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FLEXIBLE PROCESS-BASED HYDROLOGICAL MODELLING FRAMEWORK FOR FLOOD FORECASTING – MIKE SHE

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Abstract
New developments of grid-based hydrological modelling have been spurred by increasing access to meteorological modelling, radar and satellite remote sensing. However, state of the art operational hydrological forecasting models are usually subcatchment-based conceptual or empirical models, using to a greater or lesser degree the physics of rainfall-runoff processes. By contrast, state-of-the-art hydrological modelling is represented by fully distributed physically-based modelling that exhibit a much greater level of complexity. Operational hydrological forecast modelling requires a trade-off between model complexity and accuracy on the one hand and on the other hand the need for rapid flood forecasts.

The approach adopted in the FLOODRELIEF project has been to develop a flexible, hydrological modelling framework based on the European Hydrological System (MIKE SHE) that permits changes in the model structure, including both conceptual and physic-based process descriptions, to be made within the same modelling tool. This framework has several advantages including the optimal use of grid-based precipitation fields from weather radar and numerical weather models, direct integration of satellite remote sensing and the unique ability to treat a range of new forecasting problems such as groundwater flooding. This tool has been applied recently under semi-arid conditions using NEXRAD data in the US NWS study catchment, the Blue River. It has now also been applied to the Upper and Middle Odra River, one of the FLOODRELIEF study basins. The Odra basin was selected 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.

Key words: distributed hydrological modelling, flood forecasting, uncertainty, model structure

INTRODUCTION

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. 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;
- Make the results more readily accessible both to flood managers and those threatened by floods

One of the contributions to these aims is the development of a novel distributed modelling approach described here. Rather than developing a number of different hydrological models in the burgeoning undergrowth of hydrological models, this approach integrates different process descriptions and representations of spatial data are provided within the same framework. This framework is based on the European Hydrological System (MIKE SHE). The aim of this paper is to demonstrate this novel and flexible hydrological modelling framework and how it takes full advantage of these new sources of data while recognising that forecast modelling requires a trade-off between model complexity and accuracy on the one hand and on the other hand the need for rapid forecasts.

WHAT IS MIKE SHE?

MIKE SHE is a comprehensive system for modelling all the major processes that occur in the land phase of the hydrological cycle. MIKE SHE in its original formulation can be characterised as a deterministic, physically-based, distributed model code. It simulates water flow, water quality and sediment transport, Refsgaard and Storm, (1995). MIKE SHE is applicable to spatial scales ranging from a single soil profile to large regions including several river catchments such as 80,000 km^2 Senegal Basin, Andersen et al., (2001). It has been tested and proved in a large number of research and consultancy projects covering a wide range of climatic and hydrological regimes, Graham and Butts, (2005).

The integrated hydrological modelling system MIKE SHE emerged from the Système Hydrologique Européen (SHE) as developed and extensively applied from 1977 onwards by a consortium of three European organisations: the Institute of Hydrology (United Kingdom), SOGREAH (France) and DHI (Denmark), (Abbott et al., 1986a & b). The SHE model is in fact an implementation of the modelling paradigm proposed by Freeze and Harlan (1969). In this original blueprint, different flow processes are described by the governing partial differential equations and these are then solved by discrete numerical approximations in space and time. The central idea is to describe a given catchment with a level of detail sufficiently fine to be able to claim a physically-based process description. The equations used in the model are with few exceptions non-empirical and well-known to represent the physical processes at the appropriate scales in the different parts of the hydrological cycle. In MIKE SHE the catchment is represented in an integrated fashion by the major processes and their interactions (Figure 1).

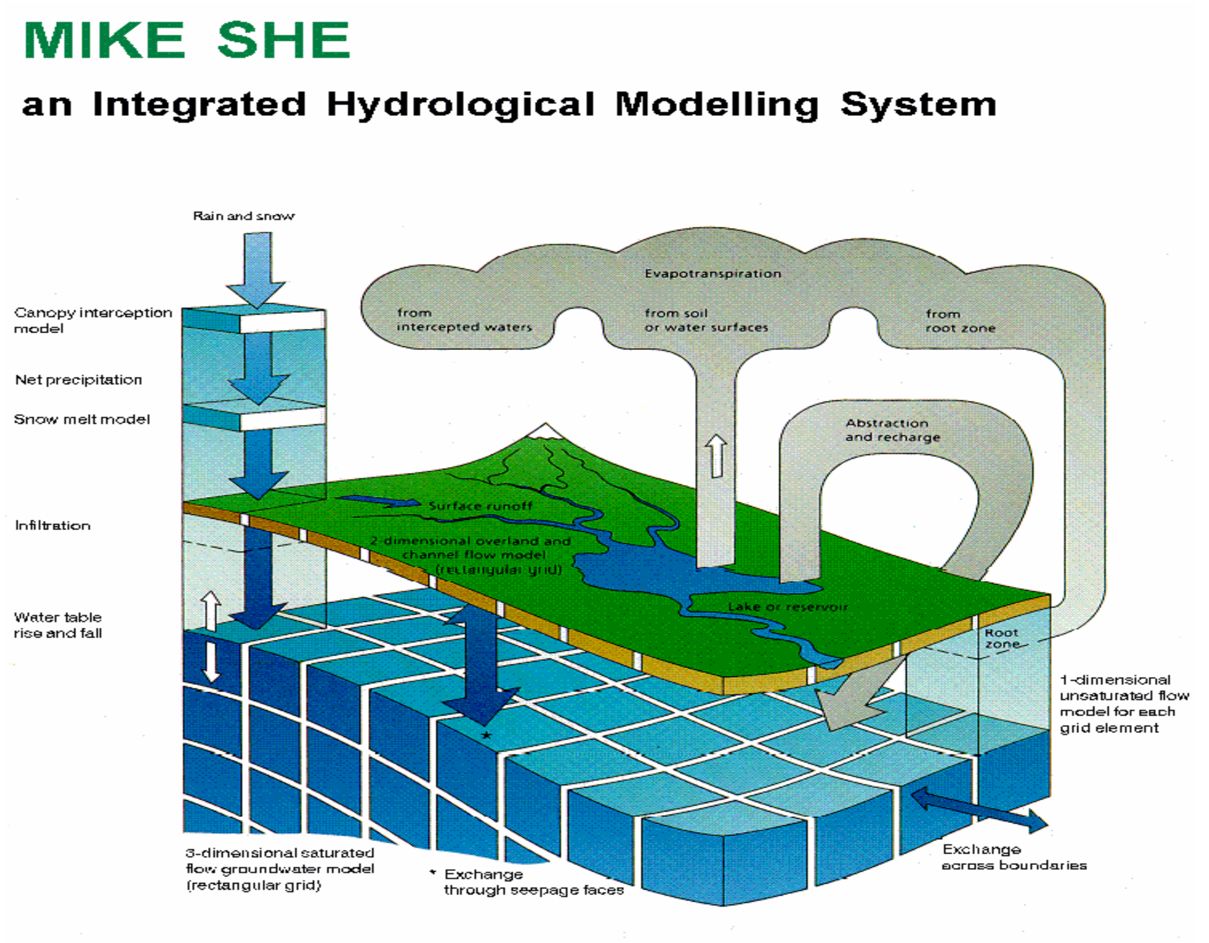

Figure 1 Process-based structure of the MIKE SHE hydrological modelling system

MIKE SHE – PARADIGM SHIFT

There are several factors that argue for the value of a modelling tool that allows changes in the model process descriptions and their representation in space, Butts et al., (2004). These can be summarised as

- The need to treat only the most important processes related to the hydrological problem to be considered;
- Allow the model to evolve as more data or information becomes available or as the modeller gains insight during the modelling process or as a deliberate strategy to start with simple models first;
- Adapt the representation of each process to the data available for that process;
- To allow different applications with different levels of complexity (for example flood design and flood forecasting) within the same hydrological system;
- The need to explore science questions such as "What are the characteristics of a basin that is more likely to benefit from distributed modelling?".

There are also some important limitations to the applicability of comprehensive physically-based models like MIKE SHE particularly for flood forecasting:

- The data requirements can be significant and prohibitive in terms of cost;

- Complex process representations may require substantial computing time, which may become important for flood forecasting or climate change modelling;
- Complex representations may lead to over-parameterisation for simpler applications like predicting basin outlet discharges;
- The representation of processes may not be valid on the grid scale of the model or the sub-grid variability may not be represented adequately.

The process-based approach used in MIKE SHE is exploited here by introducing alternative process descriptions with different levels of complexity, physics and spatial variability. This provides a flexible model that allows changes in the model process descriptions as well as addressing the limitations of using a model like MIKE SHE for flood forecasting. The main developments for flood forecasting carried out within FLOODRELIEF are:

- The ability to use alternative process description especially simple conceptual process descriptions more appropriate for flood forecasting;
- 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.

APPLICATIONS OF MIKE SHE FOR FLOOD FORECASTING – BLUE RIVER, USA

This study catchment was used to explore the use of the new flexible model framework using radar-based rainfall data. An evaluation of alternative models for the same catchment was carried out using this framework. The 1232 km^2 Blue River basin is one of the test basins within the Distributed Modeling Intercomparison Project (DMIP) organised by the Hydrology Lab of the National Weather Service (NWS). The location of this catchment is shown in Figure 2. The Blue river basin is located in south-central Oklahoma and flows into the Red River at the Texas-Oklahoma border. 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 application in flood forecasting.

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. A more detailed description of the study basins is given in Smith et al., (2004). 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 2.

Using the new tool 10 different model structures were identified as plausible models. The different model structures included both lumped and distributed routing, lumped, subcatchment-based and distributed rainfall-runoff models, grid-based modelling using physics-based flow equations, different conceptual process descriptions and lumped, subcatchment-based and gridded radar-rainfall input, Butts et al., (2004). Each of the different models was calibrated and then evaluated in an independent validation period. A number of interesting results were obtained,

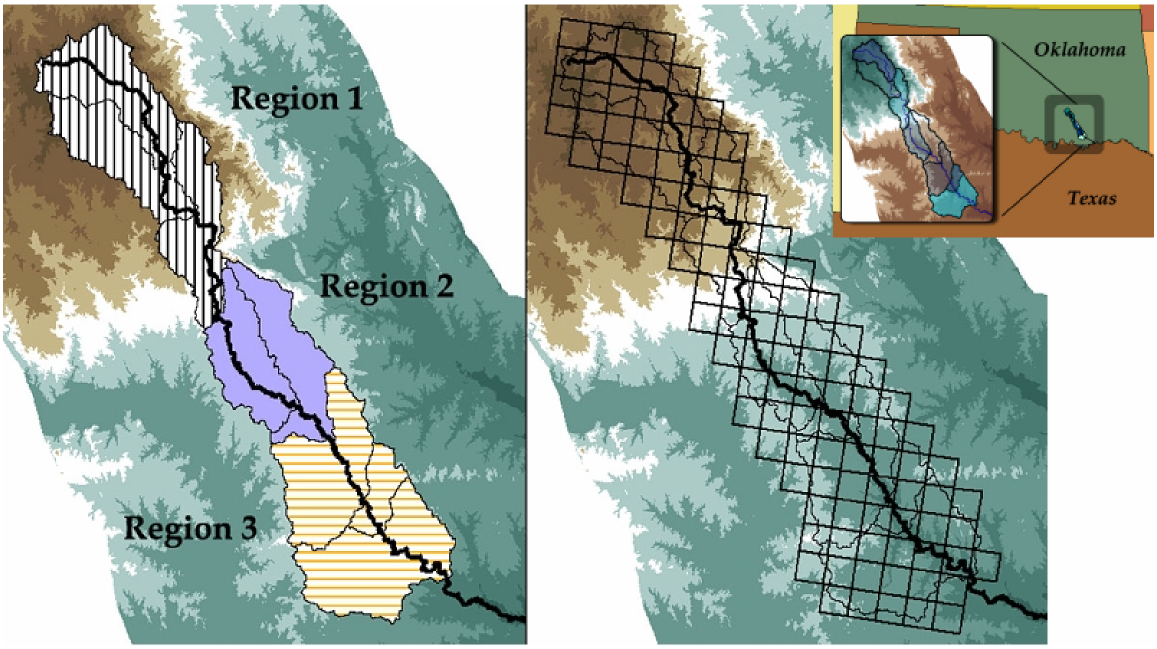

Figure 2 Different spatial discretizations were used to model the Blue River. The figure on the left shows the 8 subcatchments used in conceptual modelling and the parameter regions used for calibration. The figure on the right shows the 4-km NEXRAD grid used for the grid-based modelling. Inset: Location of the Blue River catchment

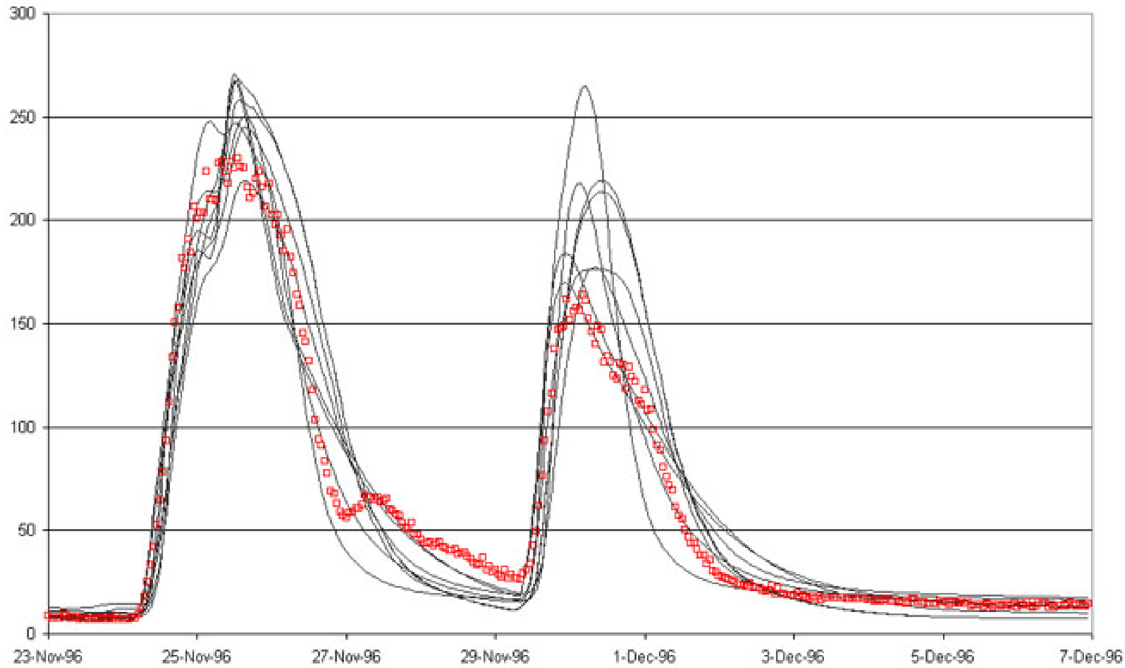

Figure 3 Two flood events in the Blue River Basin, The symbols show the observed flows and the solid lines the predicts using 10 different calibrated models (Butts et al., 2004a&b)

Firstly as seen in Figure 3 even though the models were calibrated using automatic methods against the same multiple criteria, they produce quite different responses. Butts et al., (2004b) suggested that the different models are better at capturing different aspects of the response to rainfall and investigated consensus modelling to determine investigate improvements in hydrological predictions using multiple model ensembles, Georgakakos et al., (2004). Another interesting finding for the Blue River catchment is that the additional information obtained by using each of the NEXRAD cells provided minimal if any benefit in simulation accuracy when compared to the same model structure using NEXRAD rainfall aggregated over larger sub-basins. It may be that there are limits to the benefits of increasing the spatial resolution rainfall data particularly where the purpose is to predict flows at catchment outlets. However this may be a result of limitations in the model structure itself, limitations in the information available in the calibration data, limitations in the accuracy and representative of rainfall, or limitations in the parameter estimation procedures and further exploration of this is required.

APPLICATIONS OF MIKE SHE FOR FLOOD FORECASTING – UPPER AND MIDDLE ODRA, POLAND

The Odra River is subject to frequent and significant flooding, most recently in 1997 and 2001. 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, Grunewald (1998). The Odra basin was selected for the FL,OODRELIEF 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.

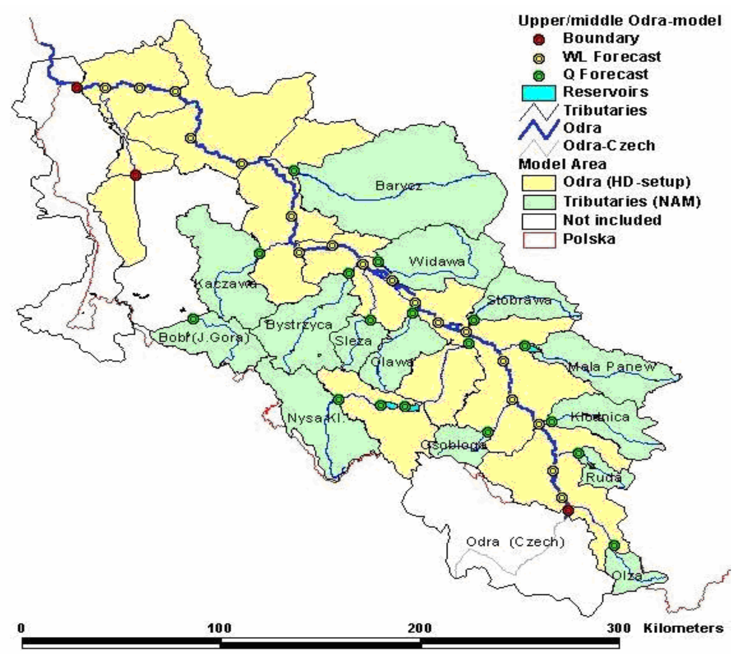

Figure 4 The catchment delineation and main river network used for the upper and middle Odra.

A key feature of this system is that the Odra River is highly developed and is characterised by a complex river network, a large number of fixed and moveable hydraulic structures (more than 95 on the main river and approximately 430 when all tributaries are included) as well as 14 flood storage reservoirs (polders). The moveable structures are operated for navigation during low flows, with special operating rules during flooding. The polders are used as active flood mitigation reservoirs during high flow, and these too are controlled by both fixed and moveable structures. In addition, there are several reservoirs in the upstream portions of the basin. Accurate flood forecasting requires comprehensive modelling of the river system, flood plains, polder subsystems, reservoirs and structures. Therefore the model was developed and calibrated in two parts, firstly the main river system and secondly the catchment inflows to the main river, Figure 4. The calibration period covers the interval between 1st Jan 1995 - 1st August 1997 including the major flood during July 1997. The results of the main river model calibrations are shown in Figure 5. For more details refer to Butts et al., (2005).

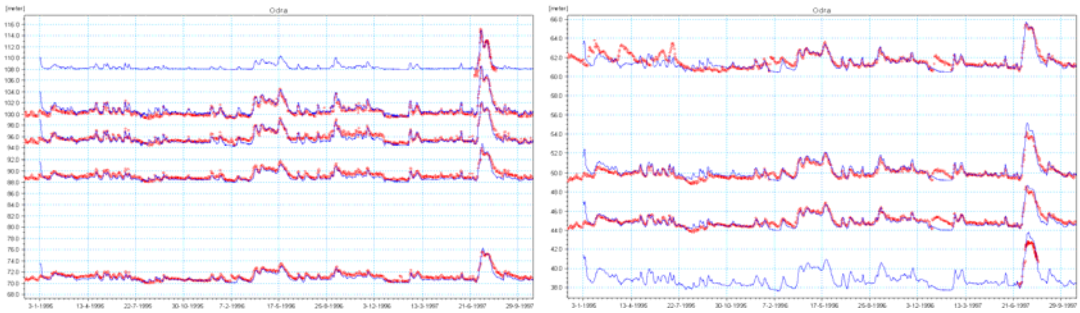

Figure 5 Comparison of the measured (symbols) and simulated (line) water levels from the river model calibration, 1995-1997 along the main river system.

To model the rainfall-runoff process generating the catchment inflows, the MIKE SHE based framework was used. In this example a simplified model description is used, exploiting the flexibility of this framework to develop a subcatchment based hydrological model. The different rainfall-runoff processes are treated as spatially distributed conceptual structures, Figure 6. Maps of the land use, soil type and the topography are used to represent the spatial variability of catchment parameters. This illustrates firstly that the framework can provide simple distributed conceptual modelling on a subcatchment basis which corresponds to the approach used in many operational forecasting systems. Their advantage for flood forecasting is the speed. The performance of rainfall-runoff modelling is shown in Figure 7 for two important mountain catchments, the Nysa Klodzka and Bobr. This shows that the chosen model structure provides satisfactory simulations. Coupled with a detailed representation of the river system including the polders and moveable structures this model provides a useful tool for flood forecast modelling of the Upper and Middle Odra River system.

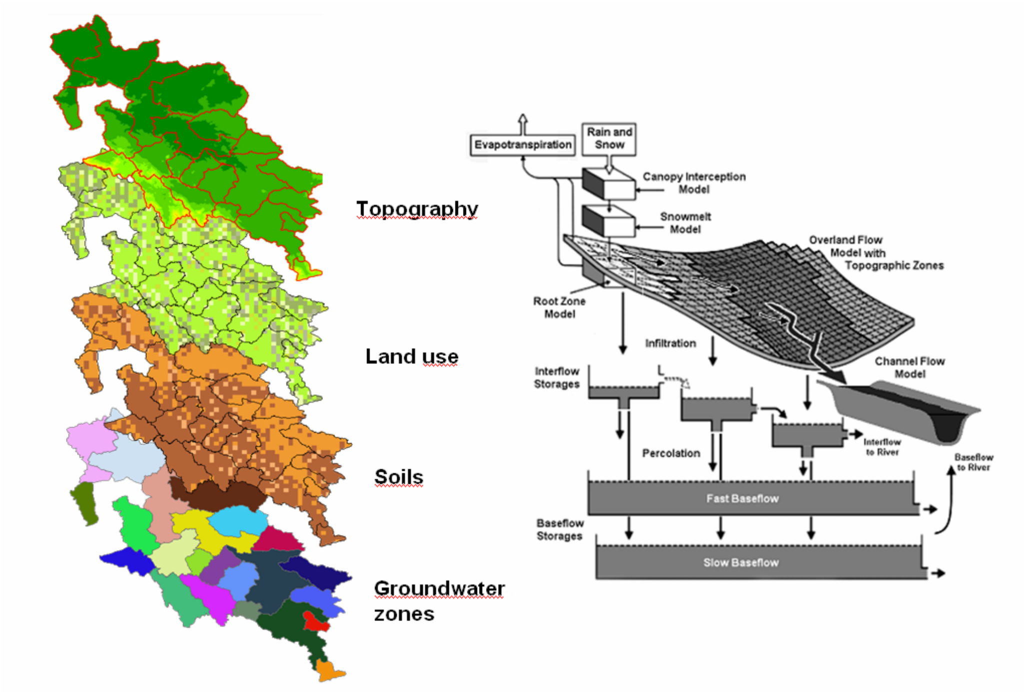

Figure 6 Left figure: The spatial input data and subcatchments used to treat the spatially distributed data. Right figure the conceptual process representation for subcatchment-based rainfall-runoff modelling.

CONCLUSIONS

A novel and flexible hydrological modelling framework, suitable for both hydrological simulation and flood forecasting, has been developed. This framework has several advantages including the optimal use of grid-based precipitation fields from weather radar and numerical weather models, direct integration of satellite remote sensing and the unique ability to treat a range of new forecasting problems such as groundwater flooding. The ability to use different model structures in this framework, with grid-based radar data as rainfall input was illustrated using the DMIP study catchment, the Blue River basin and has been used in investigations of model structure uncertainty, Butts et al, (2004a&b). The model framework was used to derive a distributed subcatchment-based conceptual model for modelling the rainfall-runoff process and a comprehensive hydraulic model for the highly flood-prone and complex Upper and Middle Odra River in Poland. This model has been successfully calibrated against measurements both in the main river system and tributary catchments, including the extreme flooding in July 1997.

The perspectives, for the application of this new modelling framework within flood forecasting, flood modelling and hydrological modelling generally, are many:

- 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.

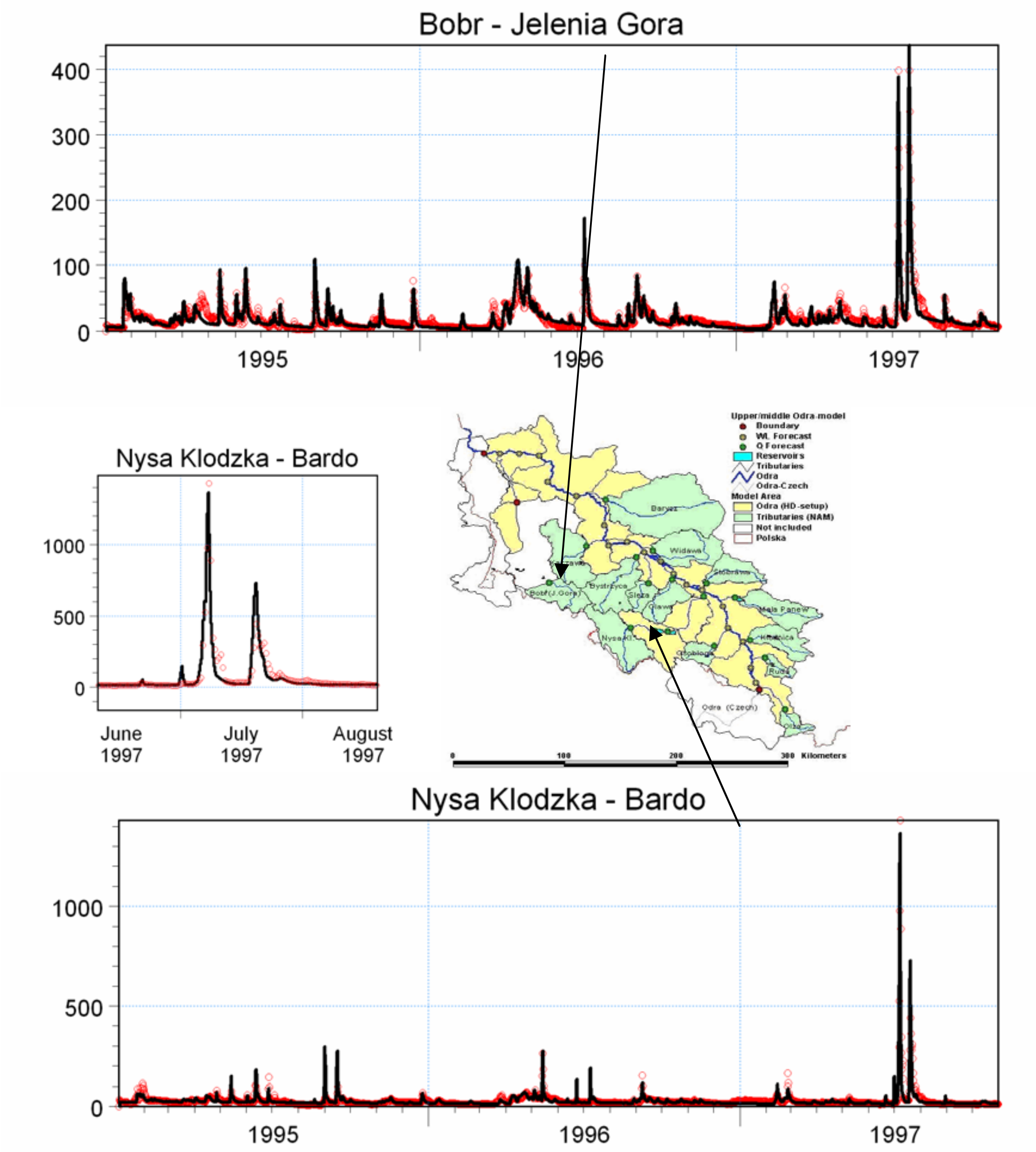

Figure 7 Spatial comparison of the measured (symbols) and simulated (line) discharges for the Bardo station on the Nysa Klodzka river and the Jelenia Gora station on the Bobr river

- 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.

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