Evaluation of Integrated Suface Water and Groundwater Modeling Tools

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1.0 Introduction

A common goal for most environmental engineering consulting firms is the continual development and expansion of the services offered to their current and potential clients. The water resources field is no exception since there are many expanding market areas that exist today. These areas include:

- River Harvesting
- Aquifer Storage and Recovery (ASR)
- Groundwater/Surface Water Management Plans
- Regional Basin Studies
- Design Build Opportunities
- Water Resources Planning
- Emerging Technologies

Four of these seven increasing market areas revolve around the natural processes of surface water/groundwater interaction. Success in these market areas requires the development of a localized marketing effort involving all of the water resources components.

1.1 Background

Coordination of water resources professionals is a critical path in developing an action plan for the expanding market areas. The following information is needed to develop the action plan:

- An outline of a potential market for existing services,
- A description of local water resources strengths,
- A list of the skills sets needed locally,
- A list of existing and proposed markets for water resources,
- A description of client needs that must be developed,
- A description of projects that the competition is getting, and
- A list of emerging technologies.

Due to increasing demand in the marketplace for integrated resource planning and management, integrated surface water/groundwater modeling is a high priority issue. The current paucity of existing tools, the absence of a well-defined market

leader, or the lack of strong competition can identify it as an area of strong potential growth.

For this research, integrated surface water/groundwater modeling refers to the simulation of the hydrologic interactions between surface water features and the underlying groundwater system. Integrated modeling can encompass both the quantity (baseflow or recharge) and quality of the interflow to and from water bodies. The integrated modeling considered for this project focuses only on the long-term, large watershed-scale or stream (river) interactions with the groundwater system, but also runoff characteristics, surface water conveyance, and groundwater flow. For purposes of this research, the modeling approach is focused on the numerical solution techniques most common in today's market (finite-element and finite-difference). Other modeling techniques (e.g. lumped parameter models) may be applicable to certain projects, but are not discussed herein.

1.2 Approach

This integrated surface water/groundwater modeling tools research project has been envisioned to occur in two phases. Phase I will focus on the description of integrated surface water/groundwater simulation modeling needs and the identification of existing tools available for this type of modeling application. An evaluation will be made of existing models that have been applied successfully. The results of the first phase will lead to Phase II, which will outline areas for further investigation, including the identification of development needs and the formulation of conceptual model-development plans.

1.3 Needs Assessment

Many projects are affected by the interaction of surface water and groundwater systems where changes in one system have a significant influence on the other. An example of such problems include those in which head changes in a groundwater system cause changes in the rate of seepage to or from lakes or overland flow in wetlands, leading to changes in the stage or spatial extent of the wetlands or the stage of a lake. However, changes in wetlands or lake stages also changes the rate of seepage to or from the groundwater system. In this example, the surface water and groundwater systems each change in response to changes in the other. If one or the other system is modeled independently, a technique must be found to represent changes in the other system in the model, but such techniques usually have serious limitations. A more accurate and sophisticated approach is to model the systems as a single integrated system where process changes in both the surface water and groundwater systems and their mutual interaction as such changes occur. This illustrates one example of the need for a model that represents surface water and groundwater systems together in an integrated framework. In some cases, the difference for addressing a client's problem is that a significantly more accurate and reliable answer can be provided.

Another example of a project that might require integrated modeling is situations where changes in river or canal discharges and stages affect the groundwater system near public supply wells or environmentally sensitive areas. However, the magnitude of the river/canal changes also depend upon the changes occurring in the groundwater system as the result of the surface water changes, such that an analysis that considers the interaction between the river/canal system and the aquifer will best serve the needs of the client. These considerations are also applicable when models are used to simulate the groundwater contribution to baseflow during drought conditions or infiltration to groundwater during a storm event. Surface water and groundwater models are limited in their ability to simulate these scenarios relative to an appropriate integrated surface water and groundwater model.

Though integrated models are highly desirable for quantitative analyses, many problems have faced scientists in their efforts to develop these tools. A model that integrates simulations of surface water and groundwater processes must account for the different scales of spatial and temporal variability of the two systems. Typical groundwater models that implement finite-element or finite-difference solution techniques discretize the model area into relatively small nodal elements or grid cells because the independent variables (head, solute concentration) computed by the model and aquifer characteristics can vary over relatively short distances. Although it is difficult to generalize over the entire class of surface water models, some treat the model area as a set of large subbasins or river segments equivalent to or transecting several nodal elements or grid cells in groundwater models. Computed variables (stage, flow rate, runoff, etc.) and specified parameters (topography, bottom elevation, roughness, etc.) often have a different spatial scale of variation than those of the groundwater system. The need for detailed spatial variability is characteristic of groundwater models and an integrated model might need to utilize groundwater nodal elements or grid cells to adequately simulate water movement between the surface and subsurface.

On a temporal scale, surface water models often use small time increments (minutes to hours) to depict changes in the system such as large storm events or releases of water in rivers or canals. Groundwater models, because of the naturally slower groundwater flow (laminar flow), require longer time periods (weeks to months or years) to simulate groundwater movement and solute transport.

Surface water models vary in their range of surface water representational capabilities as they may be designed for rivers, canals, wetlands, lakes, watersheds, storm sewers, or estuaries. Typically, surface water model components:

- may provide for the explicit simulation of wetlands, lakes, rivers, or canals,
- may be watershed models that relate rainfall and evapotranspiration to surface water runoff, groundwater infiltration, and soil storage or
- may be urban runoff models that relate rainfall to flows in sewer networks.

Mathematically, surface water models may vary in whether surface water is represented in one, two, or three dimensions and whether the surface water is considered to have a uniform or spatially varying stage or whether stage is considered to be constant or time-varying.

Groundwater models vary in their groundwater representational capabilities, which may be designed to simulate only flow, uniform-density flow coupled with solute transport, or variable-density flow and solute transport. Mathematically, the solutions may be for head, pressure, or solute concentration, and the aquifer may be considered confined or unconfined. The solution may be in two (horizontal flow only) or three dimensions (horizontal and vertical flow) in a Cartesian coordinate system or in a two-dimensional cylindrical coordinate system. Integrated surface water/groundwater models might have the same degree of variability or comprehensiveness in both surface water and groundwater components.

The use of an integrated surface water/groundwater model might not be appropriate in all projects, and the appropriate model to use would require evaluation on a project-by-project basis. The use of an integrated model would likely require a large amount of data to model both the surface water and groundwater components of the hydrologic cycle. Additional data might be required to model the interaction between the surface water and groundwater components. Therefore, an integrated model would require more time for development, calibration, and simulation execution relative to a surface water or groundwater model. These requirements would likely increase the cost of a project in relation to one only using a surface water or groundwater model. The cost increase might be considered justified if the client's needs are effectively met.

2.0 Investigation

Although numerous surface water and groundwater models have been well developed and extensively used through years of research and field applications, few models have been developed with the objective of fully integrating both the surface water and groundwater components of the hydrologic cycle. Some surface water models have rudimentary groundwater components, but owing to the limitations of these components, it is primarily used for surface water projects. Similarly, some groundwater models have surface water components but are primarily used for groundwater projects. A few surface water and groundwater models have been linked subsequent to their initial development and a period of sole use for either surface water or groundwater studies.

In evaluation of the use of a fully integrated surface water and groundwater model, four possible alternatives exist.

- Use of a developed, fully-integrated surface water and groundwater hydrologic model,
- Use or development of an intermediate modeling package linking established groundwater and surface water models,
- Expanding or developing the surface water capabilities of developed groundwater modeling software, and
- Expanding or developing the groundwater capabilities of developed surface water modeling software.

2.1 Preliminary Model Evaluation

The identification of available tools for hydrological modeling was accomplished by completing an extensive literature review followed by a study of the capabilities of the surface water and groundwater components of the models. Seventy-five models found during the literature review and considered in the preliminary evaluation are listed in **Table 2-1**. Only those models on this list that met the criterion of including simulators of both surface water and groundwater processes were further evaluated. The nine models selected for further evaluation included MIKE SHE, HMS, FHM-FIPR, SWATMOD, MODFLOW, DYNFLOW, MODBRANCH, SWMM, AND HSPF.

Only in the cases of MIKE SHE and HMS were the linkage of groundwater and surface water components created as part of a unified model development process. This fact illustrates the relative difficulty in designing integrated surface water/groundwater models. Both models are relatively recent products. FHM-FIPR, SWATMOD, and MODBRANCH were created by linking previously developed surface water and groundwater models. MODFLOW and DYNFLOW are groundwater models that have been enhanced with the addition of interactive surface water packages. SWMM and HSPF are surface water models that have been enhanced with groundwater representational capabilities.

Table 2-1 Water Resource Models Evaluated for this Project								
Primary Function								
Madala	Curríana	Octions	Groun					
woders	Surface Water	Transport	Saturated Zone	Unsaturated or Vadose Zone	<i>water</i> Quality			
3DFEMFAT			Х	Х	Х			
3DFATMIC			Х	Х	Х			
AQUA3D			Х		Х			
AquaDYN	Х							
AQUASEA	Х	Х						
AQUIFEM-N			Х		Х			
AT123D					Х			
CFEST			Х		Х			
CHAMP			Х	Х	Х			
CHEMFLO			X		Х			
CTRAN/W			Х		Х			
DYNFLOW			Х					
DYNTRACK					Х			
FEFLOW			Х		Х			
FEMWASTE					Х			
FEMWATER			Х					
FESWMS	Х							
FHM-FIPR	Х		Х					
FLONET			Х		Х			
FLONET/TRANS			Х		Х			
FLOPATH			Х		Х			
HEC-HMS	Х							
HIVEL2D	Х							
HMS	Х		Х	X				
HSPF	Х							
HST3D			Х		Х			
HYDROGEOCHEM(2)			Х	X	Х			
ICPR	Х							
MicroFEM			Х		Х			
MikeSHE	Х	Х	Х		Х			
MLAEM/2			Х					
MOC			Х		Х			
MOCDENSE			X		X			
MODBRANCH	X		Х					
MODFLOW			X					
MODSIM	X		-					
MOTIF			X		Х			
MT3D			-		X			
PTC			X		X			
QHM	x							
QUAL2EU	X	x						

Table 2-1 (con't)Water Resource Models Evaluated for this Project								
Primary Function								
Models			Groun					
	Surface Water	Sediment Transport	Saturated Zone	Unsaturated or Vadose Zone	Water Quality			
RANDOM WALK			X		Х			
RBFVM-2D	X							
RMA2	X							
SED2D-WES		Х						
SESOIL				X	Х			
SHEET2D	Х							
SLAEM			Х					
SOLUTRANS			X		Х			
SUTRA-3D			Х		Х			
SWAT	Х	Х						
SWATMOD	X	X	X					
SWIFT			Х		Х			
SWMM	Х	Х						
SWRRB	X							
TARGET			Х		Х			
THALES	Х							
TOPMODEL	X							
TWODAN			Х		Х			
VS2DT			Х	Х	Х			
WinFLOW			X					
WinTRAN				Х				
WSPRO	X							
Specialized								
BioF&T (2D or 3D)			Х		Х			
BIOPLUME					Х			
ENRMOD	X				Х			
MOFAT			Х		Х			
BioSVE					Х			
MARS			Х		Х			
MOVER			Х		Х			
WHPA			Х					
PESTAN			Х	X	Х			
SOILVENT					Х			
BIOSLURP			Х		Х			
KYSPILL			Х	X	Х			

The surface water components of the nine models were found to be:

- MIKE SHE and HMS have overland flow and channel simulators,
- MIKE SHE can model sediment transport,
- MODFLOW and DYNFLOW have modular packages that explicitly represent various types of surface water bodies,
- MODBRANCH is a stream network routing model,
- FHM-FIPR, SWATMOD, and HSPF are watershed models, and
- SWMM is an urban runoff model.

The groundwater components of the nine models were found to be:

- MIKE SHE and HMS have components for saturated-zone and unsaturatedzone flow,
- MIKE SHE also models solute transport, processes, and mass transfer of solutes,
- FHM-FIPR, SWATMOD, DYNFLOW, and MODBRANCH use MODFLOW or a close equivalent,
- MODFLOW has optional packages for solute transport (MOC3D, MT3D) and particle tracking (MODPATH) and DYNFLOW has a package for groundwater transport (DYNTRACK and DYNCON), and
- SWMM and HSPF have limited groundwater simulation capabilities.

A more detailed description of each of the nine models follows a discussion of the evaluation criteria that will be used.

2.2 Evaluation Criteria

In order to compare these surface water/groundwater technologies, an evaluation program was developed. The evaluation process began with the development of a decision matrix outlining the evaluation criteria. Use of this decision matrix facilitated a relatively objective analysis of the models being evaluated. **Table 2-2** describes the evaluation criteria utilized in the comparison. The ability of the technology to meet the primary objective of effectively integrating groundwater and surface water simulations was recognized as a first-magnitude priority. However, because of the variation in the types of surface water and groundwater components of these models, assigning rankings would necessarily depend on the specific uses intended for the model package. Therefore, no attempt was made to assign rankings based solely on the model's range of surface water and groundwater capabilities. However, it was possible to establish rankings based on the factors listed in Table 2-2.

Table 2-2 Evaluation Criteria Definitions and Priority									
	Evaluation Criteria	Driority	Definition of Rankings						
#	Description		0	1	2	3			
1	Regulatory Acceptance	1	New product, not known to most regulators	Known to some regulatory users	Known to most regulatory users	Industry Standard			
2	Cost	1	High	Moderate	Low	Public Domain			
3	Ease of Use (Interface)	1	No interface available	No interface available Basic Built-in or public domain GUI* available Proprietary GUI a		Extensive Built-in GUI available			
4	Intermodel Connectivity	1	Not Feasible	Possible but difficult	Can be easily coupled with other models	Fully integrated, therefore not applicable			
5	GIS Integration	1	None	Some GIS ArcView extension available to aid in preprocessing	Some GIS ArcView extensions available to aid in pre- and postprocessing	Comprehensive GIS tools available for pre- and postprocessing			
6	Service & Support	1	Not available	Available but difficult to obtain	Readily available at moderate cost	Readily available at low cost			
7	Model Limitations	1	Specialized Model	Limiting Moderately limiting		Minimally limiting			
8	Limit on Model Size	1	Very High	Moderate	Minimal	None			
9	Expandability	2	Very difficult to add new program components	Not Applicable	Not Applicable	Relatively easy to add new program components			
10	Platform-Flexibility of Operating System	2	Only usable on Linux or Unix systems	DOS Only	WinNT, Win95, Win98	WinNT, Win95, Win98, Unix, Dos, Linux			
11	Experience Required	2	Extensive	Moderate to Extensive	Moderate to Minimal	Minimal			
12	Percent of Market Share	2	Still in Development/ Used in University	Minimal Number of Users	Moderate Number of Users	Extensive Number of Users			
13 Documentation and 2 2		Not Available	Little	Moderate	Extensive				

*GUI – Graphical User Interface

The thirteen criteria listed in Table 2-2 were recognized as having either secondary or tertiary importance and were assigned appropriate priority values. The models were assigned a value between zero to three (zero – does not meet criteria, three – fully met criteria) to represent the degree to which the model met each criterion. These values, together with the priority value, were used to determine an overall score for each modeling technology. The meaning of the values for each criterion used in the evaluation of the models is described in Table 2-2.

The following is an explanation of the significance of the criteria used for evaluating the nine models:

- 1. *Regulatory acceptance*. The ability to use a model in support of permitting issues is of great importance. As a result, this was listed as a relatively high priority. Models such as MODFLOW and SWMM that are industry standards were given high values of three in this category, while models with fewer regulatory users were given lower values of zero to two, depending on the model's acceptance by regulatory users.
- 2. *Cost.* Public domain models were given high values in this category, while proprietary software was ranked according to relative price.
- 3. *Ease of use*. The user-friendly aspect of a model was evaluated based on the availability of a graphical user interface (GUI). The highest rating (three) was given to models that incorporated a relatively comprehensive GUI in the model software. A ranking of two was given for models having available, well-developed, proprietary GUIs. Ratings of one and zero were given for basic or no available GUIs, respectively.
- 4. *Intermodel connectivity*. The ease with which a model can be coupled with other models, and, thus, provide a means for coupling the surface water and groundwater terms, was evaluated. Models already having a broad range of interactive surface water and groundwater terms have little need to be interconnected with other modeling software. Thus, these models were given the highest ranking. Models such as MODFLOW that have been linked with other modeling packages in order to integrate the surface water/groundwater terms, were also given higher rankings of two.
- 5. *GIS integration.* GIS is a continually developing technology for spatial data base manipulation that can be useful for setting up models or presenting model results. The ability of a modeling system to effectively integrate and/or utilize GIS for data input, management, manipulation, etc. was considered. Some modeling tools, such as MIKE SHE, are fully integrated with GIS, and thus earned a higher ranking.
- 6. *Service and support.* The availability of support services for the modeling system was considered. Some of the models evaluated are still under development, and as such, obtaining support might be difficult.

- 7. *Model limitations.* Numerous arbitrary restrictions in a model code can reduce the number of problems that it can be applied to. A lower rating (zero) would be assigned to models that are very specialized, such as contaminant remediation models. A higher rating is for models that have numerous possible applications. The highest rating is for models that have been developed as generic tools for a wide variety of applications.
- 8. *Limit on model size*. The limit on model size can be an important issue; thus, models were evaluated based on this possible restriction.
- 9. *Expandability.* This relates to the ease of adding new program components. In MODFLOW, this is relatively easy, while in MIKE SHE it is difficult due to the proprietary nature of the program.
- 10. *Platform-flexibility of Operating System.* Higher rankings were given to models that could operate on multiple platforms such as Microsoft Windows, UNIX, and Linux. Lower rankings were given to models only available on a single platform.
- 11. *Experience required.* The amount of experience required affects the amount of training time required for the model user to become efficient at using the model. The rating is based on numerous factors including model complexity, extent of model use, available support, and support software complexity.
- 12. *Percent of market share*. Prior users have solved many application problems and may have established that a model is a user-friendly and effective tool. The current percent of market share of a model relates to the model's usefulness and acceptance as an industry standard. Thus, modeling systems were evaluated according to the number of users.
- 13. *Documentation and training*. The availability of model documentation and training aids in understanding the model development, model limitations, and appropriate applications for the model. If not easily obtainable, the lack of good documentation can significantly increase the number of man-hours required for learning how to use a model.

2.3 Models Selected for Evaluation2.3.1 MIKE SHE

The Danish Hydraulic Institute's (DHI) model, MIKE SHE, one of the few hydrologic model that was initially developed to integrate surface water and groundwater modeling capabilities. With additional DHI programs (MIKE 11 and MOUSE) that are easily linked to MIKE SHE, the capabilities of MIKE SHE are further expanded.

MIKE SHE is used to simulate flow and transport of solutes and sediments in both surface water and groundwater. Areas of application include, but are not limited to, conjunctive water use, water resources management, irrigation management, wetland

protection, surface and groundwater interaction, and contaminant transport (DHI, 1999a). The MIKE SHE model is proprietary software developed and distributed by DHI. Product support and training for MIKE SHE is readily available since the program is continually being enhanced by DHI.

MIKE SHE is comprised of two basic modules: MIKE SHE PP and MIKE SHE WM. MIKE SHE PP is the pre- and post-processing module. MIKE SHE WM is the water movement module that is comprised of five modules: evapotranspiration (ET), unsaturated zone flow (UZ), saturated zone flow (SZ), overland and channel flow (OC), and irrigation (IR). Several additional add-on modules are available for particle tracking, contaminant transport, soil plant systems, and other specialized modeling applications (DHI, 1999b).

The MIKE SHE program can be fully integrated with GIS and several applications (MIKE SHE converters, GeoEditor, UZ editor, Irrigation GIS, and DAISY GIS) are available. The GIS integration was developed in collaboration with Environmental Systems Research Institute, Inc. (ESRI) ArcView. MIKE SHE converters are available for conversion of ArcView data to model input. The GeoEditor is used for geologic interpretation and creation of three-dimensional geological models. UZ editor and Irrigation GIS are used to setup the MIKE SHE UZ and IR modules, respectively. Finally DAISY GIS is used for defining and running MIKE SHE DAISY, a soil-plant simulation add-on module (DHI, 1999a).

2.3.2 HMS

The Hydrologic Model System (HMS) was developed based on the BSHM (Basin-Scale Hydrologic Model) (Yu, personal communication). The HMS model is comprised of four sub-models that can be run independently or concurrently. The sub-models are the Soil Hydrologic Model (SHM), Terrestrial Hydrologic Model (THM), Groundwater Hydrologic Model (GHM), and Channel Groundwater Interaction Model (CGI). SHM simulates vertical moisture flow while THM simulates overland and channel flow. The GHM simulates groundwater flow utilizing a finite difference grid. CGI simulates leakage between streams and the aquifer based on Darcy's Law.

The HMS model incorporates GIS and remotely sensed data sets for model development. In addition, the GHM sub-model has two solution methods. These methods are designed for solution either on scalar computers (standard PCs) or on vector and parallel processors. This combination allows for the model to run on vector-parallel processors for faster run times (Yu, 1997). This processor based solution scheme is described in Section 3.3.

HMS is currently in the development stage at the University of Nevada-Las Vegas. Current development is for the purposes of linking the HMS model to atmospheric simulators, improving the groundwater model, and adding a lake sub-model to simulate wetlands. HMS has not yet been used outside the university setting.

2.3.3 FHM-FIPR Hydrologic Model

The FHM model links two public-domain models: HSPF and MODFLOW. The FHM model development began in 1988 funded by the Florida Institute of Phosphate Research (FIPR). FHM was developed to simulate the interaction of surface water and ground water in shallow water table systems. GIS was incorporated into the integrated model for data preparation, storage and presentation.

Either the surface water model (HSPF) or the groundwater model (MODFLOW) can run independently or an integrated combination of the two models can be run. Typically, the sequence would consist of separate calibrations of the surface water and groundwater models followed by integrated modeling (Ross *et al.*, 1997). The model package consists of four modules: the FHM model code, preprocessor, postprocessor, and GIS interface. The model code first uses HSPF to calculate runoff, infiltration, recharge, surface evapotranspiration and storage on an hourly basis. The code then uses MODFLOW to calculate groundwater flow for a daily time step. This sequence is repeated until the simulation time is completed.

Although the FHM model is relatively new, it utilizes widely used models for performing water flow calculations. The model code has numerous software checks for errors during the simulation and a water balance is compiled for the surface water and groundwater components (Ross *et al.*, 1997). The code allows simulations for design storm events, continuous seasonal or annual simulations. It is limited to a calendar or water year simulation time for integrated simulations. Independent surface water and groundwater simulations do not have this limitation. Other limitations of the FHM model include:

- Ten rainfall stations
- Ten potential evapotranspiration stations
- Ten surface water diversions
- Fifty subbasins
- Fifty reaches
- Uniform MODFLOW grid of a maximum of 106 rows and 60 columns
- MODFLOW stress period of one week

Development of FHM is still ongoing and little use has occurred outside the academic community. The University of South Florida, part developer and distributor of FHM, has conducted field studies. However, SDI Environmental Services Inc. of Tampa, Florida, used FHM to model the Central Northern Tampa Bay Region by modifying the FHM code and developing a new code, ISGW (SDI, 1997).

2.3.4 SWATMOD

Another model code that links two widely used surface water and groundwater models is SWATMOD. SWATMOD links the USDA model SWAT with the USGS model MODFLOW. SWAT is a watershed-scale model used to predict water, chemical, and sediment movement in large basins. The model is used for long time periods and not for single event flood modeling. The linked models are used to simulate long-term surface water and groundwater interactions, and do not simulate flood events. The SWATMOD model has been used to predict conditions during simulation of water shortage periods (Sophocleous *et al.*, 1999).

SWATMOD was originally developed as an integrated surface water/groundwater model that could model an aquifer with distributed parameters and variable pumping. SWATMOD is a physically-based model operating on a watershed scale and capable of long time-period simulations (Sophocleous *et al.*, 1999). A limitation in the model design is the inability to model the unsaturated zone beyond the root zone. Therefore percolation (recharge) is applied directly to the groundwater table.

The model development required the modification of both the SWAT and MODFLOW codes. In addition, subroutines were developed that linked the two models. HYDBAL passes data between SWAT and MODFLOW and tracks the water balance of SWAT. MODSWB links SWAT's hydrologic basins with MODFLOW's grid and converts SWAT's fluxes into flow rates for MODFLOW (Sophocleous *et al.*, 1999). SWATMOD can be run in one of two modes. The first mode is where MODFLOW is treated as a subroutine of SWAT and is called at the end of each aquifer time step. The second mode involves SWAT and MODFLOW being performed successively and linked through a separate hydrologic balance data file (Sophocleous *et al.*, 1999).

2.3.5 MODFLOW

Probably the most widely used modeling software in use today is MODFLOW. Recognized as an industry standard for groundwater simulation, MODFLOW is a computer program that simulates three-dimensional groundwater flow using a finitedifference technique for solution of the governing flow equations. MODFLOW solves both confined and unconfined flow equations to simulate the behavior of groundwater flow systems under several types of natural and artificial stresses. The basic model is able to represent variations in hydraulic properties of porous media, natural and artificial recharge, discharge (e.g., rainfall infiltration, infiltration from or discharge to streams, well withdrawals, or injection), and differing boundary conditions. An aquifer is discretized into an orthogonal array of cells to which aquifer characteristics and hydrological stresses are assigned. Located at the center of each cell are nodes at which the groundwater head and flux are calculated. Boundary conditions at each node can be assigned a specified head (1st type), a specified flow (2nd Type), or can be defined as a head-dependent flow boundary (3rd type). Flow into and out of the model can be simulated through the use of external source and sink terms. Flow between the nodes (both horizontally and vertically) is calculated using

Darcy's equation. Various textual and graphic pre- and postprocessors are available (McDonald and Harbaugh, 1988).

One of the greatest strengths of MODFLOW is its modular format, which allows for additional capabilities to be easily incorporated. The program is divided into a main program and a series of independent packages. A package is a group of subroutines, or modules, which deals with a specific aspect of the simulation. Changes to a package or an addition of a new package do not require major changes to other packages in MODFLOW. Additional simulation modules are made available by the authors and by third parties. The boundary conditions in the original version of MODFLOW require prior knowledge of the stage, and/or seepage rates in surface water systems. These boundary conditions also do not provide a way to automatically update stage as a result of changing water fluxes into and out of surface water bodies (Rumbaugh, 1999). However, packages have already been developed to address some specific issues of surface water/groundwater interaction. Examples of such packages include:

- The Stream-Routing Package. This package is not a true surface water flow model, but rather it is an accounting program that tracks the flow in one or more streams which interact with groundwater. The program permits two or more streams to merge into one with flow in the merged stream equal to the sum of the tributary flows. The program also permits diversion from streams (Prudic, 1989; ESI, 1999).
- *The River Package*. This package contains routines that calculates flow between the river and underlying aquifer based on the head difference and sediment conductance.
- The Lake Package. This package contains routines to calculate water budgets for a lake that overlies many groundwater cells. The package updates lake water level, volume, and areas as a result of the computed water budget. This package is useful in predicting the effect of certain types of subsurface developments, such as well pumping or mining, on nearby water bodies (HIS GEOTRANS, 1999; Merritt and Konikow, 2000).
- *The Wetland Package*. This module is capable of simulating flow routing, the export/import of water to wetlands, groundwater interflow, and evaporation from wetlands. Surface water flow can be either overland/vegetation plain flow (in forested areas) or channeled/preferential flow (in sloughs) (Restrepo and Montoya, 1997).

MODFLOW also has packages for solute transport simulation (MOC3D) and particle tracking (MODPATH). Recognized as an industry standard for the simulation of subsurface flow, many pre- and postprocessors have been developed for use with MODFLOW. Among the best known are Groundwater Vistas by Environmental Simulations Inc., Visual MODFLOW by Waterloo Hydrologic, and Groundwater Modeling System (GMS) by the Department of Defense. Most of these programs also incorporate the use of GIS in the managing and manipulating data for input into MODFLOW. Furthermore, software such as HSI GEOTRANS' MODFLOW Data Reader has been developed to facilitate the import of model output data into a GIS environment.

2.3.6 DYNFLOW

DYNSYSTEM is a finite element model consisting of a package of simulation programs and associated pre- and post-processing software focused on the subsurface, but also incorporating surface water interflow simulation capabilities. Camp Dresser & McKee (CDM) began the development of DYNSYSTEM in 1982 with the creation of the DYNFLOW groundwater flow simulator. This was followed soon thereafter by the development of DYNTRACK; DYNFLOW's companion groundwater contaminant transport program. CDM continues to develop and support DYNSYSTEM. Over the 18 years since DYNFLOW was first created, new capabilities and functions have been developed based on the needs of the clients. Each one of the following capabilities with example applications is provided within DYNFLOW.

Level 1 – Simple surface water interaction is simulated in DYNFLOW with any one of several options for defining the surface water/groundwater boundaries, similar to the options in MODFLOW and other groundwater flow models. Boundary condition functions include fixed head, "river package" type, general head boundary, and the "rising water" (conditional) feature. This latter feature has been a key component of DYNFLOW surface water/groundwater applications. The model allows the unconfined water table to rise or fall, and if it intersects the land surface it becomes a fixed head drain – allowing for simulation of wetlands, ephemeral and intermittent streams, and other similar hydrologic features.

The Level 1 capabilities have been applied on almost every DYNSYSTEM modeling project. Recent applications have included wetland/surface water/groundwater interaction simulation for optimization of groundwater supply pumping, and groundwater plume containment within a complex alluvial valley system with mixed recharge-discharge conditions along the major valley streams.

Level 2 – POND/WETLAND elements simulate surface water features including ponds and lakes. DYNFLOW performs a water balance on each POND/WETLAND, including groundwater discharge/recharge, evaporation, consumptive use and transpiration, pumped extraction, return flows, direct precipitation, and other factors. The model computes the new POND/WETLAND water level based on the change in storage and the head-area-volume curve for each POND/WETLAND. The POND/WETLAND water levels become fixed heads at the nodes forming each POND/WETLAND during the next time step. A complete surface network can be constructed, using POND/WETLAND elements for the surface water storage features, and one-dimensional DYNFLOW elements for surface water routing in streams, rivers, and canals.

The Level 2 DYNFLOW surface water simulation methods have been used on several projects. This technique has been used to assess water level changes in a large pond

downgradient of a contaminant plume and for meeting aesthetic and recreational needs. Another example application involved a uranium-tailing pond for which the POND function was used to help design surface water handling and treatment facilities.

The Level 2 capabilities can also be used to simulate wetlands and perched groundwater. One example of such a system was a hazardous waste project involving the disposal of treated groundwater to a natural pond. Wetland creation and sustainability issues have been addressed using this modeling approach.

Level 3 – DYNSYSTEM capabilities now include integrated surface water/groundwater modeling, similar to the "stream" package in MODFLOW. Streamflow computations include watershed runoff, upstream inflows, instream diversions, interbasin transfers, and backwater calculations.

The groundwater and surface water simulators are linked internally, and both models are balanced at each simulation time step. Regarding the linking method, DYNFLOW contains commands for specifying which groups of groundwater finite element nodes connect hydraulically to segments of simulated surface water bodies in the modeled network. Time stepping proceeds with groundwater and surface water models alternating computations in each step. All of DYNFLOW's surface water boundary types are available for use in running the coupled groundwater-surface water simulation module.

Each of the DYNSYSTEM simulation tools uses the finite element method, with grid development provided by DYNPLOT and/or commercially available software. DYNSYSTEM links into GIS and CAD software, both for input and output while DYNPLOT provides sufficient functionality for most projects' needs. Links to such software as ArcInfo/ArcView, AutoCAD, Surfer, GMS, Argus, and other packages broadens the graphics capabilities, and helps meet specific client and project staff requirements.

2.3.7 MODBRANCH

The U. S. Geological Survey (USGS) one-dimensional model of unsteady flow in open-channel networks (BRANCH) was linked to MODFLOW. The result of this link, MODBRANCH, simulates the interaction between streamflow and subsurface flow in areas with dynamic, hydraulically connected groundwater and surface water systems coupled at the stream/aquifer interface. MODBRANCH was documented by the USGS (Swain and Wexler, 1993) and is now public domain software.

Streams in a network are divided into segments identified with cells of the MODFLOW grid in a manner similar to other MODFLOW packages that simulate rivers and streams. Terms that describe leakage between stream and aquifer as a function of streambed conductance and the difference between stream stage and head in the aquifer were added to the continuity equation of BRANCH. Because BRANCH and MODFLOW solutions are coupled by the leakage term, an iterative scheme was developed in which BRANCH and MODFLOW solutions were repeated alternately

until head and stage both converged to limiting values. Because time steps used in the MODFLOW solution for heads can be much larger than the small time intervals often needed for the surface water simulation, provisions were made for completing multiple BRANCH time intervals within each MODFLOW time step. In order to make the time periods of the MODFLOW and BRANCH solutions coincide, the groundwater time step is required to be an integral multiple of the surface water time interval.

In order to make MODBRANCH more compatible with the MODFLOW package, the surface water component was modularized in a manner similar to most MODFLOW packages. However, because the interactive solution scheme requires multiple repetitions of each MODFLOW time step, the modified BRANCH package cannot be used with the standard MODFLOW package and requires a special version of MODFLOW.

MODBRANCH has been applied by the USGS to problems in southern Florida involving the interaction of canals used for water management and the surficial aquifer system and to river/aquifer problems in the Pacific Northwest. Pre-processor and post-processor GUIs for MODBRANCH have been developed within the USGS.

2.3.8 SWMM

The U. S. Environmental Protection Agency (EPA) Storm Water Management Model (SWMM) is a public domain, mathematical model used for simulation of urban runoff quantity and quality and flow routing to storm and combined sewers. The model simulates real or synthetic storm events on the basis of rainfall (hyetograph) and other meteorological inputs and system characteristics to predict outcomes in the form of water quantity and quality values. All aspects of the urban hydrologic and quality cycles are simulated, including surface and subsurface runoff, transport through the drainage network, and storage and treatment. Control options may be investigated using SWMM, with associated cost estimates available for storage and/or treatment. Effectiveness can be evaluated by inspection of hydrographs, pollutographs, pollutant loads, and modeled changes in receiving water quality.

Basically, SWMM consists of a number of components, known as modules or "blocks," which can be linked to run sequentially so that the output of one module provides input to another. The blocks can be grouped in the following manner:

- Input Sources The RUNOFF Block generates surface and subsurface runoff based on arbitrary rainfall and/or snowmelt hyetographs, antecedent conditions, land use, and topography. Dry-weather flow and infiltration into the sewer system may be optionally generated using the TRANSPORT Block.
- Central Cores The RUNOFF, TRANSPORT, and EXTENDED TRANSPORT (EXTRAN) Blocks route flows and pollutants through the sewer or drainage system.

 Correctional Devices - The STORAGE/TREATMENT Block characterizes the effects of control devices upon flow and quality. Elementary cost computations is also made.

Additional blocks, known as Service Blocks, can be used to analyze or manipulate data generated from or used as input to the previously mentioned blocks. Quality constituents for simulation may be arbitrarily chosen for any of the blocks, although the different blocks have different constraints on the number and type of constituent modeled.

Of all the blocks just described, the two most widely used are RUNOFF and EXTRAN. The EXTRAN Block is the only block that does not simulate water quality. EXTRAN is a dynamic flow routing model that route inflow hydrographs through an open channel and/or closed conduit system, computing the time history of flows and heads throughout the system. Its use is intended for application to systems where the assumption of steady flow for purposes of computing backwater profiles cannot be made. EXTRAN represents the drainage system as links and nodes, allowing simulation of parallel or looped pipe networks; weirs, orifices, and pumps; and system surcharges. The program solves the full dynamic equations for gradually varied flow using an explicit solution technique to step forward in time.

The RUNOFF Block simulates the runoff rates developed from subareas using a kinematic wave approximation. Hydrologic routing techniques are then used to route the overland flows through a pipe, culvert, channel, and/or lake network. Within the RUNOFF Block is the GROUND subroutine where groundwater flow is modeled in both the unsaturated and saturated zones. The groundwater component is a lumped model for both zones and is based on individual water balances. The GROUND subroutine's only gains and losses from the saturated zone are deep percolation, evapotranspiration, and groundwater flow. Inflow to GROUND is limited to only the infiltration from SWMM's WSHED subroutine. These inflow and outflow limitations do not allow SWMM to model spatially varying processes such as pumping or irrigation.

2.3.9 HSPF

HSPF is the U.S. EPA Hydrologic Simulation Program – Fortran. Following a decade of previous development, Hydrocomp Inc. adapted the model in 1976 from the Stanford Watershed Model. The model code has been continually developed since that time and pre- and postprocessors have become available. A review of HSPF applications has shown several instances of HSPF linked with other flow and water quality models (Ross *et al.*, 1997; SDI, 1997).

HSPF is a conceptual watershed simulation model that can model both water quantity and quality. HSPF subdivides the watershed basin into subbasins of homogeneous properties. The model is a lumped model but can provide sufficient detail if the watershed is delineated into several subbasins. HSPF can be used to determine runoff flow rate, sediment load, or contaminant concentrations in the watershed. The time history of the water quality and quantity at defined points in the watershed can be simulated.

HSPF is public domain software that can be used on most operating systems. The code was written in Fortran 77 allowing the user to recompile the code to fit the intended use. The ability to modify the HSPF code allows the coupling of the model to groundwater software such as MODFLOW. Uses of HSPF have included urban drainage studies, river basin planning, reservoir operations, flood mapping, sedimentation problems, and water quality problems.

2.4 Evaluation Results

For each of the nine models just described, rankings for the thirteen criteria discussed in Section 2.2 were assigned. The priority values were assigned a value to give greater impact to the higher priorities. Priority 1 was assigned a value 5. Priority 2 was assigned a value of 1. This assigned value was multiplied by the ranking assigned for each criteria of each model and totaled to give an overall score. The results of the ranking evaluation are provided in **Table 2-3**.

With respect to the thirteen criteria, MIKE SHE earned the highest ranking and HMS, MODBRANCH and SWATMOD earned the lowest. However, it is likely that the information presented in this list and contained in the research upon which it is based is more important than the actual ranking. By no means do the results presented in Table 2-3 define the best available tool for integrated surface water/groundwater modeling. The scores represent the standing of each model relative to the thirteen secondary and tertiary criteria previously described. This table is meant as a supplement to the numerous factors involved in defining a plan for integrated modeling.

Table 2-3 Evaluation Results of Selected Integrated, Coupled, Groundwater and Surface Water Models											
Evaluation Criteria		Prioritv*	Models Evaluated								
#	Description		Mike SHE	HMS	FHM- FIPR	SWATMOD	MODFLOW	DYNFLOW	MODBRANCH	SWMM	HSPF
1	Regulatory Acceptance	1	2	0	1	0	3	2	1	3	3
2	Cost	1	0	2	3	3	3	3	3	2	3
3	Ease of Use (Interface)	1	3	1	1	1	2	1	2	2	2
4	Intermodel Connectivity	1	3	3	3	3	3	2	3	1	2
5	GIS Integration	1	3	3	3	2	0	1	0	1	1
6	Service & Support	1	2	1	1	1	0	1	0	1	0
7	Model Limitations	1	3	3	2	2	2	2	2	1	1
8	Limit on Model Size	1	2	2	1	2	3	3	3	3	3
9	Expandability	2	0	3	3	3	3	3	3	3	3
10	Platform-Flexibility of Operating System	2	2	0	1	2	1	1	1	1	1
11	Experience Required	2	1	1	2	2	2	2	2	2	2
12	Percent of Market Share	2	2	0	1	1	3	2	1	3	3
13	Documentation and Training	2	3	0	1	1	2	3	2	2	2
	Maximum Score	135									
	Overall Score		98	79	83	79	91	86	79	81	86
	Percent of Maximum Score		73%	59%	61%	59%	67%	64%	59%	60%	64%

* Priority 1 Value = 5; Priority 2 Value = 1

3.0 Related Technologies

Just as current business growth depends largely upon new developments in computer technology and telecommunications, current progress in modeling technology depends upon the progress being made in several technologies that facilitate model development and application, and also upon new approaches to modeling. One such technology is the use of Geographic Information Systems (GIS) with modeling, or GIS integrated with modeling. A new approach to the simulation of hydrologic systems lies in the development of stochastic modeling. Other technologies are the development of parallel processing in computer systems and the development of new types of computer operating systems.

3.1 Hydrologic Modeling with GIS

By far the most significant new technology from the standpoint of simulation modeling is the progress being made in automated techniques for spatial data base manipulation and spatial data analysis, sometimes referred to as Geographic Information Systems (GIS). GIS has revolutionized the task of designing models and interpreting and reporting results of model applications.

In both surface water and groundwater modeling, data management plays a major role. The compilation, analysis, and formulation of model input are the major phases of any modeling study, as is the creation of high-quality, graphical model output. Much of the data required for model development, including land use maps, soil types, production well locations, basin delineation, water quality, recharge, evapotranspiration, parcel data, etc. are being made available in the form of GIS coverages. A GIS allows users to take advantage of the vast quantity of data available today for water resource applications.

The development of the model-input data sets now commonly follows the use of GIS to develop a conceptual model of the area/region to be modeled. The conceptual model is the assignment or distribution of material property values within the modeled area. The development of a conceptual model prior to the development of a numerical model and the definition of a numerical grid or mesh has always been the first step in model development. Traditionally, most preprocessing programs for groundwater modeling have required the user to construct a computational grid that encompasses the model domain. Model parameters such as boundary conditions and material properties are then selected for each node or cell with in the model domain. This approach to model development requires extensive data entry effort. A major disadvantage is that a significant modification to either the conceptual model or the distribution of nodes or cells with in the model domain requires much of the data entry to be repeated

A growing number of groundwater modeling pre- and postprocessors, including GMS and GWVistas, allow the transfer of the point, polygon, and line coverage data stored in GIS coverages into a nearly infinite number of grid formations. If modifications to the conceptual model or the grid of the numerical model are required, they can be accomplished in relatively short time (Nelson, 1996).

Furthermore, the use of GIS helps to address one of the major concerns in the water resources market: the effect on groundwater and surface water supplies of land use changes. By the use of GIS integrated with hydrologic modeling, the consequences of changes in land use can be identified and/or quantified (Ross *et al.*, 1995). This can be applied to effects both on water quantity and water quality.

New GIS packages and extensions are continually being developed to aid in the analysis and formulation of input data for both groundwater and surface water models. Extensions developed for ArcView GIS, such as XTOOLs, HSI-GeoTrans MODFLOW Data Reader, SWMM Tools, and many more are simplifying the compilation and analysis of data for model development.

One of the main shortcomings of many pre- and postprocessors is their ability to display model information or results in a georeferenced format (Inbau, 1997). The generation of high quality report figures is a limitation of many of these software programs. Through the use of a GIS, report quality figures for both model information and results can be quickly generated (Brown, 1996). Furthermore, new ESRI GIS packages such as 3D Analyst aids in the development of impressive 3D renderings of model results (Hu, 1995).

MIKE SHE, FHM, and other models are being developed to incorporate GIS software (e.g. ArcView) to assist in model development, storage of model parameter data, and analysis of model results. Proprietary pre- and postprocessor software has also begun to utilize the capabilities of GIS to assist in water resource modeling. Future model use, especially interactive surface water/groundwater modeling, will benefit from the use of GIS software particularly because of the increase in the volume of data needed for model development.

3.2 Stochastic Modeling

The application of stochastic modeling to water resources problems began in the late 70's and early 80's (Gelhar, 1974; Freeze, 1975; Dagan, 1982). Given the mathematical complexity of this approach that combines the disciplines of advanced calculus, stochastic theory, probability and geostatistics, it is primarily within the academic world where it has been a continual and active field of investigation. Most of the research publications on stochastic modeling have mainly addressed flow and transport problems related to either surface water or groundwater rather than their combination, with the exception of a recent paper by Destouni and Graham (1995).

The most significant advantages of stochastic modeling over its deterministic counterpart are its ability to:

- account within a systematic and probabilistic framework for the spatiotemporal variability of the most variable input parameters of a system to be simulated,
- quantify the level of uncertainty associated with the input data,

- measure the output data uncertainty associated with the input uncertainty, and
- provide risk assessment quantification that is a useful decision tool for policy makers.

Given the complexity of surface water/groundwater interactions at the watershed scale, the application of stochastic modeling to an integrated surface water/groundwater system can be initially envisioned from a numerical perspective. The simplifying assumptions required to derive analytical solutions that are easy and fast to use might preclude the use of this approach because these assumptions are most likely not going to be valid in the real world. Thus, Monte-Carlo simulations remain a powerful alternative that offers flexibility in simulations. Unlike a sensitivity analysis, Monte-Carlo simulations will produce a detailed output simulation that covers all the realizations of input parameters rather than some of its extreme values. This type of numerical simulation is well fitted to account for spatio-temporal variability of natural phenomena such as rainfall, recharge, evapotranspiration, and transmissivity as well as anthropogenic phenomena such as well field pumping and urban and agricultural development.

3.3 Simultaneous Parallel Processing

When using integrated surface water and groundwater models, requirements for computer resources increase, resulting in longer computer run times. One way of decreasing model run time is to use parallel processors. In parallel processing, multiple processors are used to execute parts of the program code simultaneously. However, the use of multiple processors will not necessarily increase the speed of model execution unless the software code is designed to perform on parallel processors. There is a limit to the number of processors where the increase in speed does not outweigh the cost of additional processors (TechTarget, 1999).

Parallel processing typically is achieved in one of two ways. The first is by using multiple processors within a single computer where the processors share the same memory and bus interface. The other approach consists of using multiple computers that are connected via a network and operate with their own memory and bus interface. Either configuration will increase the speed of running program code capable of parallel execution (Dietz, 1998).

Part of the HMS system described in Section 2.2.2, the GHM sub-model solution, was compiled to operate on either traditional computers or parallel systems. The GHM module has two solution techniques for the partial differential, groundwater flow equations. The solution techniques are the forward solution and backsubstitution (FB) and the reduction and backsubstitution (RB) (Yu, 1997). The FB method (scalar) is the traditional solution technique and is not amenable to the use of parallel processing. On the other hand, the RB method (vector) was compiled to run on parallel processing systems, but is capable of running on either system.

A study was conducted to measure the increased performance of the vector-parallel system. (Yu, 1997). The combination of the vector-parallel method reduced the real time for model execution by 2.2 to 2.8 times over the vector method. The vector-parallel method real time execution was reduced by up to 36 times over the FB method (Yu, 1997). This increase in real run-time may not be cost beneficial for simple models, but for large complex models the savings could be significant.

3.4 Alternative Operating Systems

Related to the use of parallel processing systems to decrease model run times, alternative operating systems exist that can decrease the model run time. Modeling software today operates primarily under the popular Microsoft® Windows environment and DOS operating systems. Other platforms that could potentially be used for water resource models include Unix and Linux operating systems. A significant advantage of operating systems not consistent with standard platforms would have to exist for the particular models. The primary advantages would be either decreasing model run times or providing special functions not available on Windows. In addition, other programs such as ArcView used in conjunction with the modeling software must also be available on these alternative operating systems.

4.0 Summary and Recommendations

Integrated surface water/groundwater modeling is as an area of strong potential growth for water resources programs. The present study has focused upon the description of integrated surface water/groundwater modeling needs and the identification of existing tools available for this type of modeling application.

Many projects are characterized by the interaction of surface water and groundwater systems where changes in one system have a significant influence on the other. If one system is modeled independently, a technique must be found to represent changes in the other system in the model, but such techniques usually have serious limitations. A more accurate and sophisticated approach is to model as a single integrated process changes in both the surface water and groundwater systems and their mutual interaction as such changes occur. In some cases, the difference for addressing a project's needs is that a significantly more accurate and reliable answer can be provided. Use of an integrated model may increase data needs, costs, and time for project completion, but this may be justifiable if the client's needs are better satisfied.

Surface water models may vary in their range of representational capabilities, which may be designed for rivers, canals, wetlands, lakes, watersheds, storm sewers, or estuaries. Typical surface water components can explicitly model such surface water bodies as streams, lakes, wetlands, or may model entire basins (watershed models) or networks of storm sewers (urban runoff models). Groundwater models can simulate heads, pressures, constant-density solute transport, or variable-density solute transport in the subsurface. The surface water and groundwater components of available integrated models have the same variety of design features and intended applications.

After a literature search, seventy-five models were compiled for a preliminary screening process. Nine models were selected for further evaluation. The selected models had a variety of surface water and groundwater simulators. MIKE SHE and HMS have overland flow and channel simulators as well as simulators of unsaturated-zone and saturated-zone flow. MODFLOW and DYNFLOW are groundwater models that have modular packages that explicitly represent various types of surface water bodies. MODBRANCH couples a stream network model with MODFLOW. FHM-FIPR, SWATMOD, and HSPF are watershed models. The first two are coupled with MODFLOW; the groundwater components of the latter are limited. SWMM is an urban runoff model with limited groundwater simulation capabilities.

Since the ability of the models to adequately integrate surface water and groundwater simulations would depend on a particular application, secondary and tertiary criteria were identified as a basis for evaluation. These were regulatory acceptance, cost, ease of use, intermodel connectivity, GIS integration, service and support, model limitations, limit on model size, expandability, platform flexibility of operating system, experience required, percent of market share, and documentation and training. The nine selected models were evaluated relative to these thirteen

secondary and tertiary criteria. In each category, the nine models were given numerical rankings of zero to three depending on the degree to which they satisfied each criterion.

From the evaluation matrix results presented in Section 2.0, MIKE SHE, MODFLOW, and DYNFLOW had the highest scores while providing integrated surface water/groundwater capabilities. FHM-FIPR and SWATMOD would also be considered for further testing since these models have linked established groundwater and surface water models. However, these programs are still being developed and would likely require further testing and development. The surface water models, SWMM and HSPF, have minimal groundwater capabilities and would require linkage to a groundwater program (such as MODFLOW in FHM-FIPR) or development of groundwater code within the surface water program. Despite all of this, the likelihood of a single software package meeting the needs of all integrated surface water/groundwater modeling projects is improbable.

One approach to the second phase of this study would be to further evaluate these models, or a subset of them, by applying them to test problems that represent the variety of surface water and groundwater conditions that can occur in various project areas. The models that are expandable have the greatest potential to be further developed to provide additional capabilities for a range of possible applications. Perhaps the most productive and challenging approach to further work would be to identify which of the surface water and groundwater components of all the models evaluated have the broadest and most useful range of capabilities, and to develop and implement plans to link these components. In this way, a "best" integrated surface water/groundwater simulation model could be developed that could be offered to clients as the most sophisticated tool available for use on numerous projects.

Since integrated surface water/groundwater modeling will increase data requirements, model development time, and model simulation time, the resources to complete these models will be even greater than before. Therefore, emerging technologies in modeling were investigated for their use in integrated modeling. These technologies were GIS integration, stochastic modeling, parallel processing, and alternative operating systems. The rapid evolution of tools for spatial data base manipulation and analysis, there is a need to apply new GIS tools for model development and reporting as such become available. Monte Carlo simulations have potential as tools to deal with problems involving a range of possible parameters in key hydrologic processes. Additionally, parallel processing can greatly increase the computing efficiency of models, especially when used for integrated modeling where the data needs are greater and the programming code is more complex.

5.0 Bibliography

5.1 References Cited

- Brown, Michael, Davis, D.H., Greenwald, R.M., Srinivassan, P., and D.S. Ward, 1996. ModelGIS, An Interface for the USGS Three Dimensional Finite-Difference Model MODFLOW. 1996 ESRI User Conference Proceedings.
- Council, G.W, 1999. A Lake Package for MODFLOW (LAK2) Documentation and User's Manual Version 2.2. HSI GEOTRANS.
- Danish Hydraulic Institute (DHI), 1999a. *MIKE SHE Pre- and Postprocessing User Manual*. DHI Software, Denmark.
- Danish Hydraulic Institute (DHI), 1999b. *MIKE SHE Water Movement User Manual*. DHI Software, Denmark.
- Dagan, G., 1982. *Stochastic modeling of groundwater flow by unconditional and conditional probabilities, 1.* Conditional simulation and the direct problem, Water Resource Research, 18(4), pp. 813-834.
- Destouni, G. and W. D. Graham, 1995. *Solute transport through an integrated heterogeneous soil-groundwater system*. Water Resource Research, 31(8).
- Dietz, Hank, 1998. *Linux Parallel Processing HOWTO*. Purdue University v.980105, <u>http://yara.ecn.purdue.edu/~pplinux/PPHOWTO/pphowto.html</u>
- Freeze, R., A., 1975. A stochastic-conceptual analysis of one-dimensional groundwater flow in nonuniform homogeneous media. Water Resource Research, 11(5), pp. 725-741.
- Gelhar, L., W., 1974. *Stochastic Analysis of Phreatic Aquifers*. Water Resource Research, 10(3), pp. 539-545.
- Hu, J., 1995. *Methods of Generating Surfaces In Environmental GIS Applications*. 1995 ESRI User Conference Proceedings.
- Inbau, Cliff and Bruce Rindahl, 1997. *GIS as a Tool for Data Input and Visualization for a MODFLOW Ground Water Model*. 1997 ESRI User Conference Proceedings.
- McDonald, M.G. and A.W. Harbaugh, 1988. *A Modular Three-Dimensional Finite-Difference Groundwater Flow Model*. U.S. Geological Survey Techniques of Water Resources Investigations Book A3.
- Merritt, M. L., and Konikow, L. F., 2000, Documentation of a Computer Program to Simulate Lake-Aquifer Interaction using the MODFLOW Ground-Water Model and the MOC3D Solute-Transport Model. U. S. Geological Survey Water-Resources Investigations Report 00-4167, in press.

- Nelson, James E., and N.L. Jones, 1996. *Utilizing the ArcInfo Data Model to Build Conceptual Models for Environmental/Hydraulic/Hydrologic Simulations*. 1996 ESRI User Conference Proceedings.
- Prudic, D. E., 1989, Documentation of a Computer Program to Simulate Stream-Aquifer Relations using a Modular, Finite-Difference, Ground-water Flow Model. U. S. Geological Survey Open-File Report 88-729, 113 p.
- Rumbaugh, James, 1999. *Groundwater Vistas Electronic Manual for MODFLOW Packages.* Environmental Simulations, Inc.
- Restrepo, J.I. and A. Montoya, 1997. *MODFLOW Wetlands Module Final Report*. Prepared for the South Florida Water Management District.
- Ross, M.A., P.D. Tara & J.S. Geurink, 1995. *Integrated Hydrologic Modeling of Large Multi-Basin Areas: Lessons Learned*. International Symposium of Groundwater Management-Proceedings, ASCE, New York pp. 396-401.
- Ross, M.A., P.D. Tara, J.S. Geurink and M.T. Stewart, 1997. *FIPR Hydrologic Model Users Manual and Technical Documentation.* Center for Modeling Hydrologic and Aquatic Systems Department of Civil and Environmental Engineering and Department of Geology, University of South Florida, Tampa, Florida, December 1997.
- SDI Environmental Services, Inc. (SDI), 1997. Water Resources Evaluation and Integrated Hydrologic Model of the Central Northern Tampa Bay Region. Final Report ISGW/CNTB Model Prepared for West Coast Regional Water Supply Authority, Clearwater, Florida dated March 1997.
- Sophocleous, M.A., J.K. Koelliker, R.S. Govindaraju, T. Birdie, S.R. Ramireddygari and S.P. Perkins, 1999. Integrated Numerical Modeling for Basin-Wide Water Management: The Case of the Rattlesnake Creek Basin in South-Central Kansas. Journal of Hydrology v. 214 pp. 179-196.
- TechTarget.com, Inc., 1999. *What Is...parallel processing (a definition)*. Last update: December 1, 1999. <u>http://www.whatis.com/parallep.htm</u>.
- Yu. Z., 1997. Application of Vector and Parallel Supercomputers to Ground-Water Flow Modeling. Computers & Geosciences, v. 23 no. 9, pp. 917-927.
- Yu, Z. and F.W. Schwartz, 1998. *Application of and Integrated Basin-Scale Hydrologic Model to Simulate Surface-Water and Ground-Water Interactions*. Journal of the American Water Resources Association, v. 34 no. 2, April 1998.
- Yu, Z., 2000. Personal communication, July 24, 2000.

5.2 Sources Not Cited

- Athow, Jr., R.P. and J.P. Holland, 1998. Use of Advanced Hydroenvironmental Modeling and Simulation in Water Resources Management. Water Resources and the Urban Envrionment Proceedings of the Annual Water Resources Planning and Management Conference. ASCE, Reston, VA, pp. 639-644.
- Batabyal, A.A., 1996. *The Queuing Theoretic Approach to Groundwater Management*. Ecological Modeling 85, pp. 219-227.
- Bernard, N. and M. Miramond, 1998. Simulation of Stormwater Infiltration Impact on Groundwater: Feasibility Study. After the Rain Has Fallen International Water Resources Engineering Conference – Proceedings. ASCE, Reston, VA, pp. 165-170.
- Beverly, C.R., R.J. Nathan, K.W.J. Malafant, and D.P. Fordham, 1999. *Development of a Simplified Unsaturated Module for Providing Recharge Estimates to Saturated Groundwater Models*. Hydrological Processes 13, pp. 653-675.
- Das Gupta, A., 1998. Significance of Surface Water and Groundwater Interaction for Water Resources Management on a Regional Scale. After the Rain Has Fallen International Water Resources Engineering Conference – Proceedings. ASCE, Reston, VA, pp. 171-176.
- Dodson & Associates, Inc., 2000. Introduction to HEC-HMS Hydrologic Modeling System. American Society of Civil Engineers Seminar, <u>http://www.dodson-hydro.com/Seminars/hmsasce.htm</u>
- Fredricks, J.W., J.W. Labadie and J.M. Altenhofen, 1998. Decision Support System for Conjunctive Stream-Aquifer Management. Journal of Water Resources Planning and Management. Vol. 124, No. 2, pp. 69-78.
- Guardo, M. and R.S. Tomasello, 1996. *Hydrodynamic Simulations of a Constructed Wetland in South Florida*. AWRA Water Resources Bulletin, Vol. 31, No. 4, pp. 687-701.
- Haruvy, N., A. Hadas and Aviva Hadas, 1997. *Cost Assessment of Various Means of Averting Environmental Damage and Groundwater Contamination from Nitrate Seepage*. Agricultural Water Management 32, pp307-320.
- HSI GeoTrans, 1999. *HSI GeoTrans A Tetra Tech Company News*. HSI GeoTrans, Sterling, VA. Vol. 14, No. 3, Summer 1999.
- HSI GeoTrans, 2000. *HSI GeoTrans A Tetra Tech Company News*. HSI GeoTrans, Sterling, VA. Vol. 15, No. 4, Winter 2000.
- Kholghi, M., M. Razack, M. Mirabzadeh, and G. Porel, 1995. *Multiobjective Simulation-Optimization Model for Conjunctive Use of Surface and Groundwater Management.*

Proceedings of Regional Conference on Water Resources Management, Isfahan University of Technology, August 28-30, 1995, pp. 657-666.

- Prudic, D.E., 1999. *Stream-Routing Package*. Electronic Manual for MODFLOW Packages, Environmental Simulations, Inc.
- Scharffenberg, W.A., 2000. *Hydrologic Modeling System HEC-HMS User's Manual* Version 2.0, US Army Corps of Engineers – Hydraulic Engineering Center, March 2000.
- Yoon, J.H. and C.A. Shoemaker, 1996. *Applications of SALQR and Evolutionary Algorithms to Optimization of Groundwater Bioremediation.* 11th International Conference on Computational Methods in Water Resources, pp. 383-389.

Yu, Z. and F.W. Schwartz, 1999. *Automated Calibration Applied to Watershed-Scale Flow Simulations*. Hydrological Processes, v. 13, pp191-209.

5.3 Web Pages

Hydrologic Model System

http://www.essc.psu.edu/hms/hms/

http://www.essc.psu.edu/hms/hms/shm.html

http://www.essc.psu.edu/hms/hms/thm.html

http://www.essc.psu.edu/hms/hms/ghm.html

http://www.essc.psu.edu/hms/hms/cgi.html

Modular Modeling System

http://wwwbrr.cr.usgs.gov/mms/html/chap1.frame.new.html

http://wwwbrr.cr.usgs.gov/mms/html/mms_paper.html

HEC-HMS

http://www.waterengr.com/hms.htm

http://www.dodson-hydro.com/Seminars/hmsasce.htm

BASINS

http://www.epa.gov/OST/BASINS/basinsv2.htm

HSPF

http://water.usgs.gov/cgi-bin/man_wrdapp?hspf

http://www.hydrocomp.com/HSPFinfo.htm

http://www.cosmiclink.co.za/iscp/models/hydro/hspf/hspf.htm

http://www.aquaterra.com/florida.html

http://www.scisoftware.com/products/hspf_model_details/hspf_model_det ails.html

SWAT

http://www.brc.tamus.edu/srin/projects/occ.html

http://www.brc.tamus.edu/swat/newmanual/intro/overview.html

http://www.brc.tamus.edu/swat/newmanual/intro/intro.html