

Process-based Ecohydrological Modelling at the River Basin Scale and Options for Regionalisation

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Abstract: The paper discusses the importance of physical basis and level of complexity in ecohydrological models at the catchment scale, their spatial structure and temporal resolution, and preconditions for regional applications of models of that kind. As an example, the process-based ecohydrological model SWIM developed for integrated modelling of interrelated hydrological processes, vegetation dynamics and nutrient cycling at the river basin scale is presented along with examples of its validation and a regional climate impact case study.

Keywords: river basin; hydrological processes; water quality; crop yield; climate change; land use change; vulnerability assessment.

1. INTRODUCTION

1.1 Ecohydrological catchment models

Ecohydrology aims at a better understanding of hydrological factors determining the development of natural and human-driven terrestrial and water ecosystems, and of ecological factors controlling water fluxes in landscape and waterbodies. It studies climatic, hydrological, biogeochemical and ecological processes in their interrelations in soil and water. River catchments with their natural boundaries and hierarchical structure can be considered as integrators of many water-related interactions and therefore they represent an appropriate scale for ecohydrological modelling.

By definition, a physically based model describes the natural systems using the basic mathematical representations of the flows of mass, momentum and energy. At the catchment scale, a physically based model has to be fully distributed by accounting for spatial variations in all variables and parameters. However the fact that a model is physically based does not necessarily mean that it is based on fundamental physical laws only. It may include also some conceptual approaches and parametrisations describing mathematically the general process behaviour.

It was demonstrated in many studies that the insertion of physical laws in a model does not by

itself guarantee its quality and reliability. Even if the physical laws included in the model are proven to represent a good mathematical description for a soil column in the laboratory conditions (like e.g. Darcy's law and the Richards' equations for unsaturated flow), where soil has been well mixed, this may not automatically be the case at the scale of grid elements used in distributed hydrological or ecohydrological models [Beven, 1996]. Besides, these equations usually require to be applied with parameters and variables assumed uniform over a spatial scale of hundreds of meters or even kilometers. However, their uniformity can hardly be justified at this scale.

The continuous dynamic models that include mathematical description of physical, biogeochemical and hydrochemical processes, and combine significant elements of both physical and conceptual semi-empirical nature can be called *process-based ecohydrological models*. An ecohydrological process-based model for river catchment inevitably contains a hydrological module as a basic element. Another necessary part is a vegetation submodel. Also, such a model usually includes the submodels for biogeochemical cycles (C, N, P) with a certain level of complexity. The hydrological, vegetation and biogeochemical submodels are usually coupled in order to include important interactions and feedbacks between the processes, like water and nutrient drivers for plant growth, water

transpiration by plants, nutrient transport with water, etc. Usually, vertical and lateral fluxes of water and nutrients in catchments are modelled separately, whereas climate parameters are used as external drivers. Many modelling studies demonstrated that such models are able to adequately represent natural processes at the catchment scale.

For example, the ecohydrological models SWAT [Arnold *et al.*, 1993] and SWIM [Krysanova *et al.*, 1998, 2000] developed for the river basin scale belong to the class of process-based modelling tools.

1.2 Model complexity

An important and not trivial question is: how detailed should an ecohydrological model be at the catchment scale? The model complexity should not be considered as a self-purpose. If a complex phenomenon or process can be described mathematically in a more simplified form and parametrised using available information, this way is preferable in comparison to the other one, when the level of detail is high, parametrisation of the model is problematic, and control of the overall model behaviour is becoming difficult.

However some modellers and model users believe that the more details are included in the model, the better, and that the more complex models guarantee better representation of reality. Nevertheless, the experience of using the complex process-based models during the last decades has led to the conclusion that the model complexity should be generally defined as a compromise solution: include only submodels which are essential and necessary, parameters which can be estimated, interrelations which can be understood and validated in simulation experiments. The overparametrisation can easily lead to the loss of control over the model behaviour.

Also, the modelling results should not be always interpreted as exact predictions, but in the first place qualitatively, as indicators of possible trends, as qualitative differences, etc. Especially, this concerns prediction of water quality, which depends on many external factors with a high level of uncertainty.

Due to their complexity, the ecohydrological catchment-scale models require 'clever users'. Such models cannot be run as a black box, understanding of the code is a prerequisite for successful applications, especially in the case of new model applications in another region, where data availability or resolution may be different.

1.3 Spatial structure and temporal resolution

Spatially distributed or semi-distributed models are usually required in the field of ecohydrological modelling in view of land surface heterogeneity, in particular for land use change impact studies. The lumped models are not appropriate for integrated ecohydrological modelling.

The simplest way to overcome the lumped structure of a model is to subdivide a catchment into subcatchments. This enables to take into account differences in topography or land use in parts of the catchment and to consider spatial variations in considered model variables and parameters. The two-level disaggregation can be implemented by (1) simulating first all the processes in the subcatchments, and (2) aggregation of the outputs for the whole catchment in some reasonable way.

The next step is to further subdivide the land surface in subcatchments into regular grid cells or irregular units using the principle of similarity. In the case of regular grid cells (method 1) the computing time can become a problem, especially for larger basins and finer spatial resolution. In the other case usually the maps of subcatchments, land use, soil, and groundwater table are overlaid to create irregular Hydrologic Response Units (HRUs), which can be later combined into the so-called hydrotope classes inside subcatchments. Then either every HRU is simulated separately (method 2), or every hydrotope class is modelled once in a time step (method 3).

The last two methods of spatial disaggregation take into account the landscape heterogeneity, and they both are more computationally efficient (especially method 3) than method 1. Method 2 may be preferred in comparison with method 3, if the HRU location in the subcatchment or its distance from the river network have to be taken into account.

In case when all main vertical and lateral flows between regular grid cells or irregular units are considered in the model, and the model accounts for spatial variations in all variables and parameters, it is called a fully distributed model. There are also other ways to take into consideration spatial variability and reduce the level of complexity in comparison with the fully distributed models. For example, this can be done considering the lateral processes only for some aggregated units, e.g. between subcatchments. If the model subdivides the catchment into relatively homogeneous subcatchments only, or if it considers HRUs or hydrotopes, but the lateral

flows are first aggregated at the subcatchment level and then routed, the model is called semi-distributed.

The spatial and temporal resolutions of the model depend on data availability and should be appropriate for its use. The spatial resolution, scale of application, and objective of the study are interrelated: a model developed for a small catchment for research purposes may have a fine spatial resolution (e.g. 50 m grid cell or even less) in order to study water flow components and their pathways, or it can be a lumped model in case if 'precipitation – runoff' relations are studied in a quite homogeneous small catchment, whereas a model for mesoscale catchments developed for predictive purposes and impact assessment can be based on a coarser resolution (e.g. 200 m).

In this paper the semi-distributed process-based ecohydrological model SWIM [Krysanova *et al.*, 1998, 2000] developed for regional impact assessment is shortly presented, and the approach to climate change impact study is described.

2. A SHORT MODEL DESCRIPTION

The modelling system SWIM (Soil and Water Integrated Model) is a continuous-time spatially semi-distributed model, integrating hydrological processes, vegetation growth (agricultural crops and natural vegetation), nutrient cycling (nitrogen, N and phosphorus, P), and sediment transport at the river basin scale with the daily time step.

In addition, the system includes the interface to the Geographic Information System GRASS (Geographic Resources Analysis Support System, [1993]), which allows to extract spatially distributed parameters of elevation, land use, soil, vegetation, hydrotope structure, and the routing structure for the basin under study. In addition, soil geophysical and geochemical parameters are derived from available regional data sets or estimated using pedotransfer functions.

A three-level scheme of spatial disaggregation "basin – subbasins – hydrotopes" or "region – climate zones – hydrotopes", plus a vertical subdivision of the root zone into a maximum of 10 soil layers are used in SWIM. A hydrotope is a set of elementary units in the subbasin or climate zone, which have the same land use, soil and average groundwater table. Climate zones defined e.g. by Thiessen polygons can be used instead of subbasins in the regional applications.

During the simulation,

- (1) at first water fluxes and pools, nutrient fluxes and pools, and plant biomass are calculated

for every hydrotope / every soil layer in a hydrotope,

- (2) after that the outputs from hydrotopes are integrated to estimate the subbasin outputs, and
- (3) finally the routing procedure is applied to the subbasin lateral flows of water, nutrients and sediments, taking into account transmission losses.

3. MODEL VALIDATION: AN OVERVIEW

SWIM was tested and validated mostly in the meso- and macroscale subbasins of the German part of the Elbe River drainage basin: for hydrological processes in more than 20 catchments with the drainage area varying from 64 to about 80,000 km², for nitrogen dynamics in two catchments and two lysimeters, for erosion in two catchments, and for crop growth regionally in the state of Brandenburg.

The model validation for nutrient dynamics, erosion and crop yield is described in other papers [Krysanova *et al.* 1998, 1999a, 1999b]. A detailed description of the hydrological validation of SWIM in meso- and macroscale basins is given in Hattermann *et al.* [submitted]. A summary of the hydrological validation of SWIM is shown in Fig. 1, where the values of the Nash-Sutcliffe efficiency and the relative difference in water balance for the simulated water discharge in 13 meso- and macroscale basins are depicted. The efficiency was calculated first for the simulation results with the daily time step, and after that for the simulation results aggregated to the monthly values. The efficiency is ranging from 0.61 to 0.89 with the daily time step, and from 0.66 to 0.94 with the monthly time step, and the difference in water balance is always lower than 5%. The results at daily time step are quite satisfactory, while the higher efficiencies with the monthly time step are quite natural.

The model validation has shown that the model is able to describe with a reasonable accuracy the basic hydrologic processes, including the spatial and temporal variability of the main water balance components; the cycling of nutrients in soil and their transport with water; growth and yield of agricultural crops; the dynamical features of soil erosion and sediment transport under different environmental conditions in catchments of temperate climate zone. This provides a justification and a sound base for studying the effects of changes in climate and land use on all these interrelated processes and characteristics at the regional scale.

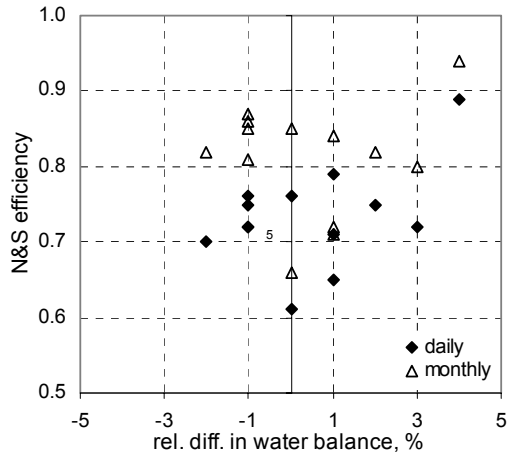


Fig. 1 A summary of hydrological validation of SWIM for meso- and macroscale basins: comparison of the simulated and observed water discharges with the daily time step and after the aggregation of results to the monthly time step using the Nash-Sutcliffe efficiency and relative difference in water balance

4. WHY IMPACT STUDIES IN THE ELBE?

A primary reason for selecting the Elbe River basin as the case study region is its vulnerability against water stress in dry periods. The basin is located around the boundary between the relatively “wet” maritime climate in western Europe and the more continental climate in eastern Europe with longer dry periods. The annual long-term average precipitation is relatively small, less than 600 mm yr⁻¹ in the lowland part of the basin. Therefore the Elbe River basin is classified as the driest among the five largest river basins in Germany: Rhine, Danube, Elbe, Weser, and Ems. Taking into account the high population density in the basin, and a possibility of decreasing precipitation in future due to climate change [Werner and Gerstengarbe, 1997], the necessity for a comprehensive climate impact study is becoming obvious.

Another important reason for detailed analysis of land use related processes in the basin is the pollution of surface and groundwater caused by a high intensity of water use, widespread of intensive agriculture in the drainage area (56%), excessive application of fertilisers and pesticides on arable land, and discharge of domestic and industrial wastes.

Nutrient pollution (nitrogen and phosphorus) is one of the most widespread forms of water pollution. Though since the beginning of 1990s

the emissions from point sources were notably decreased in the eastern Germany due to reduction of industrial sources and introduction of new and better sewage treatment facilities, the diffuse sources of pollution represented mainly by agriculture are still not sufficiently controlled. The application of the process-based ecohydrological model could be beneficial for the evaluation of the effects of diffuse pollution control measures. In this case the model application is the best suitable tool to analyse, how different factors and processes may influence nutrient fluxes from soil to groundwater and to river network over large spatial and temporal scales.

In the Global Change impact studies as mentioned above particular interest is in the effects of the expected changes in climate and land use on hydrological processes, in terms of water balance components and water quality, and on agriculture, especially crop yield. Below an example of climate change impact study is shortly presented.

5. CLIMATE CHANGE IMPACT STUDY

The main objective of the study was to investigate vulnerability of water resources and agriculture in the state of Brandenburg, Germany (~30,000 km²) against expected climate change. The state of Brandenburg largely overlaps with the lowland part of the Elbe River basin.

The IPCC [Watson *et al.*, 1996] attempted to summarise the uncertainties involved in climate impact assessment. According to them, there are at least three main sources of uncertainties in estimating the effects of climate change on hydrological processes at the regional scale:

- climate scenarios based on GCM simulations (especially precipitation),
- conversion of ‘the signal’ from the General Circulation Model (GCM) scenario to the regional scale using different methods of downscaling, and
- regional models used to simulate impacts.

The level of uncertainty could be reduced by considering different climate scenarios, and by a comprehensive test and validation of the applied regional model in advance.

Our approach to cope with uncertainties in climate impact study involved the following steps:

- using a number of different climate scenarios (equilibrium and transient),
- using a range of different CO₂ forcings, e.g. corresponding to 1.5 and 3.0 °C, and

- considering variants without / with the direct CO₂ effect on plant photosynthesis and transpiration.

Besides, an extensive validation of the model in advance is assumed. As a first step, hydrological validation was performed in three mesoscale river basins in the area. After that, the crop module was validated regionally for Brandenburg, using crop yield data for districts. The considered crop spectrum included the most important crops in the region: winter wheat, winter barley and silage maize.

The reference scenario represents the observed climate over the period 1951 - 1990. To reflect the uncertainties in the prediction of global warming by current GCMs, two equilibrium scenarios, SE15 and SE30, and two transient scenarios, ST15 and ST30, assuming temperature increase by 1.5 and 3.0 °C, respectively, were used. The scenarios were developed from GCM results using a statistical downscaling method (Werner & Gerstengarbe, 1997).

Three scenario periods were compared: 1980 - 1990 (reference period), 2020 - 2030, and 2040 - 2050. The atmospheric CO₂ concentrations for the reference period and two scenario periods were set to 346, 406 and 436ppm, respectively. Precipitation is lower for all scenario periods than that in the control period. It is significantly lower for scenario SE15 in both scenario periods (-15.2% and -15.9%), and in the period 2040 - 2050 for both transient scenarios (-13.4% and -12.1%).

In addition to direct climate change, the adjustment of net photosynthesis and evapotranspiration to altered atmospheric CO₂ concentration was studied considering two additional factors:

- adjustment of the potential plant growth rate per unit of intercepted photosynthetically active radiation by a temperature dependent *correction factor alpha*; and
- assuming a reduction of potential leaf transpiration due to higher CO₂ (*factor beta*), which is coupled to the factor alpha.

Different approaches for the adjustment of net photosynthesis and evapotranspiration to altered atmospheric CO₂ have been used in modelling studies. In our study a semi-mechanistic approach for the adjustment of net photosynthesis [see Krysanova *et al.*, 1999b) derived from a mechanistic model for leaf net assimilation [Harley *et al.*, 1992] was applied. The method takes into account the interaction between CO₂ and temperature.

Simulation runs have been carried out in three variants:

- (1) without the adjustment of net photosynthesis and transpiration,
- (2) with factor alpha, and
- (3) with both factors alpha and beta.

In this way we accounted for current uncertainty regarding significance of stomatal effects on higher CO₂ at the regional scale.

Table 1 Average changes in water fluxes and crop yield (%) in Brandenburg for scenarios SE15 and SE30 in 2040-2050 in the cases: 'climate change only' (CCO), 'climate change + factor alpha' (CC + α), and 'climate change + factors alpha and beta' (CC + α + β)

	CCO	CC+ α	CC+ α + β
Scenario SE15			
<i>evap</i>	-4.7		
<i>runoff</i>	-18.5		
<i>gw rech</i>	-51.5		
<i>w. barley</i>	-13.8	-5.5	+6.8
<i>w. wheat</i>	-22.3	-14.5	-4.3
<i>maize</i>	-1.1	+5.4	+23.1
Scenario SE30			
<i>evap</i>	+1.3		
<i>runoff</i>	-7.1		
<i>gw rech</i>	-30.7		
<i>w. barley</i>	-6.2	+2.9	+12.2
<i>w. wheat</i>	-18.7	-10.9	-1.9
<i>maize</i>	+1.5	+8.3	+26.7

The simulation results are partly presented in Table 1 for two scenarios SE15 and SE30 in three variants listed above. The Table shows changes in water fluxes and crop yield: *evap* – evapotranspiration, *runoff* - a sum of direct runoff and interflow, *gw rech* - groundwater recharge, *w. barley* - winter barley, *w. wheat* - winter wheat and *maize* - silage maize. According to the simulation results summarised in Table 1, actual evapotranspiration is expected to increase slightly for scenario SE30. Despite of the higher average temperature, it decreased for scenario SE15 due to significantly lower precipitation. Runoff and groundwater recharge always decreased, whereas groundwater recharge responded more sensitively to the anticipated climate change (from -30.7 to -51.5 %).

The crop yield of winter wheat and winter barley was decreased in both scenarios considering the 'climate change only' case, whereas winter wheat was most sensitive to climate change (22.3% decrease). The impact of higher atmospheric CO₂ (alpha factor) compensated partly for climate-related crop yield losses. The assumption that in

addition a stomatal reduction in transpiration is taking place at the regional scale (alpha and beta factors) lead to further increases in crop yield, which were larger for maize than for barley and wheat.

Reduction in regional transpiration due to higher CO₂ may partly compensate for the decrease in runoff and groundwater recharge (feedback of vegetation on hydrological flows). Across the scenario runs, a high sensitivity of the main model outputs (three hydrological flows and crop yield) to precipitation was found.

A full description of the climate change impact study for Brandenburg is given in Krysanova & Wechsung [2001].

6. CONCLUSIONS

The inclusion of physical laws in a model does not by itself guarantee its quality. The physical laws may not be valid at the scale of grid elements used in hydrological or ecohydrological models, and the parameters used may not be uniform over hundreds of meters, which is usually the case in real model applications. The process-based ecohydrological models are able to adequately represent natural processes at the river basin scale. However, due to their complexity, such models require 'clever users'. They cannot be run as a black box, understanding of the code is a prerequisite of successful applications.

The model complexity is not a self-purpose, a simplified mathematical process description is preferable, if it can be justified. The model complexity should be generally defined as a compromise solution by including only necessary submodels and parameters, which can be estimated and evaluated in simulation experiments. The modelling results should be evaluated first of all qualitatively, and not as exact predictions. After appropriate validation in representative catchments considering all processes of interest, the model can be applied at the regional scale for impact studies.

An example of the model SWIM validation and subsequent application at the regional scale is demonstrated in the paper. It proves that an appropriately scaled model can adequately describe basic ecohydrologic processes in river basins. While results from the SWIM model validation appear quite satisfactory, further development is foreseen for some processes, like nutrient retention in catchments and changes in atmospheric CO₂ and their influence on plant growth and evapotranspiration.

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