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MIKE SHE-ECOLAB – AN INTEGRATED CATCHMENT-SCALE ECO-HYDROLOGICAL MODELLING TOOL

Michael Butts*, Maria Loinaz†, Peter Bauer-Gottwein†, Robert Unnasch◊, Dayna Gross‡

*Department of Water Resources, DHI,
Agern Allé 5, 2970 Hørsholm, Denmark
e-mail: mib@dhigroup.com, http://www.dhigroup.com/

†Department of Environmental Engineering, Technical University of Denmark
Miljøvej, Building 11, 2800 Kgs. Lyngby
e-mail: pbau@env.dtu.dk, http://www.env.dtu.dk
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◊The Nature Conservancy,
950 West Bannock, Boise, ID 83702, USA
e-mail: bunnasch@tnc.org, http://www.nature.org

‡The Nature Conservancy, Silver Creek Preserve
PO Box 624, Picabo, ID 83348, USA
e-mail: dayna_gross@tnc.org, http://www.nature.org

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Summary. Two of the key objectives of the European Water Framework Directive (WFD) are: 1) to protect and enhance the status of aquatic ecosystems (and terrestrial ecosystems and wetlands directly dependent on aquatic ecosystems) and 2) to provide for sufficient supply of good quality surface water and groundwater as needed for sustainable, balanced and equitable water use. These requirements, together with the growing acceptance of the integrated water resource management approaches that treat catchment management holistically, provide a strong motivation to develop integrated hydrological and water quality tools that can address problems related to ecological status and restoration. In particular, managers need to be able to quantify changes in ecosystem status caused by changes in catchment management.

A new and powerful eco-hydrological modelling tool has been developed, combining a generic ecological modelling tool (ECO Lab) with a fully integrated catchment modelling tool representing surface water, soil- and groundwater as well as water quality processes. This study is part of the Danish project Riskpoint (http://www.risk-point.dk/) aimed at developing environmental risk assessment tools. The capabilities of this new tool within different components of the hydrological cycle are demonstrated and evaluated using analytical solutions, laboratory and field data. The tool is then used to develop an integrated hydro-ecological model to simulate the flows and temperatures in the Lower Wood River Valley, Idaho, US and relate physical environmental stressors in the catchment to the ecosystem status of Silver Creek. The results presented show that the modelling tool is able to reproduce the temperature dynamics in the Silver Creek ecosystem, which is critical for the fish population. Future work will examine the effect of different management scenarios on the temperature levels and dynamics in this ecosystem.

1 INTRODUCTION

In Europe, with the Water Framework Directive (WFD), water managers are being asked to address ecological status in the context of water resource and water quality management at the catchment scale. Two of the key objectives of the WFD are:

1. to protect and enhance the status of aquatic ecosystems (and terrestrial ecosystems and wetlands directly dependent on aquatic ecosystems)
2. to provide for sufficient supply of good quality surface water and groundwater as needed for sustainable, balanced and equitable water use

These goals highlight two key issues of growing concern in water resources management. The first is the recognition that in addition to the quantity and quality of water resources, the biological and ecological status of these resources has both an environmental and socio-economic value. The second issue is the increasing requirement for the joint management of surface water and groundwater.

Surface water-groundwater interaction is an important process in riparian areas that can directly impact water budgets and allocations, as well as biogeochemical and ecological conditions and processes. Groundwater resources often have a complex dependency with adjacent water courses, wetlands and stream networks. Groundwater is on the other hand is an important factor in freshwater wetlands and in controlling low flows and maintaining environmental flows.

The management of both resources is therefore both complicated but necessary. However surface water and groundwater have, by tradition, been managed separately, often by completely different authorities, despite the fact that groundwater and surface water are inextricably linked. Where water is scarce, conjunctive use of surface and groundwater can result in either sustainable use of water resources or serious over-exploitation. For example, in semi-arid regions the accurate representation of groundwater-surface water interactions is critical to modelling of low flows. Furthermore while there are a growing number of surface water- groundwater models, there are relatively few that include ecological impacts and river management[1].

This paper presents the development and evaluation of an integrated hydro-ecological model that can address these limitations. The hydrological component consists of the comprehensive process-based hydrological model, MIKE SHE which can represent flow and transport processes within the river network, groundwater, the unsaturated zone and surface flows. A generic ecological modelling tool (ECO Lab) has been incorporated in the MIKE SHE modelling framework to represent a range of water quality and ecological processes within the river, surface water, soil- and groundwater. The capabilities of this new tool have been evaluated using analytical solutions and laboratory data. The tool has also been used to develop an integrated hydro-ecological model to simulate the flows and temperatures in the Lower Wood River Valley, Idaho, US and the spring-fed Silver Creek ecosystem with the aim of providing a tool for watershed ecosystem management. This paper presents some of the initial results of this development.

2 THE MODELLNG FRAMEWORK

MIKE SHE is a fully distributed, process-based hydrological model and includes process models for evapotranspiration, overland flow, unsaturated flow, groundwater flow, and channel flow and their interactions[2]. MIKE SHE has evolved from the SHE modelling concept described in Abbott et al[3,4]. In the original concept the different flow processes are described by the governing partial differential equations and these are then solved by discrete numerical approximations in space and time using finite differences[5]. More recently, this process-based model has been used to develop a more general hydrological framework that allows the different model structures to be applied within the same modelling framework[6]. In this manner each of these processes can be represented at different levels of spatial distribution and complexity, according to the goals of the modelling study, the availability of field data and the modeller's choices[6].

This modelling framework also integrates the capabilities of a comprehensive river and channel model, MIKE 11. MIKE 11 is a modelling system for the simulation of flows, water levels, sediment transport and water quality for rivers, flood plains, irrigation systems, estuaries and other water bodies[7]. 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. Alternatively, diffusive wave, kinematic wave, and quasi-steady state approximations can be used or simpler hydrological routing schemes such as Muskingum and Muskingum-Cunge may also be selected.. The model is 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. Within the MIKE SHE framework the interactions with the river include inflows via base flow from groundwater, drain flow and overland flow and losses through the river bed.

ECO Lab is a flexible numerical laboratory for ecological modelling. Essentially ECO Lab is a process equation solver that calculates the rate of change of any type of state variable given any number of related variables, processes and forcing. The assumption is that the biological and chemical transformation processes affecting state variables (ES_i) in an ecosystem can be formulated as a set of coupled ordinary equations:

$$ES_i = \frac{d\,(ES_i)}{dt} = \sum_{i=0}^{n} process_i \tag{1}$$

The process functions can consist of mathematical functions, built-in functions, numbers, forcings, constants, and state variables. The arguments are separated by operators such as +-*/, and the syntax also supports other types of expressions such as 'IF THEN ELSE' expressions. The mathematical and built-in functions are functions that are already defined in ECO Lab and can be used directly by referring to them. An example of a built-in function computes the oxygen saturation concentration using arguments such as salinity and temperature. Similarly, ECO Lab has a number of templates that describe well-known processes such as eutrophication templates that describe nutrient cycling, phytoplankton and zooplankton growth, growth and distribution of rooted vegetation and macro algae in addition to simulating oxygen conditions. Alternatively, a user can formulate customized process descriptions. ECO Lab relies on other models to calculate flow and transport processes and acts as a post-processor at each time step to calculate the process dynamics. In this manner spatial and temporal predictions of a wide range of water quality and ecosystem response studies can be simulated.

To develop a comprehensive eco-hydrological modelling tool, a coupled model was developed where the MIKE SHE modelling framework is used to model the flow and transport and then ECO Lab is used to model water quality and ecological processes within either the ground water, surface water, channel system or soil water. To test and evaluate this tool, the simulation results have been compared to analytical solutions, field and laboratory data. One example of this is given below. Tuxen et al.[8] examine the fate of selected pesticides under aerobic conditions in column experiments using aquifer material and low concentrations of pesticides. Their results include both experimental results together with simulations using a solute transport accounting for kinetic sorption and degradation. Several replications are presented together with model parameters. Experimental results for replications for the pesticide isoproturon shown in Figure 1 were successfully simulated using MIKE SHE – ECO Lab. The simulation results were calculated using average values of the process parameters derived from the different replications.

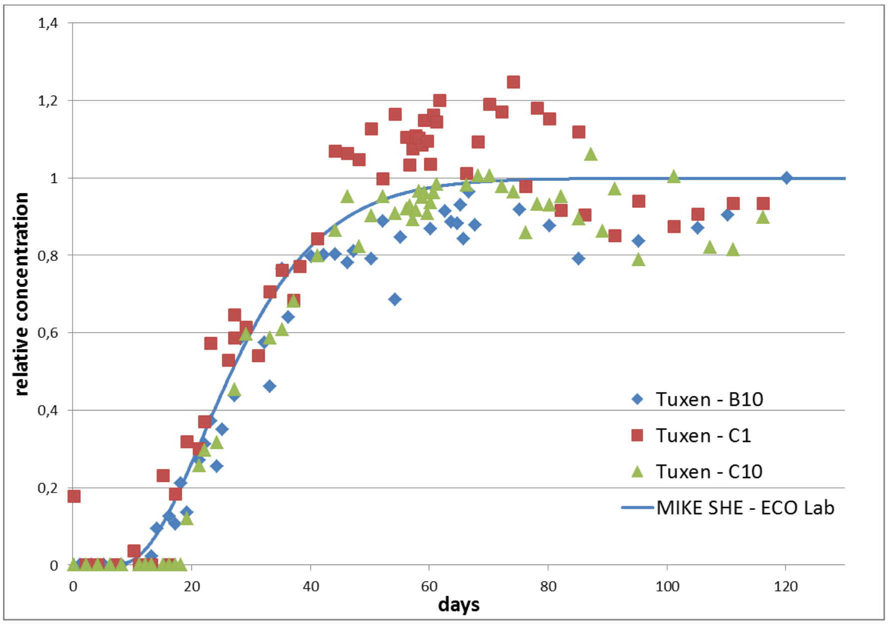

Figure 1. Comparison of the breakthrough curve simulated using MIKE SHE – ECO Lab and the experimental results for column experiments of Tuxen et al. (2000) for the pesticide isoproturon.

3 THE BIG WOOD RIVER VALLEY AND SILVER CREEK

The Big Wood River Valley is a semi-desert mountain valley with low precipitation and high evaporation. Approximately 60% of the lower valley is cultivated, of which 80% is irrigated. Population increases, irrigation technology, climate, and land use changes have stressed water resources and limited water supply[9].

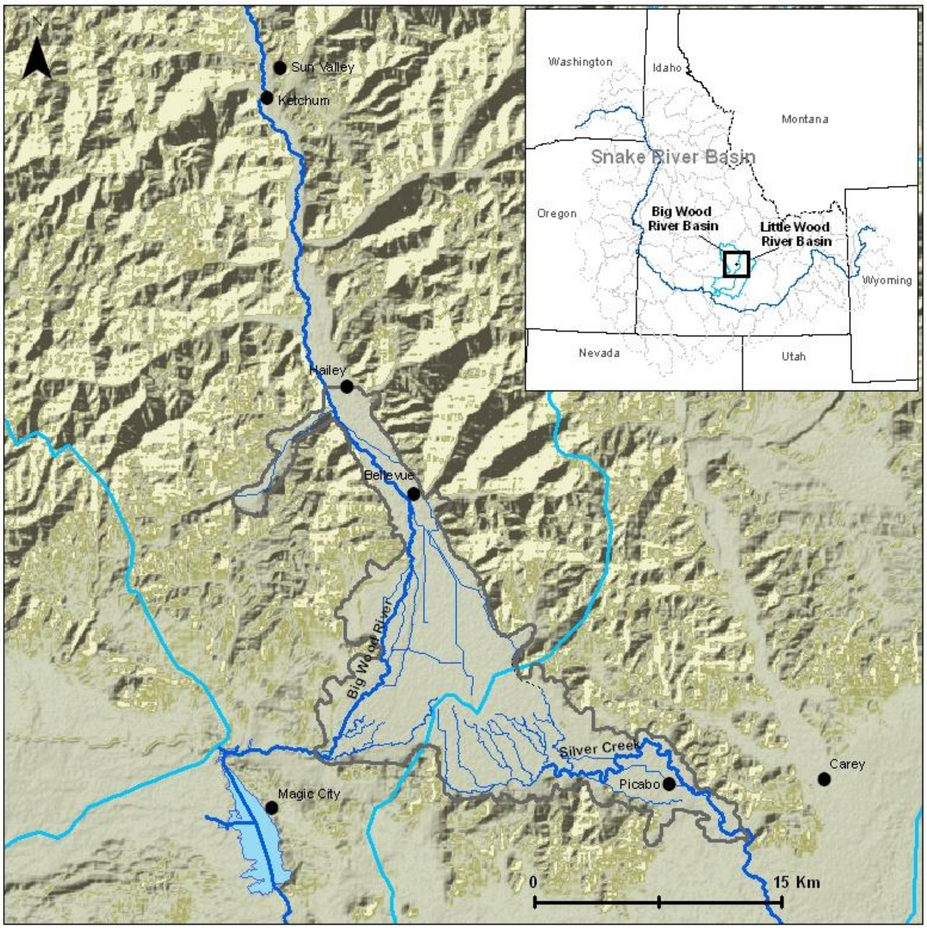

Figure 2. The location and topography of the Big Wood River and Silver Creek.

The Wood River Valley Aquifer is located between two surface water basins (Figure 2) and receives seepage flow from the Big Wood River. Downstream of the aquifer, Silver Creek is a spring-fed system abundant in wildlife and not only a valuable trout habitat but a world-renowned fly-fishing destination. As a spring-fed system, it is necessary to understand the large-scale surface water-groundwater interactions to predict the fluxes in the system. There are several environmental stressors affecting the ecosystem such as changes in channel morphology, fine sediments, water temperature, and nutrients are influenced by land use changes in the catchment. Higher temperatures and decreased flows in Silver Creek during summer are threatening the aquatic habitat.

The overall objectives of this study are therefore:

- To develop an integrated hydro-ecological model to simulate the flows and temperatures in the Lower Wood River Valley and relate physical environmental stressors in the catchment to the ecosystem status of Silver Creek.
- To quantify changes in ecosystem status caused by changes in catchment management

To address these objectives MIKE SHE models for both the Big Wood River and Silver Creek have been developed and calibrated to represent the fluxes. A detailed description of the model development and calibration is given Loinaz et al.[10] The modelling approach adopted was to develop a large-scale regional model to estimate the groundwater fluxes to Silver Creek. A local model of Silver Creek was then established using the regional model results as boundary conditions, (Figure 3).

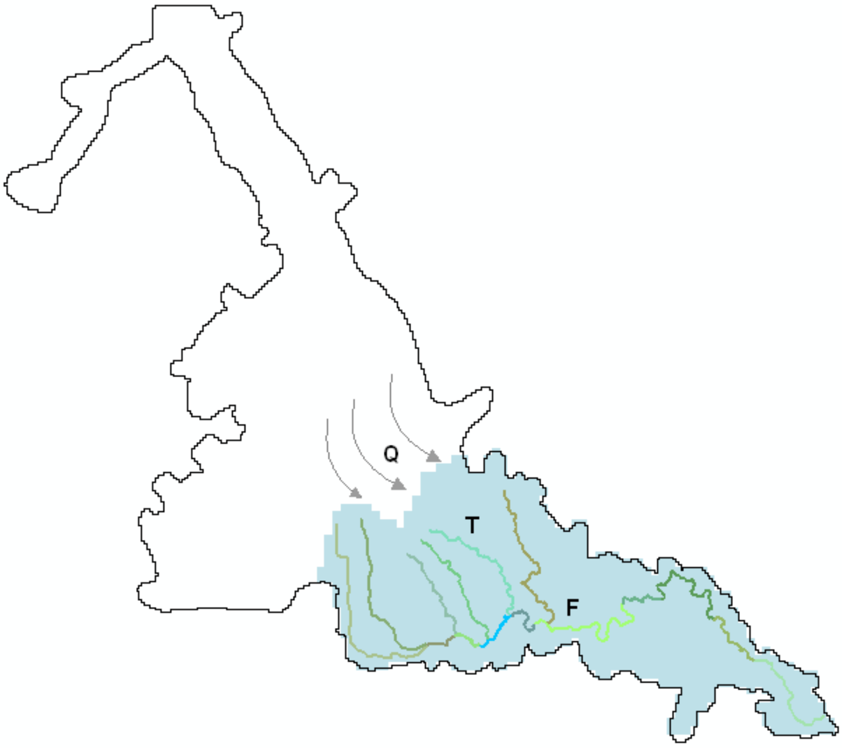

Figure 3. The Silver Creek local model domain (shaded) used to model river temperature

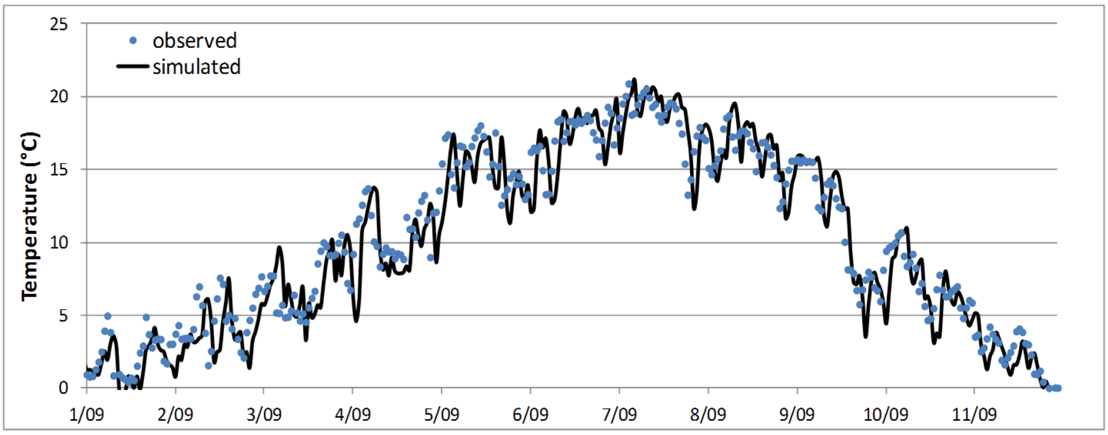

Figure 4. Calibration of the Silver Creek temperature model

Using ECOLAB, a river temperature model was developed and tested against analytical solutions. This model formed the basis of a temperature model for the Silver Creek ecosystem. A more detailed description of this model is also is given in Loinaz et al.[10] The simulation of temperature at one of the temperature measurement stations on Silver Creek shown in Figure 4 suggests that the flow and temperature model developed for Silver Creek is able to simulate the temperature dynamics under current conditions. Future work based on these developments will examine the sensitivity of these model results to different process parameters and to examine the effect of changes in physical conditions in the stream and different management scenarios on the temperature levels and dynamics in the Silver Creek ecosystem, which is critical for the fish population. Initial results indicate that changes in both the management and physical conditions of a stream can have great impact on the surface water temperature signals.

4 CONCLUSIONS

Surface water-groundwater interaction is an important process in riparian areas that can directly impact water budgets and allocations, as well as biogeochemical and ecological conditions and processes. The combination of MIKE SHE and ECO Lab appears to be a useful tool for integrated catchment-scale hydro-ecological problems. This new modelling system has been successfully evaluated against analytical solutions and laboratory data. In modelling the Silver Creek ecosystem, temperature is an important ecological variable that is critical for the fish population. A proper understanding of the effect of different management strategies within this basin depend on both an accurate representation of the flow processes and water management in the Wood River Valley. Future work will examine the effect of different management scenarios on the temperature levels and dynamics in the Silver Creek ecosystem.

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