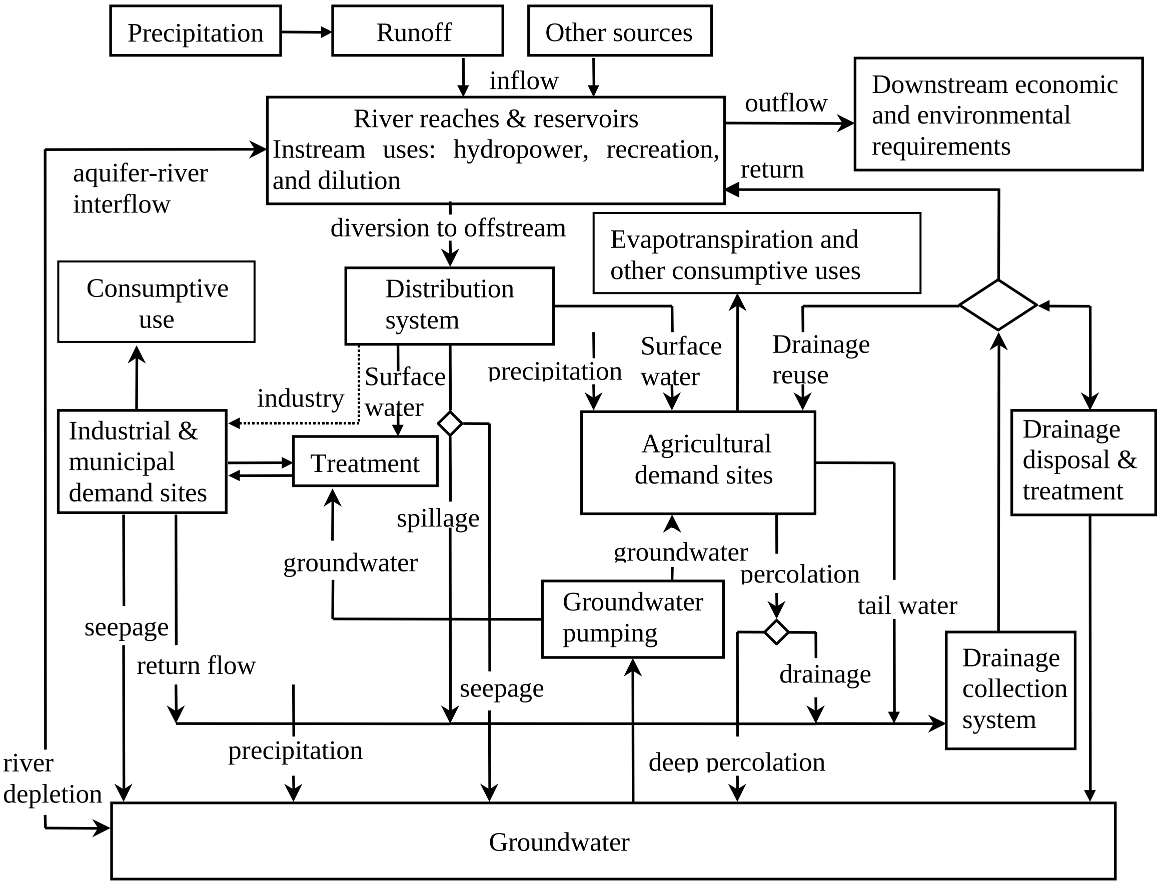

Figure 2. Schematic diagram of the components of a river basin system (adapted from McKinney et al., 1999).

Scaling of Processes - Fig. 3 illustrates a framework for river basin management modeling, including relationships and decisions at various scales (basin, agency, and user). Water can be used for in-stream purposes (hydropower generation, recreation, waste dilution, etc.) as well as off-stream purposes (agricultural and municipal and industrial (M&I) water uses). Integrated water management attempts to maximize the socio-economic benefits to the basin stakeholders, such as the economic value of M&I water use, profit from irrigation, and benefits from in-stream water uses, but also minimize environmental damages due to waste discharges, irrigation drainage, and negative impacts on in-stream uses.

At one level, institutional directives such as water rights and economic incentives (e.g., water price, crop prices, and penalties on waste discharge and irrigation drainage) constrain or induce hydrologic system operations and M&I and agricultural water use decisions. The management of water quantity and quality in a basin is based on the operation of reservoirs, aquifers, and conjunctive surface and ground water systems. The connections between water supply and demand and between upstream and downstream users are important considerations when considering return flows in the basin. The regulation of spatially distributed flow sources, pollutants, and water demands have to be considered in a water management DSS and mathematical models must be integrated over the proper scale within the river basin network (basin, regional, or local scale).

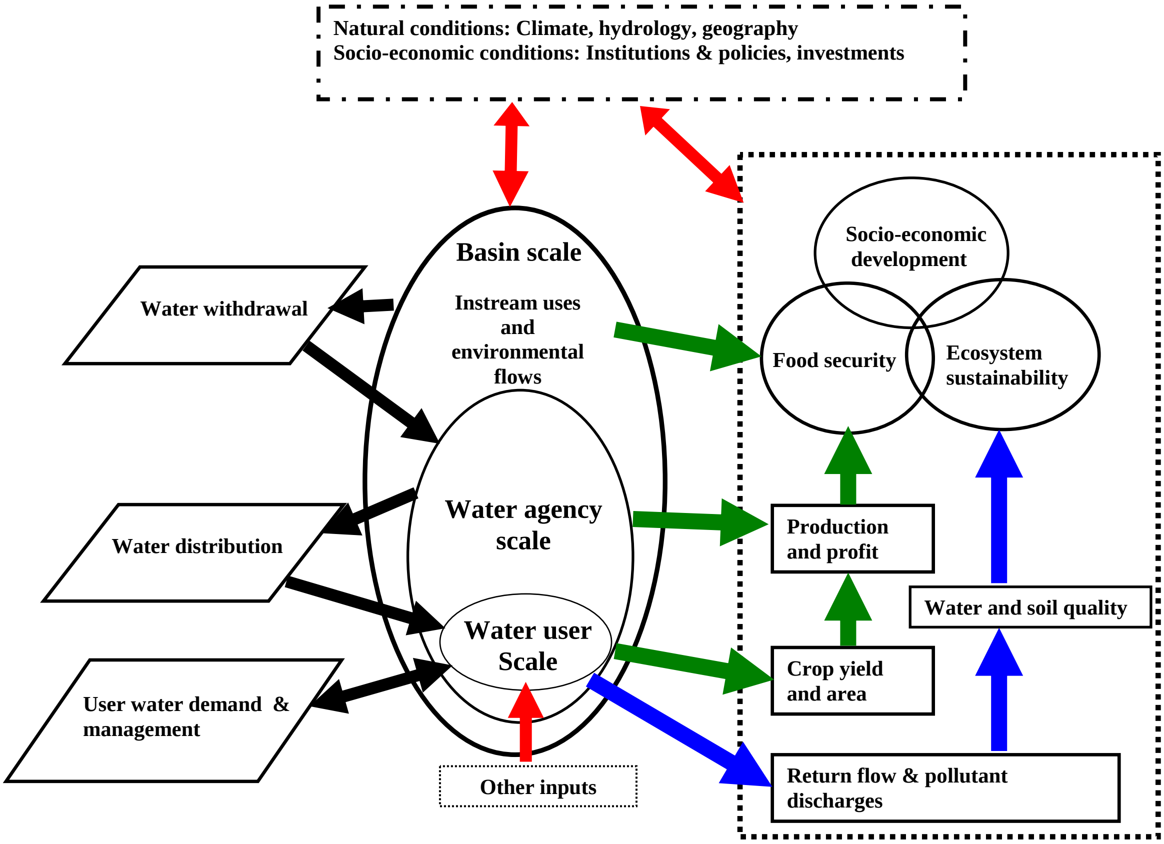

Figure 3. Framework for river basin modeling at various scales (adapted from McKinney and Cai, 2002).

A water management DSS at the basin scale should:

- *Integrate physical and policy relationships* in an endogenous system that will adapt to the environmental, ecological, socio-economic, and legal-political status of the basin;
- *River basin networks form the basis* upon which mathematical models are built (including e.g., water supply system, delivery system, water users system, waste water disposal and treatment system, and the connections between these subsystems);
- *Spatial and temporal distribution* of water flow and pollutant transport in the basin are represented in the models at appropriate scales, and water demands from all water-using sectors and the inter-sectoral water allocation policies;
- *Economic net-benefits* are evaluated (including ecological values) from water use in municipalities, agriculture and industry; and
- *Policy instruments* are incorporated, including regulations, economic incentives and voluntary arrangements (e.g. for pollution control, water conservation or ecosystem protection).

3. Available Decision Support Systems

This section focuses on systems which meet the criteria of DSS discussed in the previous section and are generally available either at no cost or for a license fee. Several systems may be missing from the list or omitted, generally because they are obsolete and have not been upgraded or maintained, or they are no longer distributed by the developers.

3.1 Emergency Water Management Decision Support Systems

3.1.1 Flood Management Decision Support Systems

CWMS (Fritz, J.A., et al., 2002) **-** The U.S. Army Corps of Engineers "Corps Water Management System" (CWMS) is an automated water management information system. The system is comprised of an integrated system of hardware and software that begins with the receipt of hydromet, watershed, and infrastructure data which are used to determine the hydrologic response of a watershed, including reservoir inflows and local uncontrolled downstream flows. Reservoir inflows are processed to compute releases to meet reservoir and downstream operation goals. River profiles are computed, inundated areas mapped, and flood impacts analyzed. Various future precipitation scenarios can be considered, hydrologic response altered, reservoir release rules investigated, and alternative infrastructure conditions evaluated.

CWMS uses a relational database (ORACLE) and the models incorporated in the system include HEC-HMS (hydrologic modeling), HEC-RAS (river analysis), HEC-ResSim (reservoir evaluation) and HEC-FIA (flow impact analysis). Access to the CWMS components is accomplished through a GUI which integrates the pieces of CWMS into one package. It includes mechanisms to evaluate the quality of incoming data, visualize information in time and space, facilitate model parameter adjustments, control and execute simulation models, and compare the results of different scenarios.

CWMS is distributed by the US Army Corp of Engineers to their staff offices. It runs on Sun UNIX-based workstations. CWMS has been deployed to over 35 Corps District and Division offices, including Nashville, TN (Barron, 2003).

SMS (EMRL, 2004) - The Surface Water Modeling System (SMS) has been developed by the Environmental Modeling Research Laboratory (EMRL) at Brigham Young University in cooperation with the U.S. Army Corps of Engineers Waterways Experiment Station (WES), and the US Federal Highway Administration (USFHWA). SMS is an interface providing access to one-, two-, and three-dimensional hydrodynamic modeling software, including pre- and post-processor software for surface water modeling. SMS models allow calculation of water surface elevations and flow velocities for shallow water flow problems, for both steady-state or dynamic conditions. Additional applications include the modeling of contaminant migration, salinity intrusion, and sediment transport (scour and deposition). SMS license fees are $9,250 for a single user including all modules and interfaces.

WMS (EMRL, 2004) - Similar to SMS and GMS, the Watershed Modeling System (WMS) has been developed by the Environmental Modeling Research Laboratory (EMRL) at

Brigham Young University. WMS is a graphical modeling environment for watershed hydrology and hydraulics. WMS also includes tools for automatically delineating watersheds and sub-basins including a direct linkage with ArcGIS. WMS license fees are $4,600 for a single user including all modules and interfaces.

Hydraulics Flooding Models in urban situation

WSE (Braschi et all, 1991) treated the aspect of hydraulic flooding modeling in urban situation considering that hydraulic cells could be considered to have a certain porosity. The considered porosity is the area not occupied by buildings in the cell. They also considered that the water transfer from one cell node to another should be calculated along preferential paths (essential roads). Following Braschi et all's ideas, the following modeling concepts can be defined:

1. water storage – the flood volume stored by structures, particularly buildings
2. water transfer – the effect of structures on the flood wave propagation.

The WSE model centers on the concepts of storage and transfer, one cannot neglected other essential hydraulic modeling considerations which apply to any flooding situation. A few of these are:

- the correct estimation of the river head losses (typically done by calibrating Manning coefficients) is absolutely necessary for the river flow capacity to be correctly simulated;
- detailed topographic data is necessary if detailed results are considered. Many studies have already shown that the topographic description is more important than the flooding Manning values (Horrit, Bates, 2001);
- hydraulic structures along the watercourse must be identified and the modeling of the structure decided upon according to the model possibilities.

FldPln is a quasi-2D numerical model; it was developed at HYDRAM laboratory of EPFL. It is a two dimensional hydraulic model taking into account the effect of the obstacles on the floodplain considered as micro-topography. This model use large computation units to allow a reasonable computation time. The micro-topography is taken into account by the mesh generation procedure that aligns Thissen polygons along the micro-topography and optimizes the size and position of the intermediate polygons (Consuegra et all 1999). With the discretization of the floodplain into cells respecting the break lines and the preferential flow paths, 1D hydraulic equations can be used to calculate the discharge between two cells due to the differences in their water elevations. Mesh generation, parameterization and simulation setup is done within MapInfo GIS software. Output data is written directly to MapInfo tables allowing easy flood hazard mapping. In this model, sometimes intercellular flow width has to be adjusted according to the maximum building density of the two cells.

FAST2D (Wenka, Valenta, Rodi 1991) followed by PREFAST (Valenta, Wenka 1996) including GIS facility are numerical models enable the simulation of free surface steady water flow in domain with complex geometry. The free surface flow version of the model was originally developed in Germany at the Institute for Hydrodinamics in Karlsruhe on the basis of an existing pure 2D model for pressure flow (Rodi et all, 1989).Further development of the model, aimed at the design and programming of a system of suitable pre- and post-processing tools, has been realized by the engineering firm Hydroexpert Ltd. In Prague in cooperation with the Bundesanstalt fur Wasserbau in Karlsruhe (Valenta, Wenka, 1996). This system PREFAST, is oriented towards the use of personal computers and was programmed as

an application based on the ADS (AutoCAD development system) for AutoCAD graphical software. The system inherits interactive user-friendly tools with a graphical interface for all steps of the model design – grid generation and modification, creating, editing and exploiting the digital terrain model, specifying obstacles, specifying the distribution of bottom roughness coefficients, and also for a graphical evaluation of the numerical simulation results.
FASR2D is coherent in terms of river-floodplain and floodplain-structural interactions. The velocities distribution is coherent with the buildings influence on flow direction. Another advantage is that only the Manning parameters need to be estimated. The disadvantage is the number of computation cells, which raise a big problem for time computation.

3.1.2 Accidental Spill Decision Support Systems

DBAM (Gils and Groot, 2002; Gils et al, 2004) **-** The Danube Accident Emergency Warning and Prevention System (DAEWPS) communicates information about transboundary flood or accidental spills events in the Danube basin. The “Danube Basin Alarm Model” (DBAM) is an operational model for the DAWEPS for simulating the travel time and expected peak concentrations of substances released during accidental spills. The DBAM was designed to provide a fast assessment of the effects of a spill using limited and readily available data. The Rhine Alarm Model (RAM) was used as the basis for DBAM, but DBAM goes one step further and calculates the spreading of pollution across the river (Greencross, 2003). DBAM was developed by an international consortium led by the Hungarian water agency VITUKI and including, among others, Delft Hydraulics specialists. DBAM was distributed to all the Danube Principal International Alert Centers (PIACs) in January 1999, and the model is operational in 11 Danube countries. The International Commission for the Protection of the Danube River (ICPDR) is preparing the full-scale calibration of the model (Gils et al., 2004).

The Hungarian PIAC tested DBAM for simulating the pollution impact of a spill of pesticide into the Danube which caused significant fish-kills and drinking water supply problems in neighboring villages (Pinter and Hartong, 2004). The movement of the contamination in the Hungarian stretch of the Danube was simulated and the time evolution of the peak concentrations was well modeled. On the other hand, the magnitude of the peaks exceeded what was actually observed in the lowermost section of the river in Hungary.

The water balance computation in DBAM is based on measured flows for a number of stations. In between those stations, incremental flows are assumed proportional to the increase of the catchment area along the river. River cross section and slope data are used in Manning’s equation to compute river flow. Discharge and velocity are calculated on the basis of actual hydrological input data: observed values of either the water level or the discharge at selected hydrological stations at the time of an accident.

The DBAM software consists of three main parts:

- A user interface program that reads network data and allows the user to perform selections and input data on accidental spills, and run simulations.
- A model program that reads the system input data defining the river and the case-dependent input files defining the spill and associated hydrology. It produces output files containing simulation results at selected locations and times.

- A result display program that reads the simulation result files together with river network data and produces graphics and tables.

RiverSpill (Samuels et al., 2003; SAIC, 2003) - RiverSpill is a GIS (ArcView 3.2) based system that models the real-time transport of constituents within a river system. RiverSpill calculates time of travel and concentration based on real time stream flow measurements, decay, and dispersion of constituents introduced into surface waters. RiverSpill contains the following capabilities: Release Type - Instantaneous or Continuous release; Agent Type - Chemical or Biological Agents; and Solution Type - Peak or non-Peak concentration. By selecting a location on a river to introduce a chemical or biological constituent, the model performs the following functions: Tracks the contaminant constituent under real time flow conditions to a water supply intake; determines the concentration of contaminant as it decays and disperses in the river; associates an intake to a water treatment plant; and identifies the population served by the plant. Instantaneous and complete mixing of the pollutant in the river water column is the most important assumption in RiverSpill. Any deviation from these conditions requires detailed analysis of physical and chemical processes. The model is currently operational for the continental U.S. and depends on several U.S. government databases. This same analysis could be using an ArcHydro representation of a watershed (personal communication, Samuels, 2004).

WQModel (Whiteaker and Goodall 2003; Whiteaker, 2004) - Whiteaker and Goodall (2003) and Whiteaker (2004) report the development of a water quality modeling module (“dll”) attached to an ArcHydro representations of a river basin. In WQModel, mass is passed to downstream locations in a basin and decays according to travel time and decay coefficients. The decay rate represents the loss of mass due to biological decay, sorption, uptake, etc, as material moves downstream. Accumulation of mass in lakes and other water bodies can also be calculated assuming the lake has constant inflow equal to its outflow, and that mass entering the lake is instantaneous and perfectly mixed within the lake.

3.2 Water Allocation Decision Support Systems

Aquarius (Diaz et al., 1997) - AQUARIUS was developed at the Department of Civil Engineering at Colorado State University in conjunction with the U.S Forest Service. AQUARIUS is a temporal and spatial allocation model for managing water among competing uses. The model is driven by economic efficiency which requires the reallocation of all flows until the net marginal return of all water uses is equal. The model is implemented in C++ under an object oriented programming framework, where each system component (e.g., reservoir, demand area, diversion point, river reach) is an object in the programming environment. In the GUI, the components are represented by icons, which can be dragged and dropped from the menu creating instances of the objects on the screen. These can be positioned anywhere on the screen or removed. Once components are placed on the screen, they are linked by river reaches and conveyance structures. The model does not include groundwater or water quality.

The model performs optimization to identify tradeoffs between water uses by examining the feasibility of reallocating water to alternative uses. Each water use is represented by an exponential demand curve (i.e., a marginal benefit function). The model is formulated as a quadratic programming model with a linear constraint set. Costs of water use are not explicitly considered in the model. The model could be used to evaluate net benefits by subtracting costs from benefits in the individual benefit functions. From the model documentation, it is apparent that making significant modifications to the model or its structure would be very difficult. Input to and output from the model is through user entered values and ASCII text files, respectively, and there appears to be no connection to spreadsheets or databases.

Although the present version of the model implements only a monthly time step, Aquarius was conceived to simulate the allocation of water using any time interval, including days, weeks, months, and time intervals of nonuniform lengths. Aquarius can be used in a full deterministic optimization mode, for general planning purposes, or in a quasi-simulation mode, with restricted foresight capabilities.

The software runs on PCs under the Windows environment. Usage is free for government agencies and for teaching and research purposes. It has been used mainly by the US forest service in various water management and ecosystem management problems.

Aquatool (Andreu, et al., 1991; Andreu, et al., 2003; Andreu, 2004) – Aquatool consists of a series of modules integrated in a system in which a control unit allows the graphical definition of a system scheme, database control, utilization of modules and graphical analysis of results. Modules include: surface and ground water flow simulation; single- and multi-objective optimization of water resources; hydrologic time series analysis; risk based WRS management. Water quality is not included. All documentation is in Spanish.

CALSIM (DWR, 2004) - The CALifornia Water Resources SImulation Model (CALSIM) was developed by the California State Department of Water Resources (DWR) and the United States Bureau of Reclamation for planning and management of the California State Water Project and the U.S. Central Valley Project. CALSIM is a hybrid linear optimization model which translates the unimpaired (i.e. natural) stream-flows into impaired streamflows, taking into account reservoir operating rules and contract water demands exerted at model nodes (Quinn et al., 2004). CALSIM uses a mixed-integer linear programming solver to route water through the river network at each time step (in contrast to the traditional Out-of-Kilter algorithm of ARSP and OASIS or the more efficient Lagrangian approach of ModSim). The model code is written in Water Resources Engineering Simulation Language (WRESL), a high-level programming language developed by the DWR, and the system of WRESL equations is solved using a proprietary solver XA (Sunset Software Inc.). The model is used to simulate existing and potential water allocation and reservoir operating policies and constraints that balance water use among competing interests (Quinn et al., 2004). Policies and priorities are implemented through the use of user-defined weights applied to the flows in the system. Simulation cycles at different temporal scales allow the successive implementation of constraints. The model can simulate the operation of relatively complex environmental requirements and various state and federal regulations. CALSIM is in a developmental state at the present time, and it is mentioned here to illustrate the type of large-scale DSS being contemplated for the California water system and to contrast some of its characteristics with other systems.

CALSIM, OASIS, RiverWare, and ModSim are similar in that they (Loucks et al., 2003):

- all use a high level language with syntax and logical operators;
- are written to simple text files which are subsequently parsed and interpreted;
- use rule-based or IF-THEN-ELSE conditional structures;

- are designed to be easy for planners and operators to use without the need for reprogramming;
- allow adaptive and conditional rules which are dependent on current system state variable information;
- include constructs for assigning targets, guidelines and constraints, along with their associated priorities; and
- include a goal seeking capability.

Similar to several other systems, CALSIM allows specification of objectives and constraints in strategic planning and operations without the need for reprogramming of the complex model (Loucks et al., 2003). CALSIM uses WRESL to define the objective function and constraints, similar to the OCL (Operational Control Language) used in OASIS and the Policy Editor employed in RiverWare. In ModSim, the optimization model is formulated directly through the GUI with no need for a modeling language, but with supplemental features of the optimization defined through the PERL scripting language. These various scripting languages allow planners and operators to specify targets, objectives, guidelines, constraints, and their associated priorities in ways familiar to them.

CALSIM lacks a comprehensive GUI for constructing and editing the river basin system topology. The model does not link to GIS at this time. CALSIM does not seem to be generally available for use; however, the development of this DSS serves as a good model for building other DSSs.

DELFT-TOOLS (Delft Hydraulics, 2004) – Delft-Tools is a framework for decision support developed by Delft Hydraulics for the integrating water resources simulation programs. Functions of the system include scenario management, data entry, and interactive network design from map data, object-oriented database set-up, presentation, analysis and animation of results on maps. DELFT-TOOLS integrates the Delft Hydraulics models: SOBEK, RIBASIM and HYMOS. SOBEK is a one-dimensional river simulation model that can be used for flood forecasting, optimization of drainage systems, control of irrigation systems, sewer overflow design, ground-water level control, river morphology, salt water intrusion and surface water quality. RIBASIM (River Basin Simulation Model) is a river basin simulation model for linking water inputs to water-uses in a basin. It can be used to model infrastructure design and operation and demand management in terms of water quantity and water quality. HYMOS is a time series information management system linked to the Delft Hydraulics models.

EPIC (McKinney and Savitsky, 2001; Schleuter et al., 2004) – EPIC (originally developed by the USAID project "Environmental Policies and Institutions for Central Asia") determines optimal water allocation in a river basin by multi-objective optimization in monthly time steps. Transport of conservative substances, e.g., salt, and management of generated hydroelectricity can also be optimized with the model. Water management alternatives can be developed for a time period of up to 15 years based on varying supplies and changing requirements of the water users.

Models created in EPIC perform optimization calculations for operation of river networks according to a ranked list of objectives. EPIC provides an interface for automatic network and model creation, as well as data input, input of constraints on reservoirs, channel flow and salinity, setting of the objective weights and visualization of results. The modeling system generates nonlinear optimization model files for solution by the General Algebraic Modeling

System - GAMS (Brooke et al., 1998). The main optimization criterion of EPIC is to minimize deficits of water delivery to users; other criteria include satisfying environmental flows, and maximizing reservoir overyear storage (McKinney & Savitsky, 2001). Policy decisions are modeled through changes in the weights on the various objective terms. A detailed description of the EPIC modeling system for river, salt, and energy management and its application to the Aral Sea basin can be found in McKinney and Kenshimov (2000) and McKinney and Savitsky (2001).

Applications of the EPIC modeling system for water management modeling have been primarily in the Aral Sea basin focusing on the Syrdarya (McKinney and Kenshimov, 2000). EPIC was used to determine water allocation tradeoffs between the needs of upstream hydroenergy production and downstream irrigation modeled on a one year basis (Antipova et al., 2002). The results were used to determine compensation for a reduction of energy production in favor of irrigation. Schleuter et al. (2004) applied EPIC to the Amudarya river to develop water allocation scenarios as the hydrological basis for ecological impact assessment. The model accurately represented current water allocation for the entire basin as well as a higher resolution description for the delta region and detailed operation calculations for the four-body Tyuyamuyun reservoir.

Mike-Basin (DHI, 2004) – MIKE-BASIN couples ArcView GIS with hydrologic modeling to address water availability, water demands, multi-purpose reservoir operation, transfer/diversion schemes, and possible environmental constraints in a river basin. MIKE-BASIN uses a quasi-steady-state mass balance model with a network representation for hydrologic simulations and routing river flows in which the network arcs represent stream sections and nodes represent confluences, diversions, reservoirs, or water users. ArcView is used to display and edit network elements. Water quality simulation assuming advective transport and decay can be modeled. Groundwater aquifers can be represented as linear reservoirs. Current developments are underway to utilize the functionality of ArcGIS-9 in MIKE-BASIN.

Basic input to MIKE-BASIN consists of time series data of catchment run-off for each tributary, reservoir characteristics and operation rules of each reservoir, meteorological time series, and data pertinent to water demands and rights (for irrigation, municipal and industrial water supply, and hydropower generation), and information describing return flows. The user can define priorities for diversions and extractions from multiple reservoirs as well as priorities for water allocation to multiple users. Reservoir operating policies can be specified by rule curves defining the desired storage volumes, water levels and releases at any time as a function of existing storage volumes, the time of the year, demand for water and possible expected inflows.

Water quality modeling in MIKE-BASIN is based on steady, uniform flow within each river reach and a mass balance accounting for inputs of constituents, advective transport and reaction within the reach. Complete mixing downstream of each source and at tributary confluences is assumed. Non-point pollution sources are handled in the model as well as direct loading from point sources. The model accounts for the following water quality parameters: biochemical oxygen demand, dissolved oxygen, ammonia, nitrate, total nitrogen, and total phosphorus. Non-point loads are represented using an area loading method accounting for the nitrogen and phosphorous loads originating from small settlements, livestock and arable lands assuming certain unit loads from each category.

MIKE-BASIN runs on Windows based PCs. First year license fees for are $3,200 / $10,000 (Single Node/Floating License) and the annual renewal fee is $800 / $2,500 (A Single Node license is restricted to running on one machine. A Floating License allows up to five concurrent sessions running on different nodes on a network). The software is sold by a U.S. subsidiary in Pennsylvania.

MIKE-BASIN is currently being used by the Idaho Department of Water Resources (IDWR) and the Bureau of Reclamation surface water budget models for various river basins in Idaho, ElectroPeru for real-time decision support system for reservoir operation and optimization , the government of Sabah, Malaysia for Environmental Planning, the Gold Coast, Australia government for the Gold Coast Drought Management Strategy, the Italian government for developing the Piedmonte Water Resources Action Plan, the Vietnamese government for support to Capacity Building of Water Resources Sector Institutes, the Honduran government for a Decision Support System for Water Resources, and the Chinese government for the Yangtze River and Estuary Study.

Czech DSS – MIKE-BASIN was used to create a DSS for development of national water management plans for meeting the legal requirements of European environmental directives (Krejciks, J., and S. Vanecek, 2000). The DSS includes data and information and modeling tools (Mike-Basin, ArcView and a database) to:

- Provide a national overview of river systems, pollution sources, water quality conditions, water supply and waste water treatment facilities, and options for improvements;
- Assess water quality conditions and estimate the costs of implementing various scenarios;
- Identify least cost strategies for meeting requirements of water supply and wastewater treatment directives; and
- Estimate economic and financial implications of EU accession

ModSim (Labadie et al., 2000; Shannon, et al., 2000 ; Dai and Labadie, 2001; Labadie, 2004) – ModSim is a generalized river basin DSS and network flow model developed at Colorado State University with capability of incorporating physical, hydrological, and institutional/administrative aspects of river basin management, including water rights. ModSim is structured as a DSS, with a graphical user interface (GUI) allowing users to create a river basin modeling networks by clicking on icons and placing system objects in a desired configuration on the display. Through the GUI, the user represents components of a water resources system as a capacitated flow network of nodes (diversions points, reservoirs, points of inflow/outflow, demand locations, stream gages, etc.) and arcs (canals, pipelines, and natural river reaches). ModSim can perform daily scheduling, weekly, operational forecasting and monthly, long-range planning. User-defined priorities are assigned for meeting diversion, instream flow, and storage targets. ModSim employs an optimization algorithm at each time step to solve for flow in the entire network to achieve minimum cost while satisfying mass balance at the nodes and maintaining flows through the arcs within required limits. Conjunctive use of surface and ground water can be modeled with a stream-aquifer component linked to response coefficients generated with the MODFLOW groundwater simulation model (Fredrick et al., 1998). ModSim can be run for daily, weekly, and monthly time steps. Muskingum-Cunge hydrologic routing is implemented in the model.

ModSim can also be used with geographic information systems (ArcGIS) (1) to generate input data for the model based on spatial databases, (2) to provide an interface for the user to modify input parameters, and (3) to display the results of the model in a way that decision makers can view the results in an easy to understand format (Gibbens and Goodman, 2000)

ModSim has been extended to treat water quality issues in stream-aquifer systems through an interactive connection to the EPA QUAL2E model for surface water quality routing, along with a groundwater quality model for predicting salinity loading in irrigation return flows (Dai and Labadie, 2001).

ModSim is well documented in both user manuals and source code comments. Model data requirements and input formatting are presented along with sample test applications useful in understanding model setup and operation. Currently, ModSim is being upgraded to use the ".NET Framework" with all interface functions handled in Visual Basic and C#. This will greatly enhance the ability of the model to interact with relational databases and all variables in the model will be available for reading or writing to a database.

ModSim is in the public domain, and executable versions of the model are available free of charge for use by private, governmental, and non-governmental users. Generally, the source code for the model is not available. However, some government agencies have negotiated agreements with the developer in which the source code is made available to the agency and the agency is allowed to change or modify the source code as necessary for agency-related projects.

Current users of the ModSim include the U.S. Bureau of Reclamation, the City of Ft. Collins, Colorado, the City of Greely, Colorado, the City of Colorado Springs, Colorado and the Imperial Irrigation District in California. Many additional applications of ModSim exist.

OASIS (Hydrologics, 2001; Randall et al, 1997) - Operational Analysis and Simulation of Integrated Systems (OASIS) developed by Hydrologics, Inc. is a general purpose water simulation model. Simulation is accomplished by solving a linear optimization model subject to a set of goals and constraints for every time step within a planning period. OASIS uses an object-oriented graphical user interface to set up a model, similar to ModSim. A river basin is defined as a network of nodes and arcs using an object-oriented graphical user interface. Oasis uses Microsoft Access for static data storage, and HEC-DSS for time series data. The Operational Control Language (OCL) within the OASIS model allows the user to create rules that are used in the optimization and allows the exchange of data between OASIS and external modules while OASIS is running. OASIS does not handle groundwater or water quality, but external modules can be integrated into OASIS. Oasis does not have any link to GIS software or databases.

OASIS has been used to model parts of the South Florida Water Management District, the Delaware River (Delaware River Basin Commission), the Roanoke River (U.S. Bureau of Reclamation, The Nature Conservancy), the Kansas River (Kansas Water Office), the Rio Grande (University of Texas at Austin), the South Fork of the American River in California, and for long term planning in the Alameda Water District in California.

RiverWare (Carron et al., 2000; Zagona et al., 2001; Boroughs and Zagona, 2002; CADWES, 2004) – The Tennessee Valley Authority (TVA), the United States Bureau of Reclamation (USBR) and the University of Colorado's Center for Advanced Decision

Support for Water and Environmental Systems (CADWES) collaborated to create a general purpose river basin modeling tool - RiverWare. RiverWare is a reservoir and river system operation and planning model. The software system is comprised of an object-oriented set of modeling algorithms, numerical solvers and language components.

Site specific models can be created in RiverWare using a graphical user interface (GUI) by selecting reservoir, reach confluence and other objects. Data for each object is either imported from files or input by the user. RiverWare is capable of modeling short-term (hourly to daily) operations and scheduling, mid-term (weekly) operations and planning, and long-term (monthly) policy and planning. Three different solution methods are available in the model: simulation (the model solves a fully specified problem); rule-based simulation (the model is driven by rules entered by the user into a rule processor); and optimization (the model uses Linear Goal-Programming Optimization).

Operating policies are created using a constraint editor or a rule-based editor depending on the solution method used. The user constructs an operating policy for a river network and supplies it to the model as “data” (i.e., the policies are visible, capable of being explained to stakeholders; and able to be modified for policy analysis). Rules are prioritized and provide additional information to the simulator based on the state of the system at any time. RiverWare has the capability of modeling multipurpose reservoir uses consumptive use for water users, and simple groundwater and surface water return flows.

Reservoir routing (level pool and wedge storage methods) and river reach routing (Muskingum-Cunge method) are options in RiverWare. Water quality parameters including temperature, total dissolved solids and dissolved oxygen can be modeled in reservoirs and reaches. Reservoirs can be modeled as simple, well-mixed or as a two layer model. Additionally, water quality routing methods are available with or without dispersion. RiverWare does not have a connection to any GIS software; however, a hydrologic database (HDB) may be available (Frevert, et al., 2003; and Davidson et al, 2002). HDB is a relational database used by the USBR and developed by CADWES to be used in conjunction with RiverWare. HDB is an Oracle-based SQL database and includes streamflow, reservoir operations, snowpack, and weather data.

RiverWare is currently being used by the Tennessee Valley Authority for daily scheduling of more than 40 reservoirs and hydroplants. The U.S. Bureau of Reclamation uses RiverWare’s rule-based simulation models on the Colorado River for policy negotiations, to estimate salinity and set monthly target operations for the entire river basin. The U.S. Army Corps of Engineers, U.S. Bureau of Reclamation and the U.S. Geological Survey have applied RiverWare’s rule-based simulation and water accounting to the Upper Rio Grande to track native water and diversions.

RiverWare runs on Sun Solaris (Unix) workstations or Windows based PCs. First year license fees for are $6,500 / $11,500 (Single Node/Floating License) and the annual renewal fee is $2,500 / $5,000.

URGWOM – RiverWare was used to create the Upper Rio Grande Water Operations Model (URGWOM) developed by the U.S. Bureau of Reclamation, U.S. Fish and Wildlife Service, U.S. Geological Survey, U.S. Bureau of Indian Affairs, the International Boundary and Water Commission (U.S. Section), and the U.S. Army Corps of Engineers (USACE, 2004b). This tool is used to support studies related to water accounting and annual operating plans for the

Rio Grande from the Colorado/New Mexico border to El Paso, Texas. The model is capable of simulating water storage and delivery operations and for flood control modeling. URGWOM is a basic "backbone" water operations DSS meant to replace the current, more cumbersome, methods that are used to plan, analyze, and evaluate river and reservoir management options.

URGWOM uses HEC-DSS as the primary database. The primary data required for the model include:

- Agriculture - crop deep percolation, canal seep, crop acreage, and estimated actual evapotranspiration rate by reach by crop;
- Diversions - flow in diversion canals, associated ditches, and drains;
- Evapotranspiration - includes crop acreage and consumptive use by reach by crop;
- Local Inflow - estimated ungaged side inflows to the Rio Grande;
- Reservoirs - includes numerous reservoir records such as pool elevation, temperature, and sedimentation;
- River Losses - computed loss (gross leakage) from the Rio Grande;
- Stage - elevation of water surface;
- San Juan-Chama Accounts - includes San Juan-Chama Contractor accounting data;
- Streams - flow in the Rio Grande and its tributaries; and
- Wastewater - wastewater treatment plant discharge.

URGWOM is used by stakeholders to examine efficient water management alternatives. Historically, the water of the Rio Grande has been used primarily for crop irrigation. However, rapid population growth in the Basin and urbanization in some areas has resulted in increasing and diversifying demands on the hydrologic system. Water management decisions are becoming increasingly complex and difficult due to the broad range of interests and issues that must now be considered. A greater variety of official entities and interest groups are asserting influence over water management decisions than ever before. As water supply limits are approached, higher levels of precision and reliability in water accounting and forecasting are required.

CRSS - The Colorado River Simulation System (CRSS) model (Schuster, 1987) was created in the early 1980s to model the Colorado River Basin in order to schedule, forecast and plan reservoir operations. Since CRSS was created to model the Colorado River Basin, many of the characteristics of the basin were hard-coded into the model, including the topography of the basin itself, the methods for calculating evaporation, bank storage and other reservoir-specific information, and the policies by which water is allocated (Wehrend, 2002). As new information about the basin and the operation policies and technology became available, CRSS had to be updated and RiverWare was chosen for this task.

Wheeler et al. (2002) report on the use of the CRSS-RiverWare system's use in five case studies:

- Interim Surplus Guidelines Study – a study of alternatives to gradually decrease California's dependency on water use beyond its apportionment over the next 15 years;
- Secretarial Implementation Agreement Study – the Interim Surplus Guidelines are contingent on certain stipulations for California, primarily transfer of water from

agricultural to municipal use; this study analyzed the effects of water transfers and potential inadvertent overrun withdrawals;
- Multi-Species Conservation Program Study – analysis of the potential effects of other future water transfers from agricultural uses to municipal and industrial uses;
- The restoration of the Colorado River Delta – comparing alternative plans for restoring a formerly rich riparian habitat; and
- The operation of Flaming Gorge Dam – comparing policies that attempt to mimic natural flow patterns and meet minimum flow recommendations and consumptive use demands.

Wheeler et al. (2002) note that modeling alternative policies on the Colorado River provides a method for reaching compromise on the operation of river basins. The cited examples indicate more accessible modeling tools make it possible for a wider range of participation in exploring policy analysis and creating new alternatives.

WaterWare (Fedra, 2002; Jamison and Fedra, 1996) - WaterWare is a decision support system based on linked simulation models that utilize data from an embedded GIS, monitoring data including real-time data acquisition, and an expert system. The system uses a multimedia user interface with Internet access, a hybrid GIS with hierarchical map layers, object databases, time series analysis, reporting functions, an embedded expert system for estimation, classification and impact assessment tasks, and a hypermedia help- and explain system. The system integrates the inputs and outputs for a rainfall-runoff model, an irrigation water demand estimation model, a water resources allocation model, a water quality model, and groundwater flows and pollution model.

3.3 Water Quality Decision Support Systems

BASINS (USEPA, 2004) - Better Assessment Science Integrating Point and Nonpoint Sources (BASINS) is a DSS that brings together large amounts of environmental data and modeling capabilities in a single package with a GIS serving as the integrative platform. BASINS has three objectives: to facilitate the examination of environmental information; to support analysis of environmental systems; and to provide a framework for examining management alternatives (US EPA, 1998). The system runs on PCs in the Windows environment and allows users to assess water quality at selected stream sites or throughout an entire watershed. It integrates environmental data, analytical tools, and modeling programs to support development of cost-effective approaches to environmental protection. BASINS is comprised of a suite of components for performing watershed and water quality analysis, including:

- Environmental and GIS databases (mainly U.S. based, but there are several applications in Europe);
- Assessment tools for evaluating water quality and point source loadings;
- Utilities, including data import and management of water quality observation data;
- Watershed delineation tools;
- Utilities for classifying digital elevation models (DEM), landuse, soils, and water quality data;
- In-stream water quality and eutrophication model (QUAL2E ver. 3.2);
- Simplified GIS-based nonpoint source annual loading model (PLOAD);

- Watershed loading and transport models:
    - HSPF, a watershed scale model for estimating instream concentrations resulting from loadings from point and nonpoint sources. *WinHSPF* is included which is an interface to the Hydrological Simulation Program Fortran (HSPF), version 12 and
    - SWAT, a physically based, watershed-scale model for predicting the impacts of land management practices on water, sediment and agricultural chemical yields in large complex watersheds with varying soils, land uses and management conditions over long periods of time.
- Model results postprocessor (GenScn) for scenario generation to visualize, analyze, and compare results from HSPF and SWAT

BASINS' databases and assessment tools are directly integrated within an ArcView GIS environment (EPA will release a version of BASINS for the ArcGIS platform sometime in 2004).

Modulus (Engelen, G., et al., 2000; Oxley, et al., 2002; Oxley, et al., 2004) - The European Commission (EC) has, through its successive 'Framework' programs, funded the MODULUS Project to integrate models developed in other EU projects to produce an environmental DSS. Modulus integrates several models through a GUI, including: climate and weather, hillslope hydrology, plant growth, natural vegetation, groundwater, surface water, crop choice, irrigation, and land-use models. Modulus is composed of a number of components (ActiveX[1] COM compliant components) each corresponding to one of the models. The components can be easily exchanged because the interface of each ActiveX component is standardized. The integration of existing models is achieved without having to rewrite existing models by using a "wrapping" technique[2] which transforms models from their native code into ActiveX components. Standard interface definitions are used to integrate each component into the DSS in the Windows environment. Modulus does not seem to be generally available for use; however, the development of this DSS serves as a good model for building other DSSs.

4. Conclusions and Recommendations on Decision Support System Creation

4.1 Lessons Learned

4.1.1 Definition of a DSS – As noted above, the generally accepted definition of a DSS is a combination of a reasonably easy to use system that integrates an interactive user interface, a database, and model(s) for the intended decision support purpose(s). Most of the reviewed systems do not meet fully the requirements of a DSS. The reviewed water management DSSs have been developed according to two general approaches:

[1] "active X" - A set of technologies that enables software components to interact with one another in a networked environment, regardless of the language in which the components were created. ActiveX is built on Microsoft's Component Object Model (COM - a software architecture that allows applications to be built from binary software components.).
[2] "wrapper" – an enclosure used to wrap a legacy application to make the legacy application available in a new computer environment.

- Stand-alone approach – where a DSS is created from scratch as a stand-alone system with a unified input data set and a core of modeling tools that tightly couple to each other, e.g., Aquatool, Mike-Basin, and ModSim; and
- Framework approach – where a DSS is created by taking a series of existing models and creating an interface that allows a user to execute the modeling procedures in a sequence, passing outputs of one model to another as input in a user-transparent manner, e.g., CWMS, and Waterware.

The DSSs and models reviewed in this report are not an exhaustive list of all the available systems and components, but they are representative of the mainstream of available products. The technologies and methods for developing and deploying water management DSSs have become mature over the past few years. However, creating and deploying a DSS for particular, site specific applications requires careful planning and significant computer and programmer experience.

4.1.2 Graphical User Interfaces - Graphical, user friendly operating systems and software have become the norm and this is seen in the fact that all of the reviewed systems have graphical, interactive interfaces integrated with models. This trend has enabled decision makers to take a more active role in using these systems in water management. It has brought more focus on the formulation of support systems that are responsive to the needs of decision makers, rather than modelers and developers.

4.1.3 Modeling Multiple Areas of Water Management - In spite of recent rapid advances in computer technology and the proliferation of software for decision support, there are few DSSs available that can help to solve problems covering more than one or two areas of water management. That is, there are systems that are good for flood prediction and management, e.g., CWMS, and others that are good for water allocation to competing uses, e.g., ModSim, RiverWare, and Mike-Basin, but there aren’t any that can cover the broad spectrum of water management from flood protection to groundwater management and everything in between.

That there are no DSSs that can handle a wide variety of water management problems is not surprising, given the plethora of physical, chemical and biological processes that need to be modeled, the disparate temporal and spatial scales of these problems, and the different data needs. Flooding problems often need models that can handle time steps on the order of tens of minutes, whereas, water allocation models use time steps of one month. Groundwater models often use time steps of one month, but the data needed for describing three-dimensional subsurface formations is very different from that required to describe a tree-like river network.

One of the difficulties encountered in modeling water management systems is the incorporation of realistic decision rules or policies. This has been especially difficult in applying some reservoir simulation models, such as HEC-RESSIM and WEAP, to situations which do not follow the standard decision rules programmed in the model. Most of the reviewed models have some ability to incorporate user designed water management policies and, recently, several (e.g., ModSim, RiverWare, and Oasis) have incorporated rule processing languages. Many of the models for water allocation have some ability to optimize water allocation given management priorities, however, only a couple of them are truly “optimization” models, e.g., ModSim, RiverWare, and EPIC.

4.1.4 Relational Databases and GIS - Quick access to and processing of large, spatially distributed databases over high-speed, readily accessible networks now offers a tremendous improvement in the way DSSs can be developed and the effectiveness with which they may be used. Few of the DSSs and models reviewed make use of modern, relational database software or techniques. The lack of database usage is a major weakness in most of these models, since the majority of water management data are being distributed in this form today, e.g., South Florida Water Management District, National Water Commission of Mexico, Romanian Waters, have major projects underway to convert all data storage and access over to database systems.

GIS is becoming a standard tool for support of water management modeling, especially in hydrologic applications such as flood management. Interfaces, such as ARCHydro, that allow GIS to connect easily to spatially referenced relational databases (geodatabases) are becoming an important tool in water management. Several of the reviewed models have good access to the ArcView GIS system (e.g., Mike-Basin, RiverSpill, and Basins), and a few others have a map image display capability. By and large, all of the systems lack serious interfaces to GIS software or geodatabases and those that do, need to update their systems to keep current with the new GIS software, e.g., ArcGIS-9.

4.1.5 Legacy Code – By and large, the reviewed model codes are old and have not been rewritten in modern, object-oriented programming languages. This is because many of the existing systems are “legacy” codes, originally developed in the 1970s, that have been maintained and upgraded incrementally over the years, usually in the original language. Typically in these models, input is read from ASCII text files that tend to preserve the formatting of Hollerith punch cards, and output is not much better, in that it is to ASCII text files that must then be processed, in most cases, by a spreadsheet or other third-party software. In the future it will become increasingly difficult to prepare input files from relational databases to use as input to these models. The models need to be updated to access the databases directly. It is worth noting that some models have their own database management systems, e.g., HEC-DSS, and RiverWare, and others have the ability to access databases, e.g., ModSim, but these seem to be the exception.

4.2 Design Aspects of a DSS.

4.2.1 Design Process - There are several factors that must be considered in designing a water management DSS. These are all related to the basic criteria used to define a DSS:

- Interactive user interface;
- Database; and
- Model(s)

As mentioned in the previous section, these elements are commonly applied to water management in various combinations, but they are rarely all integrated into a single, seamless system for decision support. Several reasons for this have been outlined, including the use of legacy code which hampers the integration of relational databases into modeling. This leads to questions about what can be done in the design of a DSS to avoid the pitfalls identified of existing systems. Davidson et al. (2002) note four main phases in the design of water management DSSs:

1. Needs assessment to identify the functional requirements of the system;
2. Design of the system;
3. Construction of the system; and
4. Maintenance and support of the system including reevaluation of needs and design.

The first phase is critical to the success of any DSS. The needs for and uses of the system have to be assessed and defined. The specific aspects of water management to be addressed by the DSS must be defined, i.e., a flood management DSS can not be expected to function as a water allocation DSS and vice versa. The users of the system need to be clearly identified and their needs for system functions assessed. Lam et al. (2004) note that DSSs can be developed for different types of users: technical users who need an interface that understands and communicates with databases and models from different programming platforms and languages, and public users who are served decision support through web-based interfaces and simplified systems.

The design of the system should follow modern and up-to-date software engineering principles, including programming languages, database systems, and interface design. The use of legacy code should be minimized and where it is used, that use should be justified. The development process can be broken down into a series of sequential steps (Davidson et al. 2002):

- Requirements definition;
- Preliminary design;
- Detailed design;
- Implementation;
- Unit testing;
- Integration testing;
- System testing;
- System rollout; and
- Maintenance.

4.2.2 Specific Aspects of Systems – there are several specific programming aspects that should be taken into account when developing a water management DSS. These include:

- The interface to be used in the DSS;
- The method of connecting DSS components together into an integrated system;
- The data model to be used to store all of the necessary information to represent the water management problem;
- The algorithms to be used in solving for flow in a surface or ground water system; and
- Any special programming and processing languages and tools necessary to represent stakeholder priorities in the DSS.

User Interface – User interfaces are easily constructed today using a variety of software development tools, including Borland Builder and MS Visual Studio. These tools have made it extremely easy to design and develop interfaces to control the functioning of almost any application or combination of applications that must work together in a software package.

Integrating DSS components - Using available software development environments, DSS components, i.e., interfaces, databases, and models, can be integrated to work together in a seamless, user interactive environment. The basis for this integrability is the use of COM compliant components[3] for each model in the DSS. The components can be easily integrated because the interface of each component is standardized. The integration of existing models can be achieved without having to rewrite existing models by using a “wrapping” technique[4] which develops the standard interface for the model. Once the standard interface has been created for a model, it can be integrated into the DSS in the Windows environment.

Network flow solvers – One of the most important developments in river basin simulation models is the use of linear optimization algorithms to solve simultaneous equations in order to mimic operating policies. Such sets of procedures can be difficult to generate for complex systems, and very different and new rule sets may be needed if structural or significant policy changes are to be investigated. In order to avoid this, river basin models can be formulated as minimum cost capacitated network flow problems solved using network flow solvers, such as the out-of-kilter algorithm (used in HEC-ResSIM) or the more efficient Lagrangian approach (used in ModSim) of Bertsekas (1994). In a network flow model, the system is represented as a collection of nodes (e.g., reservoirs, diversions, stream tributary confluences, and other system features) and arcs. Nodes are connected by arcs representing the flow (discharge rate). The network flow solver computes the values of the flows in each arc so as to minimize the weighted sum of flows, subject to constraints on mass balance at each node and upper and lower flow bounds. The weights are penalties expressing relative priorities in user defined operating rules. The user must provide lower and upper bounds on diversions, instream flows, and reservoir storage levels and assign relative priorities for meeting each flow requirement and for maintaining target reservoir storage levels. The network solver computes the flows and storage changes in a particular time interval (say, a day or a month), and then uses the solution as the starting point for calculations in the next time interval.

A distinguishing feature of these hybrid simulation/optimization models is the use of optimization on a period by period basis (not fully dynamic over the entire planning horizon, as in the EPIC system) to “simulate” the allocation of water under various prioritization schemes, such as water rights, without perfect foreknowledge of future hydrology and other uncertain information. Systems employing optimization in this manner include: ARSP, ModSim, OASIS, Ribasim, RiverWare, WEAP and CALSIM II. ModSim is further distinguished by the use of iterative structures using an imbedded scripting language which allows including non-network “side constraints” in the optimization.

Rule processing languages - Several of the reviewed DSSs make use of special programming languages for further defining system operating rules. These languages include Tcl (Ousterhout, 1994), Perl (Schwartz and Christiansen, 1997), Python (van Rossum, 1995), Java (Arnold, et al., 2000) and CLIPS (NASA, 1994). Tcl (used in RiverWare) is an interpreted scripting language that can be easily embedded into existing C applications to perform any task that could be performed by a compiled C function and they can be changed without rebuilding the C program. Perl (used in ModSim) is a very fast interpreted scripting

[3] “COM” - Microsoft's Component Object Model, a software architecture that allows applications to be built from binary software components and enables software components to interact with one another in a networked environment, regardless of the language in which the components were created.
[4] “wrapper” – an enclosure used to wrap a legacy application to make the legacy application available in a new computer environment.

language that can be used to quickly develop small to moderate sized programs and extended to include user-defined functions.

4.2.3 Sustainability and Institutional Capacity

4.2.3 Sustainability and Institutional Capacity - The issue of sustainability needs to be addressed in looking at possible DSSs or models to be deployed in a large-scale manner such as a National Water Agency. If a commercial software product is purchased today, what assurance does the purchaser have that the company will still be in business and supporting the software in the future? Similarly, if public domain software is obtained, what is the likelihood that the developers will maintain interest in supporting the software? If the company migrates their software to a different system, will the customer be informed and offered upgrades at reasonable cost? If a system is implemented in a UNIX or LINUX operating system, but the company decides later to switch to the more common Windows environment, will the customers be offered the new product and at what cost? It is worth noting that may of the commercially available models described above are essentially “dressed-up” versions of public-domain software that is maintained by government agencies. Developers of the original public-domain codes may decide not to fund the support and maintenance of these models in the future. There is a history of government developers providing adequate notice of these types of changes (i.e., obsoleting old codes).

A major problem arises when agencies receive software for free from commercial developers or purchase a single license and then do not purchase adequate licenses to achieve the desired deployment of the software and do not purchase annual license renewal, support and upgrades. This leaves the agency in the position of deploying software without any possibility of support or upgrade in the future.

Agencies need to have adequate human resource capacity to understand the physical, chemical and biological aspects needed to model water management problems. In addition, capacity is required to maintain, modify and develop new database and modeling software and systems as to achieve the goals of the agency.

In addition, agencies need to prepare and implement adequate training for staff and stakeholders to understand and properly use installed software. This needs to be part of the design and implementation of a water management DSS. As an example, the CALSIM II model was developed almost entirely as an internal California Department of Water Resources and US Bureau of Reclamation effort with little input from stakeholders until after model development was complete. The model was released to a user community with little provision made for training, support or documentation. This has turned out to be a major problem for the developers who have had to go back and design a support and training mechanism for the user community (DWR, 2004; Loucks et al., 2003). Agencies planning to deploy modeling tools and systems need to give these issues considerable thought and plan for training and support.

4.3 What Should a Water Management DSS Look Like?

There are several ways that one may approach the problem of developing a DSS for water management:

- One general DSS solving all aspects for water management in a region; or

- A package of dedicated DSSs for different water management problems (loosely) integrated in a package or packages.

Unless one wants to start from scratch and program all elements of a DSS, then the second approach may be preferable.

The DSS may contain the some or all of the following parts:

1. Emergency Water Management –
   a. Data collection - Collection of precipitation, streamflow and infrastructure data by automated sensor systems and transmission and entry into a central database,
   b. Runoff modeling - Streamflow forecast models, such as the National Weather Service RFS model or the Princeton University TOPLATS model, to predict runoff resulting from single storm events or longer term conditions,
   c. Flood management – catchment modeling of precipitation and runoff generation coupled with reservoir operation for flood control and flood damage assessment using the US Army Corps of Engineers CWMS system with appropriate warnings issued. In addition, the FLDWAV package could be used to predict the consequences of infrastructure failure.
   d. Accidental Surface Water Spill Management – Modeling of advective transport of chemical constituents from a spill site to downstream vulnerable or critical sites with appropriate warnings issued, using a system similar to the USEPA Riverspill model.

2. Surface water allocation – using monthly aggregated streamflow data from the database described above. This could be accomplished with the Mike-Basin, or ModSim models.

3. Surface water quality management – using daily streamflow data from the database described above. This could be accomplished with the QUAL2e, HSPF, WASP models for rivers, and the CE-QUAL-W2 or DYRESM models for lakes and reservoirs.

4. Groundwater allocation – using the USGS MODFLOW model for simulation of groundwater flow along with MODOFC for management.

5. Groundwater quality management – using the MT3D model for simulation of chemical constituents in groundwater.

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Appendices

Models Used in Decision Support Systems

A.1 Hydrologic Models - Event-based

Hydrologic models simulate the hydrologic processes by which precipitation is converted to streamflow. These models are often used to provide input hydrographs to river hydraulics models and river management models. A portion of precipitation may be lost from through interception, depression storage, infiltration, evaporation, and transpiration (Chow et al., 1988). The remaining precipitation flows overland and through the soil, collects as flow in swales and small channels, and eventually becomes runoff to streams. Land use, drainage improvements, storage facilities, and other development activities significantly affect the processes by which precipitation is converted to streamflow. Snowfall and snowmelt as well as rainfall are important in many areas.

Hydrologic models are categorized generally as event or continuous models. Event models simulate individual storm events and neglect soil infiltration and other abstractions. Continuous models simulate long periods of time which include multiple precipitation events separated by significant dry periods with no precipitation. Modeling water quality in a watershed requires the use of a continuous watershed model.

Simulating the runoff response of single rainfall events is based on the unit hydrograph or kinematic wave approaches and involves the following tasks for each individual sub-watershed of the basin of interest (Wurbs, 1994):

(1) A precipitation depth is specified for each time interval;
(2) The runoff volume, resulting from the precipitation in each time interval, is computed;
(3) Either a unit hydrograph or kinematic routing is applied to convert the incremental runoff to a runoff hydrograph at the sub-watershed outlet
(4) Hydrologic routing hydrographs through stream reaches and reservoirs. Channel routing methods include: Muskingum, Muskingum-Cunge, modified Puls, working R and D, average lag, and kinematic wave.

HEC-HMS (HEC, 2001) - The USACE Hydrologic Engineering Center – Hydrologic Modeling System (HEC-HMS) is an event based precipitation-runoff model. In addition to the basic watershed modeling capabilities, HMS includes several other optional features involving: partially automated parameter calibration, multiplan-multiflood analysis, dam safety analysis, economic flood damage analysis, and flood control system optimization.

An HMS precipitation-runoff modeling application typically involves dividing a watershed into a number of sub-watersheds for analysis. HMS provides flexible options for developing and/or inputting precipitation data, which may reflect snowfall and snowmelt as well as rainfall. Precipitation volumes are converted to direct runoff volumes using one of the following optional methods: Soil Conservation Service curve number method; initial and uniform loss rate; exponential loss rate function; Holtan loss rate function; or Green and Ampt relationship. Runoff hydrographs are computed from the incremental runoff volumes using either the unit hydrograph or kinematic routing options. A unit hydrograph may be input to HMS. Watershed modeling also involves routing hydrographs through stream reaches and reservoirs. HMS uses hydrologic storage routing for reservoirs. The following channel routing options are provided: Muskingum, Muskingum-Cunge, modified Puls, working R and D, average lag, and kinematic wave. HMS includes modeling capabilities such as snowmelt rather than just rainfall; flood control economic analyses; and partially automating parameter calibration.

A.2 Hydrologic Models - Continuous

Continuous watershed simulation models allow simulation of streamflow over long periods of time and maintain a continuous accounting of the water in storage in the watershed (Singh, 1992). Due to the longer time simulated, interception, depression storage, infiltration, subsurface flow, baseflow, evaporation, and transpiration processes can be directly accounted for in the models.

HSPF (Johanson et al. 1980, 1984) – A discussion of Hydrological Simulation Program – Fortran (HSPF) can not really begin without mentioning the Stanford Watershed Model (SWM) developed at Standard University in the early 1960s (Crawford and Linsley 1966). SWM and its variations are composed of a set of water budget accounting procedures which incorporate computational routines for the various hydrologic processes such as interception, infiltration, evapotranspiration, overland flow, channel routing, and so forth. Time series input data include precipitation, potential evapotranspiration, and, if snowmelt is modeled, additional meteorological data. In the model, precipitation is stored in the snowpack and in three soil-moisture zones (upper, lower, groundwater). The upper and lower storage zones account for overland flow, infiltration, interflow, and inflow to groundwater storage. Groundwater storage supplies baseflow to stream channels. Evaporation and transpiration may occur from any of the three storage zones. The runoff from overland flow, interflow, and base flow enters the channel system and is routed downstream. Model output includes continuous outflow hydrographs.

Derivatives of the Stanford Watershed Model include (Viessman et al. 1989; Ponce 1989) the Kentucky Watershed Model, Texas Watershed Model, Ohio Watershed Model, U.S. Department of Agriculture Hydrograph Laboratory (USDAHL) Model, Sacramento Model, National Weather Service River Forecast System (NWS-RFS), Hydrocomp Simulation Program, and Hydrological Simulation Program-Fortran (HSPF).

HSPF, the current successor model to SWM, provides relatively sophisticated capabilities for continuous simulation of a broad range of hydrologic and water quality processes. HSPF is "a comprehensive package for simulation of watershed hydrological and associated water quality processes on pervious and impervious land surface, in the soil profile, and in streams and well-mixed impoundments" (Donigian et al., 1984). HSPF consists of a set of modules arranged in a hierarchical framework, built around a time series management system. The various simulation and utility modules can be invoked individually or in various combinations. The structured design of the model facilitates users adding their own modules, if they so desire. HSPF simulates watershed hydrology and water quality for both conventional and toxic organic pollutants. Input data include time histories of rainfall, temperature, and solar radiation; and information regarding land-surface characteristics, such as land-use patterns and soil properties, and land-management practices. The model predicts flow rates, sediment loads, and nutrient and pesticide concentrations. HSPF allows integrated simulation of land and soil contaminant runoff processes with in-stream hydraulic and sediment-chemical interactions. HSPF simulates three sediment types (sand, silt, and clay) in addition to a single organic chemical and transformation products of that chemical. The transfer and reaction processes modeled are hydrolysis, oxidation, photolysis, biodegradation, volatilization, and sorption. Sorption is modeled as a first-order kinetic process in which the user must specify a desorption rate and an equilibrium partition coefficient for each of the three solid types. Benthic exchange is modeled as sorption/desorption and desorption/scour with surfacial benthic sediments.

There are three main modules in HSPF (PERLND, IMPLND, and RECHRES) that simulate hydrological and chemical processes in pervious landcover, in impervious landcover, and in reaches. PERLND treats the land surface and the underlying soil profile as a series of connected storage reservoirs, each of which either receives inputs, or spills output, or both. IMPLND is much simpler than the PERLND due to the absence of the soil profile, since no water is considered to move beyond the land surface. RESCRES routes both water and chemicals entering a reach from the land segment to the downstream point. HSPF simulates sediment transport processes at the hill slope and reach levels. The model assumes that the transported sediment material consists of sand, silt, and clay. Several options are available for the model user to estimate the sediment load from the land to the reach and the final load at the outlet.
Various chemical constituents can be modeled in HSPF. It is assumed in the model that constituents undergo various chemical processes in the pervious land segment (this is not the case for the impervious land). The model considers adsorption and desorption of constituents to material in the soil and sediments, mineralization/immobilization processes, and plant uptake. Constituents removed from the land either in dissolved form or associated with sediment are delivered with runoff to the main river channel where chemical stream processes occur until the outlet is reached.

PRMS (Leavesly et al., 1983) - The U.S. Geological Survey (USGS) Precipitation-Runoff Modeling System (PRMS) performs computations on both a daily and smaller time-interval storm scale using variable time steps (DeVries and Hromadka 1993). During a storm event, time intervals as small as a minute may be used to compute runoff using kinematic flood routing for a watershed represented by interconnected flow planes and channels. A daily interval is used between storm events. Streamflow is computed as mean daily flow. In PRMS a watershed is represented by a number of hydrologic response units (HRUs) each of which is assumed to have homogeneous hydrologic characteristics. Hortoninan infiltration is modeled with the Green-Ampt infiltration method. HRU parameters include surface slope, aspect, elevation, soil type, vegetation type, and distribution of precipitation. PRMS performs water and energy balances for each HRU, and the watershed response is the sum of all pertinent HRU responses. PRMS can be used in combination with the USGS ANNIE data management program, and a modified version of the National Weather Service (NWS) Extended Streamflow Prediction (ESP) model to provide a comprehensive watershed modeling system.

The Modular Modeling System (MMS), an outgrowth of the development of PRMS, is an integrated system of computer software that is being developed to provide the research and operational framework needed to support development, testing, and evaluation of physical process algorithms and to facilitate integration of user-selected sets of algorithms into operational environmental-process models (Leavesley et al., 1996; Leavesley et al., 2004). MMS includes PRMS. A geographic information system (GIS) interface, the GIS Weasel, has been developed to support MMS in model development, application, and analysis. The

GIS Weasel permits application of a variety of GIS tools to delineate, characterize, and parameterize the topographic, hydrologic, and biologic features of a physical system for use in a variety of lumped and distributed parameter modeling approaches. The integration of the GIS Weasel and MMS provide a flexible framework in which to integrate and apply environmental models and analytical tools. MMS currently runs under the UNIX operating system, but it is being rewritten in Java to be available on multiple computer systems.

SHE (Abbot et al., 1986a, b) - The European Hydrologic System or Systeme Hydrologique Europeen (SHE) was developed jointly by the Danish Hydraulic Institute, United Kingdom Institute of Hydrology, and SOGREAH in France with financial support from the Commission of European Communities (Abbott et al. 1986; DeVries and Hromadka 1993). SHE is a physically based, distributed parameter watershed modeling system which incorporates the major hydrologic processes including precipitation, snowmelt, canopy interception, evapotranspiration, overland flow, saturated and unsaturated subsurface flow, and channel flow. Spatial variability of the hydrologic processes is represented by a rectangular grid in the horizontal plane and vertically by a series of horizontal planes at various depths. SHE may be applied in analyzing irrigation schemes, land-use changes, water development projects, groundwater contamination, erosion and sediment transport, and floods. The Systémè Hydrologique Européen (SHE) model and its derivatives (e.g., MIKE SHE) are proprietary, with source code not available.

SWAT (Neitsch, 2002) – Soil and Water Assessment Tool (SWAT) is a continuous hydrologic simulation of water, sediment and chemical movement created by Texas A&M University, for the USDA Agricultural Research Service. SWAT is a river basin scale model developed to quantify the impact of land management practices in large, complex watersheds. Given values for basic climatic variables, the model calculates canopy storage, infiltration (using SCS Curve number method), surface runoff, ponds, evapotranspiration, lateral subsurface flow, tributary channels and return flow. The model also calculates land cover/plant growth, erosion, nutrients, pesticides and management. Water management options in the model include water use (domestic or agricultural) water transfer between reservoirs, reaches or sub-basins or exportation from the basin. SWAT is coded in FORTRAN-90 and is transportable to a variety of platforms, including PC compatibles.

SWAT is a continuous model working at the basin scale to look at the long term impacts of management and timing of agricultural practices (Neitsch et al., 2001). The model was created by merging SWRRB (Simulator for Water Resources in Rural Basins) (Williams et al., 1985), and ROTO (Routing Outputs To the Outlet) (Arnold et al., 1995). The goal of developing the SWRRB model was to predict the effects of management decisions on water and sediment yields for ungauged rural basins throughout the United States (Arnold and Williams, 1987).

The hydrological phase in SWAT provides the required parameters for the chemical constituent calculations in the watershed. The most important parameter is the runoff volume computed by the modified SCS curve number method. Another significant flow parameter is the lateral subsurface flow or interflow which represents a stream flow contribution originating below the soil surface but above the zone of saturation. The model applies the kinematic storage method to estimate this stream flow component. The model solves the water mass balance equation in shallow aquifers to estimate base flow contribution. Sediment removal from the land surface is calculated by the Modified Universal Soil Loss Equation (MUSLE).

A.3 River Hydraulics Models

River hydraulics models simulate flow conditions in natural and improved streams and rivers, and associated floodplains, and in man-made channels. Required data include channel geometry and roughness data and either steady-state or time-dependent inflow rates. Steady, varied flow models compute flow depths as a function of location along the channel. Unsteady flow models calculate discharges and flow depths as a function of time and location. These models are typically used in combination with rainfall-runoff, water quality, and river basin management models. Flow in rivers typically modeled as either one- or two-dimensional, steady (unchanging with time) or unsteady and uniform (unchanging when traversing up or down stream) or nonuniform or varied.

DYNHYD (Ambrose et al., 1993) – The DYNamic HYDraulics (DYNHYD) model is a link-node hydrodynamic model simulating velocity, volume, and water depth under river flow phenomena. The equations of conservation of mass and energy are solved by the method of finite-differences to predict water velocities, flows, water heights, and volumes. The model is driven by variable upstream flows and downstream heads and assumes that flow is predominantly one-dimensional. Bed characteristics are parameterized using Manning's *n*. Wind that can either oppose or concur with flow can also be accounted for within the model. DYNHYD is a one-dimensional model, simulating velocity in the direction of the channel, but is applied to two-dimensional (vertically integrated) systems by approximating the system by a network of nodes with interconnected one-dimensional channels. It is generally operated in conjunction with a transport (i.e., water quality) model lacking a hydrodynamic capability, e.g., WASP. The model assumes a simple channel geometry, rectangular in cross section with cross sectional area is proportional to depth. Thus this sort of model would not be appropriate for applications to rivers with floodplain areas or gentle lateral side slopes. Generally, DYNHYD5 cannot be applied to stratified water bodies or water bodies without well-defined primary flow directions. The more usual configuration for DYNHYD is a steady or slowly varying inflow regime, for evaluation of critical-condition or normal-condition water quality. Since DYNHYD is a time-advancing model, in principle it can handle dynamic events, such as flood hydrographs. However, its limited accuracy would probably result in poor accuracy for a "fully dynamic event" such as a flood event in a flashy stream (Ward and Benneman, 1999a). The software is available in the public domain (executable and source code) from Scientific Software, at: http://www.scientificsoftwaregroup.com/.

FLDWAV (Fread and Lewis 1988) - The National Weather Service (NWS) Operational Dynamic Wave Model (DWOPER), Dam-Break Flood Forecasting Model (DAMBRK), and Flood Wave (FLDWAV) are dynamic routing models developed by the Hydrologic Research Laboratory of the National Weather Service. DAMBRK is a specific purpose dam-breach model that stemmed from the general purpose DWOPER. The NWS Flood Wave (FLDWAV) program combines DWOPER and DAMBRK into a single model and provides additional hydraulic simulation methods within a more user-friendly model structure (Fread and Lewis 1988). FLDWAV, like DWOPER and DAMBRK, is based on an expanded form of the St. Venant equations that includes the following hydraulic effects: lateral inflows and outflows; off-channel storage; expansion and contraction losses; mixed subcritical and supercritical flow; nonuniform velocity distribution across the flow section; flow path differences between the flood plain and a sinuous main channel; and surface wind shear. The model can simulate dam breaches in one or several dams located sequentially on the same stream. Other conditions that can be simulated include: levee overtopping; interactions between channel and floodplain flow; and combined free-surface and pressure flow. FLDWAV also has a calibration option for determining Manning roughness coefficient values.

The NWS Dynamic Wave Operational Model (DWOPER) program is used routinely by the National Weather Service River Forecast Centers and has also been widely applied outside of the National Weather Service. DWOPER has wide applicability to rivers of varying physical features, such as branching tributaries, irregular geometry, variable roughness parameters, lateral inflows, flow diversions, off-channel storage, local head losses such as bridge contractions and expansions, lock and dam operations, and wind effects. An automatic calibration feature is provided for determining values for roughness coefficients. Data management features facilitate use of the model in a day-to-day forecasting environment. The model is equally applicable for simulating unsteady flows in planning and design studies.

The NWS Dam Break (DAMBRK) program has been extensively applied by various agencies and consulting firms in conducting dam safety studies. DAMBRK simulates the failure of a dam, computes the resultant outflow hydrograph, and simulates the movement of the flood wave through the downstream river valley. An inflow hydrograph is routed through a reservoir optionally using either hydrologic storage routing or dynamic routing. Two types of breaching may be simulated. An overtopping failure is simulated as a rectangular, triangular, or trapezoidal shaped opening that grows progressively downward from the dam crest with time. A piping failure is simulated as a rectangular orifice that grows with time and is centered at any specified elevation within the dam. The pool elevation at which breaching begins, time required for breach formation, and geometric parameters of the breach must be specified by the user. The DWOPER dynamic routing algorithm is used to route the outflow hydrograph through the downstream valley. DAMBRK can simulate flows through multiple dams located in series on the same stream.

DWOPER does not include the dam breach modeling capabilities of DAMBRK. DAMBRK is limited to a single river without tributaries and thus does not provide the flexibility of DWOPER in simulating branching tributary configurations.

HEC-RAS (HEC, 2002) **–** The River Analysis Systems (RAS) is an accepted U.S. standard for calculating river hydraulics. The model was originally developed in the 1960s and has evolved through numerous modifications and expansions. Originally, RAS was intended for computing water surface profiles for steady gradually varied flow in natural or man-made channels. The computational procedure is based on the standard step method of solution. The computations proceed by reach, with known values at one cross-section being used to compute the water surface elevation, mean velocity, and other flow characteristics at the next cross-section. Both sub-critical and supercritical flow regimes can be modeled. The effects of obstructions to flow such as bridges, culverts, weirs, and buildings located in the floodplain may be reflected in the model.

RAS can be used for simulating one-dimensional steady or unsteady flow, sediment transport and movable boundary open channel flow. The RAS system contains three components for: (1) steady flow water surface profile computations; (2) unsteady flow computations; and (3) movable boundary hydraulic computations. All three components use a common geometric data representation, and common geometric and hydraulic computation routines. RAS is comprised of a graphical user interface, separate computational engines, data storage/management components, graphics, and reporting capabilities.

Although RAS is a stand-alone model, it is often used in combination with HMS. A typical HMS/ RAS application involves predicting the water surface profiles which would result from actual or hypothetical precipitation events. Precipitation associated with an actual storm, design storm of specified exceedence frequency, or design storm such as the probable maximum storm, is provided as input to the HMS model. HMS performs the rainfall-runoff and routing computations required to develop hydrographs at pertinent locations in the stream system. Peak discharges from the HMS hydrographs are provided as input to RAS, which computes the corresponding water surface elevations at specified locations. RAS is also sometimes used to develop discharge versus storage volume relationships for stream reaches which are used in HMS for the modified Puls routing option.

A.4 Water Quality Models

CE-QUAL-W2 (Cole and Wells, 2003) - CE-QUAL-W2 is a 2D laterally averaged hydrodynamic and water quality model, designed for application to watercourses with prominent longitudinal variation that are deep enough for density stratification to be important. W2 models longitudinal and vertical hydrodynamics and water quality in stratified and non-stratified systems, multiple algae, epiphyton/periphyton, CBOD, and generic water quality groups, internal dynamic pipe/culvert model, hydraulic structures (weirs, spillways) algorithms including submerged and 2-way flow over submerged hydraulic structures, dynamic shading algorithm based on topographic and vegetative cover. Basic eutrophication processes are modeled, such as, temperature-nutrient-algae-dissolved oxygen-organic matter and sediment relationships. The model has complex dissolved oxygen and nutrient budgets in the mass-balance part of the model, including the ability to simulate algae blooms. The water quality algorithms incorporate 21 constituents in addition to temperature, including nutrient/ phytoplankton/ dissolved oxygen (DO) interactions during anoxic conditions. Any combination of constituents can be simulated. The effects of salinity or total dissolved solids/salinity on density and thus hydrodynamics are included only if they are simulated in the water quality module. The water quality algorithm is modular, allowing constituents to be easily added as additional subroutines if the user desires. Despite the "user friendly" objective of the structured, commented code and the substantial users manual, model set-up and execution are difficult (Ward and Benneman, 1999). The model has seen 20 years of applications, including: TVA’s Douglas Reservoir; Taylorsville Lake in the Upper Salt River Basin, Kentucky; Cheatham Lake on the Cumberland River below Nashville; the proposed Isikli Reservoir of the Ankara Water Supply System, Turkey; Brownlee Reservoir on the Snake River, Oregon; and Lake Waco in Texas. The model release includes executables, source codes, and examples for the W2 V3.1 model, preprocessor and GUI (http://www.cee.pdx.edu/w2/).

DYRESM (Antenucci and Imerito, 2003; Hipsey, et al., 2003) - Dynamic Reservoir Simulation Model (DYRESM) is a one-dimensional hydrodynamics model for predicting the vertical distribution of temperature, salinity and density in lakes and reservoirs. It is assumed that the water bodies comply with the one-dimensional approximation in that the destabilising forcing variables (wind, surface cooling, and plunging inflows) do not act over prolonged periods of time. DYRESM has been used for simulation periods extending from weeks to decades. Thus the model provides a means of predicting seasonal and inter-annual variation in lakes and reservoirs, as well as sensitivity testing to long term changes in environmental factors or watershed properties. DYRESM can be run either in isolation, for hydrodynamic studies, or coupled to CAEDYM for investigations involving biological and chemical processes. DYRESM-CAEDYM couples the one-dimensional hydrodynamics model DYRESM with the aquatic ecological model CAEDYM. This allows for investigations into the relationships between physical, biological and chemical variables in water bodies over seasonal and inter-annual timescales.

The Computational Aquatic Ecosystem Dynamics Model (CAEDYM) is an aquatic ecological model that may be run independently or coupled with hydrodynamic models DYRESM or ELCOM. CAEDYM consists of a series of mathematical equations representing the major biogeochemical processes influencing water quality. At its most basic, CAEDYM is a set of library subroutines that contain process descriptions for primary production, secondary production, nutrient and metal cycling, and oxygen dynamics and the movement of sediment.

QUAL2E (Brown and Barnwell 1987) - The Enhanced Stream Water Quality Model (QUAL2E) is a one-dimensional (longitudinal) model for simulating well-mixed streams and lakes (Brown and Barnwell 1987). A watercourse is represented as a series of piece-wise segments or reaches of steady, non-uniform flow. Flows are constant with time and uniform in each reach, but can vary from reach to reach. QUAL2E allows simulation of point and non-point loadings, withdrawals, branching tributaries, and in-stream hydraulic structures. The model allows simulation of 15 water quality constituents including: dissolved oxygen, biochemical oxygen demand, temperature, algae as chlorophyll, organic nitrogen, ammonia nitrogen, nitrate nitrogen, organic phosphorus, inorganic phosphorus, coliforms, an arbitrary non-conservative constituent, and three arbitrary conservative constituents. QUAL2E has optional features for analyzing the effects on water quality, primarily dissolved oxygen and temperature, caused by diurnal variations in meteorological data. Diurnal dissolved oxygen variations caused by algal growth and respiration can also be modeled. QUAL2E also has an option for determining flow augmentation required to meet any pre-specified dissolved oxygen level. QUAL2E and its variations stem from early models, including DOSAG model which solves the steady-state oxygen sag problem for a multi-segment river reach, and QUAL (TWDB 1971) which was developed by expanding DOSAG. QUAL II (Roesner *et al*. 1973) was developed for the Environmental Protection Agency by expanding and improving QUAL. Qual2E is in the public domain and can be downloaded from:
http://www.epa.gov/docs/QUAL2E_WINDOWS/#files
The Qual2E User's manuals are available at:
http://www.epa.gov/waterscience/basins/bsnsdocs.html#qual2e

REMM (Pomerleau, R. 1997) - The Riverine Emergency Management Model (REMM) is a computer program and associated river, chemical, and geographic data files which computer the time of travel, and optionally, the fate of a chemical spill, on a river system for various flow conditions. Its primary purpose is to give emergency planners the capability to make a reasonable determination of the travel time and the fate of chemical spills at locations downstream from a given location. REMM incorporates chemical fate algorithms coupled to travel time computations; fate processes for specific chemicals may be modeled; property and fate data on over 100 chemicals are provided in an on-line chemical property database; properties and fate of crude oil, gasoline, and fuel oil are addressed using specialized programming; provides a "landmark descriptions" database to help the user identify locations of interest. Databases include water intakes, bridge and pipeline crossings, populated areas, and other sensitive or critical locations.

R-TOT (Waldon, 1999) - River Time of Travel (R-TOT) model has been developed to provide travel time, time of passage, and peak contaminant concentration for spills. R-TOT includes REMM as a component and extends its capabilities to provide real time management support to users who do not have extensive training or hydrologic knowledge. Through a graphical user interface R-TOT: implements spill modeling of travel times of the spill's leading edge, peak, and trailing edges and projects spill duration; incorporates chemical fate algorithms coupled to travel time computations; gives advice and warnings to users; and provides an on-line database with property and fate data on over 100 chemicals. The model uses available hydrologic, hydraulic (stage-velocity-discharge data), and geographic data.

Shen et al. (1995) developed a two-dimensional Lagrangian computer model for simulating chemical or oil transport in rivers. The model considers the spilled chemical to be transported in the river as a mixed layer over the depth of the flow and a bottom layer along the bed, with continuous exchange between the two layers. The transport and fate processes include advection/diffusion, sorption/desorption, settling, resuspension, diffusive exchange between sediment/water interface, and can include volatization, photolysis, hydrolysis, and biodegradation. The model has been applied to the upper St. Lawrence River, but this model would be difficult to apply in an emergency when minimal data are available (Waldon, 1999).

WASP (Ambrose et al., 1993; Wool et al., 2003) - The Water Quality Analysis Simulation Program (WASP), maintained by the Environmental Protection Agency, is a generalized modeling framework for simulating aquatic systems including rivers, reservoirs, estuaries, and coastal waters. WASP is designed to provide a flexible modeling system. WASP is a dynamic compartment-modeling program for aquatic systems, including both the water column and the underlying benthos. WASP allows the user to investigate 1, 2, and 3 dimensional systems, and a variety of pollutant types. The time varying processes of advection, dispersion, point and diffuse mass loading and boundary exchange are represented in the model. WASP also can be linked with hydrodynamic and sediment transport models that can provide flows, depths velocities, temperature, salinity and sediment fluxes. Water quality processes are modeled in special kinetic subroutines that are either selected from a library or supplied by the user. EUTRO and TOXI are sub-models which can be incorporated into WASP to analyze conventional pollution involving dissolved oxygen, biochemical oxygen demand, nutrients and eutrophication and toxic pollution involving organic chemicals, metals, and sediment. WASP has no hydrodynamic capability and must be linked with another model for this purpose; the most common linkage is to DYNHYD which comes as part of the WASP software. Other hydrodynamic programs have also been linked with WASP RIVMOD handles unsteady flow in one-dimensional rivers, while SED3D handles unsteady, three-dimensional flow in lakes and estuaries.

WASP has been used to examine eutrophication of Tampa Bay, FL; phosphorus loading to Lake Okeechobee, FL; eutrophication of the Neuse River Estuary, NC; eutrophication Coosa River and Reservoirs, AL; PCB pollution of the Great Lakes, eutrophication of the Potomac Estuary, kepone pollution of the James River Estuary, volatile organic pollution of the Delaware Estuary, and heavy metal pollution of the Deep River, North Carolina, mercury in the Savannah River, GA.

WASP6 comes with a data preprocessor that allows for the rapid development of input datasets, either by cut and paste or queried from a database. A Post-Processor provides an efficient method for reviewing model predictions and comparing them with field data for calibration. WASP has been used for about twenty years and is a well-established water quality model, supported by the USEPA. The current version is WASP6.2, released in November, 2003 to the Windows operating system. WASP is written in FORTRAN and executables and source code are in the public domain and can be downloaded from (http://www.epa.gov/athens/wwqtsc/html/wasp.html).

A.5 Reservoir Operation Models

Reservoir/river operation models are used for various purposes including: planning studies to formulate and evaluate alterative plans for solving water management problems; and feasibility studies of proposed construction projects as well reoperation of existing existing reservoir systems. Reservoir/river system analysis models have traditionally been categorized as: simulation, optimization, and combinations of simulation and optimization.

ARSP (Boss, 2004) - Acres Reservoir Simulation Package (ARSP) was developed by Acres International Corporation and is currently being marketed and supported by BOSS International. ARSP is a general multi-purpose, multi-reservoir simulation program which determines the allocation of water through simulation according to user specified priorities. The model considers natural inflows, precipitation, evaporation, and evapotranspiration as input data and storage and release of water by reservoirs, physical discharge controls at reservoir outlets, water flow in channels (e.g., streams, power channels, diversion channels, and irrigation channels), consumptive demands (e.g., agricultural, industrial, and municipal), hydropower releases, and losses in channels. Operating policies are defined by prioritizing water demands. Water resource system allocation problems involving hydropower generation, flood control, water quality, domestic and industrial water supply, irrigation demands, low-flow augmentation, environmental requirements, fish and wildlife concerns, inter-basin diversion requirements, recreation interests, and navigation requirements can be modeled. Monthly, weekly, daily, hourly, and user-definable time-steps can be used. ARSP does not deal with water quality or groundwater issues. No links to GIS or databases.

ARSP uses the Out-of-Kilter algorithm for determining flow in a network during a single time period. ARSP does not determine optimal system performance for more than a single time period and decisions depend on user defined penalties assigned associated with reservoir storage levels through the use of “rule curves.” The rule curves are specified input data and are often revised in successive simulation runs to determining the ‘optimal’ rules for the allocation of the water resource for a simulation period.

ARSP runs on PCs in the Windows environment. It has been applied in a wide variety of situations mainly involving reservoir design and operation, both in Canada and throughout the world. ARSP fees are $2995 for single license and $995 for upgrades.

Lam et al. (2004) discuss the use of the RAISON Object System (ROS) software (Lam et al., 1994) to link the ARPS reservoir operation model, the AGNPS nonpoint source pollution model, a relational database (Acess), a spreadsheet (Excel), and a GIS (ArcGIS). The linkages between all of these components are made via component object model (COM) technologies (Microsoft, 2004) which allows applications to be built from binary software components and supports execution and communication between programs written in any language under the Windows environment.

Dynamic Simulation Software () – Some mention should be made in this review of dynamic simulation software as it has been applied to water resources modeling. This includes the software STELLA (High Performance Systems, 1992), POWERSIM (Powersim, 1966), VENSIM (Ventana, 1996), and GOLDSIM (Goldsim, 2003). These are dynamic simulation packages that stem from the system dynamics modeling method "Dynamo" invented by J. Forrester at MIT in the 1960's. The latest generation of these packages all use an object-oriented programming environment. The models are constructed from stocks, flows, modifiers, and connectors, and the software automatically creates difference equations form these based on user input. These methods all include components for: (1) identification of stocks and flows in a system; (2) graphically representing dynamic systems in "stock-and flow-diagrams"; and (3) a computer language for simulating the constructed dynamic systems. Models can be created with by connecting icons together in different ways into a model framework so that the structure of the model is very transparent. STELLA has been applied to modeling water allocation from reservoirs to water users on the Mexican side of the Rio Grande/Rio Bravo basin (Vigerstøl, 2003). STELLA has also been used extensively in the U.S. Army Corps of Engineers "Shared Vision Planning" process (USACE, 2004).

HEC-ResSim (HEC, 2003) - Reservoir System Simulation created by the U.S. Army Corp of Engineers – Hydrologic Engineering Center as the successor to HEC-5. Res-Sim has a graphical user interface (GUI) and utilizes the HEC Data Storage System (HEC-DSS) for storage and retrieval of input and output time-series data. ResSim is included in CWMS. ResSim is used to simulate reservoir operations including all characteristics of a reservoir and channel routing downstream. The model allows the user to define alternatives and run their simulations simultaneously to compare results. Network elements include reservoirs, routing reaches, diversions, and junctions. In ResSim, watersheds include streams, projects (ie reservoir, levees), gage locations, impact areas, time-series locations and hydrologic and hydraulic data for that specific area. Schematic elements in ResSim allow you to represent watershed, reservoir network and simulation data visually in a geo-referenced context that interacts with associated data. ResSim can access an Oracle Database to read and write time series data. Reservoirs are complex elements that are made up of the pool, the dam, and one or more outlets. The criteria for reservoir release decisions, an operation set, are drawn from a set of discrete zones and rules. The zones divide the reservoir by elevation and contain a set of rules that describe the goals and constraints that should be followed when the reservoir's pool elevation is within the zone. Alternatives are developed to compare results using different model schematics (physical properties), operation sets, inflows, and/or initial conditions. To assist in analyzing simulation results, included within ResSim are default plots, a variety of summary reports, and HEC-DSSVue. ResSim does not deal with water quality, environmental in-stream flows, recreation, etc. The only aspect it does deal with is power generation as a characteristic of the reservoir.

WEAP (Raskin, et al., 1992; SEI, 2004) – The Water Evaluation and Planning System (WEAP) developed by the Stockholm Environment Institute's Boston Center (Tellus Institute) is a water balance software program that was designed to assist water management decision makers in evaluating water policies and developing sustainable water resource management plans. WEAP operates on basic principles of water balance accounting and links water supplies from rivers, reservoirs and aquifers with water demands, in an integrated system. Designed to be menu-driven and user-friendly, WEAP is a policy-oriented software model that uses water balance accounting to simulate user-constructed scenarios. The program is designed to assist water management decision makers through a user-friendly menu-driven graphical user interface. WEAP can simulate issues including; sectoral demand analyses, water conservation, water rights, allocation priorities, groundwater withdrawal and recharge, streamflow simulation, reservoir operations, hydropower generation, pollution tracking (fully mixed, limited decay), and project cost/benefit analyses. Groundwater supplies can be included in the WEAP model by specifying a storage capacity, a maximum withdrawal rate and the rate of recharge. Minimum monthly in-stream flows can be specified.

One disadvantage of WEAP is the method of defining reservoir operational characteristics and it does not allow easy comparison of different sets of operational procedures (Lancaster, 2004). WEAP is constrained to an operational regime that determines releases based on reservoir water level. Under normal operating conditions, above the "top of buffer" reservoir level, releases must be 100% of demands. In the buffer zone, monthly releases are limited to a defined percentage of the total water available for release. In the inactive zone, no releases are allowed. Demand sites may be assigned a priority level, but the prioritization scheme is such that 100% of first priority demands are met before any releases for lower priority demands. These WEAP limitations result in a reservoir management scheme that, in many cases, does not adequately reflect current procedures and is not flexible for testing alternative reservoir management strategies.

Another significant disadvantage of WEAP is that the data input routines do not facilitate connections with electronic data formats, such as GIS, spreadsheets or relational databases (Lancaster, 2004). The model does not allow data from tables exported from GIS to a spreadsheet to be copied and pasted into WEAP. To import time series data, e.g., from a GIS database, into WEAP, ASCII text files must be created. WEAP does not link with GIS but does have a GIS-based graphical interface which allows the user to input an ArcView "shapefile" as a background picture to build a model on. After a WEAP simulation is completed, the results can be displayed in a table which can be downloaded into an Excel spreadsheet. Once the data is in the spreadsheet, the time series data can be uploaded to a geodatabase (Lancaster, 2004).

WEAP is relatively straightforward and user-friendly for testing the effects of different water management scenarios. The results are easy to view for comparisons of different scenarios. Changing input data to model newly proposed scenarios can be readily accomplished, as long as it is not necessary to make any changes to the ASCII file of historical data.

WEAP runs on Windows based PCs. License fees are $1,000 (Single Node for government or not-for-profit organization). The software is sold by a U.S. subsidiary in Boston.

WEAP is in widespread use throughout the world, including: Beijing Environmental Master Plan Application System; Water resources study for the Upper Chattahoochee River, Georgia, USA; Water management options in the Olifant River basin, South Africa; and the Rio San Juan pilot study, Mexico. Many more examples are available on the SEI website (SEI, 2001).

A.6 Groundwater Models

ASMWIN (Kinzelbach and Rausch 1995; Kinzelbach, 1986; Swiss Federal Institute of Technology, 2004) - Aquifer Simulation Model for WINdows (ASMWIN)**,** developed by the Swiss Federal Institute of Technology (ETH), is a horizontally or vertically, two-dimensional groundwater flow and transport model. The solution of the flow equation uses a finite difference method solved with the method of preconditioned conjugate gradients (PCG) or the IADI-method (Iterative alternative direction implicit procedure). An automatic model calibration procedure using the Marquardt-Levenberg algorithm is available in ASMWIN. The interpolation of the velocity uses the methods by Prickett or Pollock. Two transport simulation modules are available: a finite-difference scheme; or a random-walk method based on Ito-Fokker-Planck theory. Pathline and isochrone computed by Euler-integration as well as transport simulation are possible for steady state flow fields only.

GMS (EMRL, 2004) – Similar to SMS, the Groundwater Modeling System (GMS) has been developed by the Environmental Modeling Research Laboratory (EMRL) at Brigham Young University. GMS provides tools for groundwater simulation including site characterization, model development, calibration, post-processing, and visualization. GMS supports MODFLOW, MODPATH, MT3DMS/RT3D, SEAM3D, ART3D (Simple analytical transport model), UTCHEM (multi-phase reactive transport), FEMWATER (3D finite-element model for saturated and unsaturated zone), PEST, and SEEP2D (2D finite-element seeepage model). GMS costs $7,600 including all modules and interfaces.

MODFLOW (Harbaugh et al., 2000) - Several versions of MODFLOW have been released: MODFLOW-88 (McDonald and Harbaugh, 1988); an enhanced version MODFLOW-96 (Harbaugh and McDonald, 1996); and MODFLOW-2000 (Harbaugh et al., 2000) that fully integrates parameter estimation. MODFLOW is a three-dimensional finite-difference groundwater model with a modular structure that allows it to be easily modified to adapt the code for a particular application. MODFLOW simulates steady and nonsteady flow in an irregularly shaped flow system in which aquifer layers can be confined, unconfined, or a combination of confined and unconfined. Flow from external stresses, such as flow to wells, areal recharge, evapotranspiration, flow to drains, and flow through river beds, can be simulated. Hydraulic conductivities or transmissivities for any layer may differ spatially and be anisotropic (restricted to having the principal directions aligned with the grid axes), and the storage coefficient may be heterogeneous. Specified head and specified flux boundaries can be simulated as can a head dependent flux across the model's outer boundary that allows water to be supplied to a boundary block in the modeled area at a rate proportional to the current head difference between a "source" of water outside the modeled area and the boundary block. MODFLOW is currently the most used numerical model in the U.S. Geological Survey for groundwater flow problems.

In addition to simulating ground-water flow, the scope of MODFLOW-2000 has been expanded to incorporate related capabilities such as solute transport and parameter estimation.

MODOFC (Ahlfeld and Milligan, 2000; and Ahlfeld, 2003) - Management of groundwater systems that are modeled with MODFLOW can be accomplished with the MODOFC program (Ahlfeld and Milligan, 2000; and Ahlfeld, 2003). MODOFC is designed to allow the user to create and solve optimization problems for hydraulic control in groundwater systems. This is accomplished by coupling the groundwater flow simulator MODFLOW with an optimization solver. Solving optimization problems involves two steps. First, the simulator is calibrated to match the conditions in the system under study, using available field data, so that the simulator provides a representation of the response of the field system to alternate pumping strategies. Second, optimization is used to solve for the set of pump rates and well locations which minimizes a function of pumping while satisfying constraints on the system imposed by the user. Minimum and maximum head constraints can be used to control excessive drawdown or mounding of the piezometric surface. Minimum head difference constraints can force groundwater to flow in a specified direction between two locations. Minimum and maximum pumping rates can be used to limit the amount of pumping or recharge allowed at a well.

Model Viewer (Hsieh, 2002) - Model Viewer is program for three-dimensional visualization of groundwater model results. Scalar data (such as hydraulic head or solute concentration) may be displayed as a solid or a set of isosurfaces, using a red-to-blue color spectrum to represent a range of scalar values. Vector data (such as velocity or specific discharge) are represented by lines oriented to the vector direction and scaled to the vector magnitude. Model Viewer can also display pathlines, cells or nodes that represent model features such as streams and wells, and auxiliary graphical objects such as grid lines and coordinate axes. Users may crop the model grid in different orientations to examine the interior structure of the data. For transient simulations, Model Viewer can animate the time evolution of the simulated quantities. The current version supports the following models: MODFLOW-2000 and MT3DMS. Model Viewer is designed to directly read input and output files from these models, thus minimizing the need for additional post-processing

MT3D (Zheng, 1990; Zheng and Wang, 1999; Zheng et al., 2001) - MT3D is a comprehensive three-dimensional numerical model for simulating solute transport in complex hydrogeologic settings. MT3D accommodates advection in complex steady-state and transient flow fields, anisotropic dispersion, first-order decay and production reactions, and linear and non-linear sorption. Starting in 1990, MT3D was released as a pubic domain code from the USEPA. MT3D is based on a modular structure to permit simulation of transport components independently or jointly. MT3D interfaces directly with the U.S. Geological Survey finite-difference groundwater flow model, MODFLOW, for the head solution, and supports all the hydrologic and discretization features of MODFLOW. MT3D has been applied in numerous field-scale modeling studies in the United States and throughout the world. The MT3D code has a comprehensive set of solution options, including the method of characteristics (MOC), the modified method of characteristics (MMOC), a hybrid of these two methods (HMOC), and the standard finite-difference method (FDM).

MT3DMS is the second generation of MT3D developed for the U.S. Army Corps of Engineers Waterways Experiment Station. MT3DMS significantly expands the capabilities of MT3D, including the addition of: a third-order total-variation-diminishing (TVD) scheme for solving the advection term that is mass conservative but does not introduce excessive numerical dispersion and artificial oscillation; an efficient iterative solver based on generalized conjugate gradient methods and the Lanczos/ORTHOMIN acceleration scheme to remove stability constraints on the transport time step-size; options for accommodating non-equilibrium sorption and dual-domain advection-diffusion mass transport; and a multi-component program structure that can accommodate add-on reaction packages for modeling general biological and geochemical reactions.