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Localization effects of land use change on hydrological models

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Abstract: Semi-distributed hydrological models generally have the advantages of short calculation times, comparative low calibration needs and high model efficiency, but lack the ability to consider localization effects of land use change. A regionalisation of these models allows a sensitivity analysis of the localization effects. HBV-D, a conceptual hydrological model is used in this study. The regionalization for the German watershed Parthe (~317 km^2) is coded in the framework of SME (spatial modeling environment) which allows a fast grid based regionalization of the model. Additional complexity at the finer scale is handled by downscaling of calibration parameters from the semi-distributed model by using auxiliary information (soil, relief). This allows a better representation of the heterogeneity in the watersheds without the need of grappling with hundreds of calibration parameters. A Monte-Carlo analysis is used to simulate the effects of the different spatial pattern of land use changes on discharge. This allows a better forecasting of land use change effects and can be used to generate uncertainty estimates for existing semi-distributed models. We focus here on the following major questions: 1. how can we downscale the calibration parameters from the semi-distributed model to the distributed model, 2. how do downscaling approaches differ, 3. how does land use composition and configuration influence discharge and 4. how do these results depend on catchment characteristics?

1 INTRODUCTION

Watersheds are a fundamental subdivision of landscapes for modeling and impact analysis. Hydrological processes are linked with land use, climatic impacts, managements interventions and other natural and anthropogenic processes within watersheds. Watershed simulation models describe physical, hydrological and in some cases biogeochemical processes, often in a dynamic way. They describe the fluxes of water and, if applicable, associated substance fluxes from the catchment surface towards the basin outlet. Typically, water transport through the saturated and unsaturated part of the soil, surface flow and interflow as well as channel flow are part of the model. The spatial aggregation of the models can differ from lumped models to semi-distributed and spatially explicit models. In hydrological modeling at the meso-scale, lumped or semi-distributed conceptual models are widespread because they offer an easy and often adequate way to simulate the discharge at the catchment outlet. While an aggregated modeling approach is well suited for many problems, a finer spatial subdivision may be necessary to describe the effects of spatially heterogeneous events like land use change or management measurements such as buffer stripes or erosion control.

Conceptually, two main methods of spatial disaggregation exist: the grid square method and the subdivision of subareas into classes, which are assumed to show a common hydrological response (hydrological response units / HRUs). For example, HBV-D (Krysanova et al. [1999]) - a semi-distributed version of the lumped original HBV model (Bergström [1976]) - is able to deal with a subdivision of a basin in sub-basins which are in turn subdivided in response units formed by eleva-

tion zones and land use zones. The processes in each response unit in a sub-basin are modeled and the aggregate water fluxes are routed towards the outlet of the basin. The model SWAT (Arnold et al. [1993]) covers the heterogeneity inside a sub-basin by hydrological response units formed on the basis of land use zones and soil zones. While it is not possible to access a location inside a response unit after the preprocessing, it is possible to derive a large number of response units by dividing the basin into very small sub-basins[1]. There is, of course, a trade-off between the number of response units and computing time. Since the handling of topology on a polygon based data structure is much more complex compared to a grid based approach, a division of the basin into a regular raster grid has performance advantages if we pass a certain threshold. In principal, each raster cell could be modeled with a different parameter set, but because this would imply the calibration of literally thousands of parameters it may not be the optimal strategy. Instead, it may be a better strategy to use knowledge gained from the calibration of the coarser, semi-distributed model or by grouping the cells on the basis of their physical characteristics. Here, we would like to show how such a parametrization of a regionalized model can be performed by estimating the distributed model parameters as a linear combination of site conditions like soil and relief. We perform a sensitivity analysis of the HBV-D model on localization effects of land use change using these parameterizations.

2 STUDY AREA

We developed our methodology for the Parthe basin southeast of Leipzig, east Germany. The Parthe is one of the major tributaries of the Weiße Elster river (compare figure 1). The basin covers about 318 km^2; it is mainly flat with elevations from 110 m at the outlet up to 230 m in the Southeast. Due to its location at the lee side of the Harz mountains the area is characterized by low precipitation. The mean annual precipitation at the weather station Brandis is 660 mm while the mean annual potential evaporation reaches 630 mm. The subsurface is predominantly formed by moraine material. Bedrock is only present in the southern and eastern part of the area. The moraine sediments are between 1 - 20 m thick and are covered by a approximately one meter thick layer of aeolic sand-loess material.

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[1]The accuracy of the underlying digital elevation model will define the lower boundary for such an attempt.
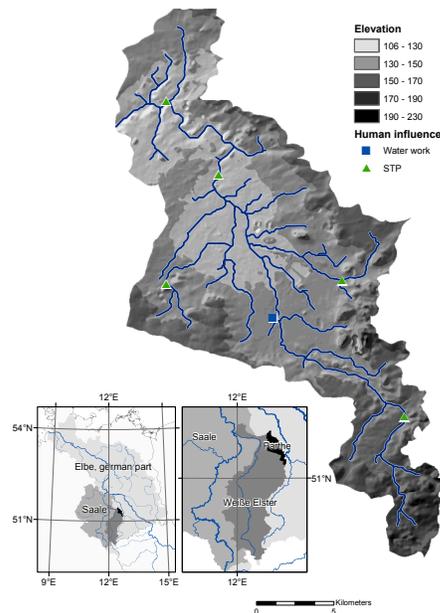

Figure 1: The Parthe basin is part of the Weiße Elster basin which is a sub-basin of the Saale which tributes to the Elbe.

The region is used intensively for agriculture: about two thirds of the total area of the basin are used by agriculture, 15% are residential areas, additional 15% are covered by forest and about 1% by open water bodies. The waterworks Naunhof I and Naunhof II withdraw 30% of the groundwater discharge that originates in the area. While the water from Naunhof I is used completely outside the basin, a part of the water withdrawn in Naunhof II is used in the area and re-enters the channel water.

3 METHOD

3.1 Conceptual model

The semi-distributed model. The HBV model has proven to be a rather robust tool for runoff simulations at the catchment scale (Bergström [1995]; Lidén and Harlin [2000]). We used a slightly simplified version of HBV-D (Krysanova et al. [1999]) to setup our spatially distributed model. The model consists of four main modules: the snow module, the soil moisture model, the runoff response module and the routing module. The snow module deals with snow accumulation, snow melt and refreezing of water in the snow pack. While the original HBV-D model handles snow distribution in the response units by a log-normal function a

much simpler approach is used here. We assume a linear relationship between the snow pack and the area covered by snow. Snow melt is modeled by a day-degree approach (1); snow melt occurs at a rate C_X [mm / (°C· d)] if the temperature T [°C] drops under the threshold T_S [°C]. Melt water and rain are stored in the snow pack until a threshold LV [mm] is reached. Water in the snow pack refreezes with a rate of F[mm/d] (2) and is multiplied with the factor C_{fr} ($0 \leq C_{fr} le 1$). Both the melt rate M [mm/d] and the refreeze rate F are modified by the land use dependent factor $C_{X_{rel}}$ [-].

$$M = \begin{cases} C_X \cdot C_{X_{rel}}(T - T_S) & \text{if} \quad T \geq T_S \\ 0 & \text{if} \quad T < T_S \end{cases} \quad (1)$$

$$F = \begin{cases} C_{fr} \cdot C_X \cdot C_{X_{rel}} \cdot (T_S - T) & \text{if} \quad T \leq T_S \\ 0 & \text{if} \quad T \geq T_S \end{cases} \quad (2)$$

Evapotranspiration A_E [mm/d] (3), infiltration (4) and draw up UP [mm/d] of water from the upper zone into the soil moisture zone (5) are part of the soil module. Water enters the soil module from precipitation, snow melt or as draw up water from the upper zone (5) and leaves the stock by perlocation (4) to the upper zone UZ or by evapotranspiration (3). Actual evapotranspiration A_E depends on the potential evaporation P_E which is calculated according to Blaney and Criddle [1950] on soil moisture SM [mm] field capacity FC [mm] and two land use dependent factors FC_{rel} and LP_{del} which are used to modify the field capacity and the threshold at which actual evapotranspiration equals the potential evapotranspiration.

$$A_E = \begin{cases} P_E \cdot \frac{SM}{\xi \cdot LP_{del}} & \text{if} \quad \frac{SM}{LP_{del}} \leq \xi \\ P_E & \text{if} \quad \frac{SM}{LP_{del}} \geq \xi \end{cases} \quad (3)$$

$$C_{uz} = \begin{cases} \left(in_{soil} \frac{SM}{\xi}\right)^{beta} & \text{if} \quad SM \leq \xi \\ in_{soil} & \text{if} \quad SM > \xi \end{cases} \quad (4)$$

With $\xi = FC \cdot FC_{veg}$

$$UP = 2 \cdot Draw \cdot \frac{LZ}{LZ_{max}} \cdot \frac{\xi - SM}{\xi} \quad (5)$$

The transfer of excess water from the soil moisture module to discharge is handled in the runoff response model. The flux of water from the soil moisture zone C_{uz} (equation 4) towards the upper zone of the runoff response model is dependent on the amount of water which enters the soil moisture zone in_{soil} (effective precipitation + melt water) the relationship between SM and FC and the factor of non-linearity $beta$. The runoff is generated by two linear reservoirs the upper Zone uz and the lower zone lz. Discharge from the upper zone (6) is divided into a fast and a slow component with the recession coefficients K_{uz_1}, K_{uz_2} respectively. These two discharge components can be understood as conceptual equivalents of surface runoff and interflow. The discharge from the lower zone (7) is modeled by a simple linear reservoir. The water flux from the upper to the lower zone is determined by the parameter $Perc$ [mm/d], and additional movement from the lower zone towards deeper ground water zones is controlled by the parameter $Deep$ [mm/d].

$$Q_{uz} = \begin{cases} K_{uz_1} \cdot uz & \text{if} \quad uz \leq uz_1 \\ K_{uz_2}(uz - uz_1) + K_{uz_1} \cdot uz_1 & \text{if} \quad uz > uz_1 \end{cases} \quad (6)$$

$$Q_{lz} = K_{lz} \cdot lz \quad (7)$$

The distributed model. For the distributed model version (HBV-SME) the equations of the semi-distributed have been coded in STELLA (Peterson and Richmond [1996]) and regionalised on a grid of the spatial modeling environment (SME; Maxwell and Costanza [1997]). This framework offers a handy way to solve an equation-based model for each cell of a raster. SME assigns a stocks and flow model to a grid and solves the equations for each cell whereas additional C++ code handles lateral flows. The model framework has been successfully applied to integrated ecological economic watershed modeling in the Patuxent landscape model (Voinov et al. [1999a]; Seppelt and Voinov [2002, 2003]).

The lateral transport functions for surface flow, interflow and ground water flow, were taken from Voinov et al. [1998, 1999b]. We assume that the lower zone represents the groundwater zone. Transport in this zone is simulated by a Darcy-flow approach which takes the conductivity and the porosity of the soil type into account. If a cell is marked as a channel cell the groundwater infiltrates with the rate K_{lz} (compare equation 7) into the channel. The channel water as well as the fast discharge component and the interflow/slow discharge component (see equation 4) is moved along the flow direction
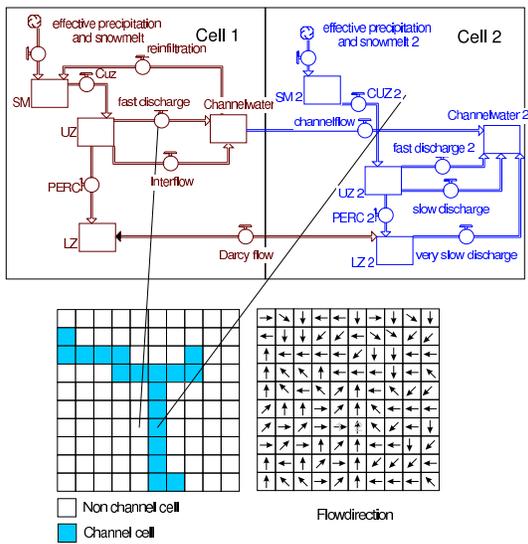
Figure 2: In addition to the vertical processes which are simulated in each cell, the distributed model must account for lateral flows between the cells. See the text for details.

calculated by standard GIS methods. The approach of Voinov et al. [1998, 1999b] allows a movement of several cells during one time step, thus allowing the choice of a daily time step even for the routing of the channel water. Figure 2 demonstrates the interaction between cells, focusing on the lateral flow between two cells and ignoring the flows from or towards the other neighboring cells. While cell 1 is a 'normal' cell, cell 2 is marked as a channel cell, i.e. it is assumed that a part of this cell is occupied by a river. Fast and slow discharge from cell 1 is routed in the flow direction by the surface flow routine. Since cell1 is not marked as a channel excess surface water re-infiltrates if it has not been moved downhill. The very slow discharge connects the lower zone stocks of cell 1 and cell 2 such that the water flow does not follow the flow direction but instead obeys the general rules of Darcy flow (the flow can be bidirectional depending on the water amount in each stock). Because cell 2 is marked as a channel cell water from the lower and the upper zone enters the channel water.

The impacts of the water withdrawal at Naunhof I and II is modeled by extracting the water from the lower zone using the available monthly withdrawal volumes. We assume that a part of the water which is used in the basin itself reenters the system via the sewage treatment plants. For the other part, it is assumed that water is mainly used for irrigation resulting in an additional water input on the irrigated areas.

Results calculated with the distributed model (see figure 3) show a reasonable fit to the observed data at gauge Thekla, Leipzig. While the Nash-Sutcliff efficiency and the Nash-Sutcliff efficiency of the log-transformed values are reasonable (0.77 respectively 0.67) the hydrograph shows some water withdrawal not captured by the model. As a result the relative water balance has a bias of +8%.

3.2 Downscaling

A first analysis of the model was performed using the calibration parameters from a manual calibration of the semi-distributed HBV-D version using a single catchment delineation subdivided by 10 elevation zones and 12 land use zones. In fact, this means that we neglected the additional variability at the finer model scale. The only additional variability of the model was introduced by the routing between the cells, which considers the location of the cell, the channel network and the porosity of the underground. The effect of land use change was simulated by changing randomly chosen cells from agricultural land use to forest. For the simulation of more realistic land use events we forced the reforestation to happen only in specified zones likes valleys, ridges, floodplains or at steep slopes.

Next, we tried to introduce additional variability on the model parameters. In a first approach we grouped the cells by using slope, aspect, clay fraction and sand fraction, and then changed the model parameters for these groups. The analysis of 19 calibrated catchments in the German Elbe catchment showed no possibility of linking the characteristics of these catchments to the cell level. The manual calibration for these 19 basins seems to have lead to model parameters that cannot be linked to the central tendencies or the variability of catchment properties. These problems may be caused by the equifinality of model calibration since the the catchment characteristics have only been used as additional information during the calibration process[2].

In a second approach, we used the assumption that the spatial heterogeneity of the model parameters θ_k

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[2]The calibration tried to minimize steep gradients between catchments with an upstream-downstream relationship to avoid the generation of discharge artefacts.
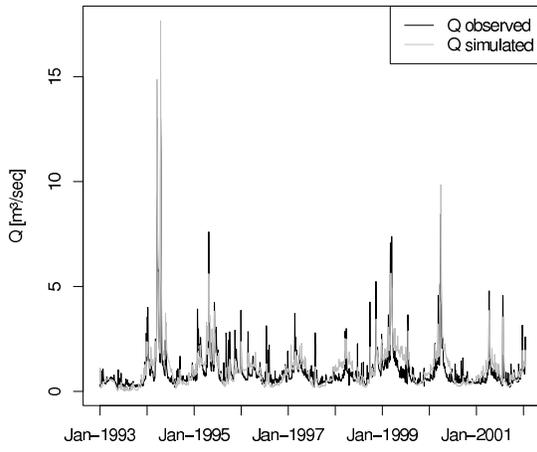
Figure 3: Comparison between daily simulated (Q sim) and daily observed discharge (Q obs) at gauge Thekla near Leipzig.

could be expressed by a linear combination of the site conditions sc:

$$
\begin{aligned}
\theta_i &= f(sc_1, sc_2, ..., sc_m) \\
&= a_{i,1} \cdot sc_1 + a_{i,2} \cdot sc_2 + ...a_{i,m} \cdot sc_m
\end{aligned}
\tag{8}
$$

A latin hypercube sampling strategy was used to explore the different parameter settings for the cell classes. The objective functions are defined by the Nash-Sutcliff criterion [Nash and Sutcliff, 1970] (equation 9) for the gauging stations Thekla, Glasten, Naunhof and Schnellbach and by the corresponding water balance values (equation 10). The parameter set which lead to the best model efficiency was then used to study the impacts of land use change on discharge generation.

$$
E = 1 - \frac{(\sum_{i=1}^{t}(Q_{sim,i} - Q_{obs,i})^2)}{(\sum_{i=1}^{t}(Q_{obs,i} - \bar{Q}_{obs})^2)}
\tag{9}
$$

$$
WB = \frac{\sum_{i=1}^{t}(Q_{sim,i} - Q_{obs,i})}{\sum_{i=1}^{t} Q_{obs,i}}
\tag{10}
$$

4 CONCLUSIONS AND RECOMMENDATIONS

It seems that the spatial disaggregation of semi-distributed models can be quite helpful for forecasting the effects of land use change on watershed discharge. The chosen raster-based regionalization approach is able to consider spatial heterogeneity of a watershed at a scale that is well suited for management options at the catchment scale. However, care should be taken to avoid the use of a cell size which calls for a process description at a smaller scale.

Fully distributed models have to face the criticism of Beven [1996, 1989] who calls these models overparameterizied lumped conceptual models. We agree with Beven [1993, 1996] that equifinality is a major problem when using conceptual hydrological models: a problem that gets worser when introducing more parameters by subdividing the basin into subunits followed by the introduction of additional parameter settings. However, we recognize the need to forecast the effect of land use change on the hydrological system. To manage this in an effective way, we examined two hypotheses for the setup of the distributed model. First, we assumed that the effective model parameters get an additional variability on the smaller scale and that this variability can be related to some of the physical properties of the cells. Second, we proposed that it would be possible to relate the physical basin characteristics to the parameters of the semi-distributed model. While the first hypothesis needs to be rejected the second one seems promising. In contrast to modeling approaches like MIKESHE (Refsgaard and Storm [1995]) where all parameters of the model can - at least in principle - be altered for each cell, we deal with classes of cells which share a common set of properties such as soil type, slope and aspect[3]. Therefore we do not assign parameters to cells but instead to classes of cells which share a set of properties.

Further research will focus on the effects of scale by the application of this methodology to the Weiße Elster and Saale catchments. Data availability and computational effort call for an enlargement of the cell size while the model structure could be maintained. The raster-based approach allows the observation of the effects of a continuous change of spatial aggregation on the regionalization parameters, which could lead to the identification of thresholds that could hopefully be used to gain a deeper understanding of distributed hydrological modeling. Again, care must be taken to avoid too large cell sizes which distort the spatial interaction on the landscape by aggregating disjunct catchments in one cell. Additionally, the relationship between

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[3] Since land use is covered in HBV-D by land use specific parameters which interact with the other model parameters we did not consider land use by the classification of the cells.

catchment characteristics and the regionalization parameters seems to be an interesting subject for further investigations.

As one purpose of this study was to estimate the sensitivity of the semi-distributed HBV-D model to the location of land use change, we used a model structure as close to the original model as possible. For further applications of the distributed model we would argue in agreement with Samaniego and Bardossy [2005] that a more parsimonious model structure would be favorable.

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REFERENCES

Arnold, J. G., P. M. Allen, and G. Bernhardt. A comprehensive surface-groundwater flow model. *Journal of Hydrology*, 142(1-4):47–69, 1993.

Bergström, S. Development and application of a conceptional runoff model for scandinavian catchments. rep. RHO, Swedish Meterological and Hydrological Institute, Norrköping, Schweden, 1976.

Bergström, S. The HBV model. In Singh, V. P., editor, *Computer models of Watershed Hydrology*, pages 443–476. Water Ressources Publications, Littletown, Colorado, USA, 1995.

Beven, K. Changing ideas in hydrologythe case of physically based models. *Journal of Hydrology*, 105:157–172, 1989.

Beven, K. A discussion of distributed hydrological modelling. In Abbott, M. B. and lastname Refsgaard, J. C., editors, *Distributed Hydrological Modelling*, pages 255–278. Kluwer Academic, Dordrecht, 1996.

Beven, K. J. Prophecy, reality and uncertainty in distributed hydrological modelling. *Advances in Water Resources*, 16:41–51, 1993.

Blaney, H. and W. Criddle. Determinating water requirements in irrigated areas from climatological and irrigation data. Scs tp, US Dep Abr. Div. Irrigation and Water Conservation, 1950.

Krysanova, V., A. Bronstert, and D. Müller-Wohlfeil. Modelling river discharge for large drainage basins: from lumped to distributed approach. *Hydrological Sciences - Journal des Sciences Hydrologiques*, 44(2):313–331, 1999.

Lidén, R. and J. Harlin. Analysis of conceptual rainfall-runoff modelling performance in different climates. *Journal of Hydrology*, 238:231–247, 2000.

Maxwell, T. and R. Costanza. A language for modular spatio-temporal simulation. *Ecological Modelling*, 103:105–113, 1997.

Nash, J. and J. Sutcliff. River flow forecasting through conceptual models. Part I - A discussion of principles. *Journal of Hydrology*, 10:282–290, 1970.

Peterson, S. and B. Richmond. Stella research technical documentation. Technical report, High Performance Systems, Inc., 1996.

Refsgaard, J. and B. Storm. Mikeshe. In Singh, V., editor, *Computer Models in Watershed Hydrology*, Water Resources Publication, pages 809–846. 1995.

Samaniego, L. and A. Bardossy. Robust parametric models of runoff characteristics at the mesoscale. *Journal of Hydrology*, 303(1-4):136, 2005.

Seppelt, R. and A. Voinov. Optimization methodology for land use patterns using spatially explicit landscape models. *Ecological Modelling*, 151(2-3):125–142, 2002.

Seppelt, R. and A. Voinov. Optimization methodology for land use pattems - evaluation based on multiscale habitat pattern comparison. *Ecological Modelling*, 168(3):217–231, 2003.

Voinov, A., R. Costanza, L. Wainger, R. Boumans, F. Villa, T. Maxwell, and H. Voinov. Patuxent landscape model: integrated ecological economic modeling of a watershed. *Environmental Modelling & Software*, 14:473–491, 1999a.

Voinov, A. A., H. C. Fitz, and R. Costanza. Surface water flow in landscape models: 1. everglades case study. *Ecological Modelling*, 108:131–144, 1998.

Voinov, A. A., H. Voinov, and C. Robert. Surface water flow in landscape models: 2. patuxent watershed case study. *Ecological Modelling*, 119: 211–230, 1999b.