MODELLING LAND USE CHANGE ON A REGIONAL SCALE

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Introduction

Phenomena and processes of global change take place and have to be investigated at all spatial scales, from local to global. However, it is primarily at the regional and local scales that political and technical measures and action can and must be taken in order to avoid critical developments and to reduce negative or undesired effects for the environment and society. Therefore, stronger research efforts are needed at these scales where the most important sources and drivers of global change are located. River basins are the preferred land surface units for water-related regional-scale studies because their drainage areas represent natural spatial integrators or accumulators of water and associated material transports and thus allow to investigate cumulative effects of human activities on the environment. Changes in river flow and water quality are valuable indicators of such effects and their consequences, and therefore need to be studied at river basin scales.

In the present study a concept is described, which allows to assess the implications of land use changes (as an important aspect of global change) on the regional water cycle. First results are presented for a meso-scale tributary basin of the Elbe river basin, which - due to the changing political and economic conditions after 1989/1990 - meets considerable socio-economic problems such as a drastic reduction of the demand for agricultural products, and accordingly increasing unemployment and social problems. Besides natural characteristics of the study region, the definition of land use change scenarios must, therefore, include socio-economic aspects evolving from the regional, national and European legislation (i.e. Agenda 2000).

Aim of the Study

The results presented here are part of the WaStor (*water and material retention in the Elbe river lowland*) project (Bork [2]), a regional sub-project of the interdisciplinary research project ‘Elbe-Ecology’ funded by the German Ministry for Education and Research (BMBF). The aims of this project are

- to study the influence of various measures of land use change on the regional water balance and the river runoff (especially for arable land)
- to analyse possible contributions of economic and ecological land use management forms for water retention and flood protection in the Elbe lowland
- to derive methods for the adaptation to socio-economic conditions, which will result in a changed land use or the abandonment of agricultural areas in the next years

- to derive adequate ('realistic') scenarios of land use change (especially for vulnerable and conflict regions) and strategies for a sustainable development in the region under study.

Study Regions

The primary scale of the 'Elbe-Ecology' project is the entire German part of the Elbe basin. Due to the regional concentration of water-related problems and socio-economic conflicts, special studies in vulnerable sub-regions are performed where more detailed data are available. Two of these sub-regions are the Stepenitz and the Stör river basins indicated in **Fig. 1**. They are part of the pleistocene Elbe lowland which is representative for humid/semihumid landscapes in Europe. Many wetland areas in these and other parts of the Elbe basin are degraded by drainage systems and other human activities and therefore need special measures to be maintained as important landscape elements of high retention capacity for water and contaminants.

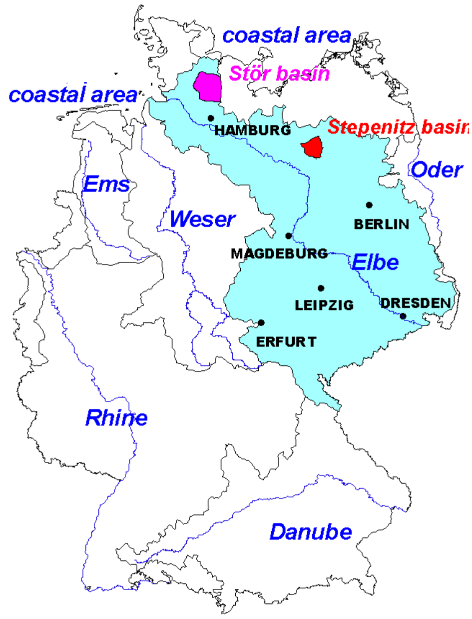

Fig. 1: The study regions Stepenitz (575 km²) and Stör (~1.100 km²), sub-basins of the Elbe river basin.

Concepts and first results of modelling land use changes are presented for the Stepenitz river basin, a mesoscale tributary basin of the Elbe basin (575 km²) situated in the state of Brandenburg, which is characterized by a series of complex hydrological and ecological problems. These problems result mainly from the intensive agricultural practices in almost 80 % of the total basin area and various measures like melioration, river-bed alignments, and drainage of natural wetlands, which were taken in the past and resulted in a considerable loss of natural retention areas. In addition, large areas are characterized by rather poor sandy soils with low agricultural productivity and thus serious economic and development problems. Another study region is the Upper Stör basin (~1.100 km²) in North Germany (Schleswig-Holstein), subject to an earlier research project (Becker and Lahmer [1], Lahmer et al. [3]) and characterized by higher annual precipitation rates, more fertile soils, a less pronounced topography and an agricultural land use of about 60 %.

Modelling Approach

Land use is one of the main boundary conditions which directly or indirectly influences many hydrological processes. To study the impacts of land use or land cover change on the hydrological cycle, appropriate modelling approaches are necessary. These must allow an effective simulation of the regional hydrological cycle and enable studies, which in detail describe both the natural spatial variabilities and the anthropogenic impacts at various temporal and spatial scales. Problems in assessing these impacts on the meso-scale generally arise from the available data which due to insufficient resolution (time step, classification etc.) strongly influence the modelling approaches to be used and often inhibit a detailed analysis.

The model used in the present study (ARC/EGMO; Pfützner et al. [7]) allows to take into account any type of land surface units, from biotopes or hydrotopes (patches with the same or similar type of vegetation, land use, hydrological behaviour etc.) as smallest units to different landscape types, which offers the opportunity to correlate biophysical and socio-economic factors. These and other areal discretisations have already been adapted in modelling major parts of the Elbe river basin (Lahmer [4], Lahmer and Becker [5], Lahmer and Becker [6]).

Development of Land Use Change Scenarios

The analysis of land use changes in a region is a rather complex task, since many different aspects must be taken into account. The question, which areas of the actual land use should be converted into which other type depends both on the physical properties of the specific location and on various socio-economic factors like the national and international legislation. In principle, agricultural land should be converted where areas are used unprofitably and the existing conditions do not fit the actual use. These natural conditions include soil properties (influencing the yield) or slope and areal structure (influencing management costs). In addition, local climatic conditions (e.g. the regional water balance) define, if and where arable land might be forested, changed into pasture or completely abandoned.

In general, the form of the scenarios developed for a region strongly depends on a) the specific aims of the investigation (water balance, flood protection, nutrient transport, socio-economic restrictions etc.), b) the model used (form and extent of physical and non-physical boundary conditions that can be taken into account, model sensitivity), c) the spatial scale (resolution of the available temporal and spatial data), and d) the specific natural and socio-economic characteristics and constraints of the study region itself. In the present study the development of land use change scenarios is performed according to the following steps:

- Comprehensive analysis of the current state of the river basin on the basis of the available data, in order to quantify the influences of various land use change measures
- Development and analysis of extreme scenarios
- Identification of sub-regions which – due to various landscape characteristics – are primary candidates for a possible land use change
- Integration of socio-economic aspects resulting from political decisions of the regional government and the national and international legislation and from economical and ecological goals
- Generation, implementation and analysis of ‚realistic' scenarios.

With respect to the physical properties of a region, model parameters must be used for the scenario calculations of a changed land use that characterize long- or medium-term states and processes, as for example root depth (access of vegetation to groundwater), interception capacity (transpiration of vegetation) or cover degree (low or high vegetation density).

Following the above steps, a catalogue of land use change scenarios will be developed and applied, which covers a considerable range of alternatives induced by the natural and economic-ecological constraints of the region. One basic aim of the simulation calculations will be to investigate whether and how land use changes or alternative management practices may induce positive effects on the regional water balance. In the end, the scenarios covering changes from ‘static’ to ‘transient’ should result in recommendations which can be used, e.g. by political stake holders. In the following, the developed concept of assessing land use changes on the regional scale and some first results will be discussed in more detail.

Analysis of Extreme Scenarios

One important step in studying the effects of a changed land use on the regional water cycle is the development and analysis of extreme scenarios which i) cover the thinkable width of hydrological basin response and ii) demonstrate the sensitivity limits of the used model. One of the shortcomings of such simple scenarios is that they do not include areas selected on the basis of more complex spatial selection criteria and, therefore are generally far from being realistic. To analyse the effects of land use changes on various regional water balance terms, two scenarios were developed and applied in the Stepenitz river basin (Lahmer and Becker [6]). Scenario 1 assumes the complete conversion of agricultural land (about 66.4 % of the total area) into forest, scenario 2 an increase in the degree of sealing for urbanized areas (e.g. settlements) from moderate, i.e. 20% (present state), to complete (100%). This concerns just 2.23 % of the total basin area. The results can be shortly summarized as follows:

- The modelling approach is generally qualified to study the influences of land use changes on the regional water cycle.
- Even land use changes restricted to relatively small fractional areas can be modelled.
- All results follow general expectations, both with respect to size and tendency.
- The results underline the hydrological importance of forested areas, which due to their high evapotranspiration and percolation show a higher water retention potential than arable land, resulting in a considerable reduction of flood runoff.
- Changes in river runoff as induced by scenario 1 would have considerable consequences for the regional water budget and the availability of drinking water.

Identification of Sub-Regions for Land Use Change Measures

The identification of areas which are primary candidates for a possible land use change is based on statistical analyses of various landscape characteristics as observed for the present state of the basin. They use correlations between the actual land use and other natural properties like soil type, slope and ground water depth, which strongly determine the actual land use. Soil properties are the primary key for farming, as they determine the qualification of an area for a specific cultivation and the maximum reachable yield. The slope plays an important role only in mountainous regions, as it enlarges the costs of farming. Areas with large slopes are principle candidates for a less intensive agricultural use or concersion. The ground water table depth (GWD) is another important local characteristic defining the agricultural use of an area. Many cultivations require GWDs between ~0.8 m and ~1.5 m (dependent on the soil type). On the other hand, pasture-land requires GWDs between ~0.4 m and ~0.8 m and, therefore is restricted to wetland or riperian areas.

The multi-criterial analyses can identify areas that for various reasons are not (or less) suited for the actual land use. Moreover, they can uncover basic problems of the used spatial data, which must be taken into account in the scenario development. Land use change scenarios based on such analyses are, however, already much more sophisticated than the extreme scenarios discussed above, since only pre-selected regions of a specific land use type are included in the simulation calculations. An example for the performed analyses is the correlation between actual land use and GWD given in **Fig. 2**, where the fractional areas of 6 important land use types on 5 GWD classes are shown. Following important conclusions can be drawn:

In contrast to the requirements for pasture-land given above, Fig. 2 reveals considerable percentages of 'pasture' also for GWD > 1 m. This means, that the land use type 'pasture' given in the land use map represents various sub-types, which are not suitable for cultivation. The land use class 'arable land' is found on all GWD classes, with an especially high fraction on areas with large GWDs (> 2 m). This reflects the generally high agricultural use in the basin, also on areas which are suited only for less intensive cultivations (e.g. cereals with a relatively small sensitivity against water stress). The high percentage of 'arable land' on GWD < 0.5 m, on the other hand, indicates that either the land use map is wrong (allocating the wrong land use type) or the spatial resolution of the available GWD map (250 x 250 m) is not sufficient, allocating too low GWDs for some areas in the study region.

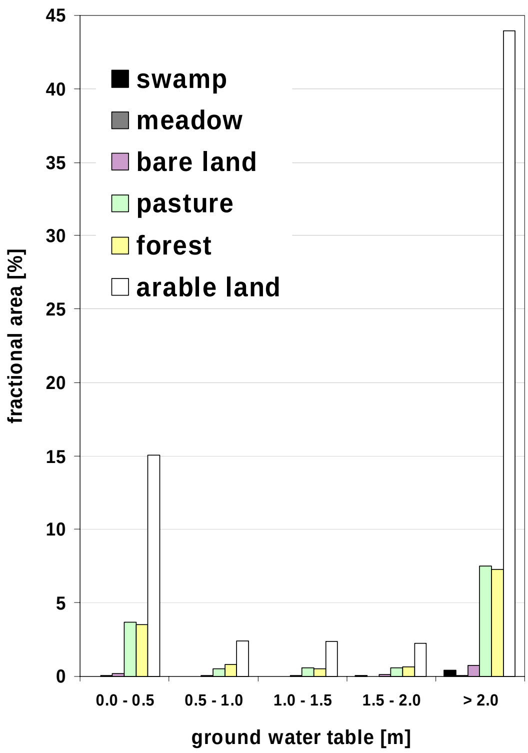

Fig. 2: Fractional areas of 6 important land use types on 5 ground water table depth classes in the Stepenitz river basin.

Thus, the correlation analysis reveals shortcomings in the basic maps, which prevent the generation of detailed land use change scenarios. In spite of the fact that arable land strongly dominates the actual land use, following general conclusions can be drawn from the statistical analyses:

- Forests are usually pushed back into areas where topography, surface conditions or soil quality are unfavourable for agricultural use.
- Topography does not play a dominant role in the Stepenitz basin, but can be used to identify areas which may be converted to e.g. (unmanaged) grassland.
- Insufficient resolution or class differentiation of the used spatial maps must be properly taken into account in generating complex land use change scenarios.

Fig. 3 demonstrates how the primary identification of sub-regions for a possible land use change based on the above discussed analyses may look like. In the figure those agricultural areas in the Stepenitz river basin are indicated, which are characterized by a GWD of 0.75 m to 1.75 m. These areas should be preserved (and not be changed) for an (even more) intensive agricultural use in the future.

Besides the physical parameters already mentioned, also the so called 'soil number' will be used in identifying areas which – under pure natural constraints – are preferred areas for a change of the actual land use. Though this indicator for the soil quality is based on rather old investigations and is relevant only for a few cultivation types, it represents an important additional indicator for the derivation of more realistic scenarios. On the other hand, the use of long-term meteorological conditions (e.g. climatic water balance or water stress factor) as primary indicator is useful only in study regions characterized by a high meteorological heterogeneity. This, however, is not the case in the flatland regions studied here, though in principle water deficit plays an important role in the Stepenitz river basin.

Table 1 summarizes the relevance of various land use change modes for arable land in the Stepenitz river basin. Forestation is the preferred change mode on areas with deep GWD (and bad soils). The forestation of pasture is not relevant at all, due to the high evapotranspiration of forests on areas with shallow GWD and the corresponding strong influences on the regional water balance. The conversion of arable land into grassland (‚dry pasture‘) is reasonable on areas with larger GWD (and considerable slope to reduce erosion). Instead of changing the land use type, agricultural areas may be less intensively used as well. Following Table 1, the ‚extensivation‘ of arable land represents an alternative to forestation on areas with deep GWD, as long as the soils are of reasonable quality. On the other hand, pasture should be extensively used on areas with shallow GWD (due to nutrient reduction). Finally, unprofitable areas (bad soils, hilly, high landscape heterogeneity) should be abandoned, either totally (without any management) or in the form of grassland (erosion protection).

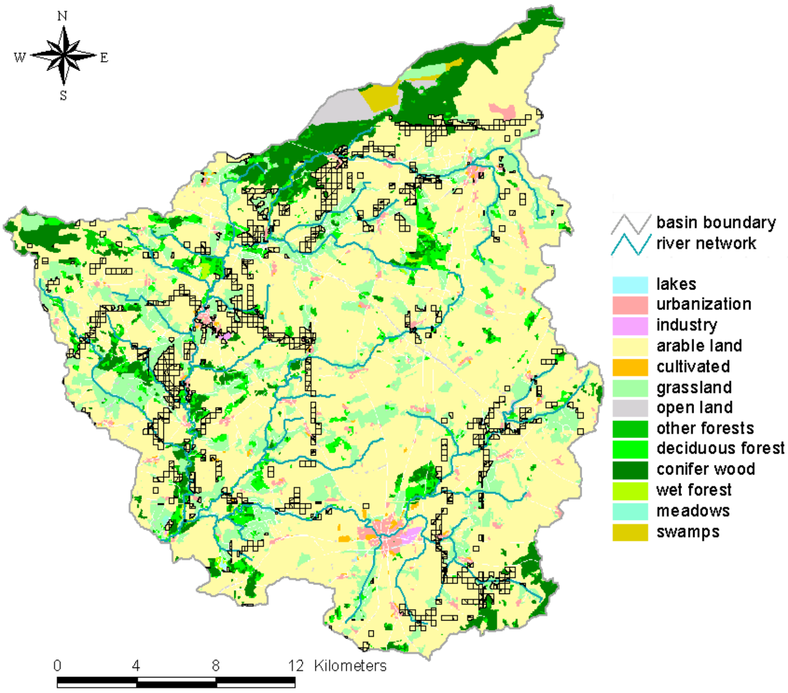

Fig. 3: Agricultural areas in the Stepenitz basin (characterized by a ground water table distance of 0.75 m - 1.75 m; black outlined areas) which should be preserved for intensive agricultural use also in the future.

Table 1: Importance of various land use changes on agricultural areas with different ground water table depth (GWD) (legend: - not relevant, 0 almost no effect, + relevant/positive effect, ++ very positive effect).

local condition	**extensive use on**		**change of land use type**	
	arable land	pasture		
			arable land into forest	arable land into pasture
deep GWD	++	-	++	0(+)
medium GWD	+(+)	+	+	+
shallow GWD	-	++	-	-

To implement such more sophisticated scenarios in the modelling system, both intra-annual variations of the vegetation cover and long-term variations of areas affected by a changing land use type must be taken into account. Such dynamic (transient) changes are realized by time functions of important hydrological parameters of the corresponding areas (i.e. sealing, root depth, cover degree, interception capacity). By this, various types of intra-annual (usually cyclic) and long-term (including trends and/or points of unsteadiness) changes can be taken into account in the simulation runs.

Fig. 4 shows first results from a simulation calculation using long-term changes of the groundwater table depth (GTD) for arable land. The time function given on the right hand side demonstrates the assumed transient change of the GTD from 15 m in 1981 down to 0.25 m in 1990. The corresponding annual evapotranspiration sums of the affected areas calculated for the constant GTD of 7.5 m and the time dependent GTD are given on the left hand side. The evapotranspiration rates start to increase considerably in 1985 for the decreasing GTD (due to increasing capillary rise) and are up to 85 % higher in the dry summers of 1989-1992.

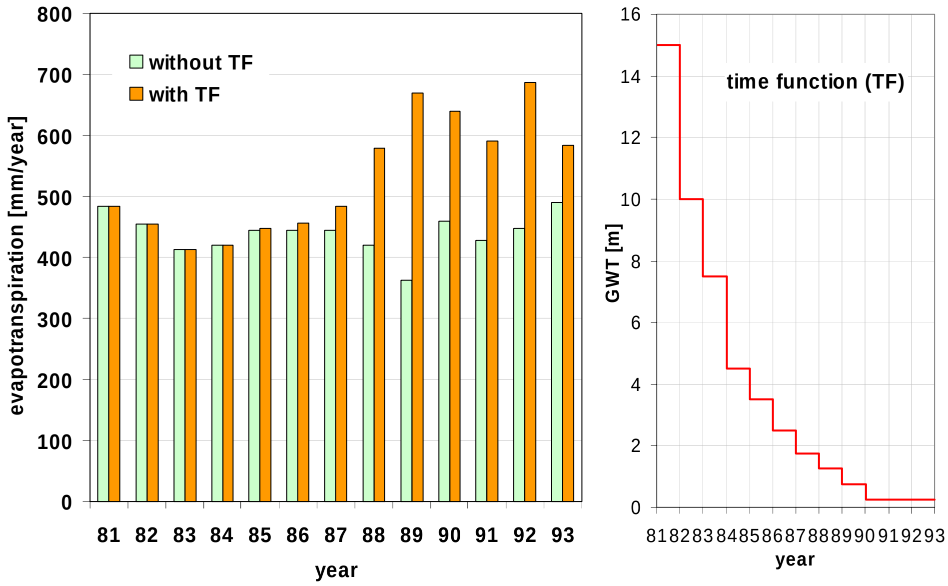

Fig. 4: Annual sums of evapotranspiration for arable land in the Stepenitz basin assuming i) a constant groundwater table depth (GTD) of 7.5 m (*without TF*) and ii) a transient change of the GTD from 15 m in 1981 towards 0.25 m in 1990 (*with TF*). The corresponding time function is given on the right.

Integration of Socio-Economical Aspects

The identification of areas for a changed land use based on natural indicators (soil quality, topographic conditions, groundwater distance etc.) must be extended by socio-economic aspects. The corresponding catalogue should include the management planning of the local government, the concerns of various stakeholders and interest groups and the projections of the national and international legislation. Especially the still outstanding reforms of the agriculture policy of the European Union (EU) (Agenda 2000) will induce far-reaching structural changes in the New German Countries. What and how many agricultural areas will be affected depends on many details like the concrete regulations, price developments (also on the global market), the structure and intensity of the actual land use, the amount of areas to be taken out of management or into extensive use, the financial support for forestation or new sustainable management forms paid to the farmers, and the adaptability of the farmers themselves. The implementation of the reforms might stimulate the farmers to drop low-quality land in favour of (even more) intensively used high-quality land and to reduce the production of intensive cultivations.

However, land use change measures to improve the regional water and nutrient retention can be successfully implemented only, if a reasonable long-term economic situation and a high employment rate of the main users (farmers) is guaranteed. From the socio-economic point of view, the opposition to the implementation of land use and management changes is the higher the better the actual economic situation and the lower the adaptation potential. On the other hand, the changes will induce relatively small effects in regions with an already high rate of extensive agricultural practices.

In order to quantify both the special regional economic conditions and the potential effects of outstanding land use change measures, representative farms in the pre-selected areas will be analysed on the basis of the actual land management and use. Besides the various natural conditions mentioned earlier, these analyses will include the assessment of structural data like the size of the farms, fractional areas used for agriculture and livestock, agricultural practices, and management intensity (conventional, extensive, ecological). Based on these analyses ‚realistic‘ land use change scenarios will be generated and analysed.

Conclusions

First results of simulating land use change on the meso-scale demonstrate the quality of the applied 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 into homogeneous areal units, 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 land use (or climate) changes. Multi-criterial analyses show that high resolution spatial data are needed to study human impacts on the hydrological cycle in a river basin. In principle, the modelling approach has turned out to be sensitive enough to cope with more sophisticated scenarios of land use changes. However, besides the physical processes and parameters that must be taken into account in long-term transient land use change scenario calculations, the implementation of socio-economic aspects represents one of the major challenges in this type of hydrological modelling.

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