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CHAPTER 10

FLEXIBLE INTEGRATED WATERSHED MODELING WITH MIKE SHE

by Douglas N. Graham and Michael B. Butts

1. INTRODUCTION

Hydrologic modeling has become an essential tool in watershed management, with two fundamental roles. The first role is to improve our understanding of the physical, chemical and biological processes within a watershed and the way they interact. The second, more practical role is to apply this understanding to manage and protect our water resources and the water environment. Many challenges remain on both fronts.

1.1 The role and challenges of hydrologic modeling of watersheds

The water resources around the world are under increasing pressure due to rapid population and economic growth, aggravated by a lack of coordinated management and governance (UNESCO, 2003). Water shortage, deteriorating water quality and flood impacts are among the most urgent problems that need attention. However, surface water and groundwater have been, by tradition, managed separately - often in completely different branches of government. It is now recognized that water resources problems cannot be treated in isolation. The problems are seldom isolated and their solution requires a holistic approach to water management that must address different, often conflicting, demands for water. Problems like wetland protection or the conjunctive use of surface water and groundwater resources require the integrated management of surface water and groundwater together with the water chemistry and ecology. Nor does water movement follow political boundaries, which creates conflicts and further fragments management activities, (Jensen et al., 2002, Refsgaard et al., 1998). Increasingly, water resources are being managed on a watershed basis, while addressing problems at the local scale. For example, the European Water Framework directive requires water resources to be managed independent of international boundaries (Directive 2000/60/EC of the European Parliament and of the Council). In Canada, the Ontario provincial government is implementing watershed-based source protection for drinking water resources (Smith et al., 2004).

Changing to a watershed-based water management system challenges not only our management structures, but it also requires new and more sophisticated tools. Traditional groundwater and surface water models were not designed to answer questions related to conjunctive use of groundwater and surface water, water quality impacts of surface water on groundwater, impact of land-use changes and urban development on water resources, and floodplain and wetland management. Instead, fully integrated hydrologic models of the watershed behavior are required. These models must not only describe the water flow processes in an integrated fashion, but they must also be able to describe the movement of sediment,

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chemicals, nutrients, and water-borne organisms and their role in watershed habitats and ecology.

The increasing demand for water resources also challenges our ability to understand and describe the underlying hydrologic processes. For example, the simple fact is that the spatial scales of the processes involved range over many orders of magnitude (e.g. from the size of soil pores to regional groundwater aquifers of many 1000's of square kilometers). The inherent heterogeneity of natural systems makes it difficult to represent these processes accurately, (Grayson and Blöschl, 2000). The impacts of human induced changes due to agriculture, urban development, and water pollution are by no means fully understood. Furthermore, the growing focus on climate change has provoked increased research into understanding the complex feedback between the atmosphere and the terrestrial hydrological cycle.

In this chapter, we look at a comprehensive watershed-modeling tool MIKE SHE. MIKE SHE can treat many water management issues in an integrated fashion, at a wide range of spatial and temporal scales. The first section provides a general background of the MIKE SHE model including a range of applications that document the flexibility of its process-based approach. Next, we review the hydrologic processes included in the MIKE SHE modeling framework and the mathematical descriptions of these processes. Finally, we provide a summary of the ongoing developments for MIKE SHE. Demonstration versions of MIKE SHE can be downloaded from the MIKE SHE website, www.mikeshe.com, along with more detailed technical information.

1.2 Hydrologic modeling and MIKE SHE

In the hydrological cycle, water evaporates from the oceans, lakes and rivers, from the soil and is transpired by plants. This water vapor is transported in the atmosphere and falls back to the earth as rain and snow. It infiltrates to the groundwater and discharges to streams and rivers as baseflow. It also runs off directly to streams and rivers that flow back to the ocean. The hydrologic cycle is a closed loop and our interventions do not remove water; rather they affect the movement and transfer of water within the hydrologic cycle.

In 1969, Freeze and Harlan (Freeze and Harlan, 1969) proposed a blueprint for modeling the hydrologic cycle. In this original blueprint, different flow processes were described by their governing partial differential equations. The equations used in the blueprint were known to represent the physical processes at the appropriate scales in the different parts of the hydrological cycle.

From 1977 onwards, a consortium of three European organizations[1] developed, and extensively applied, the Système Hydrologique Européen (SHE) based on the blueprint of Freeze and Harlan (Abbott et al., 1986a & b). The integrated hydrological modeling system, MIKE SHE, emerged from this work (see Figure 10.1).

Since the mid-1980's, MIKE SHE has been further developed and extended by DHI Water & Environment. Today, MIKE SHE is an advanced, flexible

[1] The Institute of Hydrology in the United Kingdom, SOGREAH in France, and the Danish Hydraulic Institute in Denmark (now called DHI Water & Environment)

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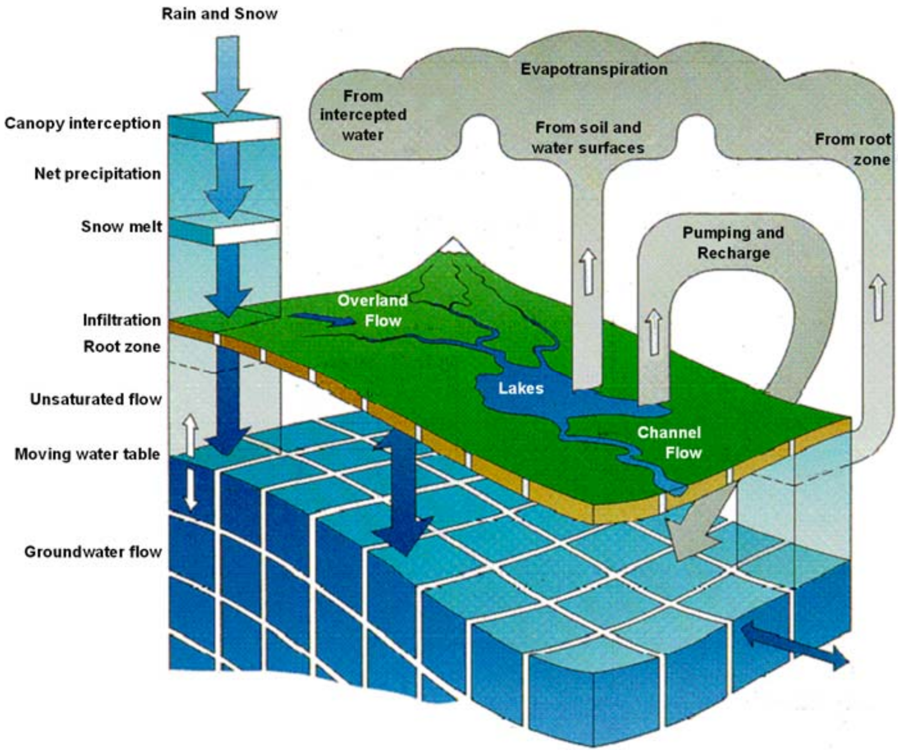

Figure 10.1 Hydrologic processes simulated by MIKE SHE.

framework for hydrologic modeling. It includes a full suite of pre- and post-processing tools, plus a flexible mix of advanced and simple solution techniques for each of the hydrologic processes. MIKE SHE covers the major processes in the hydrologic cycle and includes process models for evapotranspiration, overland flow, unsaturated flow, groundwater flow, and channel flow and their interactions. Each of these processes can be represented at different levels of spatial distribution and complexity, according to the goals of the modeling study, the availability of field data and the modeler's choices, (Butts et al. 2004). The MIKE SHE user interface allows the user to intuitively build the model description based on the user's conceptual model of the watershed. The model data is specified in a variety of formats independent of the model domain and grid, including native GIS formats. At run time, the spatial data is mapped onto the numerical grid, which makes it easy to change the spatial discretisation.

MIKE SHE uses MIKE 11 (Havnø et al. 1995) to simulate channel flow. MIKE 11 includes comprehensive facilities for modeling complex channel networks, lakes and reservoirs, and river structures, such as gates, sluices, and weirs. In many highly managed river systems, accurate representation of the river structures and their operation rules is essential. In a similar manner, MIKE SHE is also linked to the MOUSE sewer model (Mark et al, 2004, Lindberg et al, 1989), which can be used to simulate the interaction between urban storm water and

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Table 10.1. Selected literature references for application areas of MIKE SHE.

Application areas	References
General MIKE SHE References (Distributed hydrologic modeling and applications)	Abbott & Refsgaard (1996), Abbott et al. (1986 a & b), Havnø et al. (1995), Refsgaard et al. (1998), Refsgaard & Storm (1995), Storm & Refsgaard (1996),
River Basin Management and Modeling	Andersen et al. (2001), Christensen (2004), Henriksen et al. (2003), Jain et al. (1992), Jensen et al. (2002), Refsgaard & Sørensen (1994), Refsgaard et al. (2003, 1998, 1992), Sandholt et al. (1999), Vazquez. (2003)
Integrated Surface Water and Groundwater	Graham & Refsgaard (2001), Kaiser-Hill (2001), Olesen et al. (2000), Refsgaard et al. (1998), Sørensen et al. (1996)
Groundwater Modeling	Christiaens and Feyen (2001, 2002), Madsen & Kristensen (2002), Sonnenborg et al. (2003), Refsgaard et al. (1998)
Groundwater Pollution, Remediation and Water Quality Modeling	Brun and Engesgaard (2002), Brun et al. (2002), Christiansen et al. (2004), Hansen et al. (2001), Refsgaard et al. (1999, 1998), Sørensen and Refsgaard (2001), Thorsen et al. (1998)
Wetlands	Copp et al. (2004), Jacobsen et al. (1999), Lasarte et al. (2002), Refsgaard et al. (1998, 1994), Refsgaard & Sørensen (1994), Thompson et al. (2004), Yan et al. (1999)
Soil Erosion Modeling	Lørup & Styzcen (1996), Morgan et al. (1999, 1998), Nielsen et al. (1996), Storm et al. (1987)
Agricultural Management	Boegh et al. (2004), Hansen et al. (2001), Refsgaard et al. (1999), Styczen & Storm (1993a,b,c), Thorsen et al. (2001, 1998)
Irrigation	Carr et al. (1993), Jayatilaka et al (1998), Lohani et al. (1993), Singh et al. (1999a &b, 1997)
Remote Sensing – Weather Radar and Satellite	Andersen et al. (2002a &b), Boegh et al. (2004), Butts et al. (2004a &b), Sandholt et al. (2003, 1999)
Land use change and anthropogenic effects	Lørup et al. (1998), Refsgaard & Knudsen (1996), Refsgaard & Sørensen (1997, 1994)
Model Parameter Estimation, Calibration and Validation	Butts et al. (2004), Christiansen & Feyen (2002a & b, 2001), Madsen (2003), Madsen & Kristensen (2002), Mertens et al. (2004), Sonnenborg et al. (2003), Refsgaard (2001a & b, 1997a & b), Refsgaard et al (1998), Refsgaard & Butts (1999), Refsgaard & Knudsen (1996), Vazquez (2003), Vazquez et al. (2002)

sanitary sewer networks and groundwater. MIKE SHE is applicable at spatial scales ranging from a single soil profile, for evaluating crop water requirements, to large regions including several river catchments, such as the 80,000 km^2 Senegal Basin (e.g. Andersen et al., 2001). MIKE SHE has proven valuable in hundreds of research and consultancy projects covering a wide range of climatological and hydrological regimes, many of which are referenced in Table 10.1.

The need for fully integrated surface and groundwater models, like MIKE SHE, has been highlighted by several recent studies (e.g. Camp Dresser & McKee Inc., 2001; Kaiser-Hill, 2001; West Consultants Inc. et al., 2001; Kimley-Horn & Assoc. Inc. et al., 2002; Middlemis, 2004, which can all be downloaded from the MIKE SHE web site). These studies compare and contrast available integrated groundwater/surface water codes. They also show that few codes exist that have been designed and developed to fully integrate surface water and groundwater. Further, few of these have been applied outside of the academic community (Kaiser-Hill, 2001).

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1.3 Application Areas in Different Countries

MIKE SHE has been used in a broad range of applications. It is being used operationally in many countries around the world by organizations ranging from universities and research centers to consulting engineers companies (Refsgaard & Storm, 1995). MIKE SHE has been used for the analysis, planning and management of a wide range of water resources and environmental and ecological problems related to surface water and groundwater, such as:

- River basin management and planning
- Water supply design, management and optimization
- Irrigation and drainage
- Soil and water management
- Surface water impact from groundwater withdrawal
- Conjunctive use of groundwater and surface water
- Wetland management and restoration
- Ecological evaluations
- Groundwater management
- Environmental impact assessments
- Aquifer vulnerability mapping
- Contamination from waste disposal
- Surface water and groundwater quality remediation
- Floodplain studies
- Impact of land use and climate change
- Impact of agriculture (irrigation, drainage, nutrients and pesticides, etc.)

Table 10.1 is a list of some easily accessible references for many of the application areas listed above. The flexibility of MIKE SHE is demonstrated in the next sections by three examples that illustrate surface water modeling for floods (Blue River, USA), groundwater modeling for well head protection areas (Island of Funen, Denmark) and integrated surface and groundwater modeling for wetland management (Everglades, USA).

1.3.1 Distributed Surface Water Modeling for Floods

The 1232 km^2 Blue River Basin is located in south central Oklahoma, USA. The watershed is semi-arid, with a significant number of convective rainfall storms that are characterized by their high intensity and limited lateral extent. This type of rainfall is difficult to characterize with a traditional, sparse network of rain gauges. The Blue River Basin is particularly interesting because of the availability of NEXRAD distributed radar-based rainfall data (see Figure 10.2a). The NEXRAD data is available at hourly intervals with a spatial resolution of 4 km by 4 km. The Blue River Basin is one of the test basins in the Distributed Modeling Intercomparison Project (DMIP) organised by the Hydrology Lab of the National Weather Service (NWS) (Smith et al., 2004 and www.nws.noaa.gov/oh/hrl/dmip/).

Since, MIKE SHE allows different hydrologic process descriptions to be linked together, multiple combinations of the process models can be evaluated based on essentially the same set of input data. The range of model structures included both lumped and distributed routing, lumped, subcatchment-based and distributed rainfall-runoff models, grid-based modeling using physics-based flow equations, different conceptual process descriptions and lumped, subcatchment-based and gridded NEXRAD radar-rainfall input (see Butts et al., 2004a,b).

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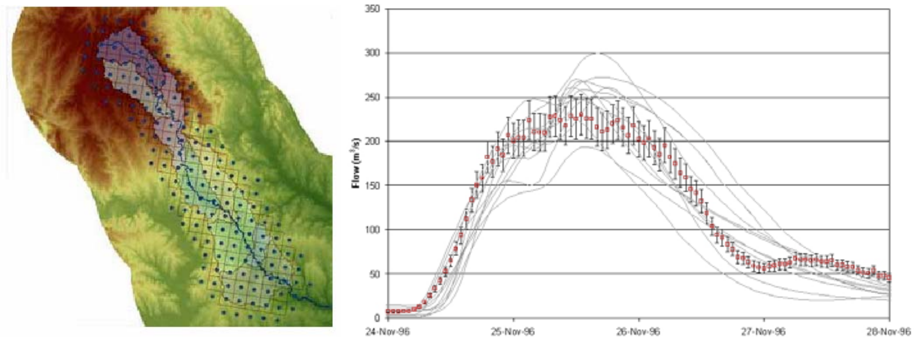

Figure 10.2. Blue River Basin project: a) The eight subcatchments used in conceptual modelling, as well as the 4-km NEXRAD grid used for the grid-based modelling. b) The output hydrographs from MIKE SHE for each of the different model structures, compared to the measured hydrograph, including the measurement uncertainty.

The results showed that model performance is strongly dependent on model structure (see Figure 10.2b). Distributed routing and, to a lesser extent, distributed rainfall were found to be the dominant processes controlling simulation accuracy in the Blue River Basin. It was further found that for practical hydrological predictions there are important benefits in exploring different model structures as part of the overall modeling approach.

1.3.2 Stochastic Delineation of Transient Well Head Protection Areas

Well head protection areas (WHPAs) are a common planning tool for reducing the risk of contamination to drinking water supply wells (Smith et al., 2004). Typical WHPA delineation involves steady-state groundwater flow modeling with deterministic backward particle tracking. This is used to determine the area that contributes water to the well within a prescribed time period-typically two to ten years. The WHPA then becomes subject to land-use restrictions to minimize the risk of contamination. However, WHPAs based solely on steady-state groundwater models ignore or simplify processes outside of the saturated groundwater zone and neglect important dynamic and transient effects.

MIKE SHE is increasingly being used to determine more realistic WHPAs that take into consideration such factors as distributed seasonal variations in ET and net recharge, unsaturated zone storage and delayed recharge, dynamic surface water boundary conditions, high volume recharge during storms, variable pumping rates, and demand and land-use changes. Such models can be used for real-time, on-line management to ensure a safe and continuous water supply.

MIKE SHE was recently used in Denmark, to evaluate the uncertainty associated with WHPA delineation, which is ignored in traditional, deterministic WHPAs delineation. MIKE SHE's automatic calibration and Monte Carlo utilities were used to determine the areas that most likely contribute water to the well and, thus, optimize planning restrictions for stakeholders (see Figure 10.3).

1.3.3 Wetland Management

Recent decades have seen significant loss and degradation of wetland areas. There is a growing realization that wetlands are not only important ecological and

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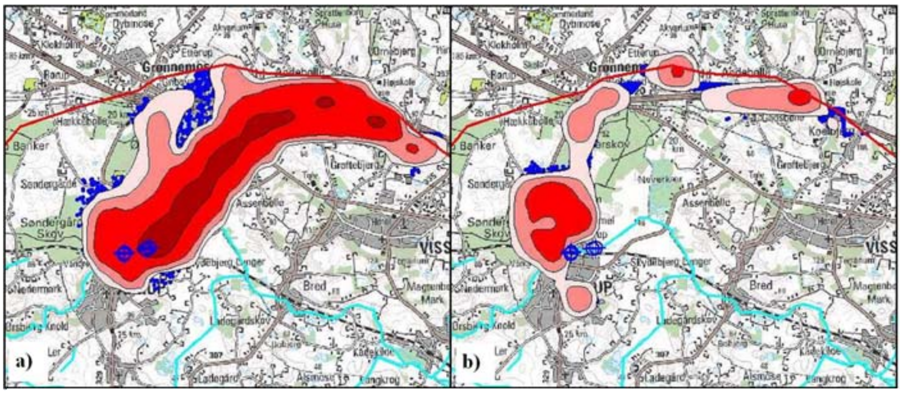

Figure 10.3 Example Monte Carlo analysis. (a) Probable well field capture zone in lower aquifer. (b) Probable infiltration zones on the ground surface. (85 transient simulations; 14 parameters; Darker areas equal higher probability.)

wildlife areas, but also provide a range of other benefits. Wetlands are sensitive, complex systems with tightly integrated surface water and groundwater. For example, relatively minor changes in groundwater level can have a significant impact on wetland function and extent by altering the groundwater-surface water exchange. Furthermore, the relation between groundwater and surface water is essentially dynamic and dominated by low flow and high flow events.

In the Florida Everglades, there is a pronounced interaction between surface water and groundwater. Nearly all areas of the Florida Everglades are either partially or completely controlled by drainage canals that provide important economic and flood control functions. MIKE SHE is being used extensively in Florida to assess the impacts of irrigation, flood control, and wetland restoration that includes both the surface water and groundwater regimes (see Table 10.1).

2. PROCESS-BASED HYDROLOGIC MODELING

MIKE SHE, in its original formulation, could be characterized as a deterministic, physics-based , distributed model code. It was developed as a fully integrated alternative to the more traditional lumped, conceptual rainfall-runoff models. A physics-based code is one that solves the partial differential equations describing mass flow and momentum transfer. The parameters in these equations can be obtained from measurements and used in the model. For example, the St. Venant equations (open channel flow) and the Darcy equation (saturated flow in porous media) are physics-based equations.

There are, however, important limitations to the applicability of such physics-based models. For example,

- it is widely recognized that such models require a significant amount of data and the cost of data acquisition may be high;
- the relative complexity of the physics-based solution requires substantial execution time;

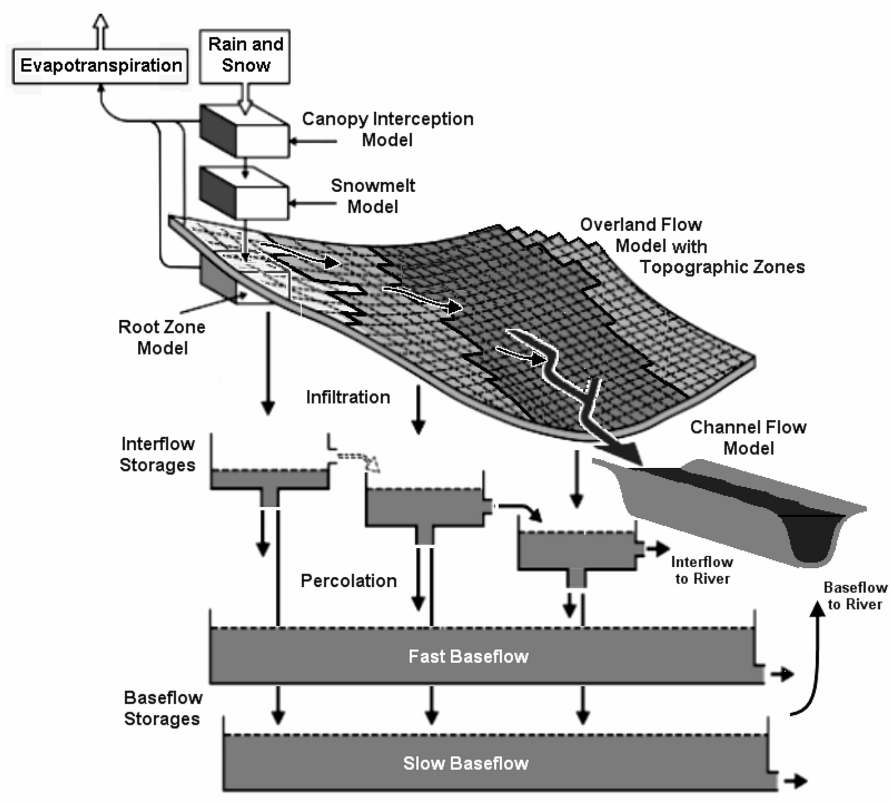

Figure 10.4 Schematic representation of the conceptual components in MIKE SHE - semi-distributed overland flow and linear reservoir groundwater models.

- the relative complexity may lead to over-parameterized descriptions for simple applications; and
- a physics-based model attempts to represent flow processes at the grid scale with mathematical descriptions that, at best, are valid for small-scale experimental conditions.

Therefore, it is often practical to use simplified process descriptions. Similarly, in most watershed problems one or two hydrologic processes dominate the watershed behavior. For example, flood forecasting is dominated by river flows and surface runoff, while wetland restoration depends mostly on saturated groundwater flow and overland flow. Thus, a complete, physics-based flow description for all processes in one model is rarely necessary. A sensible way forward is to use physics-based flow descriptions for only the processes that are important, and simpler, faster, less data demanding methods for the less important processes. The downside is that the parameters in the simpler methods are usually no longer physics meaningful, but must be calibrated-based on experience.

The process-based, modular approach implemented in the original SHE code has made it possible to implement multiple descriptions for each of the hydrologic processes. In the simplest case, MIKE SHE can use fully distributed conceptual

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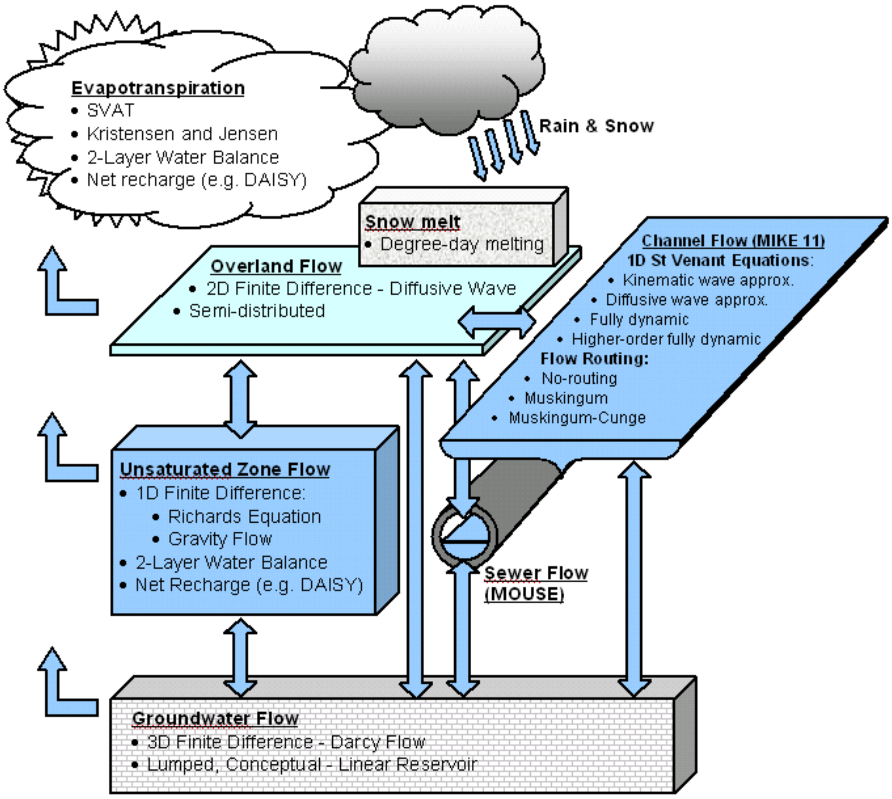

Figure 10.5 Schematic view of the process in MIKE SHE, including the available numeric engines for each process. The arrows show the available exchange pathways for water between the process models.

approaches to model the watershed processes (Figure 10.4). For advanced applications, MIKE SHE can simulate all the processes using physics-based methods. Alternatively, MIKE SHE can combine conceptual and physics-based methods-based on data availability and project needs. The flexibility in MIKE SHE's process-based framework allows each process to be solved at its own relevant spatial and temporal scale. For example, evapotranspiration varies over the day and surface flows respond quickly to rainfall events, whereas groundwater reacts much slower. In contrast, in many non-commercial, research-oriented integrated hydrologic codes (e.g. MODFLOW HMS, Panday et al., 1998; InHM, Sudicky et al., 2002), all the hydrologic processes are solved implicitly at a uniform time step, which can lead to intensive computational effort for watershed scale models.

The rest of this section outlines the hydrologic processes included in MIKE SHE and a brief description of each of the current methods available for each process (see Figure 10.5 for a schematic overview of the processes and methods in MIKE SHE). More detailed mathematical descriptions of the processes are available in the MIKE SHE Reference manual, which can be downloaded from the DHI web site. Further information on more specialized functions, such as macro

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pore flow, can also be found here. More general information on the hydrologic processes can be found in relevant hydrology textbooks (e.g. Maidment, 1992).

The processes are presented in the following order:

1. Precipitation and Evapotranspiration
2. Unsaturated Flow
3. Overland Flow
4. Channel Flow
5. Pipe and Sewer Flows
6. Saturated Groundwater Flow
7. Agriculture, and
8. Water Quality,

plus a brief description of the parameter estimation and water budget tools.

2.1 Precipitation and Evapotranspiration

The atmospheric processes that drive the hydrological cycle are generally not modeled explicitly in watershed models. This is the case with MIKE SHE, although coupling of MIKE SHE with numerical weather models is being explored in current research projects. Precipitation is usually a direct input in MIKE SHE, whereas radiation and water vapor transport in the atmosphere is typically bound up in evapotranspiration (ET). Evapotranspiration refers to the sum of the processes of direct evaporation from free water surfaces and transpiration of sub-surface water either directly or via plants. Evapotranspiration is an important component of the water balance. Evapotranspiration can be 70% of rainfall in temperate climates and even exceed annual rainfall in arid areas (Bedient and Huber, 2002).

Evaporation occurs from all free water surfaces, which not only includes lakes and rivers, but also rainfall trapped on leaves, as well as snow surfaces. Evaporation from the soil is controlled by the soil wetness, soil hydraulic properties and the location of the groundwater table. Transpiration, on the other hand, is strongly related to plant physiology - the depth of the roots, the ability of the roots to extract water from soils, the characteristics of the leaves, etc. Plants can regulate their transpiration depending on the availability of water, which means that transpiration is also a function of the soil moisture content in the unsaturated zone. Thus, ET can have a high degree of spatial variation that changes daily and seasonally, but also in response to climate and land use change. ET and infiltration to the unsaturated zone together determine the timing and magnitude of groundwater recharge, as well as overland flow generation.

MIKE SHE calculates the Actual ET. This is different from the Potential ET and the Reference ET. Potential ET is the theoretical maximum amount of ET - that is the amount of evaporation from a large open body of water under existing atmospheric conditions. Reference ET is the theoretical maximum ET from an idealized reference grass crop that has as much water as it needs (Shuttleworth, 1992). The various ET methods in MIKE SHE differ only in their data requirements and the way they determine Actual ET.

2.1.1 Soil Vegetation Atmosphere Transfer (SVAT)

This MIKE SHE land surface model is a two-layer system (soil and canopy) linked together by a network of resistances (Shuttleworth and Wallace, 1985; Shuttleworth and Gurney, 1990). The model consists of a single, semi-transparent, canopy layer located above the soil layer, such that the only way for heat and moisture to enter or leave the soil layer is through the canopy layer. According to the resistance analogy, the fluxes of latent and sensible heat between nodes are driven by differences in humidity and temperature, respectively, and controlled by a number of resistances. The resistances depend on the internal state of the land-surface-vegetation system as well as the atmospheric conditions. Compared to the original model structure proposed by Shuttleworth and Wallace (1985), MIKE SHE's two-layer model has been extended to include evaporation and sensible heat flux from ponded water on the soil surface and on the leaves. Two-layer models have been successfully tested for many different types of vegetation and under different climatic conditions (e. g. Daamen, 1997; Iritz et al., 1999; van der Keur et al. 2001; Lund and Soegaard, 2003; Boegh et al., 2004). The primary advantage of such a model is that Actual ET is calculated directly from standard meteorological and vegetation data. Reference ET is not a required input.

2.1.2 Kristensen and Jensen Method

The Kristensen-Jensen model (Kristensen and Jensen, 1975) is based on empirically derived equations, determined through work done out at the Royal Veterinary and Agricultural University (KVL) in, Copenhagen, Denmark. The empirical equations in the model are based on field measurements. The required input includes time series for the Reference ET, the leaf area index and the root depth, plus values for several empirical parameters that control the distribution of ET with the system, (Refsgaard & Storm, 1995).

First, net rainfall is calculated by subtracting water intercepted by the leaves. Net rainfall is added to the ground surface where it either infiltrates or ponds. Evapotranspiration is first removed from intercepted rainfall, followed by ponded water at the Reference ET rate. If the Reference ET is not yet satisfied for the current time step, then water is removed from the root zone via transpiration. The actual soil moisture content, soil field capacity and wilting point in each vertical cell are used to control the amount of transpiration. The vertical distribution of transpiration is controlled by the root depth and a root shape factor to distribute the ET within the root zone. The Kristensen and Jensen method can only be used with the Richards equation and gravity flow methods in the unsaturated zone.

2.1.3 Two-layer Water Balance Method

MIKE SHE also includes a simplified water balance method for both the unsaturated zone storage and ET. The Two-Layer Water Balance model divides the unsaturated zone into a root zone, from which ET can be extracted, and a zone below the root zone, where ET does not occur (Yan and Smith, 1994). Similar to the Kristensen and Jensen model, ET is extracted first from intercepted water (based on the leaf area index), then ponded water and finally via transpiration from the root zone, based on an average water content in the root zone. In the absence

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of ET, the average water content in the root zone decreases linearly with depth. However, ET reduces the water content in the root zone, creating unsaturated zone storage. The minimum water content in the root zone is the wilting point water content, but this can only occur when the water table is below the root zone. The Two-Layer Water Balance ET method requires time series for the root depth and the leaf area index, as well as the Reference ET.

The main purpose of the Two-Layer Water Balance ET method is to provide an estimate of the Actual ET and the amount of water that recharges the saturated zone. It is primarily suited for areas where the water table is shallow, such as in swamps and wetland areas. The model does not consider the flow dynamics in the unsaturated zone and, thus, is less suitable for areas with deeper and drier unsaturated zones. However, it is possible to calibrate the input parameters so that the model performs reasonably well under most conditions.

2.2 Unsaturated Flow

The unsaturated zone is usually heterogeneous and characterized by cyclic fluctuations in the soil moisture as soil moisture is replenished by rainfall and removed by evapotranspiration and recharge to the groundwater table. Unsaturated flow is assumed to be primarily vertical, since gravity dominates infiltration. Therefore, to reduce the computational burden, unsaturated flow in MIKE SHE is calculated only vertically. Although, this is sufficient for most applications, it may limit the validity of the flow description in some situations, such as on steep hill slopes, or in small-scale models with lateral flow in the unsaturated zone. The inherent heterogeneity of natural soils means that any unsaturated flow description must either ignore sub-grid variations and processes or devise strategies to account for them. As there is very little measurement information available at the grid scale, different strategies have been devised to derive large scale or effective parameters from small scale measurements (Refsgaard and Butts, 1999). Thus, the flow description in the unsaturated zone is effectively conceptual.

There are four solution options in MIKE SHE for calculating infiltration through the unsaturated zone:

- the full Richards equation, which requires relationships for both the moisture-retention curve and the effective conductivity,
- a simplified gravity flow procedure, which assumes a uniform, vertical unit-gradient and ignores capillarity,
- a simple two-layer water balance method for the root zone and the zone between the roots and the water table, and
- the calculation of net recharge by other means, which is then input directly as recharge to the saturated zone.

The full Richards equation is the most computationally intensive, but also the most accurate when the unsaturated flow is dynamic. The simplified gravity flow procedure provides a suitable solution when you are primarily interested in the time varying recharge to the groundwater table based on actual precipitation and evapotranspiration and not the dynamics in the unsaturated zone. The simple two-layer water balance method is suitable when the water table is shallow, groundwater recharge is primarily influenced by evapotranspiration in the root

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zone, and the delay between precipitation and recharge to the saturated zone is small or not of interest. The direct input of net recharge is typically used when a more sophisticated model is required, such as DAISY (Hansen et al., 1990; Abrahamsen and Hansen, 2000) - a soil-plant-atmosphere model that is well suited for agricultural related studies.

2.2.1 Richards Equation

For vertical flow, the driving force for transport of water in the unsaturated zone is the vertical gradient of the hydraulic head, which includes both a gravity and a pressure component. In the unsaturated zone the pressure head is negative due to capillarity. Based on the continuity equation and Darcy's law, vertical flow in the unsaturated zone can be described by the so-called Richards equation. The Richards equation requires two functions - one for the pressure head as a function of saturation and the other for the hydraulic conductivity, also as a function of saturation. Evapotranspiration acts as a water sink in the upper soil layer and root zone portion of the unsaturated zone.

MIKE SHE calculates the unsaturated flow using a fully implicit finite difference solution (Refsgaard & Storm, 1995). For each time step, the upper boundary condition is either a constant flux (the rainfall rate at the ground surface), or a constant head (the level of ponded water on the ground surface). In most cases, the lower boundary is a pressure boundary determined by the water table. MIKE SHE includes an iterative coupling procedure between the unsaturated zone and the saturated zone to compute the correct soil moisture and the water table dynamics in the lower part of the soil profile. Particularly in this part of the model, it is important to account for the variable specific yield above the water table, as the specific yield depends on the actual soil moisture profile and availability of that water.

2.2.2 Gravity Flow

Gravity flow is a simplification of the Richards equation, where the pressure head term is ignored and the vertical driving force is due entirely to gravity. In this case, the continuity equation is solved explicitly from the top of the soil column downward. The flux out the bottom of the soil column is accumulated over the unsaturated zone time steps and added as a source to the saturated zone calculation at the start of the next saturated zone time step. The input to the model requires only the conductivity-saturation relationship.

Compared to the Richards equation, the gravity flow solution is several times faster and unconditionally stable. It is primarily used for coarse soils (capillary pressure is small) and when you are primarily interested in accurate evapotranspiration and delayed recharge to the groundwater table.

2.2.3 Two-Layer Water Balance

The Two-Layer Water Balance method divides the unsaturated zone into a root zone and a zone below the root zone. Infiltration discharges immediately to the saturated zone whenever the unsaturated zone storage is zero. The method simply calculates the amount of water that recharges the saturated zone, while

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accounting for unsaturated zone storage but ignoring the delay. This method is described in more detail in Section 2.1.3 of this chapter.

2.2.4 Lumped Unsaturated Zone Calculations

In principle, unsaturated flow should be calculated individually for every soil column in the model domain. However, for large models the unsaturated flow calculations can become the most time consuming part of the solution. The number of unsaturated zone calculations can be reduced by solving the flow equations once and applying the results to all similar cells (e.g. to those with the same rainfall, soil type, and depth to the groundwater table). Such lumping preserves the water balance, but may represent local dynamics less accurately.

2.2.5 Coupling to the Saturated Zone

The saturated and unsaturated zones are linked by an explicit coupling. That is, they are solved in parallel, rather than being solved in a single matrix with an implicit flux coupling of the unsaturated and saturated flow differential equations. The great advantage of explicit coupling is that the time steps for the unsaturated and saturated zones can be independent. This means that MIKE SHE can take advantage of the difference in the time scales of unsaturated flow (minutes to hours) and saturated flow (hours to days).

The coupling between unsaturated zone and the saturated zone is limited to a coupling between the entire unsaturated zone and the top calculation layer of the saturated zone. If the water table is below the bottom of the top saturated zone calculation layer, a free drainage boundary for the lower unsaturated zone boundary is assumed.

2.3 Overland Flow

Ponded water can occur, for example, when rainfall cannot infiltrate fast enough, when groundwater flows onto the surface (e.g. in wetlands), or when streams flood over their banks. Ponded water is routed downhill as surface runoff. The flowpath and quantity is determined by the topography and flow resistance, as well as losses due to evaporation and infiltration along the path it takes. Water flow on the ground surface is calculated using a finite-difference, diffusive wave approximation of the Saint Venant equations, or using a semi-distributed, slope-zone approach based on the Mannings equation.

2.3.1 Finite Difference Method

For two-dimensional surface water flow, it is common to simplify the governing equations by neglecting momentum losses due to lateral inflows, and local and convective accelerations. This is known as the diffusive wave approximation, which is implemented in MIKE SHE using a 2D, finite-difference approach.

Net rainfall, evaporation and infiltration are introduced as source/sinks, allowing the surface to dry out in more permeable soil areas. The solution assumes a sheet flow approximation, which may be crude for regional applications. Local depressions in the topography, as well as barriers, such as roads and levies, are conceptually modeled as detention storage. Detention storage restricts overland flow and allows water to more easily evaporate or infiltrate.

Ponded water is transferred to and from and the other hydrologic components at the beginning of every overland flow time step. Normally, overland flow is solved using the same time step as the unsaturated flow, whenever unsaturated flow is included in the model. Otherwise, the overland flow is calculated using the saturated flow time step. However, overland flow can be calculated using a completely independent time step, if necessary.

2.3.2 Semi-distributed Overland Flow

The semi-distributed model for overland flow in MIKE SHE is based on an empirical relation between flow depth and surface detention, together with the Manning equation describing the discharge under turbulent flow conditions. Such a method was implemented in the Stanford watershed model (Crawford and Linsley, 1966) and its descendants, such as HSPF (Donigian et al., 1995), and has been applied in other codes such as the WATBAL model (Refsgaard and Knudsen, 1996).

This semi-distributed conceptual overland flow uses a simplified representation of flow down a hillslope to describe surface flow within a topographical zone. The drainage of overland flow from one topographic zone to the next, and from the catchment to the river channels is represented conceptually as a cascade of overland flow areas. In the semi-distributed method, the current level of surface detention storage is continually estimated by iteratively solving the continuity equation. Overland flow interacts with the other process components, such as evapotranspiration, infiltration, and drainage to the channel network. These interactions are treated in the same manner in both the semi-distributed and the 2D finite-difference methods.

2.4 Channel Flow

Topography channels overland flow into small rivulets, streams and eventually rivers. Since, streams and rivers are found in low-lying areas, they also tend to be discharge points for groundwater. If topography and streambed bathymetry are known in enough detail, then channel flow can be calculated as two-dimensional surface flow (e.g. Sudicky et al., 2002). However, this requires very detailed elevation data and a large computational effort, even for small watersheds. The alternative is to assume that rivers are one-dimensional, which leads to a uniform surface elevation and flow rate across the channel. This is reasonable for most cases but may be untenable in detailed studies of river scour, bank erosion and other local phenomena where a detailed velocity distribution is important.

In MIKE SHE, the one-dimensional assumption is used and 1D channel flow is calculated by DHI's MIKE 11 program. MIKE 11 computes unsteady water levels and flow in rivers and estuaries using an implicit, 1D, finite-difference formulation. In the most advanced case, the complete non-linear equations of open channel flow (Saint-Venant) are solved using the 6-point Abbott-Ionescu method (Havnø et al. 1995). Alternatively, the diffusive wave, kinematic wave, and quasi-steady state approximations can be used. The program can be applied to branched and looped networks, and to quasi two-dimensional flow on flood plains. It is applicable to vertically homogeneous flow conditions ranging from steep rivers to tidally influenced estuaries. Both subcritical and supercritical flow can be calculated, depending on the local flow conditions. The flow over a wide variety of structures can also be simulated, such as broad-crested weirs, culverts, regulating structures, control structures, bridges and user-defined structures.

MIKE 11 also includes simple hydrologic routing methods, which are suitable when the detailed flow dynamics in the river are not of interest. The routing methods included in MIKE SHE are the Muskingum and the Muskingum-Cunge methods, as well as instantaneous flow routing. The former two methods account for the time it takes for a water pulse to move downstream, whereas the instantaneous method routes the flows through the system in a single time step.

2.4.3 Coupling between MIKE SHE and MIKE 11

The MIKE 11 river network is made up of digitized points (chainage locations) and calculation nodes (cross-section points). This river network is interpolated to the edges of MIKE SHE's rectangular grid for overland and saturated flow exchange with MIKE 11. Since the exchange occurs on the edges between grid cells, the more refined the MIKE SHE grid is, the more accurately the spatial distribuion of the exchange will be represented. The entire river system is always included in the hydraulic model, but MIKE SHE will only exchange water with the sub-set of the MIKE 11 river model that intersects the MIKE SHE overland flow/groundwater grid.

The calculated exchange flows are fed to MIKE 11 as lateral flow to or from the corresponding calculation points. Where floodplain inundation is allowed to occur, the water levels at the MIKE 11 calculation points are interpolated to specified MIKE SHE grid cells to determine if ponded water exists on the cell surface. If ponded water exists, then the unsaturated or saturated exchange flows are calculated based on the ponded water level above the cell.

2.5 Pipe and Sewer Flows

Urban drainage systems, sanitary and storm sewers affect surface and subsurface hydrology in urban areas. They can drain both overland flow and groundwater, and they can cause contamination of both surface water and groundwater. MIKE SHE can be coupled to the MOUSE sewer model (Mark et al, 2004, Lindberg et al, 1989) to simulate the effect of urban drainage and sewer systems on the surface/subsurface hydrology. MOUSE can simulate 1D, unsteady flow and water quality in branched and looped pipe networks, with a mixture of free surface and pressurized systems. Groundwater in MIKE SHE can be coupled to MOUSE's pipe network, based on the wetted perimeter and a leakage coefficient. MIKE SHE's overland flow can drain to open sewer canals and unsealed manholes. Lastly, drainage from MIKE SHE's saturated zone and paved areas can be discharged to a specific manholes.

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2.6 Saturated Groundwater Flow

Groundwater plays a significant role in the hydrological cycle. During drought periods groundwater discharge sustains stream flow. Irrigation and abstraction can influence natural recharge and discharge, thereby changing the flow regime in a catchment. However, watershed scale models for planning purposes typically do not require detailed knowledge of water movement but information on water balances and trends. On the other hand, sub-watershed models for assessing wetland impacts of a new water works will require detailed analysis of groundwater/surface water interaction. This range of detail can be handled in MIKE SHE by using a fully implicit, 3D finite-difference scheme similar to MODFLOW, or a conceptual, linear reservoir approach.

2.6.1 Finite Difference method

In MIKE SHE, the spatial and temporal variations of the hydraulic head in the saturated groundwater zone is described mathematically by the 3D Darcy equation and solved numerically by an iterative implicit finite difference technique. There are two groundwater solvers available: a successive over-relaxation (SOR) technique and a preconditioned conjugate gradient (PCG) technique, which is nearly identical to the one used in MODFLOW (Hill, 1990).

Also similar to MODFLOW, MIKE SHE includes sub-surface agricultural drains. However, by routing the water collected in the drains to streams or sewers, MIKE SHE is able to use the drainage function to conceptually model the impact of near surface drainage on the surface water hydrograph.

2.6.2 Linear Reservoir method

Representing natural catchments with detailed groundwater models is often problematic due to data, parameter estimation and computational requirements. In this case, subsurface flow can often be described satisfactorily by a conceptual approach. The conceptual method can be viewed as a compromise between limitations on data availability, the complexity of hydrological response at the catchment scale, and the advantages of model simplicity.

In the linear reservoir method, the entire groundwater catchment is subdivided into groundwater sub-catchments. Each sub-catchment is divided into a series of serial, shallow reservoirs, plus one, or more, deep baseflow reservoirs. Each baseflow reservoir is further subdivided into two parallel reservoirs. The parallel reservoirs can be used to differentiate between fast and slow components of baseflow discharge and storage. Water will be routed through the linear reservoirs as interflow and baseflow and subsequently added to the river as lateral inflow in the lowest interflow reservoir.

2.7 Agriculture

Pasture and crops take up 37% of the Earth's land area and approximately 70% of all available fresh water is used for irrigation (UNESCO, 2003). However, in most settings water for irrigation is neither metered, nor easily forecast because irrigation is applied only when it is required. Irrigation is further complicated by water rights and complex management rules. MIKE SHE's Irrigation Module can simulate a wide range of irrigation practices with multiple sources. Irrigation management can be simulated using distributed temporal crop water demand. It includes the conjunctive use of surface and groundwater with the option of setting irrigation priorities and control strategies based on soil moisture levels.

MIKE SHE is also frequently used with DAISY, a detailed soil-plant-atmosphere model (Hansen et al., 1990; Abrahamsen and Hansen, 2000). DAISY has been optimized to work as an open and flexible agro-ecosystem modeling system, well suited for agricultural related studies. DAISY can be used to model changes in crop yield as a function of water and nitrogen availability, irrigation optimization and nitrate and pesticide leaching. When used with MIKE SHE, DAISY replaces MIKE SHE's unsaturated zone and vegetation/ET processes.

2.8 Water Quality

Advection/dispersion methods are used to address problems where the exchange of contaminants between the hydrologic processes is important - that is transport in and exchange between overland flow, channel flow (MIKE 11), unsaturated flow, and saturated groundwater flow. The advection/dispersion equation is solved by the explicit QUICKEST method (Leonard, 1979). MIKE SHE can simulate transport of water and solutes in macropores, with exchange to the surrounding bulk matrix. It can also simulate equilibrium and kinetic sorption (including hysteresis), first-order decay that depends on soil temperature and soil moisture content, sequential biodegradation, and plant uptake with transpiration. In addition to the advection/dispersion method, a random walk particle tracking method is also available for the saturated groundwater zone.

Ecological modeling is a relatively immature discipline that involves many different processes and networks of interacting subsystems. To this end, a general ecological modeling tool (ECOLab) has been developed that enables engineers and ecosystem experts to develop their own ecosystem models appropriate to site specific ecological conditions. ECOLab is now linked to MIKE 11, to address problems such as eutrophication, and the retention and removal of nutrients and pollutants in wetlands.

2.9 Parameter Estimation, Auto-calibration, and Sensitivity Analysis

A deterministic model will be subject to uncertainty. The uncertainty arises because the mathematical process descriptions are not true reflections of the underlying physical processes. Add to this, measurement error, sub-grid scale variability of parameters, and inexact initial and boundary conditions. This inevitably leads to a range of possible models that are equally probable yet may have quite different outcomes.

MIKE SHE includes a set of tools for automatically adjusting model parameters in response to model outcomes (Madsen, 2003). MIKE SHE's auto-calibration tool is based on the global search, Complex Shuffled Evolution (SCE) algorithm. Global search methods are particularly well suited to hydrologic models because the objective function is rarely smooth with respect to the parameter values, which can cause trouble for gradient based methods. MIKE SHE's AUTOCAL tool can calibrate to multiple objective functions, with

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automatic weighting. Also available is a set of tools for automatically distributing the model simulations across an office network to efficiently take advantage of unused computer resources.

2.10 Water Budgeting

The hydrologic cycle is all about water exchange and the analysis of this exchange is the water budget. Questions regarding sustainability and environmental impacts are directly related to the water budget. Since MIKE SHE includes all of the processes in the hydrologic cycle, MIKE SHE includes a sophisticated water budgeting tool for summarizing, mapping and plotting the exchange of water between all of the hydrologic processes.

4. LOOKING AHEAD

MIKE SHE continues to be extended and enhanced by DHI to meet the needs of its growing user community. Some of the more important developments are described below.

MIKE SHE, together with MIKE 11, is being used to meet the growing need for flood modeling, flood forecasting and flood hazard assessment. MIKE SHE, together with MOUSE, is being used to calculate the impacts of urban flooding. However, the propagation of flood waves and detailed 2D surface flow is difficult on flat terrain when infiltration is important. To address this problem, we are linking 2D surface water models (using MIKE 21) to MIKE SHE.

Several initiatives are in progress to keep up with the advances in computer architecture. These include migrating the code to the new 64-bit processors, optimizing the code for parallel processing, adding faster multi-grid solvers, and upgrading the numeric engines to run on alternative operating systems.

The EcoLab tools add complete flexiblity for water quality calculations in surface water. The same flexibility will be available for all of the hydrologic processes in MIKE SHE when the EcoLab toolbox is fully implemented in MIKE SHE.

Significant advances have been made in MIKE 11 to account for a variety of ice conditions, as well as freezing and thawing in the river channel. We are working to add important processes for spring flooding, such as latent heat and the moisture content and temperature of the snow pack, as well as the influence of frozen soils on runoff generation.

Many users want to link MIKE SHE to their own codes to simulate specific processes, such as vegetation growth code, or economic optimization. This will be possible in the near future thanks to the HarmonIT project (www.harmonIT.org) of which DHI is one of the lead partners. The HarmonIT project is an EU-sponsored research initiative to create and prove an Open Modeling Interface (OpenMI), which is a set of standards and tools for linking disparate hydrologic modeling codes together. For example, the OpenMI concept is being used to couple MIKE SHE to meteorological models to examine atmospheric feedbacks in the hydrological cycle.

5. SUMMARY

It is no longer acceptable to manage groundwater and surface water independently of one another. Advances in data collection and availability, as well as computer resources, have now made distributed, physics-based watershed modeling feasible in a wide range of applications. MIKE SHE is one of the few commercially available codes that has been widely used for integrated hydrologic modeling. MIKE SHE's process based framework allows each hydrologic process to be represented according to the problem needs at different spatial and temporal scales. This flexibility has allowed MIKE SHE to be applied at spatial scales ranging from single soil profiles, to the field scale, and up to the watershed scale. Furthermore, each process can be represented at different levels of complexity. MIKE SHE has a modern, Windows-based user interface that includes advanced tools for water quality, parameter estimation and water budget analysis. MIKE SHE is continually being developed and extended and will soon be capable of detailed flood modeling, include more advanced water quality models, and be part of a growing community of OpenMI compliant hydrologic modeling tools.

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