Macro- and Mesoscale Hydrological Modelling in the Elbe River Basin

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Abstract

A GIS-based modelling approach is used for hydrological simulation calculations in the German part of the Elbe river basin (96.428 km², macroscale) and in the Stepenitz sub-basin (575 km², mesoscale). The approach includes variable spatial aggregation and disaggregation methods necessary to study the regional impacts of climate and land use changes on the hydrological cycle. The adequate interpolation of climatic input variables turns out to play an key role in large scale hydrological modelling. The results obtained for various water balance components and for two land use change scenarios demonstrate that the developed concept can be applied to river basins of different size and characteristics and is especially suited for regional impact studies.

Key words: Hydrological modelling at different scales, GIS-coupling, spatial aggregation and disaggregation methods, water balance calculations, land use and climate change

1 Introduction

Global change phenomena and processes take place and have to be investigated at all spatial scales, from local to global. Stronger emphasis on regional and local scales is needed at the land surface where the most important sources and drivers of global change are located, as for instance areas with changing land use/land cover, industrial complexes, cities, traffic with emissions of trace gases, different types of waste, etc. It is primarily at these scales that political and technical measures and action can and must be taken to avoid critical developments and to reduce negative or undesired effects. The regional scale is crucial for an improved understanding not only of the different causes of global change and the contributing processes, but also of its impacts on the environment and society.

River basins are preferred land surface units for regional scale studies because they represent natural spatial integrators/accumulators of water and associated material transports at the land surface. For the present hydrological study, the German part of the Elbe river basin covering an area of nearly 100,000 km^2 was chosen (see **Fig. 1**). It is the driest of the five largest German river basins, so that water stress and water deficiencies occur earlier and more frequently in the case of droughts than in other parts of Germany.

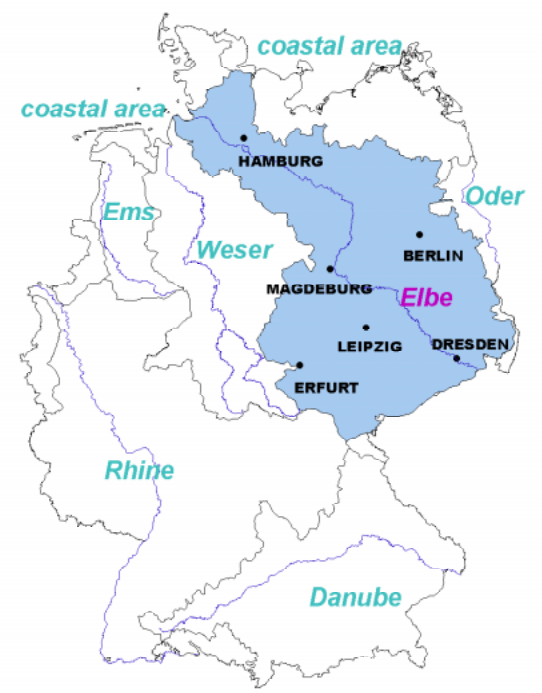

Fig. 1: The German part of the Elbe river basin, covering an area of nearly 100,000 km^2.

The approach used in the present study applies methods of a GIS-based modelling concept, which were developed at the mesoscale, to a macroscale river basin. It is based on variable spatial disaggregation and aggregation techniques, which allow an effective simulation of the regional hydrological cycle. It consequently uses the GIS-based derivation of model pa-

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rameters from generally available spatial data. The application in the Elbe river basin and in some of its sub-basins demonstrate that the disaggregation of a study region into subareas of similar hydrological behaviour represents an effective modelling concept. The simulation calculations performed in these basins of various size and characteristics show that the developed concept can be generally applied.

The results presented in the following cover spatially distributed values of various water balance components for the whole Elbe basin (Lahmer 1997) and some more detailed analyses for the Stepenitz river basin, a tributary basin of 575 km² size about 200 km north of Magdeburg (see Fig. 1). These analyses also include some first results in modelling land use changes.

2 Methodology

The concept of fully distributed physically based models has been questioned in recent years, because their application is constrained by the availability of required input data and their use in prediction at the regional level is often of limited value (e.g., Gleick 1986, Beven 1993). Therefore, simplified (conceptional) models with physically meaningful parameters are needed which can be applied at different scales. Such models must be able to use directly the information provided by various digital maps and to handle different temporal and spatial discretization levels. In addition, they must enable simulations based on spatial units of various size and heterogeneity.

The modelling concept applied in the Elbe river basin is based on results obtained in the Upper Stör basin, a mesoscale river basin of about 1.100 km² in the northern part of Germany (north-east of Hamburg, see Fig. 1), where some essential problems of large- and mesoscale hydrological modelling were successfully addressed (Lahmer et al. 1997, Becker and Lahmer 1997). The spatially distributed and temporal dynamic modelling performed with the modelling system ARC/EGMO (Pfützner et al. 1997) resulted in the following general conclusions:

- It is appropriate to distinguish two domains of hydrological processes, that of vertical and that of lateral fluxes, because then different disaggregation, aggregation, and scaling techniques can be applied in both domains to simplify modelling, if required.
- Mixed landscapes should be subdivided (disaggregated) into units of unique hydrological regime (hydrotopes or Hydrological Response Units HRU), which significantly differ in their hydrological process characteristics, in particular in vertical processes modelling, for two reasons: (i) In contrast to aggregated (lumped) modelling, important areal process differentiations can be described appropriately, and (ii) the physical soundness of the applied models is better preserved and model parameters can be more directly derived from real land surface characteristics.
- Polygons of different form and size are best suited to represent the mosaic structure of real landscapes. In regions with similar climate such spatially distributed polygons can be combined (aggregated) into larger modelling units (e.g. hydrotope classes) to simplify large scale modelling and to reduce computing time (fractional area concept). The ‘intra patch’ areal variability of parameters can be represented adequately by areal distribution functions.
- In lateral flows modelling, simple approaches like single storage reservoirs or simplified diffusion type models have turned out to be most efficient. They can be applied to large river basins and sub-basins.

2.1 Spatial disaggregation to elementary units

One basic problem in meso- and macroscale hydrological modelling is the disaggregation of the landscape into areas characterized by a significantly different hydrological process behaviour. With respect to the vertical processes, differences in land use, vegetation type, soil characteristics, groundwater depth and topography are most important. The degree in spatial disaggregation depends on the resolution of the available data and must be determined for each study region, in order to take into account properly the discontinuities of the landsurface. The principles of spatial disaggregation applied in the

Elbe river basin follow the special needs of large scale modelling (Lahmer and Becker 1998) and will be outlined in the following.

Table 1: Pre-classified land use classes for the German part of the Elbe river basin, including the original classification of the used CORINE land use map, the number of elementary units defining the aggregated classes and their fractional areas.

CORINE classification	**aggregated land use classes** nr. and name	nr. of EUs	fractional area [%]
1,2,3,4,5,6,11	1 urban areas	9212	6.69
10,18,26,35	2 meadows	8739	9.47
12,19,20,21,27	3 arable land	23429	53.37
16,23,24,25,29	4 forests	17487	27.48
40,41	5 open water bodies	4278	1.43
7,8,9,30,32	6 pasture	892	0.96

Basis of all simulation calculations performed with ARC/EGMO is the so called ‘elementary unit map’, generated by a Geographic Information System (GIS) from all necessary digital information (land use, vegetation cover, soil characteristics, topography, ground water level, river net, sub-basins etc.) in the pre-processing stage. This map consists of ‘elementary units’ (EUs), which represent the smallest modelling units of the modelling approach and can be considered homogeneous with respect to their hydrological behaviour. In general, the resolution of the EU map is directly determined by the resolution of the used basic maps.

Since for macroscale applications the number of EUs may be rather high, some maps should be spatially aggregated already in the pre-processing stage. In case of the whole German part of the Elbe river basin, the CORINE land use map was the basic map for data preparation, due to its high resolution and hydrological importance. The available 28 land use classes were pre-classified into the 6 classes given in **Table 1**, taking into account the hydrological and ecological sensitivities of the underlying subclasses. The aggregated land use class ‘urban areas’, for example, now includes the original 7 subclasses ‘closed urban areas’, ‘open urban areas’, ‘industrial areas’, ‘street and railway systems’, ‘ports’, ‘airports’, and ‘recreational areas’. The dominant land use class in the Elbe basin is ‘arable land’ (fractional area of 53.37 %) followed by ‘forests’ (27.48 %) and ‘meadows’ (9.47 %). All important characteristics of the aggregated land-use classes (like degree of sealing, root depth, interception capacity, and degree of covering) are provided by relate tables coupled to the digital map and can be directly used in the GIS-based simulation calculations.

Combining the pre-classified land use map with the soil map (55 different soil types in up to 8 layers), the digital elevation model (DEM, 1 x 1 km resolution), the groundwater level map (pre-classified into 3 classes with < 1m (‘shallow’, 15.7 % fractional area), 1-2 m (6.54 %) and > 2 m (‘deep’, 76.64 %) groundwater level depth), and the map of 93 sub-basins results in a map of 64.550 elementary units. In **Fig. 2** a section of about 85 x 70 km of this map is shown, demonstrating the various size (up to 216 km², with a mean size of about 1.5 km²) and shape of these modelling units. The EU-map emphasizes one of the advantages of the polygon-based disaggregation approach, which results in larger spatial units in homogeneous parts of the basin and in smaller spatial units in parts of high heterogeneity. This aspect is especially important in simulating land use/land cover changes (as

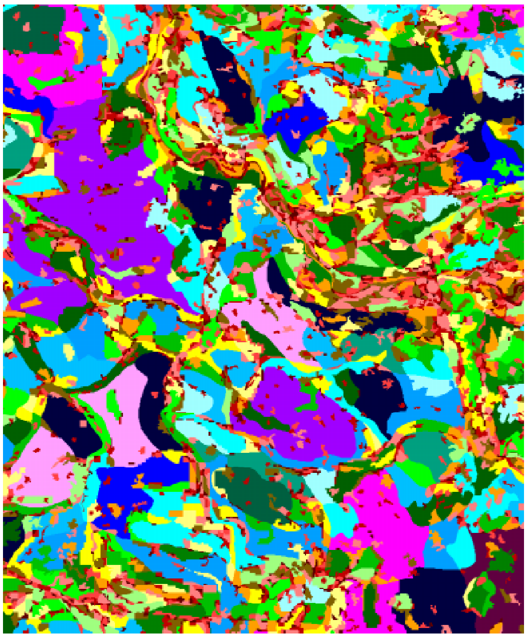

Fig. 2: Section of about 85 x 70 km of the elementary units (EU) map generated for the German part of the Elbe basin. The total map consists of 64.550 EUs.

performed in the Stepenitz sub-basin, which was disaggregated into 30.675 EUs), which normally is restricted to rather small and widely distributed parts of the study region.

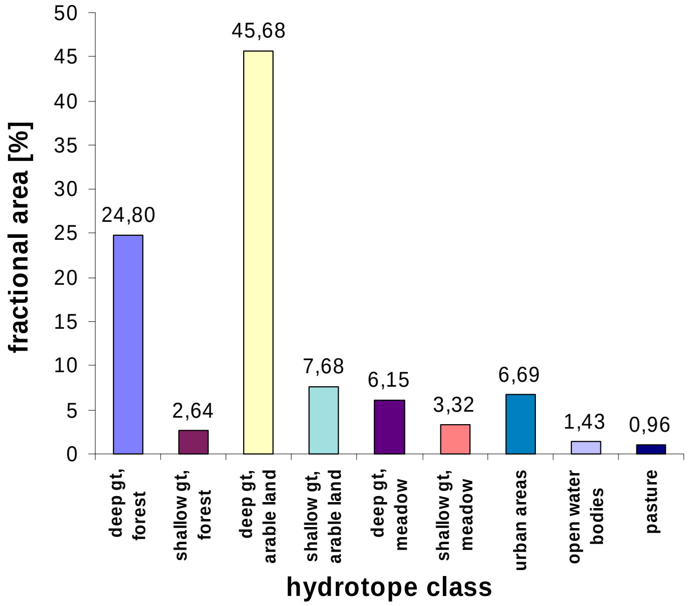

Fig. 3: Fractional areas of the 9 hydrotope classes used for the simulation runs in the Elbe river basin (gt=groundwater table).

2.2 Spatial aggregation to hydrotope classes

Calculations based on elementary units represent the most precise approximation to reality, since they correspond strongly to the original spatial discretization. However, in case of meso- or macroscale applications it is often more effective to aggregate the EUs to larger spatial units, since their number (and the corresponding simulation times) can be rather high. This is an important aspect in climate or land use impact studies, where long time periods (50 to 100 years or even more) must be simulated on a daily basis using different scenarios. On the basis of earlier studies (Lahmer et al. 1997, Becker and Lahmer 1997), the EU maps of the Elbe basin and the Stepenitz sub-basin were aggregated to hydrotopes (spatially connected EUs characterized by an unique hydrological regime) and hydrotope classes (location independent combinations of similar hydrotopes within a larger areal unit; 'semi-distributed modelling approach') which refer to essential (hydrologic, geographic) characteristics of the study region. Since different EU-characteristics can be used for their definition (depending on the scale and the problems to be solved), simulations based on hydrotope classes are flexible with respect to the definition of each class and the number of classes.

One important task is to define a reasonable and adequate hydrotope classification for each specific study region. This classification should include hydrological aspects and separate areas differing considerably in their evapotranspiration and runoff behaviour. In addition, the dominant characteristics of the study region should be taken into account. In case of the Elbe basin, a classification into 9 hydrotope classes was chosen. For the dominant land use classes arable land,

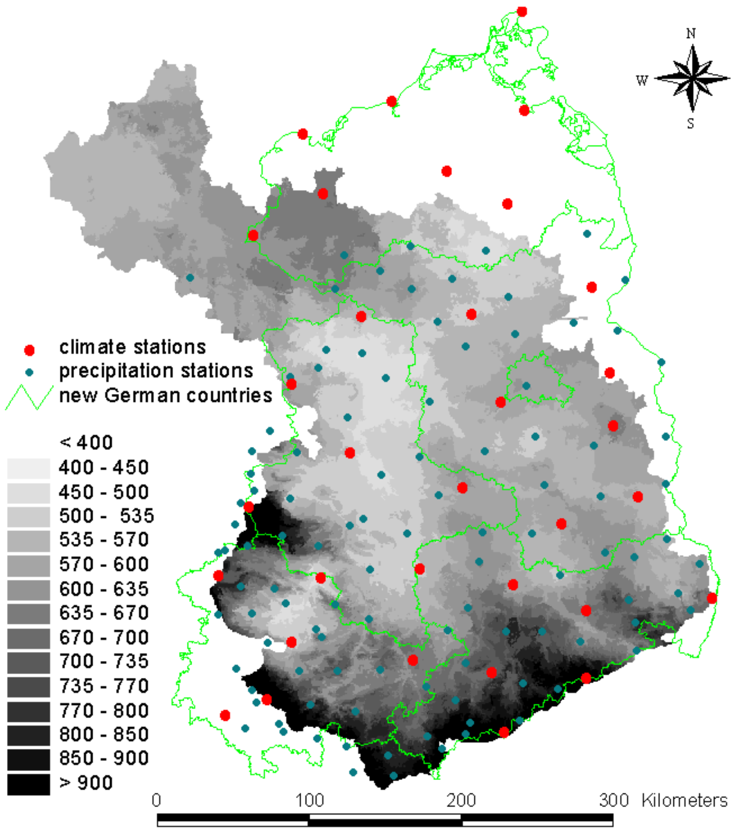

Fig. 4: Mean annual precipitation [mm] in the Elbe river basin for the period 1983-1987, calculated from 33 climate and 107 precipitation stations on the basis of 64.550 elementary units.

forests and meadows (see Table 1) areas with shallow and deep groundwater table (gt) were distinguished. In addition, the classes open water bodies, urban areas, and pasture were classified, due to their high evaporation and runoff formation characteristics, respectively. The classification given in **Fig. 3** shows that the agricultural and forested areas on deep groundwater table (fractional areas of 45.68% and 24.80%) are the dominant hydrotope classes in the Elbe river basin. The simulation calculations in the Elbe basin which will be discussed in the following chapter were performed either on the basis of the 64.550 elementary units or the 9 hydrotope classes (corresponding to 766 hydrotopes) given in Fig. 3.

3 Results

3.1 Spatial interpolation of meteorological input variables

The spatial distribution of meteorological input variables plays a key role in meso and large scale hydrological modelling, due to its high influence on the calculated water balance components. The interpolation method used in the present study ('extended quadrant method') has proven to be very effective in interpolating meteorological point data for every time step (one day) of the simulation period. Dependencies of the variables from elevation can be taken into account as well. For the water balance calculations in the Elbe basin 33 climate and 107 precipitation stations were used for the spatial interpolation of precipitation, mean temperature, relative humidity, and sunshine duration.

Results of such interpolations are shown in **Fig. 4** for precipitation and in **Fig. 5** for the climatic water balance (difference between precipitation and potential evaporation calculated according Turc 1961 and Wendling and Schellin 1986). The daily interpolation patterns calculated on the basis of 64.550 EUs are aggregated to annual means for the period 1983-1987, respectively. The location of the used climate and precipitation stations are given as well. Mountaineous regions in the southern and western parts of the basin show high precipitation rates of up to 900 mm or more. The climatic water balance is strongly dominated by the precipitation distribution and clearly indicates the driest and thus most vulnerable sub-areas of the Elbe basin, which are found in the central and north-eastern part. In these sub-areas the mean annual precipitation is about 400 mm and the climatic water balance is zero (or even negative). Thus, this map indicates regions in the Elbe basin characterized by water deficit. In general, the spatially distributed maps of meteorological input variables demonstrate the quality of the used interpolation algorithm. They also emphasize the importance of a high density meteorological network in case of large heterogeneities of these variables, in order to calculate realistic distributions of water balance terms.

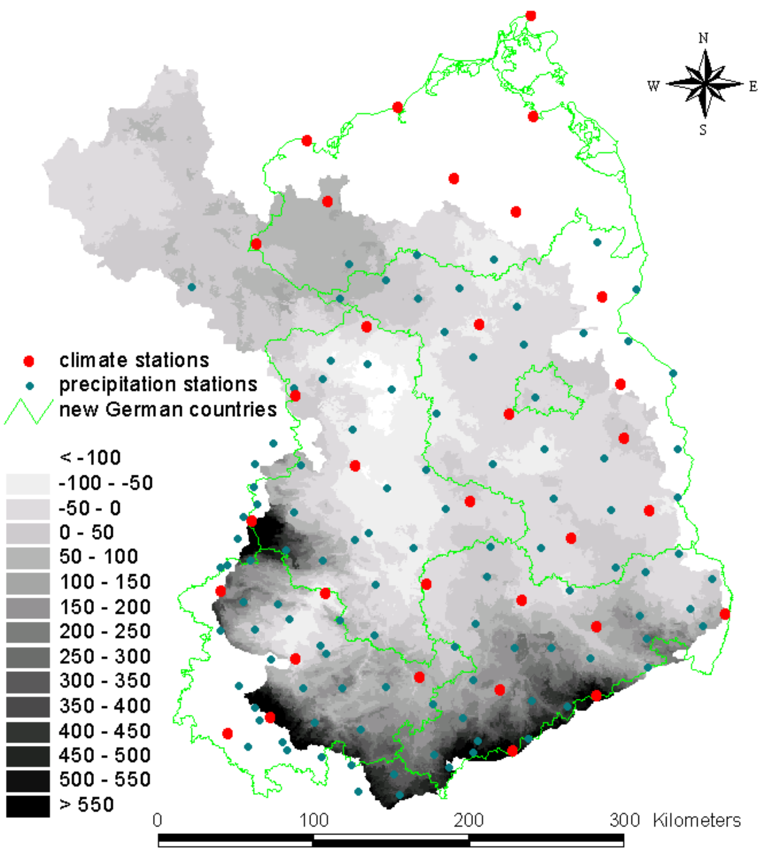

Fig. 5: Spatial distribution of the climatic water balance [mm] in the Elbe river basin for the period 1983-1987 (mean annual values calculated on the basis of 64.550 elementary units).

3.2 Calculation of water balance components

Water balance calculations in the Elbe river basin were performed on a daily basis for the period 1983-1987, both for EUs and the 9 hydrotope classes given in Fig. 3. Among the various hydrological processes taking place in complex landscapes, evapotranspiration, groundwater recharge and surface runoff are most essential. The results obtained for these water balance components are characterized by (i) the spatial distribution of the meteorological input variables and (ii) the heterogeneities of the underlying elementary units with respect to land use, soil, and groundwater level.

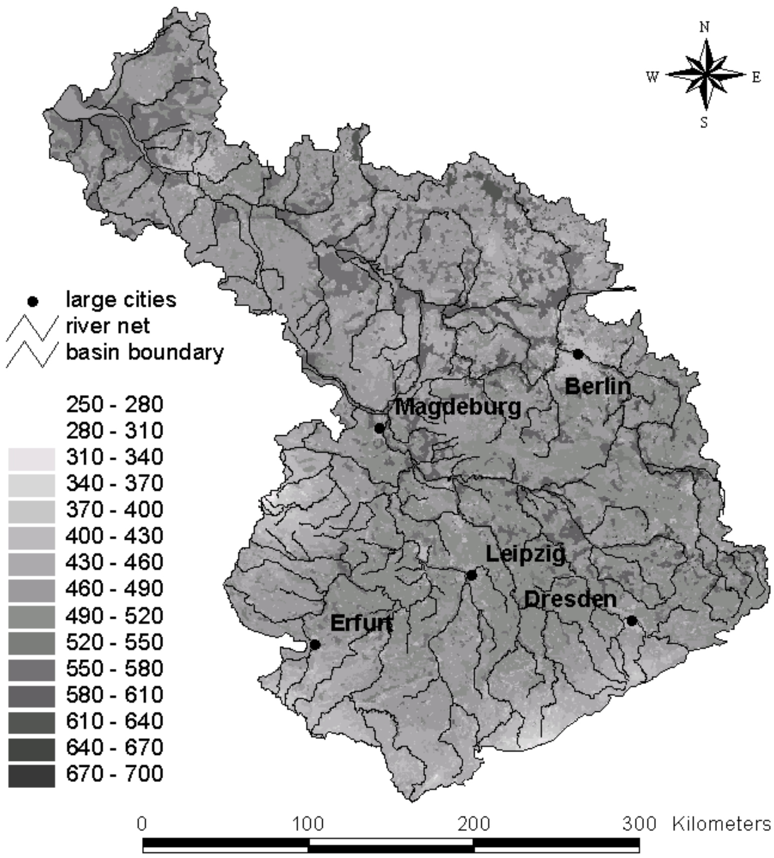

Fig. 6: Mean annual evapotranspiration [mm] in the Elbe river basin for the period 1983-1987, calculated on the basis of 64.550 elementary units.

As an example for the macroscale application in the Elbe basin, mean annual values of evapotranspiration for the period 1983-1987 are given in **Fig. 6**. The calculations performed on the basis of 64.550 elementary units demonstrate that the gross structure of the spatial distribution is dominated by the meteorological input (especially precipitation and temperature). Fine structures, on the other hand, are mainly due to differences in land use. Open water bodies show the highest evaporation values (up to 700 mm/y), followed by riparian and wetland areas. Due to their higher direct runoff formation, settlements are characterized by relatively low evaporation values.

Table 2: Hydrotope classes in the Stepenitz river basin used for the calculation of water balance components, including the number of elementary units (EUs) defining these classes and their fractional areas (gt=groundwater table).

hydrotope class	nr. of EUs	fractional area [%]
deep gt, arable land	8240	51.27
shallow gt, arable land	1045	15.13
deep gt, forest	3165	9.25
shallow gt, forest	1015	3.49
deep gt, meadow	2706	9.65
shallow gt, meadow	673	3.72
areas with low sealing	1061	2.23
areas with high sealing	3690	1.15
pasture	465	1.22
open water bodies	8116	2.89

Examples for the other two water balance components mentioned above will be given for the mesoscale Stepenitz river basin, where similar calculations were performed in order to analyse the current hydrological state for comparisons with land use scenario calculations. The GIS-based data preprocessing of the basic maps used for this basin resulted in a map of 30.176 elementary units. These units were spatially aggregated into the 10 hydrotope classes (corresponding to 557 hydrotopes in 64 sub-basins) given in **Table 2**. The only difference to the classification used for the Elbe basin is the differentiation of areas with low (20%; e.g. settlements, industrial areas, railway tracks etc.) and high sealing (100%; e.g. highways and other streets). The meteorological input is based on 9 climate and 24 precipitation stations in and around the basin.

In **Figs. 7** and **8** the spatial distributions of the water balance components percolation (leading to groundwater recharge) and surface runoff calculated on the basis of these hydrotope classes are shown for the period January 1983 to June 1988. Again, the results simulated on a daily basis are aggregated to annual means. In contrast to the results in the Elbe basin, the distributions are strongly characterized by the differences in land use, vegetation cover, soil properties and especially groundwater level of the underlying hydrotope classes. This is due to a more homogeneous meteorological input for this rather small basin and less pronounced heterogeneities of landscape characteristics (especially elevation, which ranges up to only 154 m as compared to 1134 m in the Elbe basin).

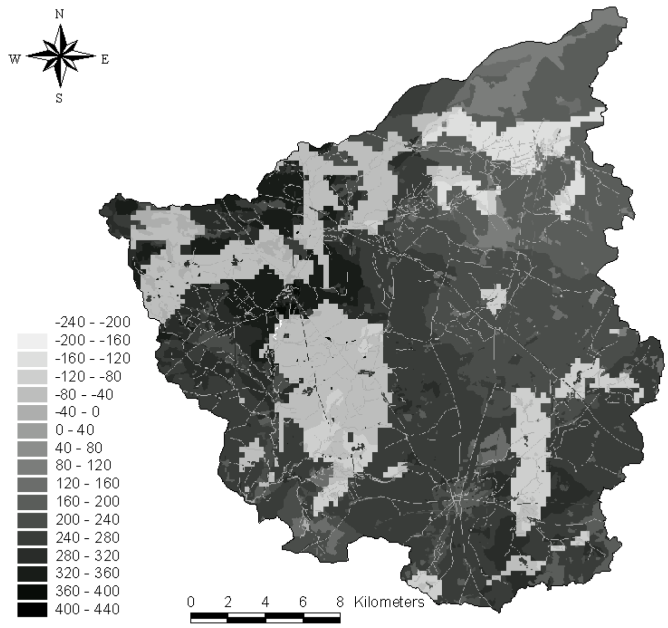

Fig. 7: Mean annual percolation [mm] in the Stepenitz river basin, calculated on the basis of 10 hydrotope classes for the period January 1983 to June 1988.

Percolation rates are low for areas with high evaporation (areas with shallow groundwater table, forests, wetlands) and high for areas with low evaporation (areas with deep groundwater table, arable land, sealed areas). Large parts of the basin show negative percolation rates corresponding to the high evapotranspiration losses of areas with shallow groundwater table. The distribution of surface runoff formation is characterized by high values for sealed areas, areas with shallow groundwater table and wetlands. In addition, this map demonstrates another advantage of the polygon-based modelling approach, because even small spatial units (like streets) are represented as subareas generating low evaporation, no percolation and high surface runoff. Using a raster-based concept, such units cannot be represented at all in maps of water balance components if they are smaller than the grid size. This aspect is very important in simulating land use changes, as these changes normally happen on widely distributed sub-areas of small or medium size in a basin.

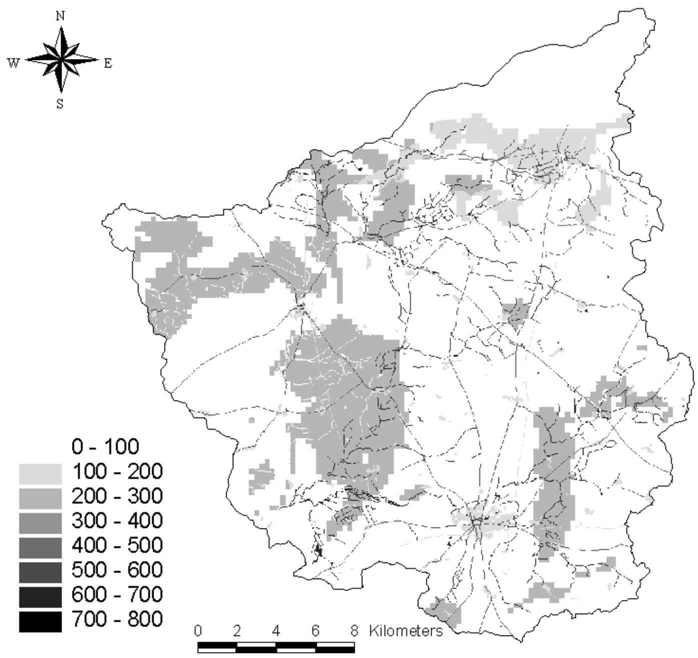

Fig. 8: Mean annual surface runoff formation [mm] in the Stepenitz river basin, calculated on the basis of 10 hydrotope classes for the period January 1983 to June 1988.

3.3 Simulating land use changes

The simulation of land use (and/or possible climate) changes in a region plays a growing role in today's hydrological modelling. First results of such simulation calculations will be given for the Stepenitz river basin, where the influences of different land-use scenarios on the water balance are currently analysed. Land use changes are manifold and include, for example, an increase of urbanized areas, forestation and deforestation, closure of agricultural land due to political decisions, or the conversion of special areas (used for other purposes so far). Modelling these changes also implies to deal with a severe scaling problem, since the basic maps available at different scales differ considerably both with respect to their spatial resolution and their degree of classification. For large scale applications, for example, the available land use map may provide some basic land cover classes like 'forests' or 'agricultural areas' without differentiating sub-types of these classes, which may be necessary for a detailed analysis of land use change. For mesoscale applications, on the other hand, the classification may be much more detailed (e.g. providing 'deciduous forest', 'coniferous forest' and 'mixed forests') but still not sufficient for a realistic simulation. This data situation strongly influences the modelling approaches to be used, because a low degree in classification implies the use of mean parameters to describe e.g. evapotranspiration and runoff generation.

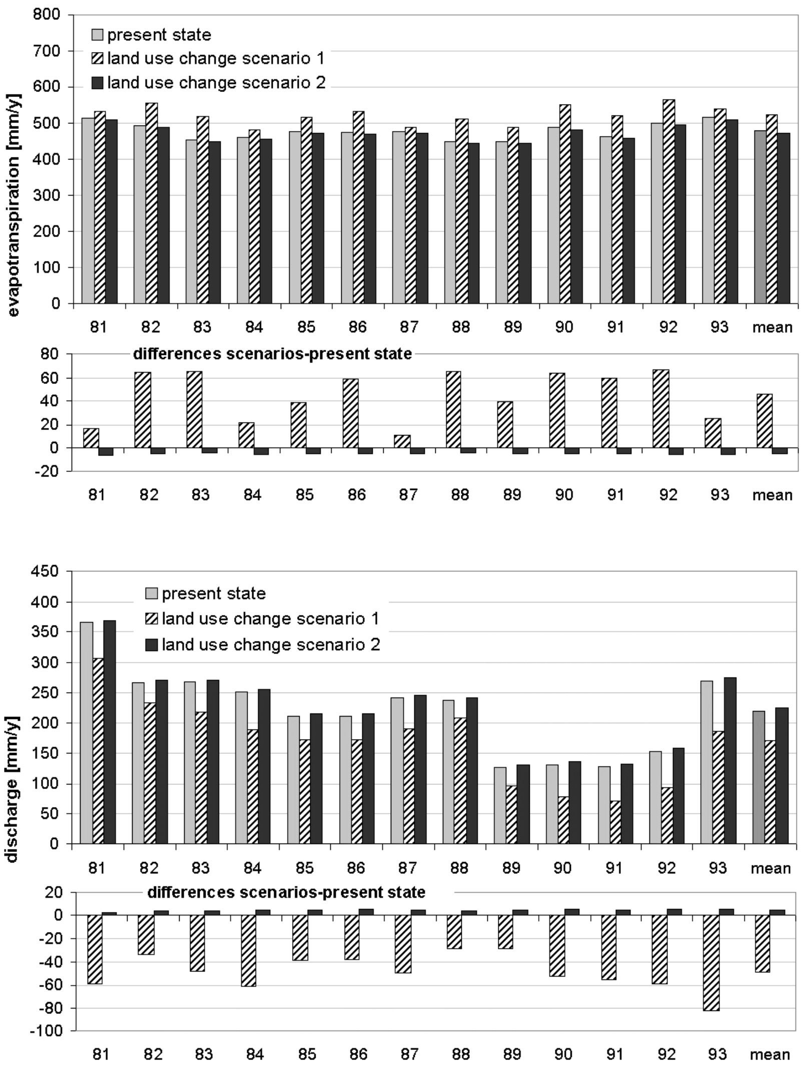

Fig. 9: Annual sums of evapotranspiration (top) and discharge (bottom) for the present state and two scenarios of land use change in the Stepenitz river basin, as well as the differences between the scenarios and the present state. Mean values (mean) for the period 1981-1993 are given on the right hand side.

In order to analyse the effects of land use changes on the regional water balance, two land use change scenarios were developed and applied in the Stepenitz river basin. Scenario 1 assumes the complete conversion of arable land (about 66.4 % of the total area for the present state) into forest. Though it represents an extreme (and unrealistic) scenario, it provides insight into the model sensitivity and the possible rate of change in the hydrological response of the basin. Scenario 2 assumes an increase in the degree of sealing for areas classified as 'low sealed' (e.g. settlements; see Table 2) from moderate, i.e. 20% (present state), to complete (100%). This concerns just 2.23 % of the total basin area. For the scenario analyses climate conditions as observed during the period 1981-93 were used as reference.

In **Fig. 9** the simulated basin response is represented for this period in terms of annual sums of evapotranspiration and basin discharge for the real land use conditions and the two scenarios of change. Due to the rather different size of the affected areas, the response is much more pronounced for scenario 1 than for scenario 2. As expected, there would be a clear increase in basin evapotranspiration of up to 15% for scenario 1, in particular in the drier period 1988-92. Accordingly, basin runoff would be reduced by up to 44%, in particular during and after dry years, which could result in critical consequences for the environment and the water supply. Scenario 2 would produce a slight increase in discharge (about 4% on the average) and a corresponding decrease of 1% in evapotranspiration.

These first results indicate that the developed modelling approach is sensitive enough to cope with a change in land use/land cover as small as about 2 %. Nevertheless, the two scenarios described here are not ‘realistic‘, as they are not derived from socio-economic analyses or political decisions. In addition, they just represent ‘static‘ scenarios, which do not reflect the dynamic development of specific land use changes, covering years or decades. Therefore, the modelling concept will be extended for future studies, in order to include ‘transient’ scenarios as well.

4 Conclusions

The results obtained in the German part of the Elbe river basin and the Stepenitz sub-basin provide a better understanding of the spatial and temporal data necessary for a physically based hydrological modelling at different scales. They also demonstrate the usefulness of the developed GIS-based modelling concept, which directly uses model parameters derived from generally available spatial data and provides spatial and temporal results of various water balance components. The disaggregation of the study area based on the available spatial maps, followed by an aggregation of areas with equal or similar hydrological behaviour has turned out to be an effective method to study long-term impacts of climate and land use changes in a river basin. In addition, the use of an interpolation algorithm to provide adequate spatial distributions of climatic input variables has proven to be a key issue in hydrological modelling at larger scales.

In order to study human impacts on the hydrological cycle in river basins of various size, both high resolution data and an appropriate modelling approach are necessary. Only then the hydrological effects of climate and/or land use changes can be modelled at various spatial and temporal scales. First results of a meso-scale land use change analysis demonstrate that the developed concept is especially suited for regional impact studies, since high resolution data are available at this scale.

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Summary

Global change phenomena must be investigated at all spatial scales, but it is the regional scale that is crucial for an improved understanding not only of the different causes of global change and the contributing processes, but also of its impacts on the environment and society. River basins are preferred land surface units for regional scale studies because they represent natural integrators of water and associated material transports at the land surface. For the present hydrological study, the German part of the Elbe river basin covering an area of nearly 100,000 km^2 was chosen. More detailed analyses, including first steps towards the modelling of land use changes, were performed in the Stepenitz sub-basin (575 km^2, mesoscale).

The GIS-based modelling approach used in the present study includes variable spatial aggregation and disaggregation methods, which are especially suitable to study regional impacts of climate and land use changes on the hydrological cycle. The approach consequently uses the GIS-based derivation of model parameters from generally available spatial data and includes an effective interpolation algorithm for climatic input variables, which turns out to play an key role in large scale hydrological modelling. Though the principles of spatial aggregation and disaggregation applied in the Elbe river basin follow the special needs of large scale modelling, the concept can be applied to river basins of different size and heterogeneity.

The data pre-processing of the available spatial data results in a map of 64.550 (Elbe) and 30.176 (Stepenitz) elementary units, respectively, which represent the smallest modelling units of the modelling approach and can be considered homogeneous with respect to their hydrological behaviour. These units are spatially aggregated to about 10 hydrotope classes during the simulation runs, in order to enable long-term simulation runs on a daily basis. This aggregation step considerably simplifies large scale modelling and reduces computing time, without a remarkable loss in simulation quality.

The results obtained for various water balance components like evapotranspiration, groundwater recharge and surface runoff formation in the Elbe basin and the Stepenitz sub-basin demonstrate that the aggregation of a study region into subareas of similar hydrological process behaviour represents an effective modelling concept. In case of the Elbe basin (macroscale), the spatial distributions of these water balance components are dominated by the meteorological input (especially precipitation and temperature), whereas they are strongly characterized by the differences in land use, vegetation cover, soil properties and especially groundwater level of the underlying hydrotope classes in case of the Stepenitz sub-basin. This is due to a more homogeneous meteorological input for a smaller basin and less pronounced heterogeneities of various landscape characteristics.

In order to analyse the effects of land use changes on the regional water balance, two simple land use change scenarios were developed and applied in the Stepenitz river basin. The simulated basin response represented in terms of evapotranspiration and basin discharge demonstrates that the modelling approach is sensitive enough to cope with land use/land cover changes of realistic size. Future scenarios of more realistic character will be derived from socio-economic analyses for the region and include a dynamic development of specific land use changes as well.