Process-based Hydrological Modelling Framework MIKE SHE for Flood Forecasting on the Upper and Middle Odra

M. B. Butts[1], J. Overgaard[1], D. Graham[1], A. Dubicki[2], K. Strońska[2], W. Szalinksa[2,4], A. Lewandowski[3], T. Olszewski[3], T. Kolerski[3], O. Larsen[5]

[1] DHI Water & Environment, Agern Alle 5, DK 2970 Hørsholm, Denmark
e-mail: mib@dhi.dk
[2] Instytut Meteorologii i Gospodarki Wodnej, IMGW-Wroclaw, P.O. Box Wroclaw 12,
Parkowa 30, 51-616 Wroclaw, Poland
[3] Geoscience and Marine Research & Consulting Co., Ltd., GEOMOR,
ul. Koscierska 5 80-328, Gdańsk, Poland
[4] Meteo France, Centre de Meteorologie Radar, Direction des Systemes d'Observation 7,
rue Teisserenc-de-Bort, 78195, Trappes, France
[5] DHI Wasser & Umwelt GmbH, Krusenberg 31, 28857 Syke, Germany
e-mail: ola@dhi-umwelt.de

Condensed abstract: Distributed hydrological modelling has the potential to improve estimates of streamflow and water levels both for hydrological simulation and for flood forecasting (Smith et al. 2004). The increased focus on distributed modelling approaches to flood forecasting is motivated by increasing access to high resolution operational rainfall estimates by meteorological modelling, radar and satellite remote sensing, as well as GIS databases of catchment properties and increasing computer power. One of the central objectives of the EU 5th framework project FLOODRELIEF (http://projects.dhi.dk/floodrelief/) is to develop improved methods for flood forecasting by exploring new approaches to distributed modelling. Within FLOODRELIEF a novel and flexible grid-based flood forecasting model has been developed based on the MIKE SHE modelling system. This new modelling tool was applied within the Distributed Model Intercomparison Project DMIP to modeling of the US National Weather Service study catchment, the Blue River Basin using NEXRAD radar-based precipitation fields. Currently this novel distributed hydrological modelling framework is being applied to the Upper and Middle Odra river in Poland. In this paper, the performance of the modelling system for these two study catchments is examined.

Key words: Distributed modelling and flood forecasting

1 INTRODUCTION

New developments of grid-based hydrological modelling have been spurred by increasing access to meteorological modelling, radar and satellite remote sensing. Together with the availability of comprehensive hydrological databases including GIS data, these new developments allow hydrologists to build and use more comprehensive distributed hydrological models. The challenge of using such models in flood forecasting is that these more detailed and sophisticated models are computer intensive in flood situations where forecasts must be produced quickly, i. e. a trade-off between model complexity and accuracy on the one hand and the need for rapid flood forecasts. Part of this trade-off is the need to represent in sufficient detail to capture the spatial variations in the hydrological parameters, meteorological driving variables and catchment responses. This leads to the scientific question, what level of spatial variability needed to accurately predict flooding? Traditionally flood forecasting has focused on predicted flows and water levels in which case it can be argued that simpler hydrological descriptions are the most appropriate. However there is an increasing demand for ever higher levels of spatial resolution and accuracy together with a need to treat flood modelling as an integrated component of water resource management.

2 THE FLOODRELIEF PROJECT

FLOODRELIEF is supported by the European Commission under the Fifth Framework Programme and contributing to the implementation of the Key Action "Sustainable Management and Quality of Water" within the Energy, Environment and Sustainable Development, Contract EVK1-CT-2002-00117. The FLOODRELIEF project (http://projects.dhi.dk/floodrelief/) aims to

- develop and demonstrate a new generation of flood forecasting methodologies which will advance present capabilities and accuracies and
- to make the results more readily accessible both to flood managers and those threatened by floods.

This is achieved by exploiting and integrating different sources of forecast information, including improved hydrological and meteorological model systems and databases, radar, advanced data assimilation procedures and uncertainty estimation, into real-time flood management decision support tool designed to meet the needs of regional flood forecasting authorities.

One of the specific contributions to these overall aims is to develop a novel hydrological modelling framework for flood forecast modelling. The motivations for this development are firstly the need to take full advantage of the increasing availability of weather radar, satellite remote sensing and meteorological modelling. Secondly, to provide a flexible modelling framework that allows the model to exploit different levels of complexity and spatial variability. The representation of different processes can then be adapted according to the modelling objectives and the data availability. It is also allows the modeller to explore different process descriptions, model structures and levels of spatial distribution in the hydrological parameters and meteorological variables.

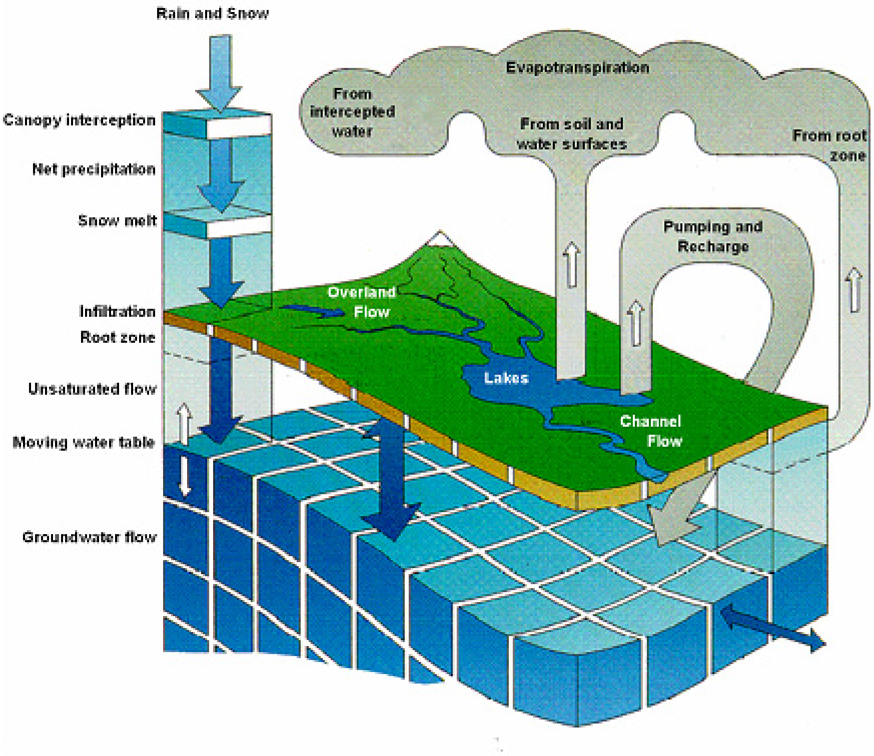


Figure 1. Hydrological Processes in MIKE SHE

3 MIKE SHE – PROCESS-BASED MODELLING FRAMEWORK

FREEZE & HARLAN (1979) proposed a blueprint for distributed hydrological modelling using a physics-based representation of the underlying catchment processes. This blueprint was the basis for the development of the European Hydrological System SHE (ABBOTT et al. 1986a, b) and MIKE SHE (REFSGAARD & STORM 1995). In MIKE SHE the catchment is represented in an integrated fashion by the major processes and their interactions (Figure 1). This framework is exploited here by introducing alternative process descriptions with different levels of complexity, physics and spatial variability (Figure 2). The original formulation is grid-based and therefore well-suited to grid-based data such as satellite remotes sensing and weather radar. In addition spatial lumping as well as zone or subcatchment-based approaches have been included. Finally a comprehensive river modelling package MIKE 11 (HAVNØ et al. 1995) has been integrated into this framework. The ability to represent structures, reservoirs and their operation, flood diversion channels and flood plain flows makes this framework particularly attractive for flood modelling and flood forecasting.

The main developments for flood forecasting applications are

- The ability to use alternative process description especially simple conceptual process descriptions more appropriate for flood forecasting. This includes the development of a new overland flow component
- Integration with the MIKE 11 river modelling tool that provides a full range of channel flow descriptions from simplified routing to fully dynamical description of river and flood plain flow, reservoirs, structures, dams, sediment transport etc.
- Direct integration of grid data either directly from Geographical Information Systems (GIS) or through the efficient handling of grid data.

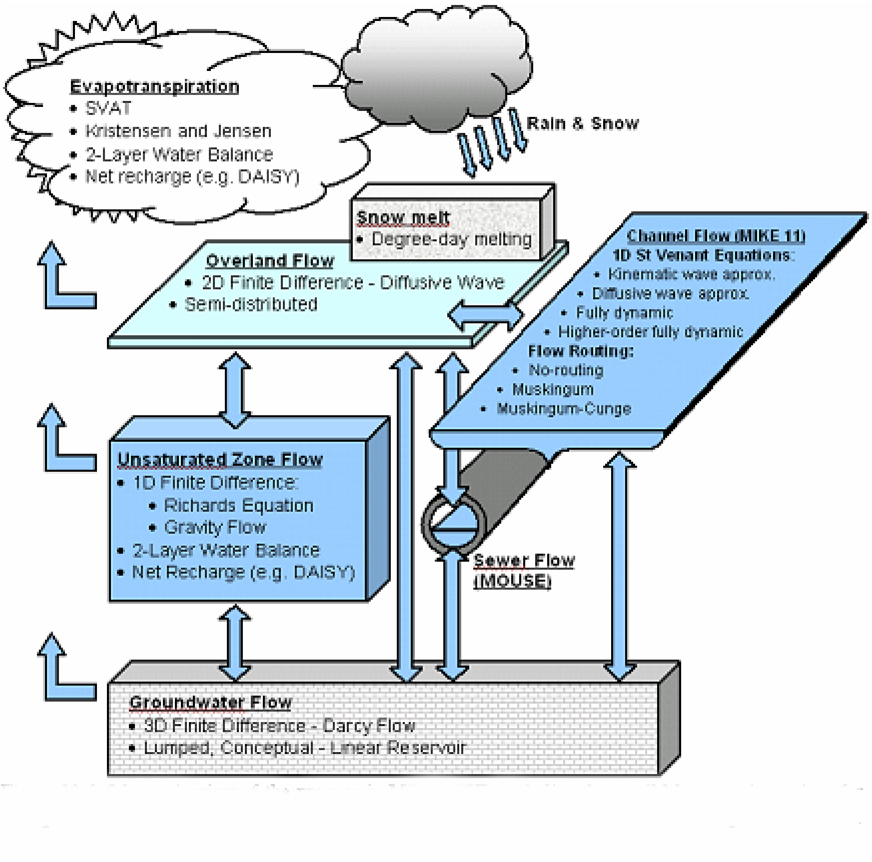


Figure 2. Schematic of process descriptions available in MIKE SHE

4 HYDROLOGICAL MODELLING OF THE BLUE RIVER CATCHMENT

The Blue River study catchment used here to evaluate the new MIKE SHE developments is one of the test basins within the Distributed Modeling Intercomparison Project organised by the Hydrology Lab of the National Weather Service (NWS). A more detailed description of the DMIP study is available in SMITH et al. 2004 and on the website http://www.nws.noaa.gov/oh/hrl/dmip/.

The purpose of the DMIP study was to evaluate the capabilities of existing distributed models and identify avenues for model improvements. For this purpose a set of 5 watersheds were selected for distributed model intercomparisons. We have chosen here to focus on the 1,232 km^2 Blue river basin in Oklahoma. The Blue river basin is located in south-central Oklahoma and flows into the Red River at the Texas-Oklahoma border.

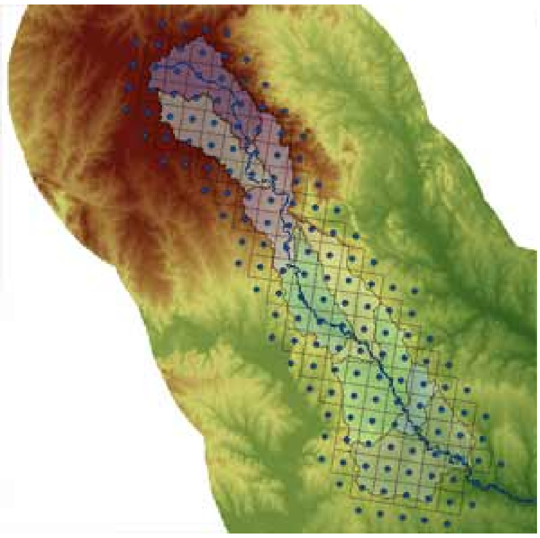


Figure 3. Blue River catchment showing the catchment boundary, topography and main river system. The 4 x 4 km² NEXRAD grid provides distributed estimates of catchment rainfall

The Blue River catchment is of interest for distributed hydrological modelling because of its unusual aspect ratio, soil variability and the availability of distributed radar-based rainfall.The watershed is semi-arid, with significant convective rainfall events. Rainfall data was available in the form of NEXRAD gridded data, at hourly intervals with a spatial resolution of 4 km by 4 km. The model grid used to model this catchment is identical to the NEXRAD rainfall grid, Figure 3.

We have applied the modelling tool firstly to demonstrate the ability of this tool to use grid-based rainfall from weather radar, Figure 4. Secondly the ability of this tool to use different model structures has been exploited to examine the performance of different model structures and to evaluate the model structure uncertainty compared to other sources of uncertainty. The results of these investigations are presented in BUTTS et al. 2004.

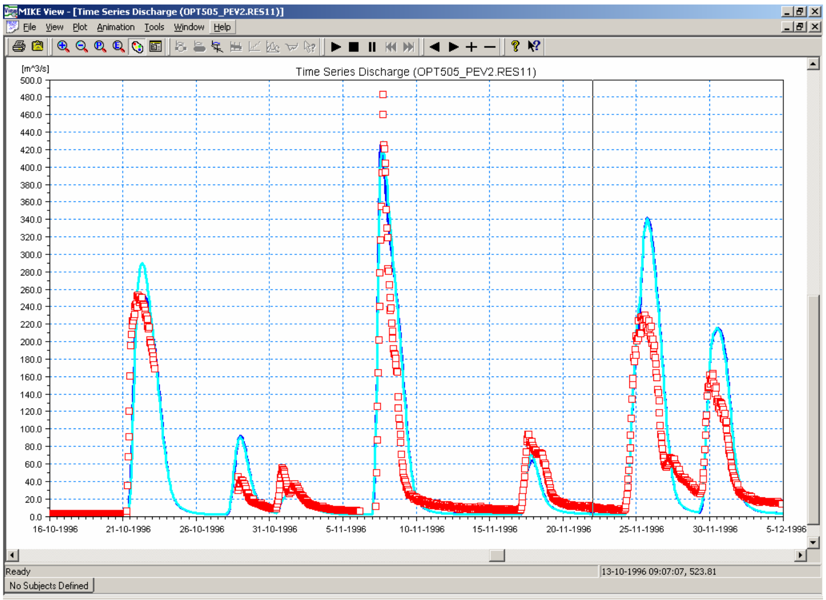


Figure 4. Comparison of measured (squares) and simulated (line) flow hydrographs for the Blue River catchment

5 FLOOD MODELLING IN THE UPPER AND MIDDLE ODRA

In July 1997, the Odra River basin was struck by an extreme flood event (DUBICKI 1998), seriously affecting the Czech Republic, Poland and Germany. In Poland alone more than 160,000 people were evacuated and damages estimated to be more than 5 billion EURO, GRUENEWALD (1998). The Odra basin was selected for the FLOODRELIEF project as a highly flood-prone catchment representing highly developed European catchments where comprehensive modelling of the river system, flood plains, polder subsystems, and structures as well as rainfall-runoff and snowmelt processes in the tributary catchments are required. Flood forecasting in the Odra requires both fast and reliable simulations for this complicated river basin and therefore a careful balance between accurate representation of the catchment flood processes, the flood wave movement and inundation extent and the need for rapid forecasts.

6 MODELLING RESULTS

The calibration period covers the interval between 1st Jan 1995 - 1st August 1997 including the major flood during July 1997. In this case study the flexibility in selecting different process descriptions is used. Spatially distributed conceptual structures are used to represent the rainfall runoff processes. The simplified representation is shown schematically in Figure 5.

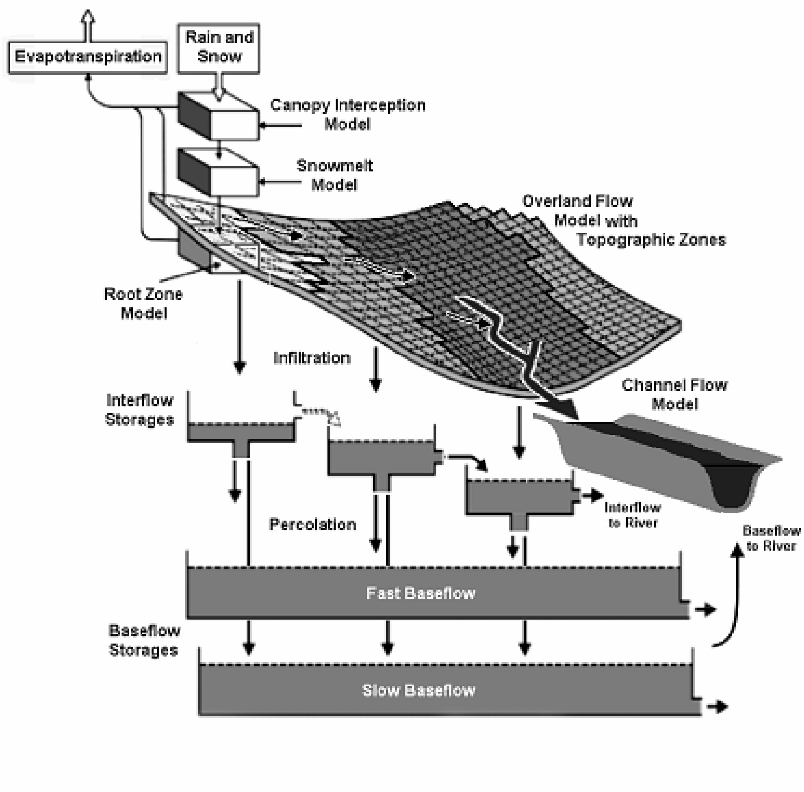


Figure 5. Schematic of the conceptual process representation used in the Upper and Middle Odra model

The topographical and groundwater subcatchments are identical in this example, Figure 6. To illustrate the performance the model the measured and simulated discharge for the Bardo station on the Nysa Klodzka River is shown in Figure 7. Closer inspection shows an accurate representation of the 1997 peak, Figure 8.

The river system described in the model covers 510 km of the upper and middle Odra starting from the Czech border (at Chalupki) and ending close to the German border (at Polecko). In addition the model includes the downstream sections of the 14 most important tributaries, Figure 6. The Odra River is maintained as a navigable river from the mouth upstream as far as Kozle. A total of 30 structures are modelled as moveable control structures, which are operated for navigation during low flows, with special rules being applied during flood periods, Figure 9.

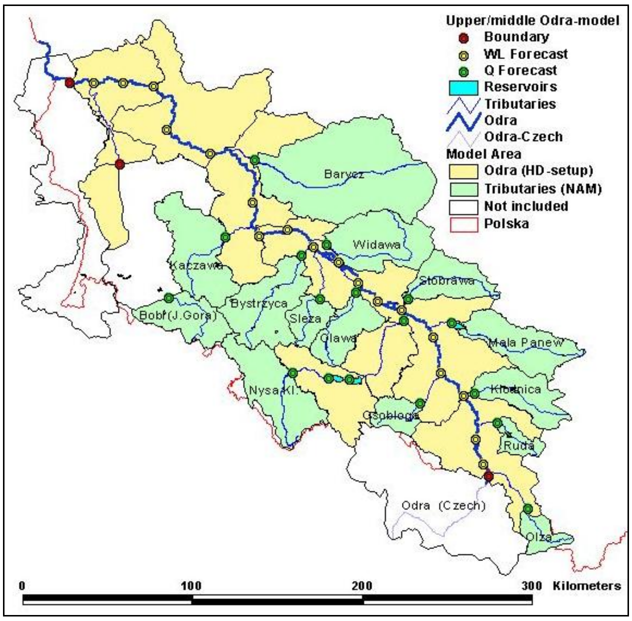


Figure 6. The Upper and Middle Odra model showing the subcatchments used in the model and the main river system

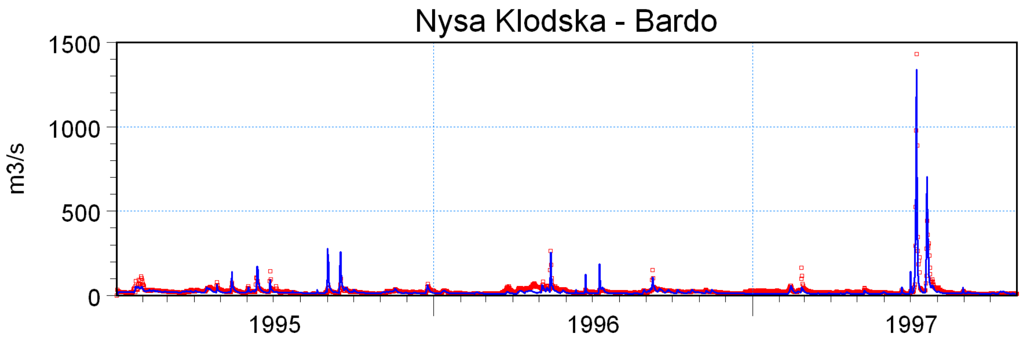


Figure 7. Measured (symbols) and simulated (line) discharge hydrograph for the calibration period for the Bardo station on the Nysa Klodzka River

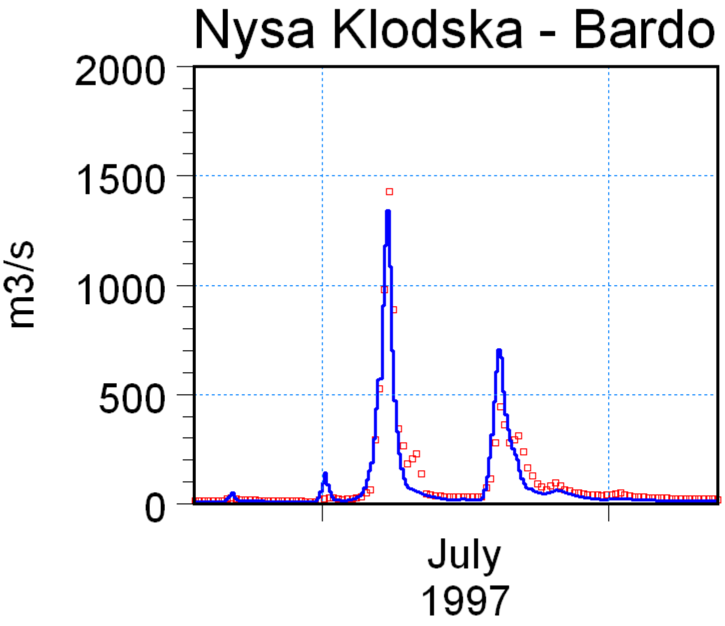
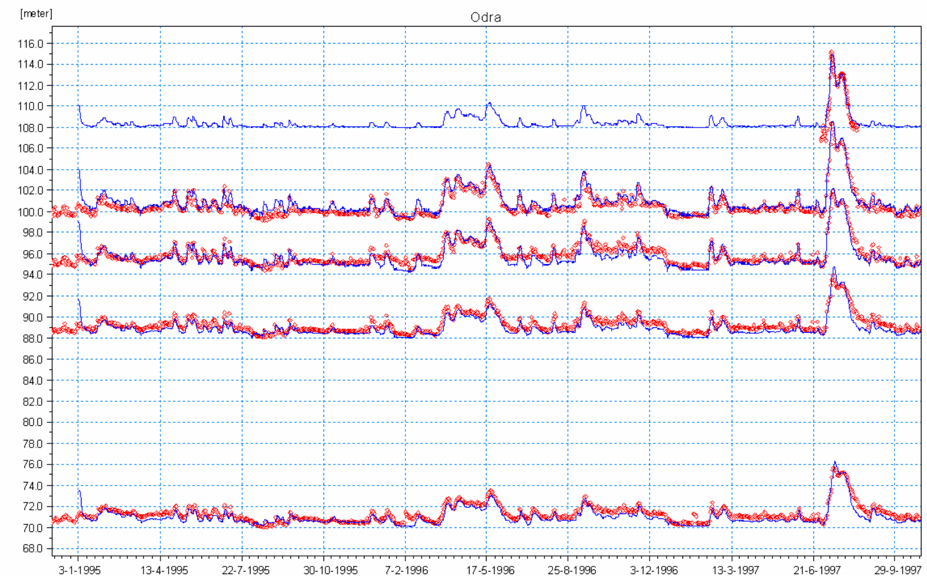


Figure 8. Flood hydrograph during the 1997 flood for the Bardo station on the Nysa Klodzka River

Figure 9. The moveable gate structure at Opatowice upstream of the town of Wroclaw



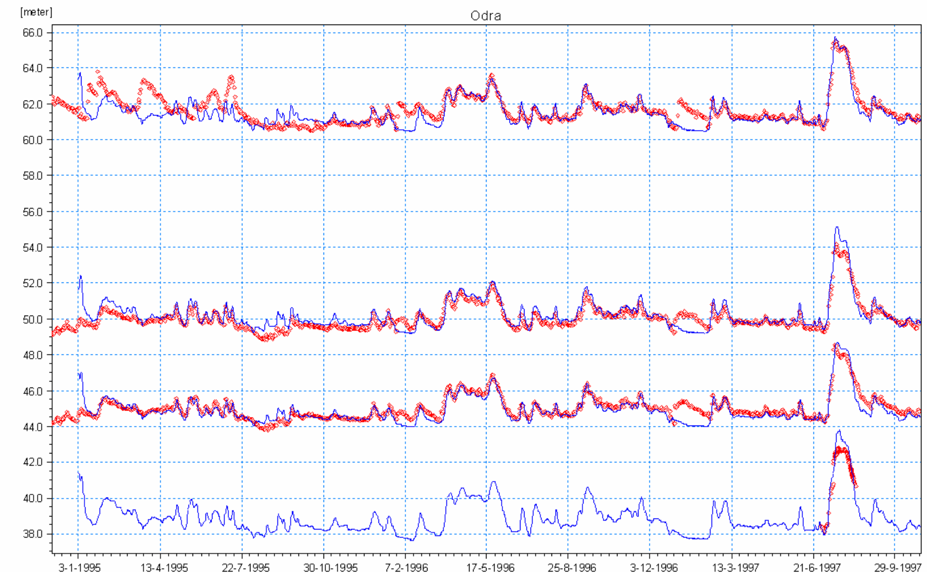


Figure 10. Comparison of the measured (symbols) and simulated (line) water levels from the calibration, 1995-1997 along the main river system, upstream uppermost.

7 CONCLUSIONS

A new hydrological modelling framework has been developed from the MIKE SHE system to a more general process-based description. This new framework allows the modeller to select between a number of different process descriptions and model structures. This has a number of advantages. Firstly the modeller can adapt the model structure according to the complexity of the model required for his or her application. Secondly the process descriptions can also be adapted to the quality, spatial and temporal distribution of both the parameters and the time series.

This new framework has been successfully evaluated for two study catchments. Firstly, the US NWS study catchment, the Blue River using NEXRAD radar-based precipitation. The second example from the Poland demonstrates that this framework can be usefully applied in flood forecasting applications.

8 PERSPECTIVES

The perspectives, for the application of this new modelling framework within flood forecasting, flood modelling and hydrological modelling generally, are many. Furthermore this tools is appropriate for flood modelling for a wide range of end-users, from floodplain managers and regional water resource managers, to those who would benefit from improved flood forecasting. Potential new applications include

- Optimal use of grid-based precipitation fields from weather radar and especially numerical weather models
- Direct integration of satellite remote sensing for 1) model set-up 2) model calibration validation 3) forecasting update or data assimilation 4) time series input of evapotranspiration, snow cover, etc.
- Unique ability to treat a range of new forecasting problems such as groundwater flooding where the comprehensive nature of the MIKE SHE models can be used
- The coupling with the MIKE 11 river modelling tools provides distributed hydrological forecasting in the floodplain together with comprehensive modelling of river structures, dams, reservoir, polders, etc. currently not found in other distributed hydrological models
- Forecasting of low flows for irrigation, water resources, water quality and navigation
- Comprehensive water quality forecasting and sediment forecasting
- Integration of flood modelling and hydrological modelling into a single tool for managing a catchment or floodplain areas and therefore provide a tools for holistic basin management
- More sophisticated flood mapping for flood forecasting and flood risk by taking into account evaporation and infiltration losses more accurately and including two-way coupling between the river and groundwater system
- Large-scale hydrological modelling for treating regional basins for water resource management, climate change modelling.

9 REFERENCES

Abbott, M. B., Bathurst, J.C., Cunge, J.A., O'Connell, P.E. and Rasmussen, J. 1986a: An introduction to the European Hydrological System – Systeme Hydrologique Europeen, SHE. 1 History and philosophy of a physically-based distributed modelling system. *Journal of Hydrology*, 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 Europeen, SHE. 2 Structure of a physically-based distributed modelling system. *Journal of Hydrology*, 87: 61-77,

Butts, M. B., J. T. Payne, M. Kristensen and H. Madsen. (2004). An evaluation of the impact of model structure and complexity on hydrological modelling uncertainty for streamflow prediction. *Journal of Hydrology*, **298**, 242-266.

Dubicki, A. The Odra flood event 1997: Characteristics of the process of rising and development of anti-flood management. *Proc. of the Second Study Conference on BALTEX*, Juliusruh, Island of Rugien, Germany, 25-29 May 1998, Published by International BALTEX Secretariat, Publication No. 11, May 1998.

Freeze, R.A. and Harlan, R.L, 1969: Blueprint for a physically-based digitally-simulated hydrological response model, Journal of Hydrology, 9: 237-258.

Gruenewald, U., 1998 Causes, development and consequences of the Oder flood. *Proceedings of the European Expert Meeting on the Oder Flood 1997*, May 1998 (Bronstert, Ghazi, Hladny, Kundzewicz, & Menzel Eds.), Potsdam Germany RIBAMOD Concerted Action, 27-36.

Havnø, K., Madsen, M.N and Dørge J., 1995. MIKE 11 – A Generalized River Modelling Package, In: *Computer models of Watershed Hydrology*, V. P. Singh ed., Water Resources Publications, Colorado, USA: 733-782.

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

Smith M.B. , Seo D-J, Koren V. I., Reed S.M. , Zhang Z, Duan Q, Moreda F. and Cong S. (2004), The distributed model intercomparison project (DMIP): motivation and experiment design, *Journal of Hydrology*, **298**, Issues 1-4, 1 October 2004, 4-26.