Presented in Proceeding of IAHR International Groundwater Symposium - Flow and Transport in Heterogeneous Subsurface Formations: Theory, Modelling & Applications, Istanbul, Turkey, June 18-20, 2008.

Evolution of an integrated surface water-groundwater hydrological modelling system

MICHAEL BUTTS & DOUGLAS GRAHAM
DHI Water & Environment, Agern Alle 5, Hørsholm, DK 2970 Denmark
e-mail: mib@dhigroup.com

Abstract Integrated hydrological modelling has become an essential tool in watershed management, with two fundamental roles. The first is to improve the understanding of the physical, chemical and biological processes in a watershed and the way they interact. The second, more practical role is to use this understanding to manage and protect water resources and the water environment. This paper presents the evolution of the MIKE SHE catchment modelling tool from a hydrological research code based on the 1969 blueprint of Freeze and Harlan, to the flexible, engineering and research water management framework it is today. This evolution is illustrated by several examples that highlight the changing needs of water resource management at the catchment scale. It traces this evolution from the first applications in Europe and India when MIKE SHE was initially developed 30 years ago to the most recent applications in modelling the complex surface water groundwater interactions in Florida, USA and exploiting remote sensing in data-sparse regions in Africa. Hydrological modelling continues to evolve towards higher resolution and integrating more complex phenomena, such as ecological conditions and climate effects. Fortunately, this is supported by parallel trends in computational resources (e.g. parallel processing, distributed computing) and software capabilities (e.g. OpenMI for linking models). Yet, modelling issues related to scale effects, subgrid processes and interpreting sparse data sets remain unresolved.
Key words integrated modelling, surface water-groundwater interaction, MIKE SHE, MIKE 11

INTRODUCTION

"A complete physically-based synthesis of the hydrologic cycle is a concept that tantalizes most hydrologists"

This vision stated by Freeze and Harlan, 1969 continues to fascinate today, nourished by growing concern over climate change and the ever-increasing complexity of water resource management at the catchment scale. From a European perspective, water managers must address the complementary aspects of Water Framework Directive and the Floods Directive, which requires the integration of both surface water and groundwater. Surface water and groundwater have been, by tradition, managed separately, often in completely different branches of government. However, water resources problems cannot be treated in isolation and it may be necessary to treat the entire water pathway from rainfall to the coast, including surface water, groundwater and urban pipe and drainage systems. Solutions require a holistic approach to water management that must address different, often conflicting, demands for water. Problems like wetland protection and the conjunctive use of surface water and groundwater typically also involve issues of water chemistry and ecology.

Freeze and Harlan (1969) proposed a blueprint for the digital modelling of the hydrologic cycle based on their assessment of the feasibility of the development of a “rigorous”, physically-based mathematical model of the complete hydrological system. In this original blueprint, it was argued that if each of the component processes within the hydrological cycle can be described by an exact mathematical representation then it should be possible to model the different flow processes using their governing partial differential equations. Interestingly, they put forth, a set of questions that must be answered before such a framework would be successful which can be paraphrased as follows; 1. Do we have the science? 2. Do we have the data? 3 Do we have the computational resources? However, we believe one more question should be added; Do we have the institutional maturity? This paper is an attempt to look back and see if the MIKE SHE model has been able to answer these questions and examine the way forward for integrated distributed hydrological modelling.

EVOLUTION OF SHE

In 1977 a consortium of three European organizations began the development of the Système Hydrologique Européen (SHE) (Abbott et al., 1986a & b) based on the blueprint of Freeze & Harlan. The aim of this development was to produce a general, physically-based, distributed modelling system for constructing and running models of all or any part of the land phase of the hydrological cycle for any geographical area. Each of the hydrological processes of water movement were modelled, either by finite difference representations of the partial differential equations of mass, momentum, energy conservation, or by empirical equations derived from independent experimental research, (Abbott et al., 1986b). Each process of the hydrological cycle was allocated to a single component. The development of each component was assigned to different organisations. In the final code, the simultaneous operation of all the components was controlled by a central FRAME component. By 1978, it was possible to develop and test the first SHE model on the River Wye catchment in Wales. However, it took a further four years of testing and development before the code became officially operational in 1982, (Abbott et al. 1986a & b).

Refsgaard et al., 1992, and Jain et al., 1992 describe one of the early applications of SHE. In this application, SHE is used as a practical engineering tool in a number of basins in India, based on engineering project work from the late 1980s. As in many of the initial applications, SHE simulation results were compared to discharge hydrographs. While this is a useful test of the ability of the models to represent the rainfall-runoff process at the catchment scale, the real strength of distributed modelling is in their ability to make predictions at internal points within a catchment rather than just at the catchment outlet. Furthermore, several subsequent studies have shown that if the goal of the model is only to reproduce catchment outflows, then lumped and semi-distributed conceptual modelling approaches are difficult to beat.

Nevertheless, these early studies identified several of the advantages and limitations of this physics-based, distributed modelling approach. One of the recurring observations at the time was that the data requirements for SHE were substantial especially when compared to simpler conceptual and empirical hydrological models. Secondly the fundamental problems of the heterogeneity parameters and processes and the need to treat this at the subgrid scale were recognised (Beven, 1989). As pointed out by Beven 1996, many currently available distributed models can be considered as lumped conceptual models at the grid scale and it is questionable whether the equations used are physically valid at the grid scale. Finally, while these early simulations were carried out at different spatial resolutions, computational limitations restricted the operational simulations were made on 2 km square grid cells.

Thus, returning to the questions posed by Freeze & Harlan, data was generally available but hard to get, partly because it resided in many different organisations and not in electronic format. This was especially true for high resolution data sets. In terms of the science, while the governing partial differential equations derived from controlled small scale experiments were known, their applicability at the field scale or for modelling was the subject of scientific debate. Finally, computational resources at the time were a limiting factor for engineering applications.

MIKE SHE

The commercial integrated hydrological modelling framework, MIKE SHE, emerged from the original SHE development in the late 1980s. Since then MIKE SHE has been further developed and extended by DHI. Today, MIKE SHE is an advanced, flexible framework for hydrologic modelling (Fig.1). It includes a full suite of pre- and post-processing tools, (Refsgaard & Storm, 1995) plus a flexible mix of advanced and simple solution techniques for each of the hydrologic processes (Butts et al., 2004, Graham & Butts 2006). MIKE SHE covers the major processes in the hydrological cycle and includes process models for evapotranspiration, overland flow, unsaturated flow, groundwater flow, and channel flow and their interactions.

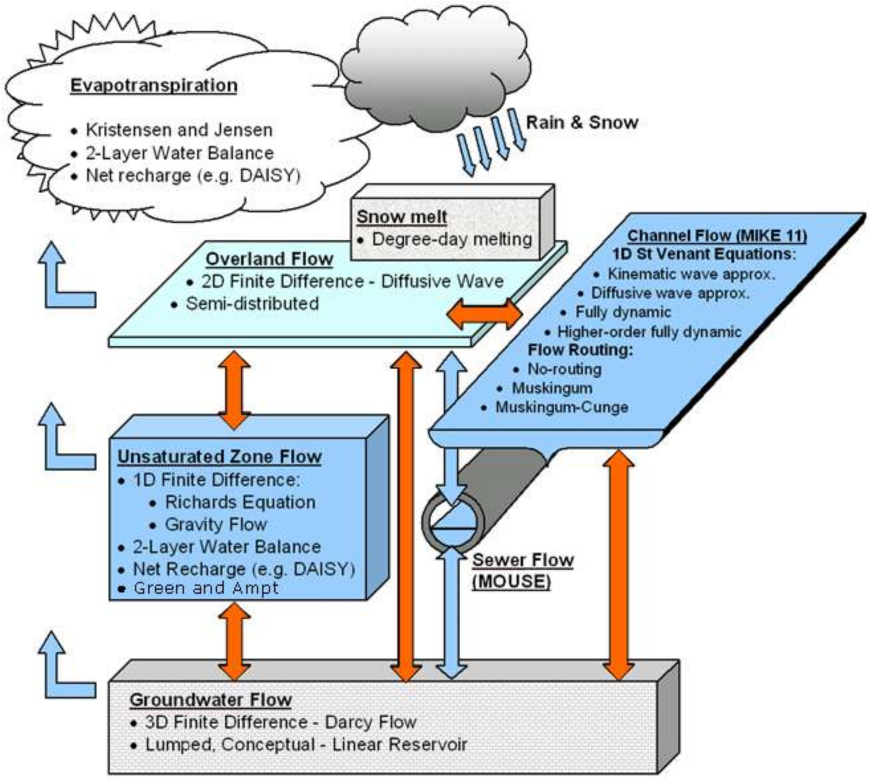

Fig. 1 Schematic view of the process in MIKE SHE, including the available numeric engines for each process. The arrows show the available exchange pathways for water

between the process models. The shaded arrows show the available pathways for solute transport.

Each of these processes can be represented at different levels of spatial distribution and complexity (Fig. 1), according to the goals of the modelling study, the availability of field data and the modeller'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 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, (Fig 1).

MIKE SHE has been widely applied in many hydrological regimes and to many water resources and environmental problems ranging from remediation of groundwater and surface water contamination from waste disposal, to river basin planning, floodplain studies and the impact of land use and climate change on water resources. A recent list of published applications can be found in Graham & Butts (2006), together with a more detailed overview of MIKE SHE. The detailed mathematical background is available in the MIKE SHE Reference manual, which can be downloaded from the DHI web site.

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 modelling 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), which can be used to simulate the interaction between urban storm water and sanitary sewer networks and groundwater.

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 modelling 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), which can be used to simulate the interaction between urban storm water and sanitary sewer networks and groundwater.

Recent Applications

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 a fully distributed conceptual approach to model the watershed processes. 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.

Two recent but quite different applications of MIKE SHE are presented here to illustrate how this flexibility can be exploited. The first is from a data-rich environment in South Florida, USA where detailed physics-based river and groundwater modelling is required. The second is a large-scale hydrological catchment model in a data poor region in Africa using conceptual process representations together with satellite remote sensing data.

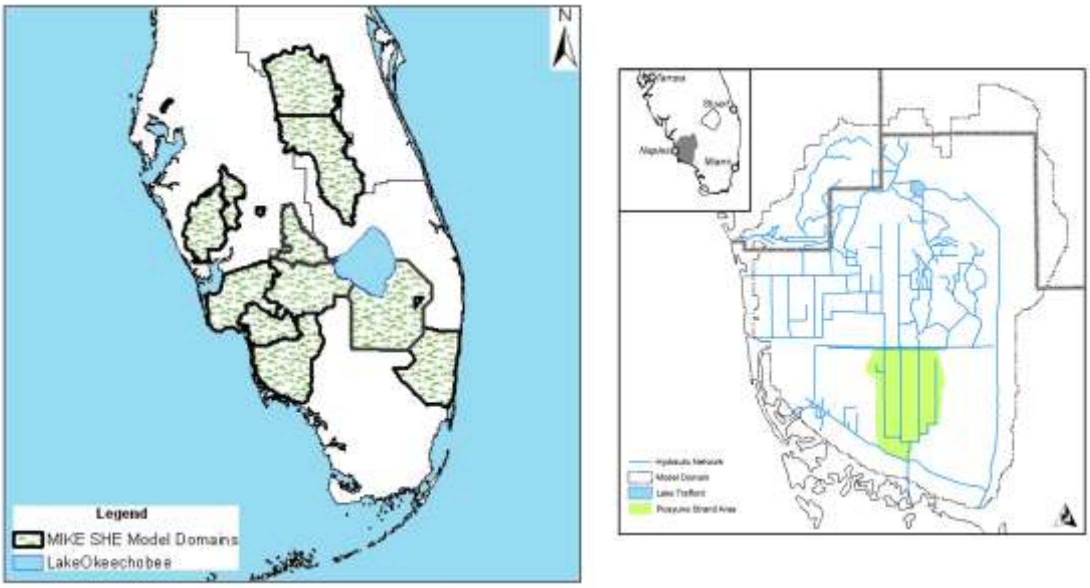

Fig. 2 Coverage of local models developed in South Florida using MIKE SHE (left) and the location and surface drainage network of the Big Cypress Basin (right)

Big Cypress Basin

The South Florida Water Management District (SFWMD) manages and protects the state's water resources on behalf of 7.5 million South Floridians and is the lead agency in restoring America's Everglades – the largest environmental restoration project in US history. Many of the projects to restore and protect the Everglades ecosystem are part of the Comprehensive Everglades Restoration Plan (CERP). The region has a unique hydrological regime, with close connection between surface water and groundwater, and a complex managed drainage network with many structures. Added to the physical complexity are the conflicting needs of the ecosystem for protection and restoration, versus the substantial urban development with the accompanying water supply, water quality and flood control issues.

MIKE SHE/MIKE11 has been applied to a number of local studies throughout the Florida region (Fig. 2) complementing the SFWMD regional model. The Big Cypress Basin (BCB) model is based on the model developed earlier in the Picayune Strand Restoration Project (PRSP), a component of the CERP. The Big Cypress Basin includes 272 km of primary canals and 46 water control structures throughout the area (Fig 2) that provide limited levels of flood protection, as well as water supply and environmental quality. The BCB model covers an area of 3092 km^2. It has been applied in various projects and has been continuously updated. The calibrated and verified BCB model was applied to two historic flood events, tropical storm Jerry August 23-25, 1995) and tropical storm Harvey (September 19-21, 1999). Detailed maps of land-use, topography, etc. are available. The BCB model was calibrated against more than 58 groundwater levels, as well as 4 discharge and 26 water level stations in the surface network. The median overland water depths predicted by the model during the 1995 wet season are shown in Fig. 3. The BCB model is able to represent the effects of different management and restoration options in both the surface water and the groundwater.

Currently, the model is being linked with the SFWMD SCADA systems to create a real-time decision support system (BCB Real Time Hydrologic Modeling System) for real-time monitoring of the basin and forecasting for flood warning, flood mapping and operational decision-making.

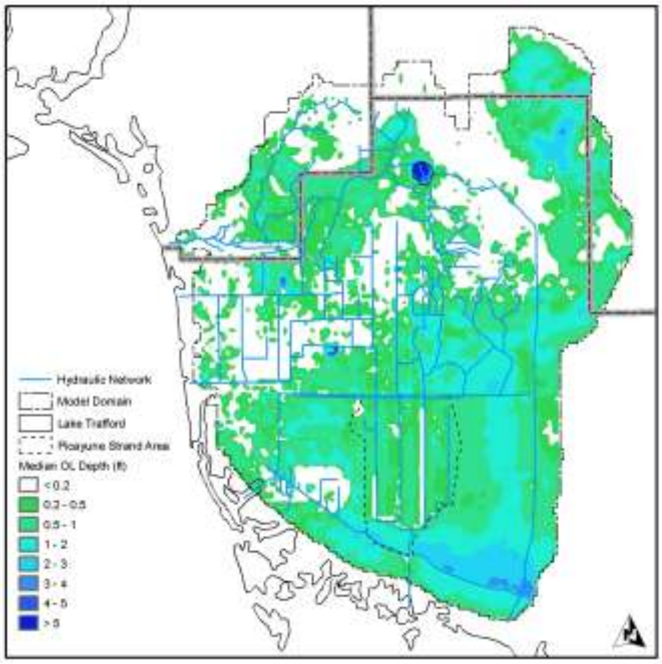

Fig. 3 Median overland water depths over the Big Cypress Basin during the 1995 wet season

Senegal River Basin

In large remote catchments, rainfall gauges are sparse and land-use maps are poor or even non-existent. In such cases, lumped-parameter catchment models are typically used. However, this may limit the ability of decision makers to use the model for analyzing the hydrologic impacts caused by changes in distributed characteristics, such as rainfall patterns, land use and vegetation. To counter this limitation of lumped parameter catchment models, Stisen et al (2008) describe a MIKE SHE-based model for the Senegal River basin, where all the hydrologic forcing functions (i.e. rainfall, reference ET, and LAI) are derived entirely by remote sensing.

The Senegal River basin is 350,000 km2 covering parts of four West African countries. There is a distinct seasonality in the rainfall, as well as a steep rainfall gradient across the basin where the rainfall ranges from 200 mm/year in the northern savannah to 1800 mm/year in the southern tropical forest. In the entire basin, there are only seven discharge stations, five rainfall stations, and one ET station. The subsurface information is particularly sparse. In the model, the spatial parameters were defined on a 6 km x 6 km model grid. MIKE SHE’s linear reservoir groundwater component was used for the saturated groundwater zone, whereas the gravity flow module was used for the vertical unsaturated flow. Sub-grid variability of recharge is conceptually included by means of the MIKE SHE bypass option. Remotely sensed potential evapotranspiration and rainfall are derived from the geostationary METEOSAT 7 visible and infrared data. Remotely sensed LAI distribution is calculated from the normalized difference vegetation index (NDVI), which is based on the reflective spectral signature of vegetation compared to other land covers. Spatial variability of the vegetation root depth is correlated to the LAI. The model was auto-calibrated, (Madsen, 2003) with an objective function based on the RMSE of at the seven gauging stations.

Stisen et al., (2008) demonstrate the potential for creating detailed hydrologic models in large catchments with sparse data. Up-to-date, satellite data is becoming more accessible and at a much lower cost than ever before, making near-real time simulations possible in large remote catchments. Much of the satellite data has a long historical record (some more than 25 years) making it possible to determine historical trends. This is essential if we are to be confident when predicting impacts of future land use and climate change. However, Stisen et al, point out the need for further research in scaling and calibration of distributed and semi-distributed models based on remotely sensed data.

CURRENT TRENDS AND CONCLUSIONS

It can be argued that technological advances have reduced many of the data and computational barriers to the application of distributed modelling. One of the more important advances is the increasing availability of new data sources. These include, wireless sensor networks, satellite remote sensing, ground and aerial-based geophysical measurements. Also, more data is becoming available at greater spatial and temporal resolution, such as high resolution digital terrain models and radar-based precipitation distribution. Combined with increased access to spatial data via GIS, databases and the Internet, hydrologists now have access to unprecedented quantities of data. However, the cost of obtaining high quality, long-term observational datasets are still high and in developing countries prohibitive. Furthermore, it appears that the investment in traditional observational networks is declining

Another important advance is the exponential growth of both computer processor speeds and data access. However, there is a strong opposing trend toward more comprehensive and complex models. These opposing trends mean that our models always seem to be constrained by computer resources. The trend towards large models is driven by several factors. Firstly, there are a growing number of complex regulatory and political developments such as the EU Water Framework directive, the US Clean Waters Act, National Water Acts. Thus, models are becoming more complex as more interactions must be accounted for and additional processes included describing temperature, water chemistry and quality, erosion and sediment transport, and ecological conditions. Secondly, since high resolution datasets of, for example topography and land-use, are available, modellers are expected to exploit these using high resolution models.

In tracing the evolution of the MIKE SHE model, it appears that significant progress has been made towards solving the challenges posed in the original blueprint.

However, the challenges remain open. The science challenges have moved towards understanding hydrology in a more holistic sense. Vastly more data is available today, but there remain significant challenges in how we use it. Computational advances are locked in an arms race with increasingly complex models. Finally, progress towards solving the institutional challenges is inhibited by institutional inertia. In the meantime, a number of drivers and trends are shaping the current development of hydrological models. Water resources and environmental engineers require modelling tools that are more complex but simple to use, more flexible and adaptable in their formulations and more directly and conveniently linked to the processes for exploring future scenarios and decision-making such as the BCB Real-time Hydrologic Modeling System. The most recent developments of the MIKE SHE modelling system strongly reflect these trends. Integration of water flows in the surface water system, the subsurface and in urban pipe networks allows more accurate representation of the flow paths and water balance. Water quality processes in all components of the water cycle are represented and linked to crop growth, irrigation demand, and sediment transport. Integrated ecological and habitat modelling is now available. To ensure that all available data are used and that the mathematical representation matches the available data, MIKE SHE allows both conceptual and physics-based representations of the hydrological processes. Thus, the model can be tailored to represent the processes at different scales and different levels of spatial discretisation from fully lumped to fully distributed approaches. Most recently, the MIKE SHE is being coupled to other models and new process description models using the OpenMI framework This provides not only additional flexibility, but also permits the use of MIKE SHE as a test bed for new process models and new model couplings. For example, the OpenMI approach is being used to couple MIKE SHE with meteorological models to explore issues concerning feedback and scale in climate change predictions, (Overgaard et. al., 2007).

The tantalizing prospect of a completely physically-based hydrological model is closer today that ever. Several research institutes are carrying this banner forward. However, we believe the real need today is more flexibility - flexibility to use the available data in the best possible way; flexibility to tailor the model to the available computational resources; and flexibility to fit the model into the project and institutional needs.

REFERENCES

Abbott, M. B., Bathurst, J. C., Cunge, J. A., O'Connell, P.E. and Rasmussen, J. (1986) An introduction to the European Hydrological System—Systeme Hydrologique Européen, SHE. 1 History and philosophy of a physically-based distributed modelling system. *J. Hydrol.* **87**, 45–59.

Abbott, M. B., Bathurst, J. C., Cunge, J. A., O'Connell, P. E. and Rasmussen, J. (1986) An introduction to the European Hydrological System—Systeme Hydrologique Européen, SHE. 2 Structure of a physically-based distributed modelling system. *J. Hydrol.* **87**, 61–77.

Beven, K. (1989) Changing ideas in hydrology – the case of the physically based models, *J. Hydrol.* **105**, 157-172.

Beven, K. J. (1996) A discussion of distributed hydrological modelling, *Distributed Hydrological Modelling* (ed. by M. B. Abbott and J. C. Refsgaard, Kluwer Academic, Dordrecht, 255-278.

Butts, M. B., Payne, J. T., Kristensen, M. and Madsen, H., An evaluation of the impact of model structure on hydrological modelling uncertainty for streamflow prediction, *J. Hydrol.* **298**, 242-266.

Freeze, R.A., and Harlan, R.L. (1969) Blueprint of a physically-based, digitially simulated hydrologic response model, *J. Hydrol.* **9**, 237-258.

Graham, D.N. and M. B. Butts (2006) Flexible, integrated watershed modelling with MIKE SHE. *Watershed Models*, (ed. by V.P. Singh & D.K. Frevert) CRC Press. 245-272, ISBN: 0849336090.´

Havnø, K., Madsen, M.N. and Dørge, J. (1995) MIKE 11 - A generalised river modelling package, *Computer Models of Watershed Hydrology* (ed. by V. P. Singh) Water Resources Publications, Colorado, USA, , 809-846.

Jain, S.K., Storm, b. Bathurst, J.C., Refsgaard, J. C and Singh, R. D. (1992) Application of the SHE to Catchments in India - Part 2: Field Experiments and Simulation Studies with the SHE on the Kolar Subcatchment of the Narmada River, *J. Hydrol.* **140**, 25-47.

Madsen, H. (2003) Parameter estimation in distributed hydrological catchment modelling using automatic calibration with multiple objectives, *Adv.Water Resour.* **26**, 205-216.

Mark, O., Weesakul, S., Apirumanekul, C., Boonya Aroonet, S., and Djordjevic, S. (2004) Potential and limitations of 1D modeling of urban flooding. *J. Hydrol.* **299**, 284-299.

Overgaard, J., Butts, M. B. and Rosbjerg, D. (2007) Improved scenario prediction by using coupled hydrological and atmospheric models, *Quantification and Reduction of Predictive Uncertainty for Sustainable Water Resources Management* (ed. by E. Boegh, H. Kunstmann, T. Wagener, A. Hall, L. Bastidas, S. Franks, H. Gupta, D. Rosbjerg& J. Schaake), IAHS Publ. no. 313, 242-248.

Refsgaard, J. C, Seth, S. M., Bathurst, J. C., Erlich, M., Storm, B., Jørgensen, G. H., Chandra, S.(1992) Application of the SHE to Catchments in India - Part 1: General Results, *J. Hydrol.* **140,** 1-23.

Refsgaard, J.C. and Storm, B.(1995) MIKE SHE, In *Computer Models of Watershed Hydrology* (ed. by V.P. Singh) Water Resources Publications, Colorado, USA, 809-846.

Stisen S, K. H. Jensen, I. Sandholt, D. Grimes (2008) A remote sensing driven distributed hydrological model of the Senegal River basin,, *J. Hydrol.* (Accepted) doi:10.1016/j.jhydrol.2008.03.006

Storm, B. and Refsgaard, A. (1996) Distributed physically-based modelling of the entire land phase of the hydrological cycle, *Distributed Hydrological Modelling* (ed. by M. B. Abbott & J. C. Refsgaard) Kluwer Academic, p55-70.