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Assessing the impact of land use change on hydrology by ensemble modeling (LUCHEM) III: Scenario analysis

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ABSTRACT

An ensemble of 10 hydrological models was applied to the same set of land use change scenarios. There was general agreement about the direction of changes in the mean annual discharge and 90% discharge percentile predicted by the ensemble members, although a considerable range in the magnitude of predictions for the scenarios and catchments under consideration was obvious. Differences in the magnitude of the increase were attributed to the different mean annual actual evapotranspiration rates for each land use type. The ensemble of model runs was further analyzed with deterministic and probabilistic ensemble methods. The deterministic ensemble method based on a trimmed mean resulted in a single somewhat more reliable scenario prediction. The probabilistic reliability ensemble averaging (REA) method allowed a quantification of the model structure uncertainty in the scenario predictions. It was concluded that the use of a model ensemble has greatly increased our confidence in the reliability of the model predictions.

1. Introduction

Assessing the impact of land use change on water resources on a local, regional and global scale is a major challenge in hydrology. Typically, this is done by setting up a hydrological catchment model for the current land use, defining the expected changes in land use within a land use change scenario, re-running the model for the future land use and analyzing the differences between these two sets of simulations (e.g. [5,14,23,25] amongst others). Arguably, conventional practices for validation of hydrological models are not suitable for assessing the ability of a model to predict the impact of future environmental change [3]. Furthermore, the extensive calibration that is required to adapt most hydrological models to the current conditions makes one wonder whether these models are applicable for cases where the boundary conditions (e.g., climate, land use) have changed.

Ideally, predictions of the impact of land use change made with a specific model should be validated by comparison with data obtained after the land use change has occurred. However, such extensive validation is seldom performed (e.g. [33]). A main reason for this is the lack of suitable datasets for this purpose, despite the fact that there have been numerous experimental studies on the impacts of land use change in single and paired catchments (see [2,8,11,28]). As an alternative, Bathurst et al. [3] proposed to use a "blind" validation technique developed by Ewen and Parkin [13] in which the modeler is not allowed sight of the catchment output data so that the model cannot be calibrated for the

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catchment under consideration. Such a blind validation test is harsh, and it is likely that many models would not pass such a test for a particular catchment.

Other environmental modeling communities also have to deal with predicting the impact of a change in boundary conditions. Most noticeable is the climate change community, which needs to predict the impact of rising CO_2 concentrations on the future climate. To deal with the uncertainty in these predictions of future climate, it has become common practice in this community to analyze scenarios with an ensemble of models instead of a single model [21]. There are two general approaches to the interpretation of ensemble modeling results. In the first so-called deterministic approach, an optimal combination of ensemble members is sought that results in better predictions than each single ensemble member (e.g. [12,16]). In the second so-called probabilistic approach, the single ensemble members are treated as possible (although not necessarily equally likely) realizations of the system response. In this probabilistic setting, quantitative methods to determine the uncertainty from an ensemble of scenario predictions have recently been proposed [17,26,29,30].

To increase the confidence in predictions of the impact of land use change on water resources, a set of hydrological models has been calibrated and validated on the same catchment and thereafter applied to the same set of land use change scenarios within the LUCHEM ("Assessing the impact of Land Use Change on Hydrology by Ensemble Modeling") project. This paper is the third in a series of four presenting the results of the LUCHEM project. The first paper ([10], this issue) describes the general set-up of the project, provides information on the relevant characteristics of the participating models and discusses the performance of these models for the current land use distribution. The second paper ([31], this issue) investigates the potential of deterministic model ensembles made up of some or all of the individual models to improve predictions of streamflow. The fourth paper ([7], this issue) investigates the effects of data resolution and spatial distribution of land use information on the simulated water balance for current catchment conditions and land use change scenarios for a subset of three models. In this third paper, the results of the application of these catchment models to the same set of land use change scenarios are analyzed. The aims of this paper are to (1) determine to what extent the models result in different simulations for the land use change scenarios and to understand the reasons behind these differences to the extent possible; (2) derive optimal (deterministic) scenario predictions of the impact of land use change from the ensemble of simulations and (3) quantify the uncertainty in the land use change predictions from the ensemble of simulations using probabilistic ensemble methods.

2. Materials and methods

2.1. Catchment description and available data

Land use change scenarios were developed and investigated for the low mountainous Dill catchment (693 km^2) in Germany. The Dill catchment is characterized by shallow soils underlain by fissured bedrock aquifers. Cambisols are the dominant soil types, covering >60% of the area. As a consequence of solifluction on periglacial slope deposits, the hydraulic conductivity of the soils is anisotropic with larger conductivities in horizontal direction. Because of the shallow soils and the anisotropic hydraulic conductivity, discharge in the Dill catchment is dominated by lateral flow. Mean annual rainfall varies between 700 and 1100 mm within the catchment and is not only dependent on height, but also decreases from west to east. The annual mean temperature is 8 °C.

The landscape is characterized by a heterogeneous small structured land use pattern. The land use is comprised of deciduous forest (29.5%), coniferous forest (24.8%), pasture (20.6%), urban areas (9.2%), fallow (9.1%), cropland (6.5%), and water (0.3%). The typical crop rotation in the region is winter barley, winter rape, and oats. Besides shallow soils and unfavorable climatic conditions, the high proportion of fallow land is a consequence of the socio-economic structure of the area. High opportunity costs result in a disproportionate number of part-time farmers. This leads to high machinery costs, which are further reinforced by relatively small average field sizes ($\sim$0.7 ha).

A detailed description of the data provided to each of the LUCHEM participants is given in a companion paper [10]. In summary, digital data on land use, soils and elevation were provided on a 25 m grid. The land use distribution in 1994–1995 was obtained from multi-temporal Landsat TM 5 images [24]. Soil information was derived from digitized 1:50000 soil maps [19]. Climatic data for the period of 01.01.1980 to 31.12.1998 from the German weather service (DWD) were also provided on a daily basis. Available data included precipitation (mm), wind speed ($m\ s^{-1}$), global radiation ($MJ\ m^{-2}\ d^{-1}$), air temperature (°C) and relative humidity (%). Precipitation was measured at 12 stations inside and six stations outside the catchment, whereas the other climatic variables were only recorded at two stations inside the catchment.

2.2. ProLand model

The land use change scenarios used in this study were derived with the ProLand (prognosis of land use) model [22,32]. ProLand assumes that land use patterns are a function of natural, economic, and social conditions in a landscape. It postulates land rent maximizing behavior of the land user. Land rent is defined as the sum of monetary yields including all subsidies minus input costs, depreciation, taxes, and opportunity costs for employed capital and labor. Depending on the economic and ecological boundary conditions, the model calculates the land rent for a set of agricultural and forestry land use systems for each parcel of land. ProLand only simulates one type of forestry, namely mixed forests consisting of deciduous and coniferous trees (*Fagus sylvatica* beech, 40%; *Quercus* spp. oak, 20%; *Picea abies* spruce, 30%; *Pinus sylvestris* pine, 6%; and *Pseudotsuga menziesii* Douglas fir, 4%). This forest production system resembles the dominant forest species distribution in the landscape investigated in this work.

The ProLand version used in this scenario analysis is based on a pixel approach. Hence, every simulated parcel of land is equivalent to the area of a 25 m pixel. The land use system with the highest land rent is selected as the optimal land use for the pixel under consideration. Farmer sentiments and costs associated with land use change are not considered. In addition, ProLand does not consider neighborhood relationships. Thus, it can happen that a pixel with a particular land use is surrounded by different land uses. This restriction is model specific and may sometimes produce unrealistic land use patterns ("an island of cropland in the forest"). The output of the ProLand model consists of data describing the economic performance of the calculated set of land use systems and a spatially explicit map of the optimal land use distribution given the provided boundary conditions. Further details of the model set-up and performance are given in [22,32].

2.3. Field sizes scenarios

As in many other regions of Europe, the inheritance system has had a tremendous effect on average field sizes in the Dill catchment. Typically, fields were split equally amongst the inheritors. As a result, the average field size decreased more and more. In