WATER DATA MANAGEMENT SYSTEMS INTEGRATIONS WITH MODELS

by

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Abstract

Various hydrologic models for use in water resources planning and management were reviewed. Lumped parameter and distributed parameter models were investigated for their uses, strengths and limitations. Geographic Information Systems (GISs) can support these models by generating automated input, increasing the accuracy of the system modeled and displaying model output graphically. Spatial Decision Support Systems (SDSSs) provides the framework for the integrated model-GIS system. This system allows the designer to more effectively judge how the model should be geared to the system.

A GIS is a beneficial tool for working with geographical data, but modeling is limited to complex overlays. Most models for water resource planning do not have well-developed capabilities for analyzing and displaying spatial data. Combining GISs with SDSSs strengthens both of these technologies. Typical model set-up encompasses a significant amount of time and effort for the modeler, who can increase the model set-up time by taking advantage of GIS functionality. Models utilizing GIS, such as urban runoff analyses, wetland effects on flood volumes and urban development effects on runoff, were investigated.

However, when any real system is generalized in a modeling exercise, there are inherent inaccuracies. Concerns with modeling in water resources, such as issues with scaling, calibration and verification, and the simplification of parameters

versus overparameterization are examined herein. The more complex model systems are compared to more generalized model efforts, such as screening level assessments. The usefulness of the screening level assessments is demonstrated by a study of pollution risks in Wickford Harbor, in East Greenwich, Rhode Island, using the locally derived MANAGE model system.

The smaller scale assessments reviewed indicate the benefit of GISs and models, which aid planners and engineers, but it is first necessary to understand the level of technology locally. Therefore, types of data collection, model systems and level of GIS use among the major water suppliers in Rhode Island were investigated.

Most of the suppliers are moving towards the more automated data collection systems and are implementing GISs and programs such as AutoCAD for more functionality. However, over fifty (50) percent of the suppliers still send crews out to collect data such as meter readings. The hard copy storage of this data impedes system-related investigations, such as detecting leaks more quickly. The most automated data collection system used by about thirty (30) percent of the suppliers is a Supervisory Control and Data Acquisition (SCADA) system that can control operations in treatment plants, as well as continuously check system water levels and pressures. This system also stores the data in a digital format ready for analyses. Modeling capabilities among the suppliers were limited to hydraulic modeling on their distribution system. Approximately two-thirds (2/3) of the suppliers were using a version of WaterCAD by Haestead Methods for management of their system. Newer versions of WaterCAD can utilize drawings in AutoCAD to run the model once the attributes of the system are added. In addition, WaterCAD also has GIS and SCADA interfaces for even more integrated analyses, which is important since many suppliers are implementing SCADA systems.

However, only about thirty-five (35) percent of the suppliers have a functioning GIS. The use of GISs and level of automation differed among the towns. Some suppliers have created their own mapping system due to the resolution of existing, state GIS datasets. A recurring sentiment voiced by the suppliers was that they would advocate all of these technology upgrades for their system, but face opposition. The opposition is mainly due to the lack of trained personnel to work with the software, and budget constraints that allocate any additional funding towards capital improvements, such as replacing older pipes.

1 INTRODUCTION

A critical management issue faced by federal, state and local agencies is how to improve the availability and usefulness of water-related information. Since these organizations do not typically use a common method for data storage, optimizing usage of this data is difficult. More efficient management and planning related to water resources necessitate an integrated decision support system (DSS) based on advances in modeling and technologies such as geographic information systems (GISs). With access to more accurate information, decision-makers can make more informed judgments about land use planning and water resources management.

Models generally make assumptions about real world processes in order to predict the behavior of systems under certain conditions. There are different types of models that are used in water resources, such as lumped parameter models and distributed parameter or physically based models (Molnar and Julien, 2000). Some of these models are able to take advantage of data in a GIS format as input, which allow them to better describe the processes studied. However, many of the more complex models used for hydrologic studies require extensive parameter input which decreases model accuracy.

A GIS is a tool that can support many models for water resources planning and management. It can be used among various agencies to combine spatial data into a common format that is easy to manipulate. GISs can store data, perform queries on data and graphically display model outputs. This tool also decreases the time that is required to set up a model by using existing, spatially derived input data. Therefore, extensive field sampling, lab analyses and manual input of data into the model can be largely avoided. In general, water resource models cannot readily analyze and display spatial information. A GIS can provide a good spatial representation of an area but cannot perform complex model assessments (Maidment, 1993). As a result, linking GISs and models benefits both technologies. Different studies that utilize a model-GIS linkage are investigated.

Whenever a real system is generalized as in a model, inaccuracies are incurred. Some of these inaccuracies include issues of scale translation or determining which scale should be used so that spatial variability in parameter estimation can be ignored. Trying to translate between the different scales can cause errors when modeling (Groffman and Wagenet, 1993). The use of a GIS can eliminate some of these uncertainties. Another contested issue with modeling is the use of the terms "calibration" and "verification," as relaying a false sense of accuracy in model prediction capabilities (Konikow and Bredehoeft, 1992). Scientists argue that modeling provides non-unique results and therefore the model code that seems verified might not provide a correct solution for future predictions. This is especially true since systems are always changing, making it difficult to predict how variables will change with time. Models are useful for increasing the understanding of how a system works, however some questions remain, e.g., how accurate models are and what limits should be placed on their prediction capabilities. Models are now being created for application to more site-specific studies. A more generalized model, such as a screening level model, initially highlights the areas in question and then a more complex model study can be performed. An example of this type of model is the MANAGE model, developed at the University of Rhode Island, which provides a site assessment of a watershed area and highlights potential sources of pollution using existing GIS datasets.

In order to use existing GIS data with the field data retained at the different state and local agencies, there must be some sort of standardized data collection system or storage format. Too much time is consumed trying to assemble datasets into common formats before they can be used as input for a model. This is where a DSS is useful. Existing technology provides us with more advanced data collection systems and GIS databases that can be used directly as input in a model with the help of a DSS (Haagsma and Johanns, 1994). In addition, a spatial decision support system (SDSS) adds the spatial analyses functions of a GIS into the toolbar of a DSS, which also strengthens the usefulness of such a system. Various tools are used to implement this integrated system for decision making.

In order to understand the status of local data management and technology, information was gathered on the water supplier's data collection systems, data transfer methods and use of modeling and GIS. The data collection methods range from manual collection of data, such as meter reading, to advanced systems like a supervisory control and data acquisition system (SCADA). The SCADA system automatically collects information from remote transfer units (RTU's) such as water pressures and tank levels, and can either display the information or place it in a spreadsheet ready for analyses. Modeling for the water suppliers was limited to hydrologic modeling, hydraulic modeling, or both. The GIS capabilities among the modelers were investigated to determine questions of scale and the applicability of the existing Rhode Island Geographic Information System (RIGIS). The use of programs such as AutoCAD and other drafting tools also was investigated among the suppliers. The remaining questions concerned the water supplier's current system capabilities and what they foresee as their future needs in order to optimize technological advances.

Finally, with the information on models that are available for use in water resources applications and knowledge of those used in Rhode Island, it was necessary to investigate the use of risk assessment and screening level models. Most water suppliers and state agencies do not have the time or money to perform extensive field investigations to determine pollution hotspots or which tracts of land should be purchased for open space acquisition. These groups benefit from the capabilities of a screening level model approach, such as the MANAGE model. This model was created by the University of Rhode Island Cooperative Extension (URICE) as a screening level model that uses existing GIS databases as input to target potential pollution hotspot areas. The use of less complex, screening levels models for water resources management was investigated.

Special attention is focused on model applications and their benefits when compared to more complex models.

Technology is progressing rapidly in society today. There are now many tools available that can aid decision-makers in water resources management such as GISs and models for hydrologic analyses. In summary, the purpose of this report is to 1) investigate models used for hydrologic studies and evaluate their usefulness and limitations; 2) examine the use of GISs and how they support models; 3) to determine the degree of information technology currently available to Rhode Island water suppliers; and 4) investigate risk assessment models and the MANAGE model with regards to water resources management.

2 BACKGROUND

The advent of the computer has increased the availability and usefulness of modeling in disciplines such as water resources. The word "model" has many meanings, but is typically defined as a representation of a real system or process (Konikow and Bredehoeft, 1992). The data processing and prediction capabilities of models permit new fields and areas to be explored in science. Models are used in the fields of land use planning, forestry, water resources management, environmental pollution, and ecosystem management. Given the many advances in the field of environmental modeling, models are constantly being created to do more and more analyses using different scales.

2.1 Modeling in Water Resources

2.1.1 History of Modeling

A hydrologic model is a representation of how water flows on land and in the subsurface environment. Modeling has existed for at least one hundred and fifty (150) years. It is based on the idea of conservation of mass, momentum and energy. The governing equations for environmental models resulted from experimentation. From this experimentation, Darcy's Law, formulated in 1856, is the fundamental equation governing flow, particularly groundwater flow. Darcy's Law was followed by the derivation of equations describing unsteady open channel flow followed by decades of analytical advances (Maidment, 1993). The 1950's brought the idea of transport of constituents in natural waters, which is a major factor in hydrologic modeling today. Computer models were then developed to deal with surface water flow and transport and groundwater flow. The most frequently used models are those that were developed or endorsed by the Federal government (Table 2.1), primarily because of the amount of testing conducted and studies completed with these models. Table 2.1 indicates both surface water and subsurface water hydrology models. As shown, the surface water models include single-event rainfall-runoff models, continuous stream flow simulation, flood hydraulic and water quality models. The subsurface models include groundwater flow, groundwater contaminant transport and variability saturated flow and transport models.

Table 2.1 Commonly Used Models for Hydrologic Modeling (Maidment, 1993)

SURFACE WATER HYDROLOGY MODELS

1) Single Event Rainfall Runoff Models

HEC-1	U.S. Army Corps of Engineers, Davis, California
TR-20	Soil Conservation Service, U.S. Dept. of Agriculture, Washington, D.C.
Illudas	Illinois State Water Survey, Champaign, Illinois
DR3M	U.S. Geological Survey, Reston, Virginia

2) Continuous Streamflow Simulation

SWRB	Agricultural Research Service, U.S. Dept. of Agriculture, Washington, D.C.
PRMS	U.S. Geological Survey, Reston, Virginia
SHE	Institute of Hydrology, Wallingford, England

3) Flood Hydraulics

	Steady Flow
HEC-2	U.S. Army Corps of Engineers, Davis, California
WSPRO	U.S. Dept. of Transportation, Washington, D.C.
	Unsteady Flow
DMBRK	U.S. National Weather Service, Silver Spring, Maryland
DWOPER	U.S. National Weather Service, Silver Spring, Maryland

4) Water Quality

SWMM	University of Florida Water Resources Center, Gainesville, Florida
HSPF	USEPA Environmental Research Lab, Athens, Georgia
QUAL2	USEPA Env. Research Lab, Athens, GA
WASP	USEPA Env. Research Lab, Athens, Georgia

SUBSURFACE WATER HYDROLOGY MODELS

1) Groundwater Flow

PLASM	International Groundwater Modeling Center (IGWMC), (Colorado School of Mines, Golden, CO
MODFLOW	U.S. Geological Survey, Reston, VA
AQUIFEM-1	Geocorp Corp.

2) Groundwater Contaminant Transport

AT123D	IGWMC, Golden, CO
BIOID	Geotrans, Inc., Herndon, Virginia
RNDWALK	IGWMC, Golden Colorado
USGS MOC	U.S. Geological Survey, Reston, VA
MT3D	S.S. Papadopulis and Associates, Inc; National Water Well Association
MODPATH	U.S. Geological Survey, Reston, VA

3) Variability Saturated Flow and Transport

VS2D	U.S. Geological Survey (USGS) Reston, VA
SUTRA	USGS, Reston, VA;

Hydrologic models need to consider subsurface flow and their ties to biological and ecological modeling. Transport of constituents in water is influenced by biological activity, which affects nearby habitats. Hydrology impacts every environmental process so it is beneficial to include all aspects of the environment into the model. Only then can the modeler feel confident that the model is simulating “real” processes. However, this is difficult because of the large difference in scale between the models, such as alternating from the scales used for hydrologic models to scales used in atmospheric modeling. Modeling in the hydrologic sense concerns basic issues such as pollution control, water utilization for municipal water supplies, the need for wildlife habitats, and flood control and mitigation.

2.1.2 Types of Models in Water Resources

In general, models are considered conceptual, analytical, numerical or combinations and variations of these categories. A conceptual model is a presumption or theory of how a system operates. It is expressed quantitatively as a mathematical model, which is the use of expressions that contain variables and constants to replace objects, forces and events (Krumbein and Craybill, 1965). Some models used for groundwater modeling are called deterministic mathematical models, which have their basis in the conservation of mass, momentum and energy (Konikow and Bredeheoft, 1992). These models describe a cause and effect relationship and generally require the solution of partial differential equations. An example of the use of a conceptual model is in the determination of a basin's response when a rainfall excess pattern is applied for urban watershed studies. More exact solutions can be obtained with analytical models, however they require highly idealized parameters. Numerical models relax these demands; however, they will yield only approximate solutions to equations. Analytical models are realistic scientifically and provide more flexibility to the modeler.

Models have two objectives: exploring the implications of making assumptions about real world processes and predicting the behavior of the real world system under different circumstances (Bevan, 1989). However, even the most complex modeling systems, such as the Systeme Hydrologique Europeen (SHE), are still simplifications of reality. There will always be a difference between the model environment and the real system. The equations behind simplification models aptly describe well-defined, spatially homogeneous systems, but this is usually not the actual case. Real systems are time varying, heterogeneous systems. For example, modeling the discharge response of a catchment for a storm event requires only a loss function and a routing equation for prediction. However, the difficulty in this simulation is that these functions are not linear due to complexities in the catchment’s topography, soil and vegetation conditions, and rainfall inputs. Therefore, it is important to understand the limitations of models.

Hydrologic modeling depends on a representation of the land surface and the subsurface since this is the environment where water flows (Maidment, 1999). In general, there are several types of hydrologic models, lumped parameter models, distributed parameter models and different variations. Commonly, watersheds are treated as lumped systems where their properties are spatially averaged and the topology of the watershed and stream network is not defined (Maidment, 1993). These lumped parameter, conceptual models have been criticized for neglecting the heterogeneity of an area and simplifying conditions. The concern is that using one value for a spatially variable parameter will not accurately predict a watershed's response to an event (Molnar and Julien, 2000). Lumped parameters models have also been criticized for the long meteorological and hydrological records that are required for their calibration. Standing alone, they also cannot take advantage of topography or land use or soil data. However, the development of GISs has introduced the potential for use of physical watershed characteristics in modeling (Greene and Cruise, 1995). Commonly used hydrologic lumped models include Oregon State University's Storm Water Management Model (SWMM) for urban runoff, Storage, Treatment, Overflow, Runoff Model (STORM), the Hydrologic Engineering Center's (HEC-1) for rainfall-runoff, the Soil Conservation Service's Technical Release No. 20 (TR-20), the Hydrologic Simulation Program in Fortran (HSPF) and the Pennsylvania State Runoff Model (PSRM) (Shamsi, 1996). Of these, it is interesting to note that HEC-1, TR-20, HSPS and SWMM utilized GIS in their development.

Typically, setting up a hydrologic model begins by subdividing the watershed into smaller subwatersheds represented as lumped systems linked by streams. This methodology is used in surface hydrologic models, which allows for definition of connectivity but still does not define area or contiguity. More recent models have treated watersheds as distributed systems where the surface terrain is described with coordinates (Hellweger and Maidment, 1999). These distributed parameter models were developed to better represent the variability of watershed characteristics. The SHE model, previously discussed, is a distributed model as well the hydrologic models DROTEL and WATFLOOD (Shamsi, 1996). These types of models require large quantities of input data that generally make them more complex and inefficient for modeling studies that necessitate more rapid assessments. Although physically based, the equations used in these models do not necessarily better describe reality than lumped models. This is because the equations associated with these models are based in smaller-scale physics, which usually requires lumping the processes to the larger scale (Bevan, 1989). This lumping process causes concern with issues of scaling parameters. Another challenge to using these models is determining the scale at which spatial variability can be neglected (Molnar and Julien, 2000). A GIS is a tool that supports these models by providing a way to better describe the spatial variability of the processes. Generally these models are structured so they can take advantage of data available already in a GIS format.

2.2 Water Resource Management and GIS

2.2.1 Geographic Information Systems

The GISs are a combination of hardware and software to allow for management, analysis and mapping of spatial information. A GIS is unique in that it is the only computer and mapping tool that can provide a database interface for creating and maintaining data, a graphic interface and the ability to relate these data though these interfaces. Municipalities, state agencies and many others can use this information management tool to organize, maintain and utilize geographic-based information. Generally, among state, municipal and other agencies, records of water data information are in different formats and split between agencies. Thus, maximum utilization of information cannot be achieved. GIS can ameliorate this problem by providing the ability to store all of this data with the ability to manipulate and query it for quicker, more cost-effective decision-making. The technology behind GISs has been around for two (2) decades and has become increasingly important for practical decision making. Applications of a GIS range from automated generation of an abutter list for municipality planning interests, to cost estimation efforts and web enabling data for public access.

A GIS provides a representation of spatial features of the Earth. Hydrological modeling benefits from a GIS because models for water resources management typically make assumptions of spatial properties or use subunits with uniform properties. These models simulate a set of scenarios, but do not have well-developed capabilities for analyzing and displaying the spatial information. Conversely, GISs have great tools for working with geographical data, but modeling is limited to complex overlays. Although different, these ideas can be brought together and strengthened by integrating models and GISs. The linkage between the two allows a modeler to address regional and larger scale processes that have not previously been modeled.

For effective planning, engineers and managers need as much spatial information about watersheds as possible, which is best achieved through the use of a GIS. Traditionally, data gathering for hydrologic modeling consumed the largest part of the model effort. Modelers started with a topographic map to determine watershed boundaries and then traced the boundaries with a planimeter to determine areas. The modeler also manually determined the length and slopes of flow paths and reach parameters such as the time of concentration. This necessitated a significant amount of time and effort for the modeler, including appreciable time to manually overlay soils, land use and topography maps to determine parameters such as curve numbers, which separate infiltrated water from runoff. Time also was spent determining weighted average precipitation from a rain event by drawing Thiessen polygons by hand. In addition, the modeler still needed to manually input all of this data into the model. Most of this information is spatially dependent and by using a GIS, much of this information can now be generated automatically and is ready for input into the model. With GIS as a spatial data analysis and management tool, this part of the model process can be conducted more efficiently and accurately. GIS also allows the physical characteristics of the watershed to be included in the model rather than averaging parameters over an area.

The development of GISs has significantly changed how spatial data are acquired and used. The physical characteristics of a watershed can be incorporated in hydrologic modeling, instead of using the lumped parameter approach. GISs contribute to modeling by utilizing spatial variation so models with several independent variables are now standard. Today, GISs are even more useful as the resolution of data is becoming more accurate. Current advances in GIS technology have made watershed input data available at grid sizes finer than thirty (30) meters (Molnar and Julien, 2000). An example of how a GIS is useful is the consideration of studies that show that in a watershed, the soils and geology are different in lower elevation areas near streams and valleys than those in the hillside. If using lumped modeling, one could see the proportion of the different geologies and soils, but would not be able to tell if one type is closer to a stream than another. By building models based on polygon coverages of soil and geology in GIS, the limitation of assuming spatially averaged properties is overcome. Another benefit comes from the development of more realistic models of streamflow generation using GIS. Most models assume that streamflow is generated during rainfall by Hortonian overland flow, which means that when the precipitation rate exceeds the infiltration rate, overland flow to the stream begins and grows as the rain continues (Viessman and Lewis, 1996).

However, in many watersheds, overland flow does not occur, and if it does, the contributing area is concentrated around stream networks. This is referred to as "partial area flow" and has not been incorporated readily into models because it is difficult to determine the area as rainfall increases and decreases (Maidment, 1993). With GIS linked to models of soil saturation, a better model of streamflow can be generated than with the assumption of Hortonian flow.

Most models deal with either surface water or groundwater, but not both. It is extremely important to have these linked since they are connected in reality. One problem is that since the partial area flow models have not been constructed, false assumptions can be made of study areas, such as around streams. A series of layer information is necessary to understand the processes on the surface and in subsurface areas. This can be represented by a GIS and has many benefits in water management decision making. In addition, technologies continue to develop that will enhance the use of GIS and hydrologic models. For example, remote sensing can help quantify land use. Remote sensing is used for many applications such as in gap studies, which highlight areas surrounding protected reserves for wildlife studies, telemetry studies for tracking large animals and even movement of polluted material. In addition, technologies that have been used in the past, such as aerial photography for land use, were hampered with positional errors that had to be removed. Now, with better technology, orthophotos are used, which display features in true ground position so that measurements can be made directly from the photos. Unlike aerial photography, the relief displacement is removed in orthophotos. This is accomplished by locating identifiable ground control points and overlaying the unrectified image with digital elevation models (DEMs) with the same areal coverage as the orthophoto. These photos can then be scanned into a GIS and used without any further manipulation. Other technologies, such as satellite imagery, can be used for broad land and sea studies. Some of the applications include determinations of wetland species, forest cover, and even sea surface temperatures and cloud cover for fishery investigations. For hydrologic purposes, land use classifications with soils and topography together can determine the amount of rainfall as runoff and the amount infiltrated during a storm. Then, with better curve numbers quantifying percent impervious for land use, data from these technologies can be used automatically.

It is now beneficial to do numerical modeling within GIS instead of using the GIS as a preprocessor, as was done in older model-GIS linkages (Maidment, 1993). Also, since hydrologic phenomena are driven by rainfall and are therefore time dependent, GIS needs to have time-dependent data structures so changes through time of the spatial distribution can be modeled. The flow of water is a three-dimensional (3D) phenomenon and to approximate this into lesser dimensions reduces the accuracy of the model. With the equations of 3D motion well understood, 3D models utilizing GIS technology represent a logical step for linking surface water and groundwater models together by extending point, line and area with a volume layer. 3D modeling is another technological advance that is rendering incorporation of a GIS necessary for future studies.

The ability to specify the values of model parameters that represent the flow environment accurately is the main limitation in modeling. This can be overcome by using a GIS. The most direct linking of GIS and models to date are two-dimensional (2D), steady state flow and transport models which are common for groundwater systems (Maidment, 1993). The analytical solutions for flow and transport can be incorporated into a GIS system. To link GIS and lumped systems, an object-oriented data model is a linking tool between the spatial-relational model in GIS and the data structure of the hydrologic model.

3 LITERATURE REVIEW

3.1 Hydrologic Modeling Linked With a GIS

Many studies have interfaced a hydrologic model with a GIS. This linkage can be an efficient planning and management tool for local and state agencies faced with water resource concerns. One application of a model-GIS linkage is a hydrologic analysis of the rainfall-runoff process in an urban watershed in Louisiana (Greene and Cruise, 1995). For this effort, the modelers wanted the GIS to be an integral part of the modeling process. Thus, a spatial database was created in PC Arc/Info by digitizing topography, soils, landuse, street networks, lot boundaries, stream channels, the drainage system and the physical characteristics of the routing element for a typical street block. The tools contained within the GIS defined the hydrologic response areas, such as the lots, with the use of overlay features (Greene and Cruise, 1995). Additional programming was used to determine areas contributing to flow at an inlet, overland flow lengths, and for gutters and storm segments. The system also was able to define the order and flow direction of the network, which represented a major improvement over manually determining and digitizing the network. Information in the database was queried to establish curve numbers for the surface and other physical characteristics. Pervious/impervious GIS layers were overlaid with soils and a digital terrain model (DTM) called a triangulated-integrated network (TIN), to determine hydraulic conductivity, slope and the rainfall excess or runoff. Basically, GIS functions converted the physical situation into a routing system for every street block in the watershed. The system needed no human input once the raw data layers were geocoded. Such ability to analyze urban problems at a variety of scales is of interest to urban planners and managers, who may want to know the effect of an impervious lot on the nearest storm sewer inlet. This study proved that using the spatial analysis capabilities of a GIS better represented the physical characteristics of the urban watershed.

Another study utilized a water runoff simulation model, QUALHYMO and GIS software to investigate suburban development options (Zheng and Baetz, 1999). This system would be useful to town planners and engineers who frequently have to determine the most beneficial uses for available land. For this study, the authors investigated how development at the urban fringe affects runoff volumes and peak flows. A subprogram within Arc/Info, TOPOGRID, was used to create a hydrologically correct DEM for watershed delineation. The use of DEMs is now very important in hydrologic modeling as DEMs are used to map stream channels and divide networks of a watershed (Zheng and Baetz, 1999). The model used for the analysis, QUALHYMO, is a water quality and quantity simulation model. Similar to the previous model, inputs required to run the model include rainfall data, soil classification and land use. Developable areas were determined by querying the database for areas fitting a pre-determined criteria (i.e. no environmentally sensitive areas, no buffer zones, etc.). This methodology was applied to the Ancaster Creek watershed located in Canada. QUALHYMO was run to simulate peak flows, time to peak and total runoff for a standard storm. In addition, four design scenarios with differing street right-of-way, dwelling type, open space and lot size, were developed to see which scenario minimized adverse effects of urbanization on hydrologic processes in the watershed. Adverse effects included flooding, deteriorated water quality and habitat degradation. GIS facilitated this study by its capabilities to delineate watersheds and graphically present the different design scenarios.

Storm water management is implemented on a local and watershed basis. Currently, for local management, separate plans are used to solve individual problems without looking at the entire picture (Shamsi, 1996). For example, towns will locate a problem, such as ponding on a roadway, and fix the immediate problem without taking into account the effects on the rest of the watershed. This type of approach only shifts the problem elsewhere, so it is more beneficial to take a watershed approach to solving this problem. This utilizes structural and nonstructural Best Management Practices (BMPs) to be applied anywhere in the watershed that could be impacted by stormwater. An important part of this planning is model development for the watersheds, where GIS can again be utilized to expedite the process by estimating the physical watershed characteristics.

Another GIS-model linkage for stormwater used a lumped model, PSRM, to determine basin runoff effects for a watershed in Pennsylvania (Shamsi, 1996). This model was chosen because its parameters could be computed from a planning level GIS. This eliminated some of the human subjectivity in estimating the input parameters such as the SCS curve runoff numbers, travel times and slope determinations. This study used both raster and vector systems to set up the model so it could be applied to watersheds of different sizes. Arc/Info was utilized for the vector-based approach of the small test watershed. The Arc/Info attribute database provided most of the data associated with the subbasin. This database was converted to a common database that was stored separately so that the model could simulate separate scenarios and the different input parameters did not have to be altered. Once this integrated system is set up, each watershed can be modeled and plans can be made for stormwater management on a watershed by watershed basis. Here a GIS is useful because modelers can quickly determine accurate input, they have access to current data so updating is simple, and it is also easy to add more coverages for more in-depth model studies.

A relatively new model is the Geographic Information System-based Modeling System for Watershed Analysis (GISWA). This is yet another tool for assessing land development options. This system uses DEMs to represent topography with the study area split into cells each having elevation and hydraulic conditions depicted. The user supplies vegetation and soil information from a GIS and rainfall data to the model, which determines the amount of water infiltrating to the water table and how it interacts with surrounding cells. Managing natural flow is important since constructing roads and cutting trees can divert flow and increase the volume of water discharging into streams (Civil Engineering, 2000). The model is important for engineers and planners to test management alternatives to see which approach minimizes impact to the natural flow of the watershed.

The use of a GIS makes it possible to automatically determine the stream and basin networks for a wide range of watershed sizes and models with hundreds of flow elements. Also, with the creation of more state and federal databases of rivers, etc., models incorporating the GIS spatial information will become increasingly accurate. Locally, municipalities, state agencies and many others can use the information management of a GIS to organize, maintain and utilize geographic-based information for their needs, such as determining the area contributing to a ponding problem on a roadway and its overall affects to the watershed. The spatial analysis functions of a GIS can interpret features, see patterns in the data, and query the data to define optimal locations for activities. Hydrologists use these functions to infer what the flow and transport patterns will be in a particular area. Automation of modeling procedures facilitated by a GIS increases efficiency of model set-up and allows more accurate descriptions of the physical world to be incorporated into models for more accurate results (Hellweger and Maidment, 1999).

To analyze the spatial variation inherent in the Earth's systems, it is necessary to integrate the spatial database of a GIS into the environmental modeling process (Wheeler 1993). Technological advances with GIS and models will continue to increase the capabilities of these systems in the future. However, this is still a growing field. Challenges to linking models and GISs include scale issues, accuracy of data, level of generalization of parameters, calibration and validation of data, and a universal lack of understanding of both models and GIS, including their components.

3.2 Inaccuracies in Modeling

Some of the challenge in linking models with a GIS stems from the inherent inaccuracies in the models. The discrepancies that occur between the observed data and the predicted responses of the systems are the cause of error in modeling

(Konikow and Bredehoeft, 1992). Conceptual errors occur where there are misconceptions about the basic processes incorporated within the model. This can occur from neglecting relevant processes or representing inappropriate processes (such as using Darcy's law where it does not apply, or choosing a two dimensional model for systems that may have transport in the third dimension). Other errors can arise from the associated equation-solving algorithm. There are also certain uncertainties in the input data reflecting the inability to describe all the processes occurring in the area studied. Another concern with modeling is the question of accuracy with which the model can be calibrated or validated. This is dependent on the error in the observations of inputs and outputs, where many inputs, such as evapotranspiration, are subject to numerous uncertainties. There is also a danger of overparameterization if simulation of all hydrologic processes is attempted. Usually, it is really only necessary for a few parameters to reproduce most of the information in a hydrologic record.

3.2.1 Scale Issues

The problem of model scale is common to both simple and more complex models. Scale issues with regards to simulation modeling refer to the translation of information across spatial domains and temporal periods (Bevan, 1989). When constructing a model, input parameters must be specified at a certain scale. However, the scale of model elements is usually different than the scale at which the input parameters were measured and the relation between these is uncertain. Usually the scale of model elements is on the order of meters or kilometers. The scale at which input parameters are measured is typically much smaller (Oreskes et al., 1994). Therefore, translating between these scales can introduce uncertainty in the model process.

Scientists deal with the translation of information, such as soil characteristics and qualities, across different scales. Better understanding of processes at large (watershed) and small (field plot) scales has increased the interest in model scale issues. Although more practical tools have emerged for translation purposes, several problems with scaling still remain. In addition, the ability to predict processes at the small scale given large-scale information is more problematic than the ability to scale up these processes. Usually scale translation fails because either key factors have been overlooked or multiple factors are interacting to create unique phenomena (Groffman and Wagenet, 1994).

Both physically-based and simpler, lumped models suffer from the same inherent scale problems. This is because the more complex models are simply lumped conceptual models. For example, a physically based model may require capillary potential as an input parameter, which is averaged over a grid square. However, it is difficult to describe a “grid square capillary potential”, and how would one measure this for validation? The capillary potential is assumed homogeneous over the grid, which tends to lump process interactions within the grid. Model grid squares are usually at most two meters by two meters (Bevan, 1986). At this size, variability of the small-scale field measurements is integrated when trying to scale a process to the model grid. In addition, increasing the scale of averaging further reduces the variance of distribution of parameter values. Since complex models also require many input parameters, there is also more interaction between parameters. This means that changing one parameter may affect numerous others.

Scaling problems are found in all fields in environmental modeling. One example occurs in the soil science field. Information about soil characteristics is necessary for most all surface water and groundwater model analyses. Translating these characteristics across spatial scales has become an important issue in modeling. Soil surveys focus on measurement and classification of soil and land characteristics, such as soil structure (Groffman and Wagenet, 1994). However, models also require information not gathered by soil surveys such as hydraulic conductivity. In addition, land qualities, which influence the suitability of the land (e.g., non-point pollution attenuation potential), are necessary input for models. These also cannot be directly measured, but are related to soil characteristics. New techniques have been created to relate the soil characteristics to land qualities, however, acquiring data from different scales has complicated the input data needs and this is where a GIS is beneficial. Petach et al., in 1991, indicated the usefulness of this technology by using simulation modeling and GIS techniques to translate soil characteristics from the scale of soil profile to the scale of a watershed. Yet, even with practical tools to translate information across scales, problems still remain. The large scale models subsume the complexity of processes at lower scales, and there is always the danger that in generalizing lower scale complexity, some process will change (Rosswall et al., 1988). These changes can affect the soil variability and thus the land qualities. When modeling, it is important to understand where the inability to translate across scales inhibits the ability to derive factors such as land qualities (Gilbert et al, 1993).

Watershed water quality and regional atmospheric chemistry questions has driven scaling up (Bevan, 1986). For larger scale (e.g., watershed) investigations, ecosystems have been used as the optimal unit of study. Ecosystems incorporate much of the lower-level complexity so they are useful for providing data for larger studies. In addition, there are many databases of ecosystem classification that exist worldwide. Linking ecosystems and land qualities will allow models to take advantage of technology such as remote sensing to produce large-area estimates of processes. However, there are still constraints when scaling data for this type of model approach. An example of a constraint for scale translation is the inability to predict nutrient outputs from agricultural watersheds with riparian (shoreline) ecosystems. Riparian ecosystems have a unique structure, and in order to scale information on nutrient transport to the watershed scale, it is necessary to understand the factors that control the process interaction within the ecosystem. Current technology can highlight a watershed with a high nutrient output. However, the nutrient output that can be attenuated by the riparian ecosystem within this watershed cannot be determined. Interactions between the polluted water and the surface water and groundwater in this ecosystem are not well understood. The scale of available databases such as soil surveys and USGS maps is not yet fine enough to detect narrow bands of soil types that vary in their ability to attenuate pollutants. Lack of resolution in measurement limits the use of this information in a modeling sense because model output is sensitive to the resolution and quality of input variables at a given scale. As GIS data resolution becomes more refined, surface and subsurface processes will be better defined for more accurate parameter estimates.

Predicting processes at small scales with the knowledge of large-scale parameters has proved more difficult than "scaling up" parameters (Groffman and Wagenet, 1994). Deriving certain land qualities requires a downscaling from the field to smaller scales. Information gathered by field studies is necessary to design management strategies for beneficial organisms (e.g., biocontrol agents). However, the lack of understanding of processes at the micro-scale impedes the ability to translate across scales. For example, it is known that factors such as fauna and soil aggregation influence interactions between soil microbes, but there is still the question of how these factors are linked to field-scale soil, chemical and biological or management variables (Parkin, 1986).

Studies completed at larger scales can be relevant to understanding processes at smaller scales. For example, remote-sensing studies of plant responses to availability of soil water can be used to identify spatial variation in soil at the field scale, but it is expressed as an average over an area. This may generalize the lower scale complexity, excluding important processes. Scale translation also fails when trying to predict the locations of areas such as denitrification hotspots and macropores. They are both produced by the interaction of multiple factors in the soil environment. However, the forces driving the interaction are difficult to predict and this presents a major constraint in modeling and the ability to translate information from large to small scales.

Scaling failures can be reduced with better interaction between modeling and field measurement. All modeling involves generalizations about which processes are important and to determine if these generalizations are correct, the models must be tested iteratively. By making predictions, the modeler can determine if something had been overlooked or if too much lower-level complexity was subsumed. Validation of models is usually too difficult. However, functional models based on statistical relationships that test model assumptions are useful to test the accuracy of the model. In one study by Hudson and Wagenet, a simplified version of a model was used to assess leaching over large areas where soil surveys at a scale of 1:24000 were the only data available. The model was able to estimate potential pesticide leaching over seven states. Soil data is one dataset that is critical for environmental modeling, however, the resolution of the data limits the more concentrated modeling efforts. Typically, environmental problems occur at scales above or below where current knowledge defines. Greater resolution of data is necessary and soil data providers need to work with modelers and field experimenters so that modeling and scale translation will be more accurate in the future.

3.2.2 Calibration and Verification

Models are embodiments of scientific hypotheses. As such, the models cannot be proven or validated, but only tested and invalidated (Konikow and Bredehoeft, 1992). Model testing can improve the understanding of the problem investigated. The main concerns with applying models to field problems lies in conceptual insufficiencies and inadequate parameter estimation. Comparing a numerical solution to an analytical solution is usually the way to demonstrate the accuracy of the results of a model. However, numerical solutions are sensitive to spatial and temporal changes so even a perfect agreement does not mean that the model code will solve the governing equations under all circumstances. Numerical methods allow for more anisotropic parameter sets and more complex geometry and boundary conditions than analytical models. However, introducing more complexity decreases accuracy in the computer-generated solution. The question remains whether all internal properties of the system are completely described. To make this determination would require extensive field-testing to attempt to solve a set of simultaneous solutions having more unknowns than equations (Oreskes et al, 1994). Therefore, one cannot arrive at a unique solution. Usually a set of parameter estimates are selected that yield the best solution (by comparison of observations to model calculations).

Calibration involves varying the parameters within an accepted range until the difference between observed and calculated values is minimized. The model is considered calibrated when it reproduces historical data within an accepted range. However, this procedure produces non-unique results; i.e., the same result can be reached with different input parameters. A bad match indicates that there could be error in the parameters, model or in the numerical solution. However, a good match still does not prove the validity of the model (Oreskes et al., 1994). It may reproduce historical data, but may not be able to predict future responses under different stresses since all systems are dynamic. Interestingly, in the field of petroleum engineering, the process of calibration is referred to as history matching. This may be a better term to define this aspect of the modeling process.

Some hydrologists suggest a two-step calibration where the dependent data set (such as hydraulic head) is divided into two parts. In the first step the independent parameters of the model are adjusted to reproduce the first part of the data and then the model is run and the results are compared to the second part of the data. The first step is referred to as calibration and the second step is referred to as verification (Wang and Anderson, 1982). Then, if comparison is favorable, the model is considered verified. The use of verification here is very misleading because a match does not verify an open system.

The terms “validation” and “verification” are often used interchangeably in hydrology. Verification has been defined as the model’s ability to solve governing equations and validation as the ability of a site-specific model to represent the cause-effect relationship in that area (Oreskes et al., 1994). Modelers have erroneously used the term "validation" interchangeably with the term "verification" to indicate model predictions are consistent with observational data. This implies that validation establishes the truthfulness of the model, which denotes legitimacy in the model's methods (Konikow and Bredehoeft, 1992). Therefore, a model that does not contain any detectable flaws can be said to be valid. This is misleading because the validity of the results is dependent on the quality of input parameters and other assumptions. The ability of the model to reproduce what has been observed (from the calibration step) enables the modeler to understand the system, but it does not necessarily mean that the predictive capability of the model is good. The philosopher, Karl Popper, argued that hypotheses cannot be declared valid, they can only be declared invalid (Konikow and Bredehoeft, 1992). In other words, no matter how many times the model agrees with the theory, one will not know if the next iteration will not contradict the theory.

The idea behind validation came from models used to assess nuclear waste repositories (Konikow and Bredehoeft, 1993). The U.S. Nuclear Regulatory Agency defines validation as assuring that a model correctly reflects the behavior of the real world. They claim that a model only has to be an adequate representation of a real system. Yet, use of the word "adequate" here is also subjective. The denotation behind the word "validation" produces an idea of correctness that most modelers would not feel comfortable claiming. Bredehoeft and Konikow argue that the connotations associated with this word mislead the public, and therefore, terms like “validation” and “verification” should be eliminated from modeling. McCombie and McKinley also share this viewpoint because they are interested in ensuring that the incorrect impression of accuracy is not conveyed to the public. All of these modelers agree that models should still be tested, evaluated and adjusted until an adequate match with some set of historical data is made. Once a match is made between historical data and model output, the model is usually used to predict the systems response some time in the future. However, it is important to predict only for a time comparable to the period that was matched (e.g., match a ten-year history, make a ten-year prediction). Longer predictions introduce the danger of making cumulative errors from mistakes in the conceptual model, model structure or parameters (Oreskes et al, 1994). The modeling community is trying to place confidence bounds on predictions rising out of the uncertainty in parameter estimates. This is a positive move because the previous, single valued predictions were too simple (Konikow and Bredehoeft, 1993). However, it is important to note that these confidence limits still do not eliminate the error of selecting the wrong model.

Earth scientists at Dartmouth College also use the term “validation” with caution. They believe that verifying and validating numerical models is impossible because natural systems are never closed and because model results are always non-unique. Models are open systems since observation and measurement of variables are full of inferences and assumptions. By claiming that a model is verified indicates that it is reliable for decision-making. However, with open systems, the outcome may be different than what was predicted. The scientists claim that the mathematical components of models can be verified, but models using these components are still open systems requiring parameters that are incompletely known (Konikow and Bredehoeft, 1992). Therefore, agreement between a measured response and model results does not indicate the output is accurately representing the real system.

Another problem with verification is that if the model is not considered verified, the modeler does not know if it is the original hypothesis or other assumptions used to construct the model that have failed (Oreskes et al., 1994). If making a comparison with observational data and the comparison is good, this only means that there is more than one model construction that will produce the same output. This problem of non-uniqueness means that two or more errors in the additional model assumptions could have canceled each other out, thus making the model inaccurate while seemingly showing a "good" match. For example, there may be small errors in the input data not affecting the present model, but which will vary for different time frames.

There is little evidence that supports long term modeling predictions. Selecting the correct model is very important because data may fit equally well into different models, but their long-term predictions can be very different (Oreskes et al., 1994). An example of this was shown in a study done on the Dakota aquifer in South Dakota. This aquifer has been considered a prototype artesian aquifer. The question posed of the model was whether the overlaying confining layer was permeable enough to allow some component of the total flow to pass through this layer. The data fit the model Theis solution assuming impermeable layers above and below the aquifer. The equations behind this solution were derived in 1935 and apply to confined aquifers with no source of recharge (Fetter, 1994). However this data also fit equally well into the Hantuch leaky aquifer solution, which allows for transient flow through the confining layers. Both models are considered validated by this set of data, however long term flow through the confining layers cannot be neglected, and therefore both models would no longer be valid.

Post-audits have been performed to check the accuracy of some model predictions that are considered "valid" models. They have indicated that the future prediction was for the most part inaccurate. Problems incurred because the period of history match was either too short to capture important model elements or the parameters were not well defined. Even with the new computer methods and programs for verification or validation such as INTRACOIN and GEOVAL, professional judgement is still needed to determine which model is appropriate for use in a particular situation and what constitutes an adequate match to the historical data (Brendehoeft and Konikow, 1993). Also, human subjectivity can never be eliminated from the modeling process. Since society's actions are based on these professional judgements, engineers and planners should use models as a tool only to enhance their knowledge of a particular situation.

3.2.3 Other Limitations

It is a common belief is that physically based or distributed models better describe the internal processes of a system than simpler, lumped conceptual models. However, this belief has not been proven in practice. In contrast to conceptual modeling, a physically based model attempts to simulate the actual processes involved such as determining the runoff response to a given rain event. However, they suffer from the same scaling problems as lumped models, and they cannot avoid the problems associated with errors in observed data. Physically based models make assumptions about how a hydrological system operates. There is a danger in accepting the equations as valid simply because they are physically based. In real applications of physically based models it is necessary to lump up the small-scale physics to the model grid scale (Bevan, 1989). These models assume that the same equations can be applied at different scales and this assumption is not generally accurate. For example, using grid square effective parameter values assumes that a grid square is homogeneous when in reality the parameter could be highly variable within this area. A single parameter value cannot reproduce the heterogeneity of responses from variable catchment responses. Therefore, small-scale physics equations should not be used, instead more complex equations are necessary that account for the effect of heterogeneity (Bevan, 1989).

Another problem with many of the more complex models used in water resources management is overparameterization. There are many parameters associated with the processes simulated. This is problematic when comparing the measurements observed versus those calculated. If it is necessary to optimize the parameter values, it is difficult to know which ones to change. The number of parameters used in these models also subjects the model to greater problems of interaction than in simpler models. It has been suggested that measurements at a few representative sites may be sufficient to obtain an initial calibration for the model (Bathurst, 1986). This approach, however, leads to more questions of how the site should be chosen, and what measurement techniques to use to obtain an effective parameter (Bevan, 1989). Usually, the time commitment necessary for making field measurements will not be an option. Therefore it may be necessary to estimate the values required from other known physical information about the area. This estimation creates uncertainty in the model prediction capabilities.

There are also problems concerning the acceptability of the more complex, physically based models. One problem in modeling phenomena such as surface flow is that there is generally little detail of flow processes and how they occur in the field. Then, if modeling is performed with several models that make, for example, different, gross assumptions about the nature of surface flow components, how does one know if one model is superior to another? It is important that there is a close connection between field observations and the model effort. It is also important that the correct parameter measurement technique be used if these models are going to perform to their potential.

Although there are limitations of physically based models, some hydrological problems can only be predicted by these types of models (Bevan, 1989). One of these problems is predicting the effect of land use changes. Since it is not possible to calibrate parameter values with observed data, the predictions must rely on parameter estimation. Planning decisions can be made from these model predictions even without extensive data using of multi-scenario modeling. This process involves using a number of different models whose outcome is matched with historical data and the model with the best data reproduction is used to evaluate the effect of future changes. However, there is still a degree of uncertainty in that different combinations of parameter values and boundary conditions can lead to the same outcome. It is therefore necessary to recognize the range of possible behaviors, since there is no method to assess the predictive uncertainty. Physically based models are best suited to be used as a research tool to explore the implications of making certain assumptions about the behavior of hydrologic systems.

So why are these models useful for assessing environmental problems? Generally, models can reinforce a hypothesis by offering evidence that strengthens what premises might have been only partly established by other methods. Models can also show discrepancies in other models and for sensitivity analyses, models can explore different scenarios or indicate what part or parts of the system need further study. There are many models, such as the MANAGE model that were created specifically to examine a certain area and indicate problems, such as pollution, where after a more specific model can be applied to the highlighted areas for a more accurate study. Modelers should ask of models, how much is based on observation and measurement and how much is based on informed judgement and convenience. This is especially important when the public is relying on models for decision making.

3.3 Decision Support Systems and Spatial Decision Support Systems

The agencies that serve the public need to ensure that the models they use accurately describe the associated systems. Models for water resources management are useful tools for state, federal and local agencies that collect water-related information for planning and resource management. However, these agencies first need to standardize their data formats in order to make the data useable in a model sense. Since there is no standard method for storing data, the formats can differ between agencies. A critical management issue is how to improve the availability and usefulness of water-related information. In order to improve the usefulness of this information, there is movement towards integrated DSSs. A DSS is defined as a information system that reduces the time it takes to make a decision while improving the quality of that decision (Haagsma and Johanns, 1994). These systems combine advanced modeling techniques with database elements to create solutions for water management issues and are specifically geared to the decision-maker.

3.3.1 Decision Support Systems

Typically DSSs contain models, databases and necessary elements to interact between them (Pingry et al., 1991). These systems assist the decision-maker in situations that exhibit poorly defined, unstructured problems, such as those found in engineering studies. Also, there are direct linkages between the database and analysis modules, and the user can access data and simulate scenarios without extensive training (Johnson, 1986).

Using a DSS involves a multi-step process of trial and error. The modeler can test different scenarios by changing certain aspects such as input parameters. This process leads to a better solution since the user gains a clearer understanding of the problem. This type of solution technique has been applied to many problems in water resources from water quality and water supply decisions to water monitoring and operation decisions. It is important to note that the most critical element of a DSS is the designer, whose judgement is utilized throughout the model building effort. Use of advanced data collection systems, better communication systems to transfer data, GIS databases and models increase the analysis capabilities of the supplier or agency. For example, in the case of a water supply application, this effort results in a better understanding of the hydraulic system. An example of a DSS that was used to manage a water supply system is shown in Figure 1.1. where thirty (30) million dollars was saved by the use of a modeling alternatives.

Melbourne Municipal Water Supply System

1. Data subsystem
   a. Real-time telemetry network monitors system flows, pressures, and reservoir levels
   b. Automatic data storage on disk
   c. Time-varying demand data stored for user access
2. Models Subsystem
   a. Regional system model for major conduits and reservoirs
   b. Hydraulic model of distribution system
   c. Direct interface with telemetry data for model calibration
   d. Simulation of system operational changes
3. Dialog Management
   a. Interactive color graphics for monitoring and control; menu-driven for easy use; and high resolution multicolor displays of system
   b. Rapid screen updates of system status and model results
4. Conclusions
   a. Represents trend toward advanced control of complex systems. In Melbourne, $130,000,000 works program reduced by $30,000,000 due to development of alternatives through modeling

Figure 1.1 Example of Water Resource Management Decision Support System (Johnson, 1986)

There are many existing databases with water resource information. It is important that the modeler be well informed about the information that is available and that may be of use. Pingry et al. point out that there are benefits and complications for a project using a DSS. Typically the largest amount of time and effort in a model study is spent searching for data, testing its consistency and integrating it into the model. Since the model is not pre-determined when using a DSS, the amount of data that needs to be gathered can be extensive. However, the flexibility of model choice gives the modeler the freedom to ignore models with impractical data requirements and not be tied to one model's requirements (Pingry et al., 1991). Instead of gearing the problem to the model, the model can be more tailored to the actual problem at hand. It is important to note that in order to support a model system such as this, a standard format is necessary for the transfer of information. Since data are also not strictly quantitative, there is also a need to integrate some engineering decision-making information into the DSS. Also, the modeler does have to review the model as it is applied to the problem. In the integrated system, the interpretation layer consists of individuals who must be able to understand the queries and computer output (Haagsma and Johanns, 1994). The stepwise process quickens as the modeler tries different options and rules them out while retaining knowledge of the earlier results. This confirmation and rejection of hypotheses enhances the model process. The modeler's judgement is still necessary in this instance since it alone determines which avenues will be pursued in the testing. Although the principals behind hydrologic modeling have not changed, the DSS must be able to be flexible enough to incorporate new functionality and advancements in modeling.

3.3.2 Spatial Decision Support Systems

A SDSS combines GIS technology with DSSs to aid decision-makers with problems having a spatial dimension. Early linking efforts used a GIS as sort of a "post processor" to display output only. The DSS was only used to retrieve data from large databases to solve structured problems. Now, with a SDSS, the models and GIS interact directly, thus creating the model-GIS linkage system. This combination increases the utility of both the GIS and the DSS. The functions of the GIS do remain separate and are simply added to the toolbox of the SDSS. The SDSS can use these spatial analysis tools with many models for water resources. Essentially, the GIS is used to derive input for the model, which then performs the simulation and displays the output graphically.

There is a significant amount of spatial data, but much of this data is not easy to integrate and share. Open standards are needed to integrate data. An SDSS offers a single framework for integrating GISs and DSSs. Primary and compound tools do the SDSS retrieval and transformation of data in a GIS. Most GISs use primary tools for data retrieval and transformation. The compound analyses involve mathematical models or expert-type systems that can interact with the attribute data to produce new information. The addition of modeling capability allows the user to simulate different scenarios for a particular problem to arrive at the best solution. A GIS provides the data, which is stored in the database, readily available for model input. The nonspatial attributes are stored separately in the GIS. GISs and models can be brought together and strengthened by their integration. The SDSS provides the framework for this linkage. This collaborative tool allows decision groups to work directly with geographic data for more accurate decision-making (Farber, Wallace and Johnson, 1998). Such a system would incorporate GIS technology such as ArcView 3.0 GIS (Environmental Systems Research Institute) so that users can interact with the data by testing scenarios and determining which alternative best suits their queries.

Challenges to this type of system include the seamless integration of technologies. It is imperative that the input in the SDSS comes from the model developers and users so it can be correctly designed to solve the problem at hand. The SDSS is able to adapt to most models. Instead of having to modify every model to match the GIS, the SDSS provides a standard interconnection between the models and the GIS. One developing tool for SDSSs is an AR/GIS toolkit for resource allocation decisions. This is a mechanism designed to interact with geographic data for evaluation of decisions. With more public involvement in municipal decisions, it is important that the public understand the factors that influence the decision-making process. With AR/GIS, the decision makers and the public can use their collective knowledge to determine design criteria and assess different scenarios for land use planning (Farber et al., 1998). The AR/GIS system is a Windows-based tool that integrates GIS with meeting system software. In an office where computers are connected by a local area network (LAN), this system can operate on the computers so individuals can brainstorm and simultaneously enter their opinions into the system. Existing policy documents, geographic data or pertinent maps of a location may also be entered and viewed collectively. This could be useful if a town needs to determine what land to purchase and in what order of priority, such as for an open space bond. To make this decision effectively, the decision-makers must decide on criteria, descriptions, models, etc.

It is preferable to use a relatively simple model to perform the evaluations so that the results can be conveyed to the group quickly. As people in the group develop proposals for land, the results will then be evaluated against the combined criteria made up of the collective goals of the members of the meeting. A benefit of performing such evaluations is that each one will be entered as a separate GIS layer for future use. This system is extremely beneficial to decision-makers since they are able to work with geographic data directly and obtain real-time feedback on impacts of critical decisions. In the future, this process will probably be facilitated by an internet management system (IMS) that will allow even more people to influence the decisions that are important to them.

4 RISK ASSESSMENT AND THE MANAGE MODEL

4.1 The Idea of Risk

The AR/GIS system allowed planners to determine what land to purchase to retain for open space or wildlife habitats by eliminating areas that could be considered at "risk." They are considered a risk due to the presence of surface/subsurface pollutants or because they were unavailable due to existing use, etc. This idea of "risk" and "risk assessment" encompasses a broad subject area. Risk assessment, in terms of water resources, is generally defined as the "measure of the likelihood that a given hazard will cause harmful events to occur, such as illness and death in people and wildlife or damage to ecosystems and property." (EPA, 1999). Risk assessment involves gathering information to understand this risk. It also brings objectivity to the overall decision making process.

One form of assessment within the field of water resources management is the evaluation of pollution risks in a watershed. The United States Environmental Protection Agency (EPA) continually works toward developing guidelines and approaches for conducting risk assessments and published the *Guidelines for Ecological Risk Assessment* in 1998 (EPA, 1998). These guidelines can be applied to many assessments including watershed management, and they can be important for towns seeking knowledge about watershed effects. Within a watershed, there are various point and non-point sources of pollution. Point sources have a known origin and the effluent discharged from these sources, e.g. municipal treatment plants, is well regulated. However, pollution also originates from other, diverse sources that are not as easily regulated such as lawns, farms, stormdrains and septic systems (Joubert and Lucht, 2000). It has been difficult to assess all of these land use impacts due to the amount of sources, cost of field monitoring and lack of available data. As a result, there has been a movement toward use of watershed characteristics to provide an indication of the overall health of the watershed. Instead of comparing water quality sampling results to a standard as is done in many modeling efforts, these indicators depict a measure of the risk that different pollutants have on water quality.

It is also important to understand the basic hydrologic cycle when considering risk to the environment. Waters can be polluted from many diverse sources, including pollution from hazardous substances transported by wind currents and falling back to the Earth as precipitation. Therefore, the idea of risk management planning in water resources must also incorporate risk of hazardous substances carried by the atmosphere. The EPA has also developed models to evaluate the transport and dispersion of these substances.

4.2 EMAP Program

The EPA created an Environmental Monitoring Program (EMAP) in 1989 to look at trends of the nation's ecological resources on a broader scale. A component of this program is the Mid-Atlantic Integrated Assessment (MAIA). This program conducts intensive assessments at a regional scale that can be altered and applied to different areas of the country. This Mid-Atlantic region encompasses Pennsylvania, West Virginia, Maryland, Delaware, Virginia and portions of New York, New Jersey and North Carolina. It also includes the largest estuary in the world, Chesapeake Bay, and many ecological systems. The goal of the EMAP program is to support environmental decision making by utilizing the best information available for management actions. Two products that resulted from this program are a landscape study and an estuary status report of watersheds in the Mid-Atlantic region. The landscape study compared watersheds using thirty-three (33) indicators of landscape condition from satellites images and other GIS databases of soils, elevation and population (EPA, 1998). It is also being used to determine potential impacts from coal mining practices in the region. The estuary study identified problem area locations and the condition of estuaries based on environmental indicators such as water quality and sediment contamination. The MAIA is also expanding the ability to not only predict current conditions, but also assess future impacts and risks. These assessments demonstrate how risk can be evaluated on a broad scale. The concept behind these applications can also be applied at a local scale for a smaller, regional study of an area.

4.3 Areal Locations of Hazardous Atmospheres

The Areal Locations of Hazardous Atmospheres (ALOHA) model was developed by both the EPA and the National Oceanic Atmospheric Administration (NOAA) for modeling transport of hazardous substances in the atmosphere (EPA, 1998). This model uses the toxicological and physical properties of a pollutant and the characteristics of the site under study to model the pollutant cloud. This allows the modeler to determine the scale of the hazard and what areas would be affected should a spill occur. The model uses a mapping program, MARPLOT, to delineate the footprint of the chemical cloud on a map of the area. As more and more land is being consumed by industry housing hazardous chemicals, it is important to be able to monitor what areas will be affected by a possible spill. The dispersion of the chemical cloud is dependent on type of chemical, atmospheric conditions and land use and terrain, for which data in a GIS would be beneficial. ALOHA is a type of screening level model that was created to obtain results quickly for emergency situations. Because of the nature of this model, it is also subject to limitations. As with any model, it is only as accurate as the information that is put into it. It also has certain other limitations, where it is unreliable for the following conditions: 1) very low wind speeds where the wind direction can be unpredictable; 2) very stable atmospheric conditions where high concentration of gases can collect in low lying areas that cannot be predicted; 3) wind shifts or terrain steering effects since the model assumes wind direction and speed are constant and the terrain is level; and 4) where concentration patchiness is a problem. Some of these limitations could be eliminated with the use of a GIS. A GIS could incorporate DEMs and terrain information about the site area into the model system. Therefore, the model would still be used as a screening level model to arrive at a quick solution, but would be able to include more detailed information of the site area for more accurate modeling assessments. Atmospheric transport of hazardous substances is an important aspect of risk assessment for water resources management as pollution originates from many, diverse sources.

4.4 MANAGE

A local approach to risk assessment for water resources is a screening-level model called MANAGE, which evaluates pollution risks in watersheds. MANAGE was developed by the University of Rhode Island Cooperative Extension (URICE) for use as a tool by communities in Rhode Island to assess non-point pollution (Joubert and Lucht, 2000). This model, which uses GIS data as input, is currently used for mapping potential hot spot pollution areas and using watershed indicators to evaluate pollution risk (Kellogg et al., 1997). It is a method of assessing nutrient loading and geographically evaluating non-point pollution. MANAGE can be useful at a community-wide or municipal scale.

Although developed and used solely in Rhode Island, it has the potential to be refined for use in other states and regions.

The model identifies pollution risks in conjunction with the town or region's local water quality goal. This type of model yields valuable information that may be acquired while working with limited data and budgets. For example, it is known that land use activities generate pollutants and this is one of the most important factors in evaluating pollution risks. This provides the basis for other indicators such as nutrient loadings (Joubert and Lucht, 2000). Most municipalities do not have the adequate budget to conduct large-scale field sampling and model assessments of their resources. The MANAGE model is able to use the data that is currently available in order to support actions such as verifying and resolving suspected problems, and forming better land development standards and non-point pollution controls. The key to this approach is the use of existing, available data to locate land development patterns that affect water resources.

The process of developing the model begins by first gathering information from existing GIS coverages for the area under investigation. Coverages used include the boundary of the study area, land use, soils, sewered areas, public water systems, community wells, roads and buffered surface waters. Using Arc/Info, the coverages are clipped using the boundary for the study area so that they are specific to the area under question. The land use is aggregated into groups and soils are aggregated into restrictive and non-restrictive soils. Then, an inventory is conducted to determine existing land uses that reduce nutrient loading and ameliorate pollution, such as forested areas. As the analysis begins, the user is queried for input on high-risk land uses such as agriculture or sewage treatment plants in an area. All of this information is stored in tables within the model system. Risk is assigned based on factors such as current and future unknowns, nutrient loadings, soil types, individual sewage disposal systems (ISDS), land use, impervious cover and soils for water flow and pollutant pathway determination. Such information is available for towns in Rhode Island though the RIGIS system. Some risks associated with land use include leaking underground storage tanks (LUSTs), and pollutants transported from runoff and leaking sewer lines, for which related information is also available through the RIGIS system. The amount of total phosphorous and nitrogen loadings to surface waters and coastal waters, as well as nitrate-nitrogen loading to groundwaters from diverse sources is also considered in the evaluation. These source estimates are based on land use and soil conditions and do not represent the actual amount that will reach a water body. Rather, they represent an indication of sources of nutrients at the point of origin. MANAGE uses a mass-balance approach to determine a water budget for a watershed and to estimate the nutrient sources to runoff and groundwater.

4.4.1 Application of MANAGE

MANAGE was used to evaluate the pollution risks throughout the Wickford Harbor watershed in Rhode Island. The risk assessment began with identification of current conditions in the watershed and vulnerable natural resources. Pollution risks were identified and ranked in order of priority. Health indicators as defined by the EPA were used to rate the risks. These indicators are customarily used to define the health of a watershed since it is difficult to assess land use impacts in conventional ways for non-point source pollution. A risk analysis was then performed using the methods described above to estimate runoff and nutrient loadings. The Town's input was necessary in the analysis process since it established specific goals for remediation that could be directly incorporated in this modeling process. This study focused on remediation of the harbor area. Also, using zoning maps, a potential build-out analysis for the area was conducted. From all of the background information that was compiled, pollution risks were determined using a spreadsheet summarizing the different watershed indicators. Using this spreadsheet, a hydrologic budget was calculated and nutrient loadings were determined as an additional pollution risk determinant. Using prediction methodology, future risks within the watershed can be highlighted as areas of concern. Even different Best Management Practices (BMPs) can be applied to the model to determine how the hot spots of pollution decrease in number when these practices are implemented.

Questions about the major sources of pollution are complex and without having to use complex modeling to assess one or two pollutants, the MANAGE approach provides efficient, accurate results that indicate potential pollution sources and risks to water quality. Therefore, if desired, interested parties may then use the results to perform a narrower study on a highlighted area, which involves a more complex modeling effort. This saves the decision-maker considerable time and effort, which may have been inefficiently directed towards a modeling study that could only examine a small area for certain pollutants. The mapping capabilities of the MANAGE model system can quickly and graphically indicate the high-risk areas. The mapping utilizes the GIS databases and overlay functions of a mapping software such as ArcView 3.0 GIS to combine, for example, the high density land use and soil features to show where likely contaminant movement will occur. Map analyses target the sites of pollution sources and also sites that can minimize pollution risk, such as forested areas. In the Wickford study, the watershed features were obtained from the RIGIS database, as well as from the "watershed health indicators," which are also available from RIGIS. MANAGE was also used to determine the best treatment options for the present and future needs. For example, in Wickford, planners were able to enter acreage amounts and treatment options to determine which option best reduced nutrient inputs.

Screening level assessments and risk-management approaches have certain advantages over complex models that require more extensive data to simulate physical and chemical responses. Some benefits include yielding a relatively quick review of the situation at a low cost, using existing GIS datasets as model input. This is beneficial to water suppliers and towns that have limited budgets to conduct this type of study. Municipalities are then able to use more of their own resources to implement pollution controls. In addition, more complex models may still be conducted from the assessment results, but for a more defined study area. For example, instead of measuring water quality at various locations over a period of time to determine a source of non-point pollution, studies using the results of a MANAGE assessment can provide an analysis of the broad picture and quickly highlight possible areas at risk. Models like MANAGE can provide average estimates of runoff, infiltration and nutrient loading, which are beneficial when comparing pollution risk among land use scenarios or in watersheds. Then, the modeler can focus on these highlighted areas for more intense work. The pollution risk mapping products such as ALOHA and MANAGE are useful for town planners to provide to councils who make the land use decisions.

5 INFORMATION TECHNOLOGY OF RHODE ISLAND WATER SUPPLIERS

Much of the water related data in a state originates from the water suppliers, who collect information such as groundwater and surface water supply levels, pumping rates, flows, pressures and water quality information. However, a critical management issue faced by agencies that regulate the suppliers is how to improve the usefulness of this information. Today, data and information such as maps, are still largely available in hard copy only, which limits its application and effective use for solving water management problems. More sophisticated data collection methods and information systems are necessary for a more comprehensive approach to water resources management. The prevailing vision is to integrate databases, maps and online information sources to enhance data exchange between federal, state and local agencies and the public. In order to work towards achieving this goal, it is first necessary to understand the state of information technology that currently exists among the water suppliers. Therefore, by use of a small-scale study, an information technology survey was developed for the water suppliers in Rhode Island. The questions examined the suppliers' information plans, their level of automation for data collection, storage and exchange, type of software in use, use of a supervisory control and data acquisition system (SCADA) and mapping and modeling capabilities. The surveys gathered from the suppliers are attached in Appendix A. Additional information concerning the mapping capabilities of the suppliers was gathered from the Water Supply System Management Plans (WSSMPs) from the Rhode Island Water Resources Board (RIWRB).

All twenty-nine (29) major water suppliers in Rhode Island have been surveyed. Almost all of the suppliers surveyed agree that the future is in digital data handling and submission, which includes reports such as the WSSMPs and maps. Most of the water suppliers seem to be moving in the right direction and currently have some plan in place that includes upgrades to their existing water data collection systems and to their software for more complex modeling analyses. However, the differences in how these plans have been implemented vary greatly among the suppliers. The constraints that the water suppliers face is financial, since much of the available money in their budget is set aside for capital improvements.

5.1 Computer Applications

All of the suppliers are using Windows-based applications, Windows 95 and the 1997 Office Suite or better, which signifies a move from DOS-based programs. The suppliers using old DOS programs, such as for billing, are moving toward more Windows-based programs. Interestingly, even with high levels of sophistication among some of the suppliers, there is a general recurring lack of connection among departments in the municipality and their ability to use the internet to provide information to the public. In many towns, the information technology authority falls to the public works/engineering departments where most are connected only by a LAN. Most departments are currently unable to connect to other departments for GIS and information sharing.

5.2 Web Presence

Some of the water suppliers themselves do not have a web presence to date. In fact, seven (7) of the suppliers surveyed do not have a web presence at all (Table 5.1). Most other suppliers are trying to link to their town's web page to allow information such as their Consumer Confidence Report (CCR) and other public interest items to be accessible to the public. To date, most of the towns that have a web page do not yet provide a link to the suppliers or provide much water-related information to the public. The towns and suppliers do seem to be moving forward quickly in this endeavor and hopefully the suppliers will be able to either host their own page or link to the town in the near future.

Table 5.1 Web Presence

	Current Web Presence	
Water Suppliers	Operator	Address
Bristol County Water Authority	Town	www.bcwa-ri.com and www.town.bristol.ri.us
Cumberland Water Department	Town	www.cumberland-ri.us
East Providence Water Department	Town	www.eastprovidence.com
East Smithfield Water District	None	
Greenville Water District	Police	home.ici.net/~spd
Harrisville Fire District	None	
Jamestown Water Division	None	
Johnston Water Control Facility	Town	
Kent County Water Authority	None	
Kingston Water District	None	
Lincoln Water Commission	None	
Narragansett Water Department	None	
Newport Water Works	Town	www.newportri.com
North Kingstown Water Department	Supplier	www.northkingstown.org
North Smithfield Water Department	Town	www.northsmithfieldri.com
North Tiverton Fire District	Implementing	
Pascoag Fire District	Supplier	www.pfd.com
Pawtucket Water Supply Board	Supplier	www.pwsb.org
Portsmouth Water District	Town	www.portsmouthri.com
Providence Water Supply Board	Town	www.providenceri.com
Rhode Island Economic Development Corporation	Supplier	www.ridec.com
Richmond Water Supply System	Town	www.richmondri.org
Smithfield Water Supply Board	Town	www.home.ici.net\spd\town\
South Kingstown Water Department	Town	www.southkingstown.com
Stone Bridge Fire District	Town	
United Water of Rhode Island	Supplier	through parent company
Warwick Water Department	Town	www.warwick.com
Westerly Water Department	Town	www.townofwesterly.com
Woonsocket Public Works	Town	www.woonsocket.com
University of Rhode Island Facilities and Operation	University	www.uri.edu/facilities/ccr.html

Pawtucket is one town that currently has an established website with information including quantity data, average daily demands, flushing information, the CCR and a system history. The individual responsible for the website is an information system manager hired by the town for this specific purpose. Other towns with notable web capabilities are Westerly, South Kingstown, North Kingstown and Pascoag. The Town of Westerly has a web page in the engineering division with links to upcoming projects, water issues, flushing, etc. South Kingstown is currently in the process of adding water-related information to their web site. North Kingstown hosts their own page with ordinances and general information available and Pascoag has a web page that is maintained by the fire district. Some of the suppliers (e.g., North Tiverton and Woonsocket) anticipate that the internet will be installed in their department within the next year. Most suppliers would like to host a web site, however they neither have the technology presently in-house, or the personnel to manage it. There are also cases where the town has a web site without a link to the water supplier. In addition, what information should be included on the website is an issue for the suppliers as system security is a major concern.

5.3 Data Collection Methods

In terms of actual data gathering, such as water meter information, tank and reservoir levels, etc., most suppliers are moving toward more automated systems. One of these systems is a meter reader that is directly connected to houses, so it has the capacity of reading information and storing it for downloading to a computer back at the office. However, over fifty (50) percent of the suppliers are still sending crews out to collect and log data, such as the meter readings, in daily log books, which are typically not transferred to a spreadsheet program. Some suppliers admitted that the only time this type of information is entered into a spreadsheet form is when they need to satisfy requirements of the WSSMPs. This backlogging of hard copy information deprives the suppliers of viewing demand curves or water level changes with time. Moving to the more automated meter collectors is one way that most of the suppliers are slowly gaining more data automation and collection. Some suppliers are even transitioning to a radio system where the meter can be read by simply driving past the house. This will significantly cut down the time and personnel needed to collect this data. The more automated meter systems also save time and effort for other departments. For example, the meters can be connected to a computer and once the data is downloaded, it can be transferred to the financial department in a format that enables development of billing documentation. Some towns are even considering upgrading to directly tie into an on-line billing system. This will be a another timesaving measure for personnel in the department.

5.4 Supervisory Control and Data Acquisition Systems

The most automated system used by suppliers is a SCADA type system. About thirty (30) percent of suppliers surveyed are using this type of system as shown in Table 5.2.

Table 4.2 SCADA Use

Water Supplier	SCADA
Bristol County Water Authority	NO
Cumberland Water Department	Have a telemetry system to log measurements (tank and well levels and flows) on paper chart recorders
East Providence Water Department	YES: see tank pressures, levels on computer screen and can do trends
East Smithfield Water District	NO
Greenville Water District	Have a telemetry system to log measurements (tank and well levels and flows) on paper chart recorders-They are ready for SCADA system
Harrisville Fire District	NO
Jamestown Water Division	Have a telemetry system to log measurements (tank and well levels and flows) on paper chart recorders

Water Supplier	SCADA
Kent County Water Authority	YES
Kingston Water District	NO
Lincoln Water Commission	NO
Narragansett Water Department	Have a telemetry system to log measurements (tank and well levels and flows) on paper chart recorders
Newport Water Works	Have a telemetry system to log measurements (tank levels, etc.) on paper chart recorders
North Kingstown Water Department	Doing a SCADA needs assessment-currently have telemetry system tied to paper recorders
North Smithfield Water Department	YES: Can see well levels, turn pumps on and off
North Tiverton Fire District	Have a telemetry system to log measurements (tank and well levels and flows) on paper chart recorders
Pascoag Fire District	Telemetry system proposed
Pawtucket Water Supply Board	Have a telemetry system to log measurements (tank and well levels and flows) on paper chart recorders
Portsmouth Water District	Have a telemetry system to log measurements (tank and well levels and flows) on paper chart recorders
Providence Water Supply Board	YES
Rhode Island Economic Development Corporation	Telemetry at plant
Richmond Water Supply System	NO
Smithfield Water Supply Board	Have a telemetry system to log measurements (tank and well levels and flows) on paper chart recorders
South Kingstown Water Department	Have a telemetry system to log measurements (tank and well levels and flows) on paper chart recorders
Stone Bridge Fire District	Have a telemetry system to log measurements (tank and well levels and flows) on paper chart recorders
United Water of Rhode Island	YES: see pumping sequence, gallons produced, etc.
Warwick Water Department	YES-can get flow data, pressures, etc.
Westerly Water Department	Have a telemetry system to log measurements (tank and well levels and flows) on paper chart recorders
Woonsocket Public Works	YES-can get flow data, pressures, etc.
University of Rhode Island Facilities and Operation	NO

The SCADA program is geared more toward running utilities. Systems that do not have their own supplies or water treatment facilities would have no need for this type of system. However for those suppliers using this system, a whole new level of automation is realized with their departments. The SCADA system can collect information and can also control a portion of a facility’s operation.

Providence's SCADA system is one of the oldest and most sophisticated systems in the state. The crews that manage the system can view the entire system on a set of computer screens. They can view their main reservoir elevation, and they are able to physically point and click on the pump stations to view pressures and also turn pumps on and off. They can even observe what chemicals are being added to the treatment chain, the pH levels that are experienced at different points in the treatment process, contact times, effluent standards and they can also regulate backwashing times. At the filters, the controllers have access to head losses and turbidity monitors. An audible alarm warns them when a process continues for too long or a water level is too high or low. Providence also provides water to nine (9) wholesalers, so they are able to monitor the suction pressure at these distribution points. The program utilizes what is called "intelligence automation" so that at any point in the facility, data are collected continually. Data are recorded at each process point in the system and is imported to excel spreadsheets where reports can be generated and viewed through their Intranet from anywhere in the building as well as from remote locations. Having the data accessible in a spreadsheet form make generating trends and historical data much easier than entering data from logbooks and then generating the necessary trends. East Providence also uses a SCADA system to monitor pressures and levels of their water tanks, operate their pumps and perform hydraulic measurements. Their information is returned to the public works department and the water department, and the City only needs to send crews out for repairs or other problems. United Water has a SCADA type system for data capture which was specifically constructed for their small system. Portsmouth and Warwick also have SCADA systems in place. Warwick's system is almost four (4) years old and it records data, such as flows and pressures, every five (5) minutes. This information is processed to an Access database for compiling trend information. System users may also view their entire system at all times on a computer screen. Warwick is also considering updating their sewer information so it will also eventually be included in the SCADA system. Woonsocket currently has two (2) SCADA systems to record data from their watershed areas, and the City is planning to add another SCADA system when they expand to their water treatment plant in the Spring of 2001. In addition, North Kingstown is in the process of designing a SCADA system and South Kingstown is implementing a SCADA system, which will be on line in 2001. Suppliers that wish to expand with their treatment plants, (e.g., Newport, Bristol Water Authority, and Pawtucket) have a SCADA system included as part of their expansion proposal.

5.5 Modeling Capabilities

SCADA is a great system for data automation and collection, but it cannot currently extend beyond these applications to complex modeling and mapping. For modeling, about two-thirds (2/3) of the suppliers surveyed to date use a version of KY Pipe or CyberNet, a hydraulic model (see Table 5.3). Some suppliers have the model in-house and others retain the model with their consultant. This model is used to determine project needs, such as pipe sizes, pumps, and tank sizes based on fire protection. The model can also assess the quality of the system, such as the age of pipes to determine weak points in the system based on pressures. The suppliers that do not have the program instruct their consultant to run it only when new infrastructure is added. This approach is mainly due to the cost of running the model and the expertise needed to interpret the results. Output from older versions of the model consisted of a series of numbers, such as pressures and pipe sizes, that needed to be interpreted by someone familiar with the program. However, the newer versions of this WaterCAD model are able to perform much more detailed analyses and interface with AutoCAD and mapping software to provide more user-friendly output structures.

Table 5.3 Modeling Capabilities

Water Supplier	Hydraulic Modeling Capabilities
Bristol County Water Authority	WaterCAD
Cumberland Water Department	KY Pipe (developed in water department)
East Providence Water Department	KY Pipe
East Smithfield Water District	Cybernet
Greenville Water District	Cybernet
Harrisville Fire District	NONE
Jamestown Water Division	KY Pipe
Kent County Water Authority	NONE
Kingston Water District	KY Pipe
Lincoln Water Commission	NONE
Narragansett Water Department	Cybernet
Newport Water Works	Cybernet
North Kingstown Water Department	Cybernet
North Smithfield Water Department	NONE
North Tiverton Fire District	NONE
Pascoag Fire District	NONE
Pawtucket Water Supply Board	LIQSS (Pare Engineering)
Portsmouth Water District	KY Pipe
Providence Water Supply Board	Cybernet
Rhode Island Economic Development Corporation	Cybernet
Richmond Water Supply System	NONE
Smithfield Water Supply Board	Cybernet and RSMS Pavement Management (Crossman Engineering)

Water Supplier	Hydraulic Modeling Capabilities
South Kingstown Water Department	Cybernet
Stone Bridge Fire District	NONE
United Water of Rhode Island	Piccolo-measures pressure and flows
Warwick Water Department	Cybernet
Westerly Water Department	Cybernet
Woonsocket Public Works	KY Pipe
University of Rhode Island Facilities and Operation	some modeling

Bristol County Water Authority (BCWA) uses the WaterCAD model in their department. BCWA also utilizes the AutoCAD interface, which is an important improvement in the software. It originally created its pipe network in AutoCAD and can work with WaterCAD in the same manner as with standard AutoCAD elements. Therefore, from a CAD drawing, any hydraulic analyses can be performed with the ability to view the output in tabular form. The scenario management part of this new version of the software allows modelers to observe how the system reacts to different conditions without having to aggregate all of the numbers. Cumberland has an older version of WaterCAD, KY Pipe, within their department. The Town uses this program outside of testing the system only when it is modified. Personnel in the Water Department have worked with the program so presently they can point and click on their computer to view a scanned picture of a pump station, and they can also see scanned drawings of the pipelines. It is noteworthy that none of the water suppliers are utilizing the data sharing capabilities of WaterCAD. Older versions of WaterCAD do not support such a linkage. The newer version of WaterCAD does allow the model to link to a GIS, SCADA or other data management system. This is important for the water supplies since many are using some form of SCADA and are implementing sophisticated GISs. The linkage is as simple as pointing to the different parts of the system and obtaining a WaterCAD analysis. More importantly, the system can import data sets from the earlier versions of WaterCAD and Cybernet. Almost fifty (50) percent of the suppliers will have a working GIS by the end of the year. With all of the data for their system in a GIS, these suppliers will save considerable time and money by importing this database into the model. Currently, fifty (50) percent of those surveyed actually have the model in-house. By linking the model and their GIS, they would be able to use the model at their own expense without having to pay additional consultant fees everytime they evaluate their system. Greenville water suppliers purchased the software for their department and can now perform queries without contracting with consultants every time that it is necessary to determine the capacity of a pipe. However, most of the suppliers are unable to use this approach due to constraints in the budget. Since most suppliers do not use their model in its entirety, it is difficult to justify the periodic cost of updating. This may be a good reason for a state agency, such as the RIWRB, to intervene and purchase the program and offer user discounts to the suppliers. In return, the RIWRB would receive demand and trend information from the suppliers in a standardized, digital format, rather than hard copy documents.

5.6 GIS Capabilities

For more complex, spatial analyses of water supply systems, implementing a GIS is a necessary step. About thirty-five (35) percent of the suppliers are currently using a GIS and all of these suppliers are utilizing some version of software by ESRI ArcView GIS as indicated in Table 5.4.

Table 5.4 GIS Capabilities

Water Suppliers	Currently Using	Under Develop-ment	Hope to Implement in 2-5 Years	No Plans
Bristol County Water Authority			X	
Cumberland Water Department	X			
East Providence Water Department	X			
East Smithfield Water District			X	
Greenville Water District		X		
Harrisville Fire District			X	
Jamestown Water Division			X	
Johnston Water Control Facility		X		
Kent County Water Authority		X		
Kingston Water District			X	
Lincoln Water Commission				X
Narragansett Water Department	X			
Newport Water Works	X			
North Kingstown Water Department		X		
North Smithfield Water Department			X	
North Tiverton Fire District			X	
Pascoag Fire District			X	
Pawtucket Water Supply Board	X			
Portsmouth Water District			X	
Providence Water Supply Board	X			
Rhode Island Economic Development Corporation	X			
Richmond Water Supply System				X
Smithfield Water Supply Board		X		
South Kingstown Water Department		X		
Stone Bridge Fire District			X	
United Water of Rhode Island			X	
Warwick Water Department			X	
Westerly Water Department		X		
Woonsocket Public Works		X		
University of Rhode Island Facilities and Operation			X	

Some of the suppliers have advanced mapping capabilities, while other suppliers have maps only in hard copy format. East Providence is one City that is currently enhancing their GIS capabilities. It already has its water distribution network and storm sewer network digitized in ArcView, to which hydrants and valves are being added with the use of a Global Positioning System (GPS). East Providence uses GIS as a management tool. The City is able to view its service areas and perform queries such as highlighting all pipes installed before 1975 or all pipes over fifty (50) years old. With ArcView, the City can answer this question in a matter of seconds as opposed to reviewing numerous maps manually and overlaying them to determine where problems lie. This allows for quicker and more accurate management decisions for efficient funding allocation.

Other suppliers even started using their own mapping system, such as the Rhode Island Economic Development Corporation (RIEDC), which indicated that the RIGIS system's data was too broad-scaled for their needs. RIEDC needed a larger scale for their smaller service area, and currently use a scale of 1"=40' for their mapping needs. RIEDC employs technicians that are currently converting paper maps into a GIS format, which will eventually include the water system, roads, and parcel data. To achieve an even more accurate depiction of the area, scanning of new orthophoto information received from the town is underway. South Kingstown is developing its GIS. The Town also found the scale of RIGIS data too broad for their more immediate needs. Presently, South Kingstown uses Arc/Info to digitize all of its waterlines with the tax maps as the base map in ArcView. Most of the towns that currently have GIS use ArcView, but South Kingston is the only supplier that also utilizes Arc/Info for their digitizing needs. Most of the Town's drawings are in AutoCAD that can be directly input into ArcView as well. South Kingstown has determined the most recent orthophoto images provided by the state is in too small of a scale (1”=5000”) for their needs (i.e., it covers too large of an area). Similar to the RIEDC, South Kingstown also would like to implement a GIS at the 1”=40’ scale. The town of North Kingstown has Arc/Info at their disposal along with ArcView, however, its digitizing efforts ended when the person working on GIS left the department. Similarly, Woonsocket has ArcView and began digitizing maps at 1”=80’ scale, but this work was not completed since their engineer left. Lack of qualified staff seems to be a recurring pattern among some municipalities that has restricted moving forward with GIS. Some towns do have trained staff, such as Narragansett, which is utilizing GIS with AutoCAD Map. Narragansett maintains their parcel data in a GIS format current to 1998, with included fields such as sewer, water and property locations. Therefore, the Town is able to perform more specific analyses with this dataset, such as water feasibility studies. Narragansett also has a scanner that can scan blueprints and create a drawing format. They plan to use the scanner to input old water distribution blueprints. The entire town has also been digitized in AutoCAD and the AutoCAD Map extension is used to import information from AutoCAD to ArcView. This will allow the Town to maintain the AutoCAD commands at their expense while working with the digitized data from ArcView. The software also allows Arc/Info coverages and shape files to be imported into AutoCAD. Pawtucket uses a program called ArcCAD in its engineering department, which is a complex drafting program that allows for full GIS functionality within the AutoCAD environment. It provides a powerful mapping and data management program that can access data from an attribute table, which is not possible with AutoCAD alone. Off the shelf AutoCAD is simply a drafting program without links to data or attributes for more complex analyses. Pawtucket is currently transferring water information into the ArcCAD program. This is significant in terms of saving the steps of entering the system into a CAD format, importing into ArcView and then adding the necessary attributes.

About thirty (30) percent of the suppliers have their distribution system in an AutoCAD format that can be imported into a GIS once implemented (Table 5.5).

Table 5.5 AutoCAD Capabilities

Water Supplier	AutoCAD Capabilities
Bristol County Water Authority	AutoCAD Map
Cumberland Water Department	AutoCAD LT
East Providence Water Department	AutoCAD R14
East Smithfield Water District	NONE
Greenville Water District	NONE
Harrisville Fire District	NONE
Jamestown Water Division	NONE
Kent County Water Authority	NONE
Kingston Water District	NONE
Lincoln Water Commission	NONE
Narragansett Water Department	AutoCAD Map, R14
Newport Water Works	YES
North Kingstown Water Department	YES
North Smithfield Water Department	NONE
North Tiverton Fire District	NONE
Pascoag Fire District	NONE
Pawtucket Water Supply Board	ArcCAD
Portsmouth Water District	NONE
Providence Water Supply Board	YES
Rhode Island Economic Development Corporation	some AutoCAD
Richmond Water Supply System	NONE
Smithfield Water Supply Board	AutoCAD 2000
South Kingstown Water Department	some CAD

Water Supplier	AutoCAD Capabilities
Stone Bridge Fire District	NONE
United Water of Rhode Island	CAD/AM FM
Warwick Water Department	AutoCAD 2000
Westerly Water Department	some AutoCAD
Woonsocket Public Works	NONE
University of Rhode Island Facilities and Operation	some AutoCAD

Some suppliers are in the process of performing a GIS needs assessment and are looking to implement a GIS in the next few years. Others (e.g., Kingston, Richmond and Lincoln, Pascoag, Stonebridge and Harrisville) do not have AutoCAD or a GIS due to the associated expenses, lack of trained personnel and other priorities. Many suppliers do support the idea of a GIS, but with money needed for infrastructure improvements, implementing a GIS is not a priority.

6 CONCLUSIONS

Models are simplifications of reality. They have certain limitations and it is difficult to determine how these limitations affect the prediction capabilities of the model. Many models treat systems as lumped systems where parameters are averaged over the study area. In reality, the different variables may be spatially heterogeneous throughout this area. The simpler, lumped models cannot account for these heterogenities, nor are they advanced enough to take advantage of more advanced technology, such as GIS datasets. GIS technology strengthens modeling since it is able to assimilate many datasets such as topography, land use and other spatial data. More complex models can utilize this technology, which accelerates the time it takes to set up the model. Conversely, these “complex,” distributed parameter models require extensive input parameters and this contributes to reduced accuracy and increases the model set up time. Such models are generally inefficient for studies that require more rapid assessments. Therefore, it seems that neither type of model is inherently superior to the other, since both have certain limitations that can decrease their prediction accuracy.

Both types of models also use calibration and verification to indicate the accuracy of the model. However, there are misconceptions about the idea of validating a model. Since models produce non-unique results, it is difficult to definitively claim that a model is valid. The non-uniqueness of the results indicates that the model may be calibrated, but it may not be able to accurately predict future responses. Society can place too much faith in models that have been deemed verified or validated. It is easy to be mislead by the appearance of truth when a model claims to be valid and claims that it is able to make accurate predictions of the systems response in the future. No matter how much effort is undertaken, uncertainty can never be eliminated. Models are a good tool for critical analyses, and they can test ideas for reasonableness, indicate which parameters are sensitive and provide insight that may not have been previously considered, but their predictive accuracy is limited. Furthermore, the terms "validation" and "verification" are misleading with regards to modeling.

Use of a GIS can facilitate modeling for water resources applications by increasing model set-up time and the accuracy of the model. GISs are becoming more prevalent in state and local agencies for model support. Instead of trying to predict future responses absolutely, the use of GIS datasets can provide a more comprehensive look at an area. This is where the usefulness of screening level assessments, such as the ALOHA or MANAGE model approaches is applicable. It allows the modeler to use existing GIS datasets to obtain a general overview of the study area with "hotspots," such as areas contributing to non-point pollution, highlighted. Then, with this information, a modeler can then focus on the highlighted area for a more intensive analysis to arrive at an exact solution. This is a more integrated approach, which allows for more judgement to be introduced to the modeling process. Such an approach is especially important for analyses such as build-out analyses for towns and regions to make quick and informed determinations of how changes will affect the surrounding watershed areas.

Yet, these tools cannot currently be used to their full capacity because although many agencies collect water-related information, it is stored in different formats that are not easily shared. Once the data is put into a GIS database, it may be much more effectively utilized. Towns can design the GISs to include their parcel data and then add overlays such as water and sewer lines, which facilitates the ability to perform queries of their datasets such as sewer feasibility studies or generation of automated abutter lists. The models and GIS complement each other. Traditional model setup is very time consuming, but with data in a GIS format, the data can be inputted automatically into a model to simulate processes such as storm water routing. Towns and governmental agencies generally do not have sufficient time or funds to perform extensive, long-term studies and must be able to model and achieve rapid results. With advances in satellite technology and remote sensing, data in a GIS format (e.g., land use) is now accurate to within a few feet and can be used for efficient determinations, which are necessary for effective land-use decision making. The decision-maker can model different development scenarios and observe, in real-time, the impacts as the scenarios are changed. This is a much more practical approach for planners and decision-makers, who do not have wait until field studies, modeling, calibration and validation are complete to make a decision related to land use.

This integrated approach to modeling, with the concentrated involvement of the decision-maker is a better approach than traditional modeling strategies where a modeler typically searches for a numerical solution. Instead of merely inputting parameter data, the modeler is more involved in the modeling process to ensure that it accurately describes the system. The DSSs and SDSSs are links to the integrated model and GIS linkage. The decision-makers work from the beginning of the modeling process to structure the model to the problem at hand; it is not simply a case where a model attempts to "fit" the problem. This was clearly demonstrated by the AR/GIS system that allowed the different land-use decision makers view GIS data in real time and model different scenarios with combined input to determine the best lands to purchase for open space. This is the type of system necessary for use by state agencies and water suppliers to enable practical decisions to be made on a daily basis.

Models are useful in gaining a better understanding of the system, but it is also important to recognize the limitations of modeling. One concern with integrated models is the accuracy of existing GIS datasets, such as the RIGIS dataset of Rhode Island. Although RIGIS data is applicable to more broad study areas, problems arise when trying to perform analyses for towns or areas smaller than statewide or regional scales. The resolution of these datasets is still too large to be useful to the towns. Some of the water suppliers that had GIS capabilities created their own mapping system, such as the RIEDC and South Kingstown, which found the RIGIS system's data was too broad-scaled for their needs. Towns and suppliers typically require analyses at scales on the order of 1"=40'or 1"=80'. Generally, towns that were working with GIS data had skilled personnel, who were transferring hard copy information and orthophotos from the towns into GIS formats for their specific needs. The State's most recent orthophotos (at a scale of 1"=5000") are also too broad-scaled to be of use to the towns, which need GIS information to locate pipelines, right-of ways (ROWs) and survey boundaries. For the majority of the suppliers without adequate personnel for GIS work, new staff would need to be hired that can both work with GIS software and also transfer data into a GIS format at larger scales than is currently available to the suppliers.

The water suppliers have compiled extensive amounts of data, however the use of many different formats hinder data sharing capabilities. Since most of the suppliers have not converted their data into GIS or CAD formats, use of the hard copy maps and data seriously limit the usefulness of the assembled information. The suppliers want to advance technologically, however, they face opposition when emerging technologies such as GIS compete against capital improvements such as repair of an old pipeline. The key factor is the understanding that, with the system in a GIS format, the suppliers can query their system to highlight, for example, pipes installed before 1975 to determine where the most necessary repairs or improvements are needed. This query takes only a few minutes, as compared to examining various maps to make a single necessary determination. The manual collection of data such as water tank levels also hinders the ability to view trend data. The SCADA systems in use by some suppliers solve this problem by collecting data automatically and storing it in a database format for different trend analyses.

In terms of modeling, none of the suppliers currently utilize hydrologic modeling; modeling was limited to hydraulic modeling on their distribution systems. One model utilized by most of the suppliers was a version of WaterCAD by Haestead Methods. However, most of the water suppliers retained the model via their consultant, who executed the model when necessary. The benefit of the WaterCAD program is that it has linkages to AutoCAD, GIS and even SCADA systems. Some of the suppliers had their entire system drawn in AutoCAD, and by using WaterCAD, they could run the model directly from the AutoCAD drawing. Going one more step, with the system's attributes in GIS, one can run the model, work with the drawing in AutoCAD, and also perform queries from the database created in GIS. This combination of elements produces a powerful system that can be used for decision making in towns, local and state agencies.

7 RECOMMENDATIONS

Complex modeling efforts are not yet common among towns, water suppliers and state and local agencies. Currently, the towns and state agencies have neither the data in a useable format nor the personnel to manipulate it into the correct format. The RIWRB was attempting to ascertain the needs of the suppliers and how it can help meet these needs. It was originally recommended that the RIWRB acquire a group license for the ArcView software, to best benefit the suppliers. However, GIS was not being used to its full capacity due to the lack of resolution of the available data, lack of trained personnel and budget constraints in the towns. The movement for GIS implementation can almost overshadow needs for more practical, everyday requirements from a "model system." Therefore, the RIWRB can best facilitate the suppliers by addressing their more practical needs. A more appropriate response may be to purchase the SCADA software for the suppliers. The suppliers can then begin incorporating their distribution systems into the SCADA for everyday system checks, work orders, trend analyses and treatment control. This action would create some common ground technologically for the suppliers to do some data sharing and other manipulations.

The next logical step is to incorporate the system into AutoCAD and use the functionality of WaterCAD to run the model from this level. It is important that the suppliers collaborate on sharing their experiences relative to the encountered difficulties and benefits of the programs. It is also recommended that the suppliers start on a relatively level field (e.g., using the same or similar model system) before trying to implement GISs. However, once the Water CAD model is implemented, they can incrementally add the GIS functionality to the AutoCAD drawing at a realistic pace rather than quickly transitioning to full GIS implementation in the next year or so. In addition, once the suppliers and towns have their information in a GIS format, they will be better able to take advantage of other tools such as the MANAGE model.

While the suppliers are automating their data collection, the state agencies can work on updating state GIS datasets to render them more refined and useful to the towns. It is important that this be a state effort, because it is impractical for the towns to create mapping for their owns needs that are neither in standard formats nor available to the public, which prevents data sharing efforts. Datasets will then be one continuous layer that will not be confined to town or supplier boundaries. If this effort were left to the towns, they may create their own mapping system. Transitioning from one town to another would result in individual digitized layers and scales that would not coincide. In addition, since most of the towns do not have internet access or the personnel to continuously provide information to the public, much of the mapping work already done by the suppliers/town is unavailable to the general public. For, example, the RIEDC started their own mapping system for their system at Quonset Point in Rhode Island. The scale is

1”=40’, which creates a very detailed view of the entire system; however, it is not available to the public. Data such as this may be beneficial to state agencies or developers looking to survey these areas. In addition, many state agencies have GIS information such as refined LUST sites and hazardous waste sites mapped on their system, available only to people in the agency through their intranet system. Again, some of this information could be shared, and could also be critical for town land use decision making. It is incumbent upon the state departments, such as the Rhode Island Department of Transportation (RIDOT), Rhode Island Department of Environmental Management (RIDEM), URI, the RIWRB and any other agency that stands to benefit from statewide GIS datasets to work together to produce more refined GIS datasets and make them available to everyone.

In terms of hydrologic modeling within the towns, the suppliers are quite removed from implementing or using any hydrologic modeling. However, the state agencies could also simultaneously work on developing a hydrologic model using the GIS data for the entire state, even down to the subwatershed level. This level of accuracy would be of significant use to the towns, which presently are without the capabilities for this type of effort. The state would also benefit, however, by providing data to the public and increasing data sharing and digital submission of data from the towns to the necessary agencies. Also, with maps formatted at the same scale, overlays can be directly accomplished without any manipulation. The state may then use these maps to evaluate watersheds at a large scale while separately incorporating the details from the town digitized systems. This would be a powerful mechanism that could be used to make more effective decisions for water resources planning and better management. To begin this collaborative effort, further research could include an inventory of various aforementioned state agencies and their current technologies. Also, development of the hydrologic model by the agencies could be the subject of a future study that focuses on a model like MANAGE or other more applicable model. Furthermore, in order to assist the RIWRB in determining what software should be purchased for the towns, it would be necessary to investigate the different SCADA software systems used by the suppliers and evaluate the benefits or problems associated with each. Since use of AutoCAD and GIS in the towns is anticipated in the future, a more focused study of the different drafting and mapping programs available would also benefit the towns as these technologies are added to their systems.

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LIST OF ACRONYMS

GIS	Geographic Information System
SDSS	Spatial Decision Support System
MANAGE	Method for Assessment, Nutrient Loading and Geographic Evaluation for Watersheds
SCADA	Supervisory Control and Data Aquisition System
DSS	Decision Support System
RIGIS	Rhode Island Geographic Information System
URICE	University of Rhode Island Cooperative Extension
SHE	Systeme Hydrologique Europeen
SWMM	Stormwater Management Model
STORM	Storage, Treatment, Overflow, Runoff Model
HEC-1	Hydrologic Engineering Center
TR-20	Technical Release #20
HSPS	Hydrologic Simulation Program in Fortran
PSRM	Pennsylvania State Runoff Model
DEM	Digital Elevation Model
DTM	Digital Terrain Model
TIN	Triangulated Irregular Network
BMP	Best Management Practice
IMS	Internet Mapping System
EPA	Environmental Protection Agency
EMAP	Environmental Monitoring Program
MAIA	Mid Atlantic Integrated Assessment
ALOHA	Areal Locations of Hazardous Atmospheres
NOAA	National Oceanic Atmospheric Administration
ISDS	Individual Sewage Disposal System
LUST	Leaking Underground Storage Tank
WSSMP	Water Supply System Management Plan
RIWRB	Rhode Island Water Resources Board
LAN	Local Area Network
CCR	Consumer Confidence Report
RIDOT	Rhode Island Department of Transportation
RIDEM	Rhode Island Department of Environmental Management