Environmental Modelling & Software 24 (2009) 26–43

Contents lists available at ScienceDirect

Environmental Modelling & Software

journal homepage: www.elsevier.com/locate/envsoft

Scenario analysis and management options for sustainable river basin management: Application of the Elbe DSS

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ARTICLE INFO

Article history:
Received 21 November 2006
Received in revised form 23 April 2008
Accepted 3 May 2008
Available online 13 June 2008

Keywords:
River basin management
Water quality
Integrated catchment model
Decision support system

ABSTRACT

We developed a decision support system (DSS) for sustainable river basin management in the German Elbe catchment ($\sim$100,000 km^2), called Elbe-DSS. The system integrates georeferenced simulation models and related data sets with a user friendly interface and includes a library function. Design and content of the DSS have been developed in close cooperation with end users and stakeholders. The user can evaluate effectiveness of management actions like reforestation, improvement of treatment plant technology or the application of buffer strips under the influence of external constraints on climate, demographic and agro-economic changes to meet water management objectives such as water quality standards and discharge control. The paper (i) describes the conceptual design of the Elbe-DSS, (ii) demonstrates the applicability of the integrated catchment model by running three different management options for phosphate discharge reduction (reforestation, erosion control and ecological-farming) under the assumption of regional climate change based on IPCC scenarios, (iii) evaluates the effectiveness of the management options, and (iv) provides some lessons for the DSS-development in similar settings. The georeferenced approach allows the identification of local inputs in sub-catchments and their impact on the overall water quality, which helps the user to prioritize his management actions in terms of spatial distribution and effectiveness.

Software availability

Name of Software: Elbe-DSS
Developer: German Federal Institute of Hydrology (BfG), Project Group ELBE-ECOLOGY
Contact address: Dr. Sebastian Kofalk, German Federal Institute of Hydrology (BfG), Department U2 – Ecological Interactions, Mainzer Tor 1, 56068 Koblenz, Germany
Direct line: +49 261 1306 5330
Switchboard: +49 261 1306 0
Fax: +49 261 1306 5333
E-mail: kofalk@bafg.de
Year first available: 2005, see Berlekamp et al. (2007)
Hardware required: PC (2000 MHz or more, 1024 MB of RAM, Windows NT/2000/XP)
Software required: Excel 97 or higher
Program languages: C++, Python, Fortran77
Program size: 500 MB including data
Availability: CD from developer
Cost: free of charge for non-profit and research institutions.

1. Introduction

Decision support systems (DSS) are interactive and adaptable computer based systems, which are applied for the recognition and solution of complex, poorly structured or unstructured, strategic management problems for improved decision-making (Turban and Aronson, 1998). They are designed for the specific needs of end user groups and are therefore often developed in an interactive process (Matthies et al., 2007; van Delden, 2000). Therefore, a DSS should contain the data and tools necessary to support the decision process of this specific group of end users. While the tools in the DSS might be taken from some sort of standard toolbox (e.g. GIS functionality) any DSS is a unique composition of such tools as well as a unique linkage to the user interface. By incorporation of simulation models, decision support systems offer possibilities to explore the behavior of the environmental system under natural influences and anthropogenic impacts without being restricted to pre-calculated scenarios.

The scientific community has put considerable effort in the design of DSSs in river basin management in recent years. Examples of current DSS in river basin management include AQUATOOL (Andreau et al., 1996), CatchMODS (Newham et al., 2004), NELUP (Dunn et al., 1996; Lunn et al., 1996; O'Callaghan, 1995), FLOODSS (Catelli et al., 1998), DSSIPM (Silva et al., 2001a,b), MULINO (Fassio

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doi:10.1016/j.envsoft.2008.05.001

et al., 2005; Giupponi, 2005, 2007), DSIRR (Bazzani, 2005) and MedAction (van Delden et al., 2007).

In addition to these ready-to-use DSSs, DSS generators such as WATERWARE (Fedra and Jamieson, 1996; Jamieson and Fedra, 1996a,b) and Geonamica (White et al., 2001) also exist. These are generic software frameworks that are used to compile a specific DSS. Rizzoli and Young (1997) and Denzer (2005) have argued that development of generic DSS generator tools is a crucial step for future research. Our experience suggests that, while tools are clearly helpful, the conceptual design of the system is more important. Currently, the research agenda for DSSs is mainly focused on technical concerns and greater emphasis needs to be given to contextual aspects of design and use (McIntosh et al., 2007). General in integrated modeling communication between scientists of different research background as well as between developers and decision makers is crucial (Borowski and Hare, 2007; Parker et al., 2002) and this fact applies especially to the development of a DSS.

The development of the Elbe-DSS was driven by the needs of German decision makers managing the Elbe catchment (Matthies et al., 2006; Berlekamp et al., 2007). User needs have been specified in several participatory meetings with decision makers. In response to these needs, and under consideration of the available timeframe of three years, it has been decided to build the DSS as far as possible using existing data sets and models. During the development process, existing data and models were extended to allow for proper integration of the models, existing external constraints (such as climate change or demographic change) and management actions (including reforestation, buffer strips and erosion control). The Elbe-DSS had thereby to consider the requirements of the European Water Framework Directive (EU, 2000) and transboundary river management issues.

In this paper, we will: (i) describe the conceptual design of the Elbe-DSS as well as the integration of models, management actions and external scenarios, (ii) demonstrate the ability of the DSS to compare different management options (reforestation, erosion control and ecological-farming) and effects of climate change based on IPCC scenarios (iii) evaluate the effectiveness of the management actions and (iv) provide some lessons for DSS-development in similar settings.

2. Integration of data and models

After a short characterization of the study area, the general system design is presented to clarify the underlying structure of the Elbe-DSS and to define some terms used in the DSS. This is followed by a description of the models used in the Elbe-DSS for water quality and precipitation run-off modeling. Afterwards, the management actions and external scenarios used in the application section are introduced. At the end of the section, performance measures of the integrated model system are reported.

2.1. Characterization of the Elbe river basin

The Elbe is one of the largest river basins in central Europe having a length of approximately 1100 km and catchment area of 148,000 km^2, of which about two-thirds are located in Germany (Fig. 1). The mean annual discharge of the Elbe river into the North Sea is 877 m^3/s. Almost 25 million people live in the river basin which spans the Czech Republic, Austria, Poland and the German federal states of Mecklenburg-Western Pommerania, Berlin, Brandenburg, Hamburg, Schleswig-Holstein, Lower Saxony, Saxony, Saxony-Anhalt, Thuringia and Bavaria. Chemical and other industries, coal (lignite) and ore mining, manufacturing, and agriculture are located in the river basin. The reunification of Germany and the related transition processes have led to major changes in land use, an overall population decrease with strong spatial patterns, and a sudden drop in the industrial production output. Various remediation measures and the collapse of industry after the German reunification have had positive effects on stream water quality. However, the Elbe and many of its tributaries are still in a poor chemical and ecological state.

The Elbe-DSS does not cover the whole Elbe basin but focuses on the German part of the Elbe basin until the weir Geestacht, where tidal effects start to appear. For input from the Czech part of the catchment we used measurements of discharge and concentrations from the Schmilka gauging station at the Czech/German border.

2.2. General system design of the Elbe-DSS

The process of building a DSS consists of more than plugging models into a graphical user interface and connecting the input and output of the different models. In contrast to scientific research models, usability is one of the main purposes of a DSS. Simulation models in a DSS are generally used outside the relatively sharply defined borders of scientific research models and have to perform in complex management situations (Argent, 2004; Jakeman et al., 2006). In addition, the models are applied by users with little modeling experience. Therefore, special care needs to be taken to ensure that models are not used to produce results outside a "credibility interval".

The design of a DSS should be tailored to the needs of the intended end users of the system, so the system design should start with the identification of such users. Afterwards, a participatory approach should be used to incorporate the needs and the knowledge of the intended end user. From our point of view, designers of a DSS should act as a filter removing ambiguities and confusing options by focusing on the most important and certain interactions. This filtering process is, of course, highly dependent on the available data sets and models; if a certain feature is highly desired by the end users but cannot be modeled properly it should not be included into the DSS. Following the classification of Rizzoli and Young (1997), our potential end users could be classified as environmental decision makers and to a lesser degree as environmental stakeholders.

Feedback from meetings with the group of interested end users has led us to a design that does not force the user to deal with internal details of the model. Therefore, the kernel of the system consists of a structure of encapsulated models that can only be accessed by defined interfaces (see Fig. 2). The interfaces have been grouped into "management actions", "external constraints" and "management objectives". Each interface consists of a user dialog and a related software component which converts dialog options into model specific parameters.

The components of the Elbe-DSS can be classified as follows (see also Fig. 2):

1. Simulation models, representing the cause and effect relationships that drive the system. These models are part of the system kernel and as such they are hidden from the user of the system. Examples are GREAT-ER, HBV-D, MONERIS and LFBilanz.
2. A database which contains input data for the models as well as background information that might improve the understanding of the system behavior and contains information about the current situation. This database is also part of the kernel and accessible only through defined interfaces. Examples are soil maps, precipitation maps or historic discharge time series.
3. "Management actions" represent an interface between the user and the encapsulated simulation models. Users can specify the management option they want to study in an easy way without having to deal with model internals. As an example, the

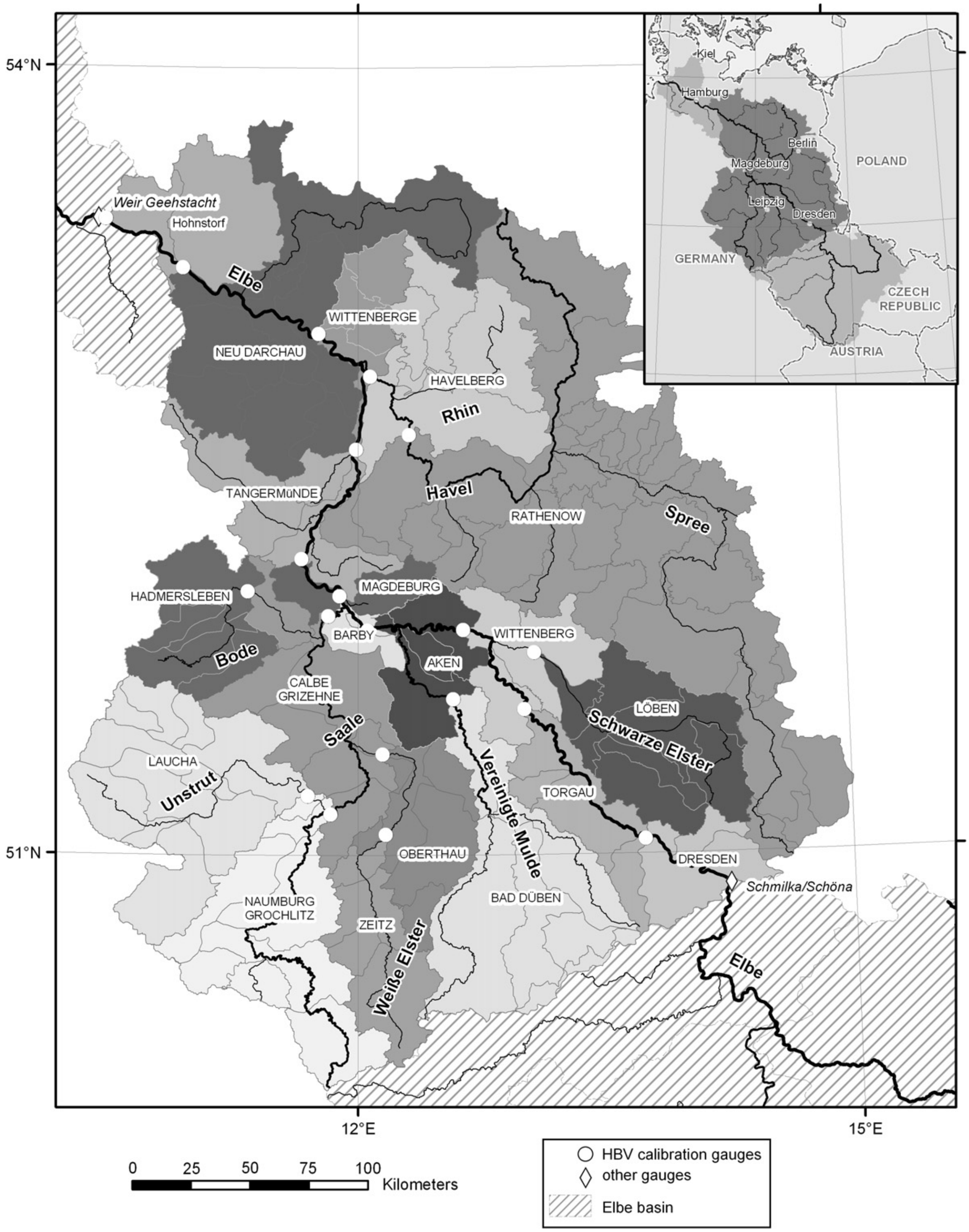

Fig. 1. Overview of the area of interest. The map shows the subdivision of the German Elbe catchment as used in the HBV-D model – not included are those sub-catchments that are influenced by the tides. The part of the Elbe catchment covered by HBV-D is shown in dark grey while the rest of the Elbe catchment is shown in a light grey. Rotated labels indicate important rivers while horizontal annotation shows the names of the gauging stations related to a sub-catchment. Thin grey lines indicate the sub-catchment structure of MONERIS. The insert shows the extent of the whole Elbe catchment, the most important German cities, as well as the other countries that are part of the area of interest.

management action "erosion control" allows the user to specify the amount of area over which he or she wants to apply strip cropping or contour farming. The resulting C and P factors are then chosen automatically.

4. "External constraints" are software components similar to "management actions" that also transform complex phenomena into model parameters. The main difference between "management actions" and "external constraints" is that the latter represent the consistent outcome of a complex storyline and do not offer as many fine tuning options as management actions. Examples are "demographic change" or "agro-political programs".
5. "Management objectives" pick up the most important and informative parts of the model results and show them in relation to the reference situation. In addition, these results might be shown in relation to legal thresholds or other meaningful factors.

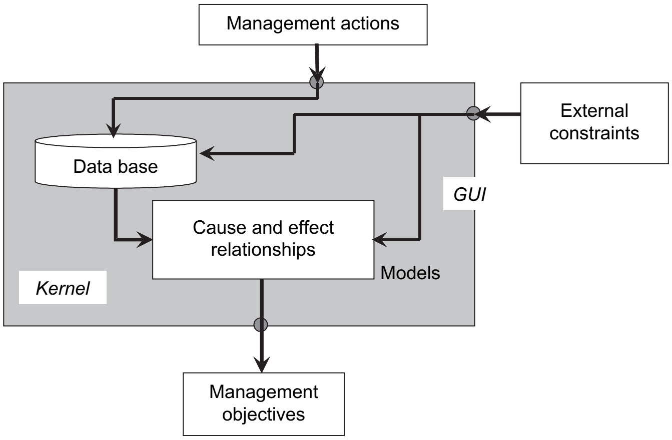

Fig. 2. General conceptual design of the Elbe-DSS. The Kernel of the system (models and data sets) is hidden from the user. The user interacts with the system via application of management actions (for example reforestation) and external constraints (like climatic change); model output is prepared under consideration of the effects on management objectives.

Examples are “Reduction of emissions”, “Improvement of water quality”, and “Reduction of nutrient inputs into the North sea”.

6. A Library which contains information about all the other components including the internal model structure and the transformation processes between the different components.

The information transfer between the different parts of the system is sometimes quite complex as it involves more than simple scaling or linear relationships. The following sections will discuss some of these internal transformation procedures. We start with a short overview of the model integration and continue with a description of the precipitation-runoff model. Afterwards, we present details about connecting the precipitation-runoff model with other models, and the connection of the model system with a small set of management actions and climate change as an example of external constraints.

2.3. Model integration in the catchment and the river network module

2.3.1. Model integration overview

We grouped the models, external constraints, management actions and objectives in the Elbe-DSS in four thematic units, so called modules (Fig. 3): the catchment module, the river network module, the main channel module and the floodplain module (Matthies et al., 2006). For brevity, we constrain our description to two out of the four modules: “catchment” and “river network”. Fig. 4 shows the model structure in these two modules. A central process in the Elbe-DSS is modeling runoff, which is handled by the HBV-D model. The precipitation-runoff model drives the estimation of diffuse nutrient emissions (MONERIS) which is associated with the concentration forecast in the river network (GREAT-ER). Changes in discharge simulated by HBV-D also affect concentration forecast in GREAT-ER. In addition to the models already mentioned, models of the modules “main channel” and “floodplain” are related to the model output of HBV-D. These models deal with flood risk, shipping and ecology of the floodplain, and aquatic ecology. Several management actions imply the use of the model LFBilanz which transforms agricultural practice into nutrient surplus.

Table 1 gives an overview about the purpose of the models, input/output relationships between the models, effected management objectives as well as about the management actions and external scenarios which influence the model parameters. All management actions can be combined with each other or with external constraints in any combination, resulting in a large number of possible combinations. We can highlight in the following sections only a few examples but Table 2 lists all management actions and external constraints available in the two modules in the Elbe-DSS. Details about the other possible settings in the Elbe-DSS as well as about additional non-model based parts of the system

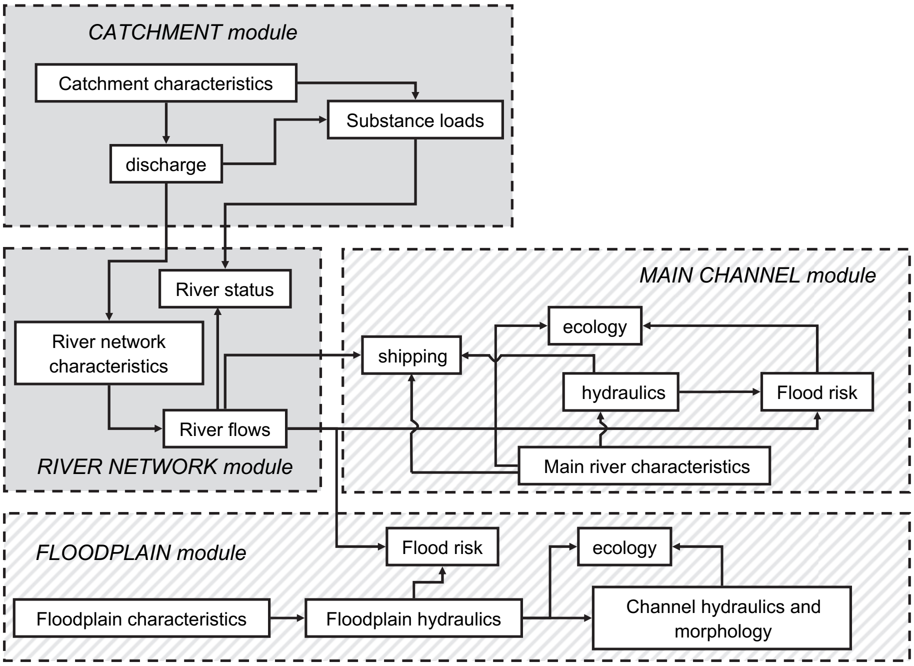

Fig. 3. Overview about the topics covered in the four modules of the Elbe-DSS and the most important interactions between the system elements. The main channel and floodplain module are not treated in this paper.

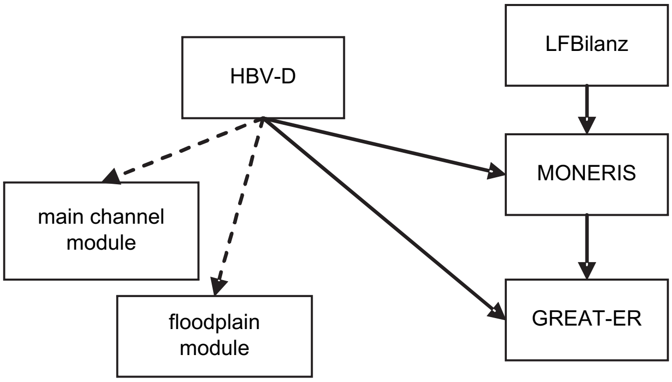

Fig. 4. Interactions between the models in the catchment module and the river network module as well as their relationship to the models in the main channel and floodplain module. The main channel and floodplain module are not treated in this paper.

like the database on fish passability of the river network can be found in Lautenbach (2005).

While the rest of this paper describes results from coupled modeling of nutrients, the analysis is not limited to nitrogen and phosphorus. The Elbe-DSS contains the necessary information to study additionally Bor, EDTA (ethylenediamine tetraacetic acid), the polycyclic musk HHCB, as well as the pharmaceuticals Diclofenac and Paracetamol.

2.3.2. *Rainfall-runoff modeling*

Rainfall-runoff simulation in the Elbe-DSS is handled by the HBV-D model (Krysanova et al., 1999), a semi-distributed version of the widespread HBV model (Bergström, 1976, 1995) which has proven to be a robust tool for runoff simulations at the catchment scale. The model considers three spatial levels: the catchment level, the sub-catchment level and the level of elevation-land use zones. All discharge within a catchment is routed towards its outlet. The discharge may originate in the sub-catchments of the catchment itself or it might originate from an upstream catchment. Each sub-catchment can be parameterized separately. Sub-catchment partitioning of the Elbe catchment (Fig. 1) had to consider the requirements of the other models in the Elbe-DSS. In accordance with the hydraulic model in the main channel module, 19 catchments have been used. These catchments have been further divided into sub-catchments similar to the MONERIS sub-catchment division. The sub-catchments are further divided in 10 elevation zones which are intersected by the land use classes. All areas which are part of the same elevation zone and the same land use class are handled as one unit – a concept similar to the hydrological response unit approach of SWAT (Arnold and Fohrer, 2005; Arnold et al., 1993).

The hydrological model consists of four main modules: the snow module, the soil moisture module, the runoff response module and the routing module. Land use affects the system by modifying snow distribution, infiltration, the interception storage and evapotranspiration. The main output of the model is the discharge at each catchment outlet. In addition, the model delivers estimates of the water fluxes, evapotranspiration, snowmelt, and fast, slow and very slow discharge processes inside each sub-catchment.

Model input consists of daily precipitation and temperature data. This information was supplied by 369 stations from the German weather service. Difficulties in data access and missing links between national research programs did not allow an incorporation of the Czech part of the catchment. Instead, water input is based on historic time series from the Schöna gauging station at the Czech/German border.

2.3.3. *Integration of precipitation-runoff with diffuse nutrient emissions*

Nutrient emissions from diffuse sources in the river network are calculated by the deterministic nutrient balance model MONERIS (Behrendt et al., 1999, 2003). It calculates average perennial means

Table 1
Overview of the models used in the catchment and river network modules, their relationship with each other and other parts of the system

Model	Spatial scale	Used for	Most important inputs	Output used as input for		Affected by	
				Model	Management. objective	Management action	External constraints
HBV-D	19 Catchments, 132 sub-catchments	Precipitation run-off simulation	Precipitation, temperature, land use	MONERIS, GREAT-ER, Main channel and floodplain models		Reforestation, renaturation of drained agriculture land, agro-political programs	Climatic change, agro-political programs, development of urban and traffic areas
MONERIS	132 Catchments	Prediction of long term average diffuse nutrient emissions	Nutrient surplus, run-off, land use, soil type, inhabitants connected to treatment plants, farming practices, drained areas	GREAT-ER	Reduction of emissions	Reforestation, agro-political programs, renaturation of drained agriculture land, erosion protection, construction of local treatment plants, buffer stripes, desealing, increasing fraction of separate sewer system, treatment of combined and separated sewer runoff, increase of the habitants connected to treatment plants	Climatic change, demographic change, development of urban and traffic areas
GREAT-ER	~33,000 River stretches of about 1.5 km length and related contributing area	Prediction of long term average point-source emissions, substance elimination in sewers and rivers, transport	Inhabitants connected to treatment plants, discharge statistics, treatment plant technique, per capita consumption, treatment plant technique, physical substance characteristics		Reduction of emissions, Improvement of water quality, reduction of nutrient inputs into the North sea	Increase of the habitants connected to treatment plants, improve treatment plant technology	Demographic change
LFBilanz	132 Catchments	Prediction of nutrient surplus on agricultural land	Crop composition, fertilizer applications, livestocks, use of different agricultural practices	MONERIS		Change of crop composition, manuring regulations, live stock sizes, eco-farming	Agro-political programs

of diffuse inputs (total phosphorus and total nitrogen) caused by erosion, surface runoff, groundwater flow, tile drainage, atmospheric deposition and impervious urban areas. Spatial units are 132 sub-catchments which have been identified in accordance with monitoring stations to allow a calibration of the model (Behrendt et al., 1999).

Table 2
Overview about the management actions and external constraints that are covered by the Elbe-DSS

Management action or external constraint	Short description	Spatial scale	Economic valuation
Management actions		Sub-basin	
Agro-political programs	Changes in nutrient surplus	Sub-basin	Yes
Buffer stripes	Reduction of emissions by erosion by reducing the sediment delivery ratio	Sub-basin	Yes
Change of crop composition	Changes in nutrient surplus; changes of the erosion potential (C-factor)	Sub-basin	–
Construction of local treatment plants	Emission reduction for inhabitants not connected to sewers	Sub-basin	Yes
Desealing	Reduction of emissions from sealed urban areas; change of the inhabitants connected to sewer systems; reduction of overflows of combined sewers during storm rain events; reduction of emission from separated sewer systems	Sub-basin	Yes
Eco-farming	See text	Sub-basin	–
Erosion protection	See text	Sub-basin	Yes
Improve treatment plant technology	Improve technology of a selected set of treatment plants; this leads to an increase of substance elimination in the treatment plants	Treatment plant	Partly
Increase of the habitants connected to treatment plants	Increase of habitants connected to treatment plants in the effected sub-basin; increase of inhabitants is a function of the number of inhabitants already connected to the treatment plant, decrease of habitants not connected to treatment plants but connected to sewers or habitants not connected to sewers	Sub-basin and treatment plant	–
Increasing fraction of separate sewer system	Increase the sealed urban area connected to separate sewer systems; decrease sealed urban areas a) connected to combined sewers, b) not connected to sewers or c) connected to sewers but not to treatment plants	Sub-basin	–
Live stock sizes	Changes in nutrient surplus	Sub-basin	–
Manuring regulations	Changes in nutrient surplus	Sub-basin	–
Reforestation	See text	Sub-basin	–
Renaturation of drained agriculture land	Conversion of tillage drained agricultural land or grassland into wetland	Sub-basin	Yes
Treatment of combined and separated sewer runoff	Several actions that decrease emissions from combined (increase of overflow basins) or separate (filter systems) sewer systems	Sub-basin	Yes
External constraints			
Agro-political programs	Changes in nutrient surplus, change of crop composition	Sub-basin	Yes
Climatic change	See text	Sub-basin	–
Demographic change	Changes in the number of inhabitants connected to a) treatment plants, b) combined sewers, c) separate sewers, d) not connected to sewers	Sub-basin	–
Development of urban and traffic areas	Conversion of land use classes	Sub-basin	–

Changes in the runoff processes are triggered by HBV-D. For the purpose of the Elbe-DSS, the HBV-D sub-catchments have been derived by an intersection between the MONERIS catchments and the HBV-D catchments. Therefore, the runoff simulated in each HBV-D sub-catchment can be related to a MONERIS catchment. If MONERIS sub-catchments belong to more than one HBV-D catchment, spatial averaging is performed.

We used the relative change of the total runoff of a sub-catchment and related this to relative changes of the MONERIS model parameters, assuming a constant relationship between the runoff components:

$$\mathbf{rc}_j = Q_i/Q_{i0} \times \mathbf{rc}_{j0} \qquad (1)$$

where $\mathbf{rc}_j$ is a vector of the seven runoff components in MONERIS for sub-catchment j and Q_i is the discharge at the HBV-D outlet for basin i. Sub-catchment j is a part of the HBV-D catchment i. Q_{i0} and $\mathbf{rc}_{j0}$ are the values for the reference situation, i.e. the default run of the integrated model without any active management actions or scenarios.

2.3.4. Integration of precipitation-runoff with concentration forecasts in the river network

While nutrient emissions are important for river basin management, it is necessary to have additional information on substance concentrations and loads in the river network. Average concentrations and loads in the river network are calculated by the aquatic fate and exposure assessment model GREAT-ER (Hess et al., 2004; Koormann et al., 2006; Matthies et al., 2001). GREAT-ER gets input from about 1900 waste water treatment plants as well as from the diffuse emissions that are calculated by MONERIS (for details on the coupling between MONERIS and GREAT-ER see Berlekamp et al., 2007). It uses the inputs together with substance-specific degradation rates and discharge statistics for the calculation of concentration and load in the river network.

In most cases, the highest concentrations can be found in smaller tributaries (Hess et al., 2004), because of relatively high emissions and low discharge. Thus, a detailed geo-referenced representation of the river network is necessary, and the river network has been split into about 33,000 river stretches of approximately 1.5 km length.

Each river stretch requires information about the median (MQ) and the fifth percentile (Q5) of discharge (Fig. 5A). Since these values are expected to change under some of the scenarios, we need to update the GREAT-ER database before we run the model. We use HBV-D to calculate the discharge time series and derive the MQ and Q5 values from these time series. However, since we do not use a fully distributed rainfall-runoff model we can only calculate the discharge time series at the 19 catchment outlets. The values for the other river stretches need to be interpolated from the discharge time series at these locations.

The interpolation of the discharge statistics for the whole river network is performed as follows: the river stretches that intersect with an outlet of one of the 19 HBV-D catchments are identified. For these river stretches, MQ and Q5 values can be derived directly from the discharge time series generated by HBV-D. For all other river stretches we do not have discharge time series and thus need to estimate these values. In a first step, we subtract the MQ and Q5 values from upstream catchments from the values at the outlets (Fig. 5B), which yield the values for the discharge that originates in

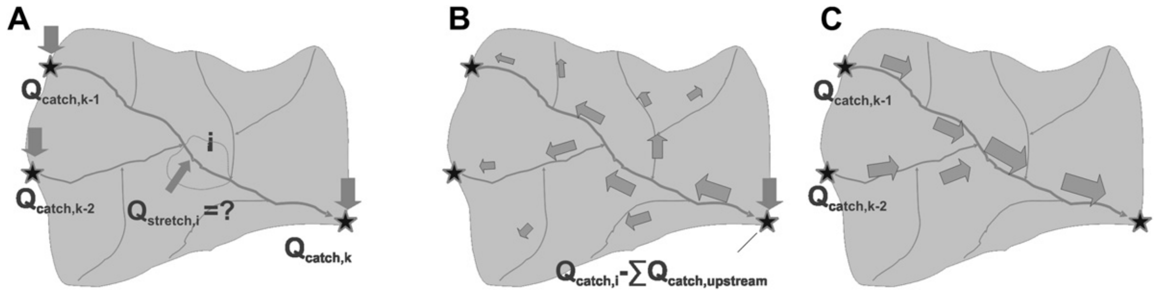

Fig. 5. Integration of HBV-D and GREAT-ER: interpolation of the discharge statistics (MQ and Q5) from catchment outlets to the river network. (A) The HBV-D results are used to derive discharge statistics for the parts of the river network that are connected to the HBV-D catchment outlets. (B) Starting from the catchment outlets, the discharge that originates from the catchment itself is distributed backwards. Thereby, the accumulated flow length of the river stretches is used as a weighting factor. (C) Discharge from upstream catchments is distributed along the flow paths.

the catchment itself. These new MQ and Q5 values are used in a second step to interpolate the MQ and Q5 values for all other stretches in the catchment. A weighted linear interpolation is used with accumulated flow length as weighting factors. The accumulated flow length of each river stretch is thereby used as a proxy for the contributing area of this river stretch.[1] If we assume that each part of the catchment contributes equally to runoff processes we can distribute the total discharge that originates in the catchment accordingly. After the interpolation has been performed for each stretch, we have to add the discharge from upstream catchments (Fig. 5C). The discharge from upstream catchments is distributed along the stretches that belong to the flow path from the upstream catchment to the outlet of the actual catchment.

2.4. *Integration of management actions and external constraints in the catchment and the river network module*

The user of the Elbe-DSS interacts with the DSS by applying management actions and scenarios which in turn trigger model runs to update the system state. To demonstrate the abilities of the Elbe-DSS, we selected a set of three management actions and one external constraint. The following subsections describe the details of these management actions and the external constraint and their integration in the Elbe-DSS.

2.4.1. *Reforestation*

Effects of reforestations of agricultural land or grassland are relevant for water basin management due to their effects on hydrologic processes. Reforestation has a direct effect on hydrologic processes through its link with the evapotranspiration regime and through its influence on the initiation of surface runoff. Reforestation leads to increasing evapotranspiration as well as decreasing surface-runoff and base flow (Fohrer et al., 2001; Johnson, 1998). In addition, reforestation reduces fertilization and leads to less erosion.

The user interface in the Elbe-DSS allows the user to specify the following settings: which land use types should forest areas replace (agricultural land or grassland)? Which areas should be affected? How much of the grassland or agricultural land should be converted to forest? Additionally, it is possible to choose between two options affecting the nutrient surplus generated by farming on agricultural land, which has a major influence on diffuse nutrient emission. A reduction of agricultural used land could be (a) counteracted by increasing yields from the resulting farming area or (b) it could be performed without such an increase in production. This would have a direct effect on the nutrient emission via tile drainage, erosion and groundwater in MONERIS.

The area effected by any management action in the Elbe-DSS can be defined by: (i) the whole catchment, (ii) a combination of the management units of the WFD or (iii) a combination of the 132 MONERIS sub-catchments. Selection of spatial units is possible by selecting on a map or by selecting from a list.

Reforestation in the Elbe-DSS affects several models: first, reforestation changes the distribution of land use classes in the chosen MONERIS sub-catchments. This has an effect on the nutrient emissions via erosion, groundwater and surface runoff. Secondly, the land use change is forwarded to HBV-D which will calculate new discharge statistics which trigger recalculations of MONERIS, GREAT-ER and some of the models in the main channel and floodplain modules (see Fig. 4 for the model interaction). In summary, reforestation leads to changing nutrient concentrations in the river system by: (i) a direct effect of land use change in MONERIS (e.g. less emission by erosion from land covered by forest compared to agricultural land), (ii) the effect of changed discharge on MONERIS (e.g. by a reduction or an increase of surface runoff), and (iii) the effect of discharge changes on concentrations in the river system.

2.5. *Erosion control*

Nutrient emissions through erosion are common in agriculturally used land and can have a significant effect on surface water nutrient concentrations. Thus, practices of preventing or controlling erosion might be important in improving water quality.

Erosion control in the Elbe-DSS affects the estimation of soil loss in MONERIS. Given the nutrient concentrations in the topsoil, soil loss influences the nutrient emissions via erosion. These nutrient emissions are linked to GREAT-ER and used for the calculation of in-stream concentrations.

The related user interface allows specification of the area over which the erosion control practice should be applied (see reforestation), the percentage of agricultural land where it should take place as well as further specifications of the action. Erosion control can be specified as a combination of:

- Change of agro-practice to soil-preserving tillage: enhancement of soil protection by mulch tillage, retaining crop residues after harvest, shallow plowing.
- Contour farming: crop row ridges from tilling and/or planting along contours generate a multitude of small water retaining dams.
- Strip cropping: alternating narrow strips of crops are grown either at right angles to the direction of the prevailing wind, or

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[1] We compared the weights found by the method of accumulated flow length with other methods (Thiessen polygons and watershed delineation function of GIS) and found only small differences.

following the natural contours of the terrain to prevent wind and water erosion.

Erosion is estimated in MONERIS by the ABAG (Schwertmann et al., 1987), a variant of the universal soil loss equation (Wischmeier and Smith, 1978).

$$A = R \times K \times \mathrm{LS} \times C \times P \tag{2}$$

where A is the soil loss in tonnes per acre, R is the rainfall-erosivity factor, K is the soil erodibility factor, LS is a combined factor representing both slope length and slope steepness. C is the cover-management factor (it is the ratio of soil loss from land under a specific crop and management system to the corresponding loss from continuously fallow and tilled land) and P is the support practice factor. It reflects the effects of practices that will reduce the amount and rate of the water runoff and thus reduce the amount of erosion. The support practice factor represents the ratio of soil loss by a support practice to that of straight-row farming up and down the slope.

Settings of the erosion control user interface are converted to the corresponding C and P factors and MONERIS is executed with these changed parameters. Since most of the end users of the system will not be able or willing to specify the corresponding C and P factors on the fly, the Elbe-DSS relieves the user from this burden.

2.5.1. *Ecological-farming*

Ecological-farming integrates a set of farming practices which could influence nutrient emission in a number of ways (Frede and Dabbert, 1998; Haas, 2001), for instance a ban on some fertilizers, restriction of the livestock density or by a reduction of the crop yields. The discussion about effects of ecological-farming practice on nutrient emissions is ongoing (Aronsson et al., 2007; Dalgaard et al., 1998; Eltun et al., 2002; Kirchmann and Bergstrom, 2001; Taube et al., 2006), so any specification will be uncertain and derived results should be interpreted with care.

We specified the following effects of ecological-farming in the Elbe-DSS which seemed reasonable (M. Bach and H.-G. Frede, personal communication):

- Limiting livestock density to 1.4 livestock units per hectare.
- Doubling the nitrogen surplus by legumes.
- Reduction of crop yields by 20%.
- Reduction of the nitrogen and phosphorus concentrations of fertilizers by 25%.

These effects are used by LFBilanz (Bach and Frede, 1998, 2005) for a recalculation of nutrient surplus on arable farm land. Nutrient surplus is linked to MONERIS where the diffuse phosphorous and nitrogen emissions are recalculated.

Since the effects of changes in nutrient surplus do not immediately influence the emissions patterns it is necessary to specify a time period after which the effects are calculated. The lag between changes in nutrient surplus on agricultural land and emissions into surface water bodies is caused by long groundwater residence times and the accumulated phosphorus surplus in the topsoil. Emissions through the groundwater path take a while to show up in surface waters – for the Elbe basin groundwater residence times can be up to 40 years or even higher (Kunkel and Wendland, 1997; Wendland et al., 2004). Before that time, groundwater emissions will show no reaction to changing nutrient surplus. For phosphorus, the immense surplus present in German topsoils on arable land damps the effect of changes in management practice.

In reaction to this time lag, we decided to implement all management actions concerning nutrient surplus with a time horizon of 10 years. This means, we simulate the system state after a virtual constant application of the management action over 10 years. The drawback of this solution is the fact that parts of the catchment with short groundwater resident times will already react to the management actions while the other parts will still relate to historic nutrient surplus situations.

2.5.2. *Climate change scenario realizations*

Climate change affects the hydrologic processes by changing precipitation patterns as well as by changes of air temperature which affects evapotranspiration and snow melt. Therefore, it is necessary for river basin managers to compare the effect of different sets of management actions with the impacts of global warming. The Elbe-DSS contains a set of regional climate scenarios compiled by the Potsdam Institute for Climate Impact Research. Since external constraints and management actions can be combined, the user could also compare the effects of management actions under different assumptions on climate change.

The regional climate scenarios are based on the results of the global climate model ECHAM4-OPYC3 (Kemball-Cook et al., 2002) with the A1-CO_2 emission scenario which leads to moderate global warming (IPCC, 2001). The air temperature forecast of this global model run was used to create regional forecasts of all climate variables by a statistical approach (Gerstengarbe and Werner, 1997; Gerstengarbe et al., 1999; Werner and Gerstengarbe, 1997). The approach maintains the stability of the main statistical characteristics (variability, form of frequency distribution, annual cycle, and persistence). This regionalization procedure is implemented in the STAR model (Werner and Gerstengarbe, 1997) from which we selected three realizations of regional climate forecast to estimate the effect of climatic change on water quality and discharge. The three realizations have been chosen such that they represent the most certain realization (scenario I – most probable realization with drop in mean precipitation), as well as two extreme realizations (scenario II without precipitation trend and scenario III with a precipitation trend).

The realizations consist of time series from 2000 to 2055 for the climate stations in the Elbe region. These have been interpolated using Thiessen polygons and are used to drive the HBV-D model. The changing discharge time series are then passed on to MONERIS and GREAT-ER, affecting nutrient emissions and concentration calculations. In addition, the number of storm events is calculated from the time series, which serves as a parameter in the MONERIS calculations of nutrient emissions by erosion and storm water overflows from combined sewers.

2.6. *System test*

2.6.1. *Precipitation-runoff*

Model performance of the HBV model for each catchment was assessed using the Nash–Sutcliff model efficiency R_{eff} (Eq. (3)) (Nash and Sutcliff, 1970), the Nash–Sutcliff model efficiency of the log-transformed values $\mathrm{LR}_{\mathrm{eff}}$ and the relative water balance.

$$R_{\mathrm{eff}} = 1 - \frac{\sum_{i=1}^{n}\left(Q(t_i)_{\mathrm{obs}} - Q(t_i)_{\mathrm{sim}}\right)^2}{\sum_{i=1}^{n}\left(Q(t_i)_{\mathrm{obs}} - \overline{Q_{\mathrm{obs}}}\right)^2} \tag{3}$$

For the performance test of the HBV-D model a time series of 26 years (1979–1995) was available which was split in a period for calibration (1979–1990) and validation (1990–1995). Simulations from the first year were not considered for R_{eff} calculation to overcome the influence of the initial conditions of the storage components. The model performed well for all stations: the model efficiency is above 0.8 for most of the gauging stations at the tributaries (see Table 3). Exceptions are: the Havel/Spree region and the Hadmersleben station on the Bode River (see Fig. 1 for the

Table 3
Results of the objective functions used for the calibration and validation of the HBV-D model

River	Elbe-km	Gauge	MQ observed [m^3/s]	Area covered by the Czech part [%]	R_{eff}		LR_{eff}		Water balance	
					Calib.	Val.	Calib.	Val.	Calib.	Val.
Elbe[a]	55.6	Dresden (D)	341.0	96.8	0.99	0.99	0.99	0.99	−0.02	−0.03
Elbe[a]	154.6	Torgau (Tor)	354.6	93.0	0.98	0.98	0.98	0.98	−0.02	−0.02
Elbe[a]	214.1	Wittenberg (W)	367.4	83.1	0.95	0.96	0.97	0.96	−0.01	0.02
Elbe[a]	274.4	Aken	442.0	75.6	0.96	0.97	0.97	0.97	0.00	0.05
Elbe[a]	295.5	Barby (Bar)	559.4	55.7	0.95	0.95	0.96	0.95	−0.01	0.02
Elbe[a]	326.6	Magdeburg (MD)	565.9	55.1	0.95	0.95	0.96	0.95	0.00	0.07
Elbe[a]	388.2	Tangermünde (Tan)	576.8	53.5	0.95	0.95	0.96	0.95	−0.02	−0.02
Elbe[a]	454.4	Wittenberge (W-e)	700.2	42.2	0.95	0.93	0.94	0.93	0.00	0.00
Elbe[a]	536.5	NeuDarchau (ND)	709.9	39.5	0.93	0.91	0.93	0.91	−0.01	0.02
Schwarze Elster		Löben (Lö)	18.5	0.0	0.84	0.63	0.77	0.63	−0.02	0.01
Vereinigte Mulde		Bad Düben (BD)	61.9	0.0	0.85	0.81	0.84	0.81	−0.01	0.02
Saale		Naumburg-Grochlitz (NG)	71.7	0.0	0.87	0.78	0.83	0.78	0.00	0.04
Saale		Calbe-Grizehne (CG)	122.0	0.0	0.86	0.79	0.87	0.79	−0.02	−0.03
Unstrut		Laucha (La)	32.8	0.0	0.83	0.75	0.75	0.75	−0.01	0.05
Weiße Elster		Zeitz (Zei)	16.2	0.0	0.85	0.82	0.82	0.82	0.00	0.00
Weiße Elster		Oberthau (Ob)	26.3	0.0	0.82	0.80	0.85	0.80	0.00	0.08
Bode		Hadmersleben (Had)	14.0	0.0	0.75	0.68	0.68	0.68	−0.03	0.07
Havel		Rathenow (Rat)	84.7	0.0	0.66	0.47	0.54	0.47	0.00	0.02
Havel		Havelberg (Hav)	105.9	0.0	0.67	0.47	0.55	0.47	−0.02	0.00

[a] Since the Czech part of the catchment was not integrated into the Elbe-DSS, the results for gauges along the main channel are inflated. Discharge from the Czech part is not modeled, historic time series are used instead. Thus, performance indicators reflect not only model performance but also measured discharge. The relation between the total catchment size and the size of the Czech part of the catchment indicated in the fifth column gives an estimate of the influence of the Czech part.

location of the gauging stations). The model efficiencies along the main channel, which are above 0.9, are inflated by the use of measured discharge from the Czech part of the catchment. The log-transformed model efficiency is, in general, somewhat lower but still satisfactory and the relative water balance error is not higher than 3% for the calibration period. For the validation period some stations, namely Löben on the Schwarze Elster as well as Magdeburg, Oberthau and Hadmersleben, showed strong decreases in model performance; the last three stations showing departures in water balance of up to 7%. We assume that the strong decrease in model performance at Hadmersleben is a result of management change at the dams in the region. The unsatisfying results for the Havel catchment are caused by the strong anthropogenic influence in the catchment as well as the flatness of the area and the great number of lakes which could not be parameterized satisfactorily.

2.6.2. *River discharge*

The MQ and Q5 values for the GREAT-ER model runs are derived from the discharge time series generated by HBV-D for the 19 catchment outlets. As would be expected, the simulated Q5 values differ much more from measured discharge data than the MQ values (results not shown).

To estimate the accuracy of the interpolated MQ and Q5 values between the HBV-D gauging stations, we included additional historic time series. Compared to the results at the HBV-D outlets, differences between interpolated and observed values increase but are still satisfactory (results not shown).

2.6.3. *Substance concentrations*

Total phosphorus and total nitrogen concentrations differ by approximately a factor two when compared with observed data along the Elbe and some major tributaries (Fig. 6). Fig. 7 shows that

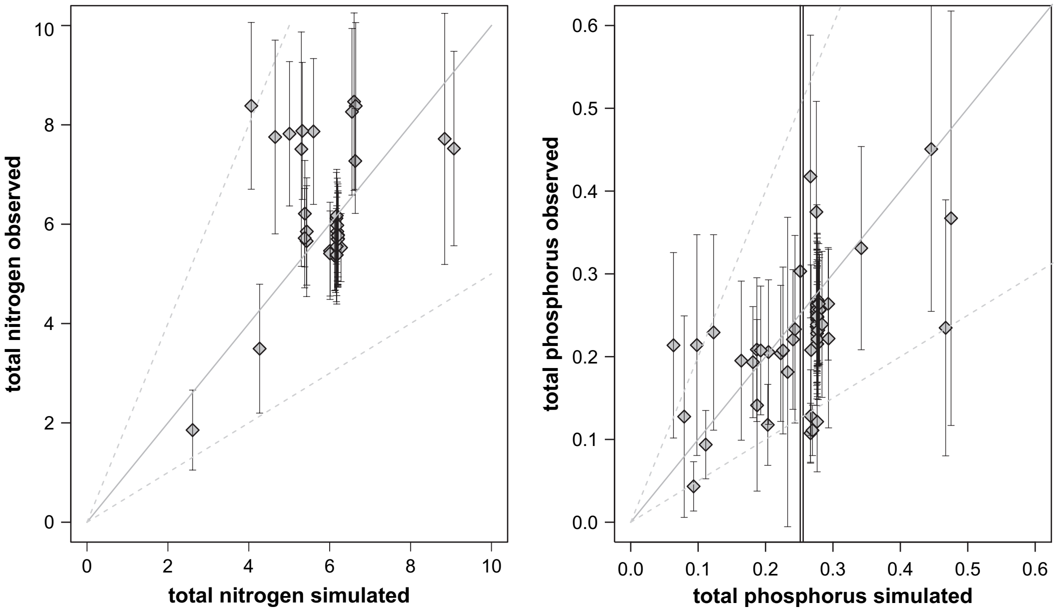

Fig. 6. Scatter plots of observed versus simulated nutrient concentrations along the main channel and major tributaries. The error bars represent the standard deviation at each location. Dashed lines indicate the 1:2 and 2:1 lines while the solid lines indicate the 1:1 line.

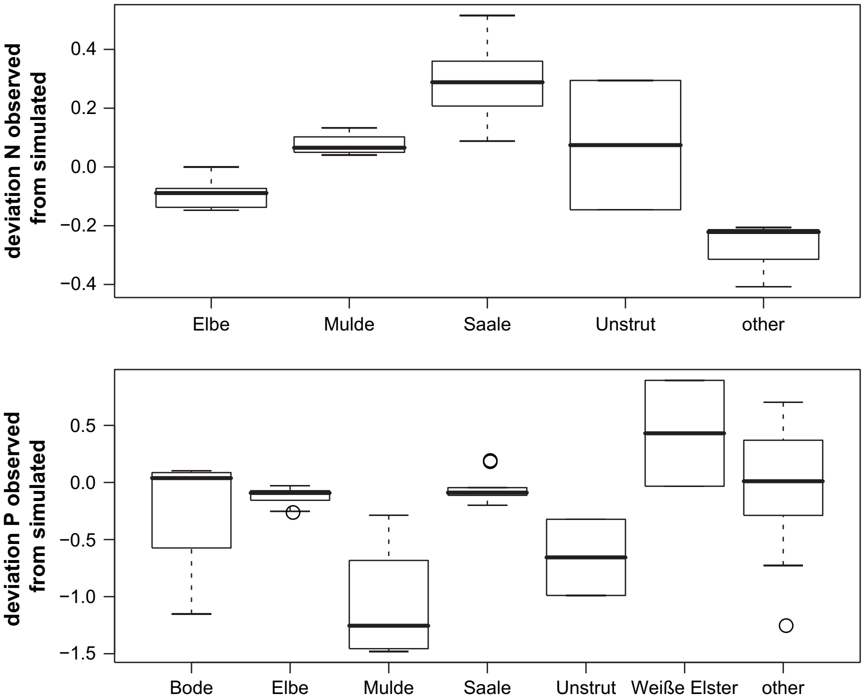

Fig. 7. Comparison of observed and simulated nitrogen and phosphorous concentrations grouped by rivers. On the *y*-axes, the relative deviation between observed and simulated concentrations at the monitoring station is shown.

the agreement between measured and simulated concentrations is in general higher for the main channel while measurements at some of the tributaries (the Saale for nitrogen, the Mulde, Unstrut and the Weiße Elster for phosphorus) show significantly higher deviations. Given the fact that discharge as well as nutrient input is modeled and no calibration of the integrated system was performed, the results are quite satisfactory.

We did not calibrate the integrated model but only the individual models to decrease the risk of ”over-fitting” the integrated model. Nevertheless, the validation of the integrated model against in-stream nutrient measurements is good to satisfactory, which indicates that the cause-and-effect relationships have been captured by the model. At the minimum, it indicates that uncertainty did not increase significantly by linking the different models.

3. Results of scenario analyses and management actions

This section will show the results of some example applications of the management actions and climate change scenarios described above. The examples have been chosen such that the results are comparable, i.e. all management actions are applied homogeneously over the whole study area. A real world application of the Elbe-DSS would try to find sub-basins that are especially sensitive to the application of such management actions to establish an efficient and cost effective basis for management.

3.1. Reforestation

Fig. 8 shows the spatial patterns of emission reduction of total nitrogen and total phosphorus as results of the application of a reforestation management action. For this scenario the conversion area was specified as 20% of the agricultural land in each sub-catchment. The management action was applied over the whole German Elbe catchment. The pattern of emission reduction reflects the distribution of agricultural land in the area as well as the importance of the different emission paths over the different sub-catchments. Since numerous emission processes are involved in reforestation, no mono-causal explanation can be given.

Reforestation leads to a drop in both MQ and Q5. A sensitivity analysis (results not shown) has shown that the relationship between the relative change of MQ or Q5 to the relative change of agriculturally used land is nearly stable for each catchment. Reforestation of agricultural land on 1% of the area in a catchment leads to a decrease of the mean discharge from 0.46% to 0.12% among the 19 catchments. There is a slight tendency for the effect to decrease with increasing mean slope in the catchment but the catchments with low relief energy show a general higher variability in this effect. Fast and slow discharge components react more sensitively to reforestation than the very slow discharge components (results not shown).

Reforestation affects nutrient emissions in two ways: (i) indirectly by the influence of changing hydrological processes in HBV-D which affects the calculation of nutrient emissions in MONERIS and (ii) directly by the effect of changing land uses classes on erosion potential and fertilization. To study these two different effects, we will first present impacts if direct effects are switched off and show afterwards the combined effects. If only the change of discharge from HBV-D is taken into account for the calculation of nutrient emissions (neglecting the direct influence of changed land use), the maximum decrease of emissions is 6% for phosphorous and 8% for total nitrogen. If, however, MONERIS is used to consider additionally the direct effect of land use change, the maximum decrease of emissions is 24% for phosphorus (median 14%) and 22% for nitrogen (median 9%). If we investigate on the contribution of the different MONERIS emission processes we are able to identify erosion as the most import process (decrease of emissions up to 45% for phosphorus and nitrogen), followed by surface run-off (decrease of emissions up to 30% for phosphorus and 15% for nitrogen) and tillage drainage (decrease of emissions up 22% for phosphorus and 16% for nitrogen). Thus, the effect of decreasing erosion potential of forest compared to agricultural land and the effect of decreasing fertilizer application outweighs the effect of hydrological changes.

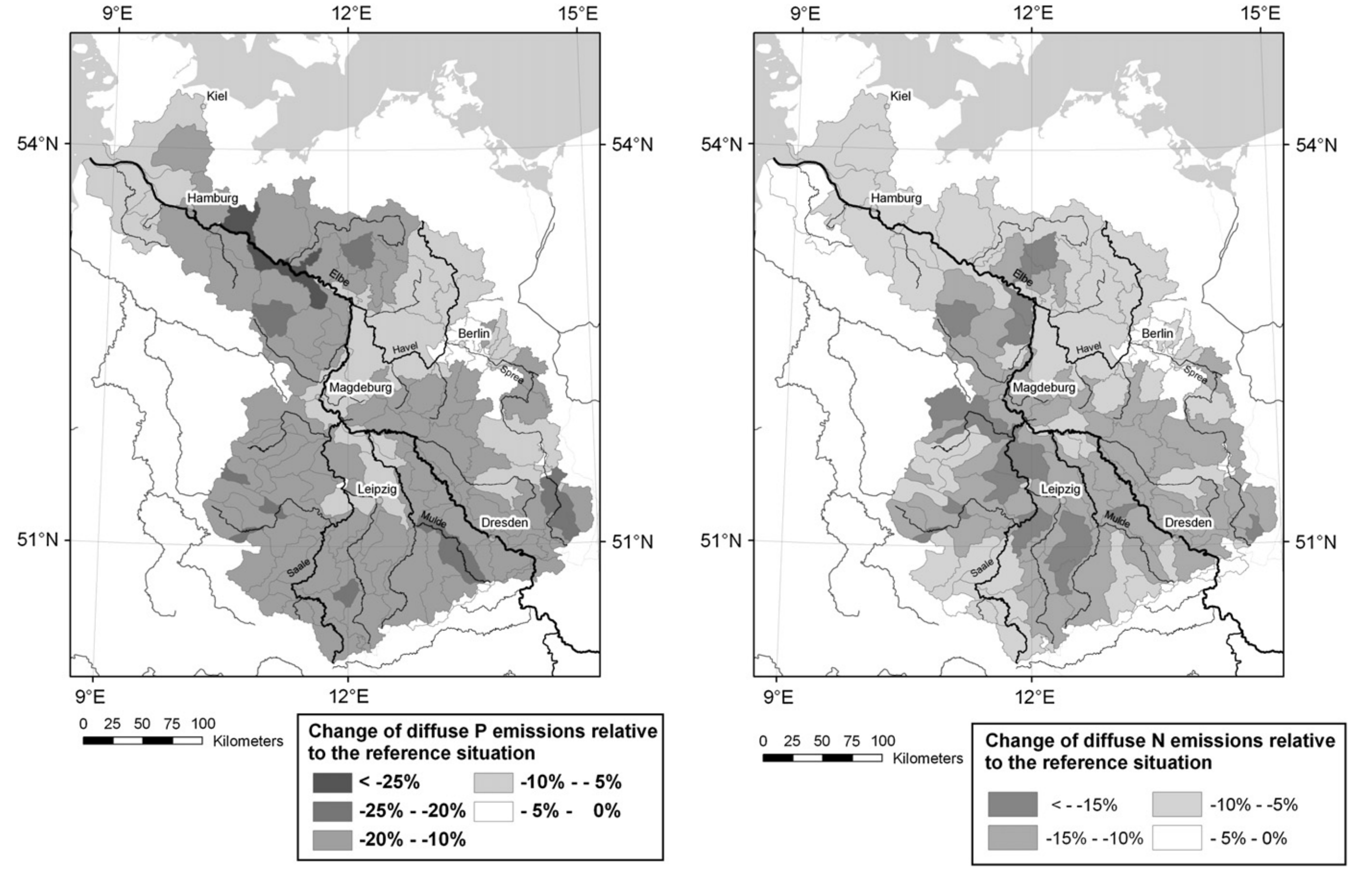

Fig. 8. Emission reduction for (right) total nitrogen and (left) total phosphorus as a result of a reforestation of 20% agricultural area per sub-catchment and without intensification within the remaining areas (see text for details).

Reforestation also has an effect on river discharge in the river network which decreases substance concentrations (results not shown). Fig. 9 shows the results of the integrated model run (HBV-D, MONERIS and GREAT-ER) as longitudinal concentration profiles along the Elbe, Saale and Spree/Havel rivers. In general, reforestation leads to a reduction of nitrogen and phosphorus concentrations. This means the dilutive effect of reduced mean discharge caused by higher evapotranspiration of forest is overcompensated by the reduction of diffuse emissions. Thus, the integrated model allows us to state that reforestation has a net positive effect on water quality.

Spatial patterns are partly due to topography. The reduction of diffuse emissions is in general higher in steeper parts of the Elbe catchment, e.g. the Mulde catchment, the upstream parts of the Saale and the Spree. In mountainous areas, reductions in phosphorus are also relatively higher compared to the effects on nitrogen. For areas affected by urban agglomerations, household emissions are another important factor. This can be shown for the Havel, where the high importance of household emissions from Berlin leads to weak reductions.

3.2. Erosion control

The results presented here were achieved by specifying a homogeneous management action for the whole German Elbe catchment. We increased the use of contour farming, strip farming and soil preserving tillage by 20% percent of the arable farming land in each sub-catchment. As expected, erosion control influenced emissions of phosphorus (decrease by 0–15%, median 2.5%) more than those of nitrogen (decrease by 0–2%, median 0.1% compare Fig. 12) and showed the strongest effect in areas characterized by steep slopes, high arable farm land fraction, high accumulated phosphorus surplus in topsoil and high soil erosion potential (results not shown).

Concentration changes along some of the major rivers (Fig. 9) show a close link to this spatial change of emission pattern. While the decrease of nitrogen is always below 2%, phosphorus concentrations drop by up to 10%. The most pronounced effects are present in the mountainous areas of the Saale catchment as well as in the upstream part of the Spree. The concentration profile along the Elbe shows significant concentration decreases at the mouth of the Vereinigte Mulde and the Saale rivers.

3.3. Ecological-farming

For the ecological-farming scenario we specified that ecological-farming practices should be used on an additional 20% of the agricultural land. The interpretation of results gained from increasing ecological-farming practices is complicated by the fact that the action does not result in an instantaneous reaction. The results for ecological-farming presented here are therefore calculated after a virtual constant application of the management action over 10 years. All other factors in this virtual scenario have been kept constant. This leads to a decrease in phosphorus emissions by 1–5% (median 1%) and for nitrogen results range from an increase of 6% to a decrease of 20% (median: decrease by 4%, compare Fig. 12). Since the livestock density in the eastern part of the catchment is below 1.4 livestock units (which correspond to the maximum density imposed for ecological-farming) these changes are mainly caused by changes in fertilizer application. The strongest reductions of

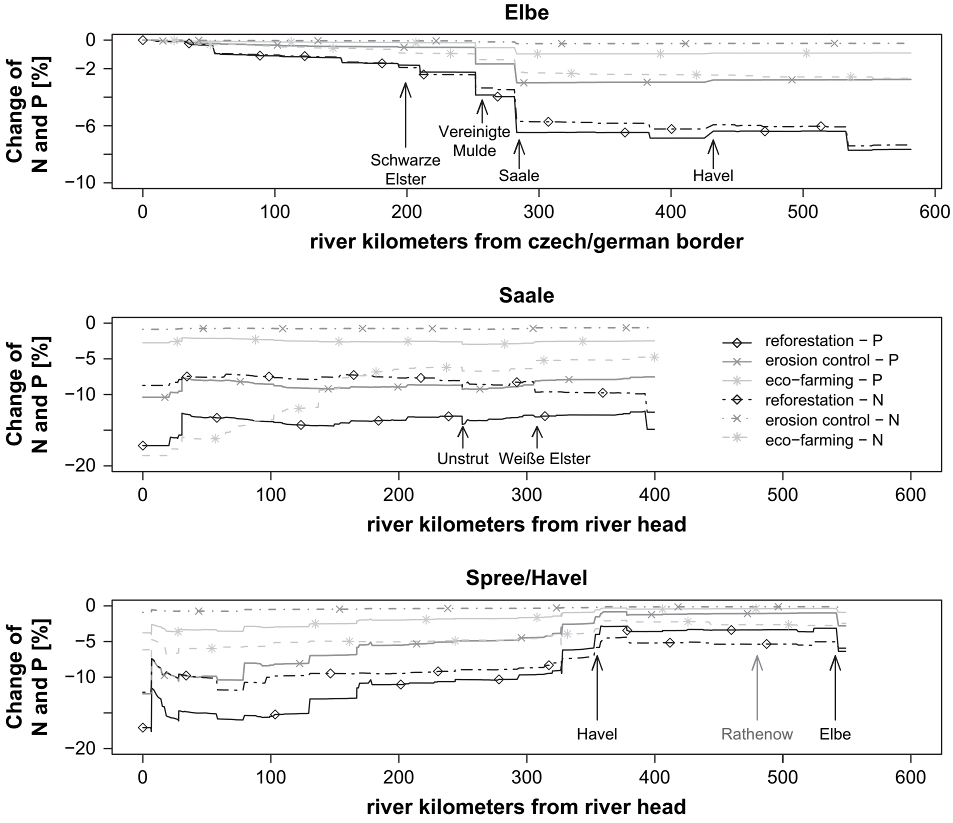

Fig. 9. Change of total nitrogen and total phosphorus concentrations along selected river profiles as a result of three management actions: (1) reforestation of 20% of the agricultural area without intensification on the remaining areas, (2) additional use of erosion control practice on 20% of the agricultural area, and (3) increasing the agricultural area managed by eco-farming by 20% of the agricultural area. The change is expressed in relation to the reference situation 1979–2000. Additionally, important tributaries (black) or gauging stations (gray) are marked. The management actions are only applied to the German part of the catchment. Therefore, concentrations in the Elbe show no effect at the German/Czech border.

nitrogen emissions can be detected for flat regions since emissions through groundwater are the main emission pathway for Nitrogen. For phosphorus, the strongest reductions can be detected in areas of high erosion potential.

The emission patterns show additional effects caused by groundwater residence time and accumulated phosphorus surplus. To separate between these effects and the actual effect of the management action we investigated how emissions would look if we extrapolate the current management practice 10 years in the future. An application of this virtual scenario would lead to a decrease of phosphorus emissions by 0–1% while for nitrogen the change ranges from an increase of 12% to a decrease of 18%.

Fig. 9 shows concentration patterns along the Elbe, Saale and Spree/Havel rivers under the ecological-farming scenario (20% increase of area managed by ecological-farming practices). Phosphorus reductions are rather low and show no strong changes along the Spree/Havel or the Elbe; the biggest effect in the main channel is due to the inflow of the Saale. The reduction of nitrogen concentrations along the Saale can be explained by the high reduction in its head sub-catchments which shows high nitrogen surplus and a very strong influence of the groundwater path. Along the Saale the change is reduced by mixing with tributaries from other less sensitive sub-catchments. The strong reduction of nutrients within the Saale river can also be seen in the Elbe longitudinal profile which shows a strong reduction due to the mixing with the Saale water – and to a lesser extend by mixing with the water from the Vereinigte Mulde river. This effect is much less pronounced for phosphorus which shows a decrease in concentration of about 2% until the river joins with the Elbe. Along the Spree the concentration reduction is about 5%. However, when the Spree flows into the Havel, high input from urban areas and from sewage treatment plants increase the concentration.

3.4. Climate change scenario realizations

The following realizations of the STAR model for the Elbe catchment are used in the Elbe-DSS: scenario I – the most probable realization, scenario II – a realization without precipitation trend and scenario III – a realization with precipitation trend. Scenario I leads to a drop in mean precipitation (Fig. 10) for all HBV-D catchments with exception of Hadmersleben which shows areas of increasing precipitation in the mountainous areas of the Harz. The decrease in precipitation reduces modeled mean discharge (referring to the discharge that originates in the catchment itself). The pattern in discharge is in general more pronounced but follows the same pattern as changes in mean precipitation. In contrast, scenario II shows increasing precipitation patterns in the south west of the Elbe catchment, in the watersheds of the Vereinigte Mulde, the whole Saale catchment and the southern part of the main channel. The highest increases in precipitation for realization scenario II are located in the catchments related to the gauges at Naumburg-Grochlitz and Hadmersleben and can be related to precipitation changes in the mountainous areas of the Harz and the Thuringian forest. Decreasing precipitation patterns for scenario II are located in the north-western parts of the Elbe catchment, the Havel and Spree watersheds and the northern tributaries to the main channel. The related change in modeled mean discharge shows a similar pattern as the change in mean precipitation but catchments whose precipitation is strongly decreased respond disproportionately.

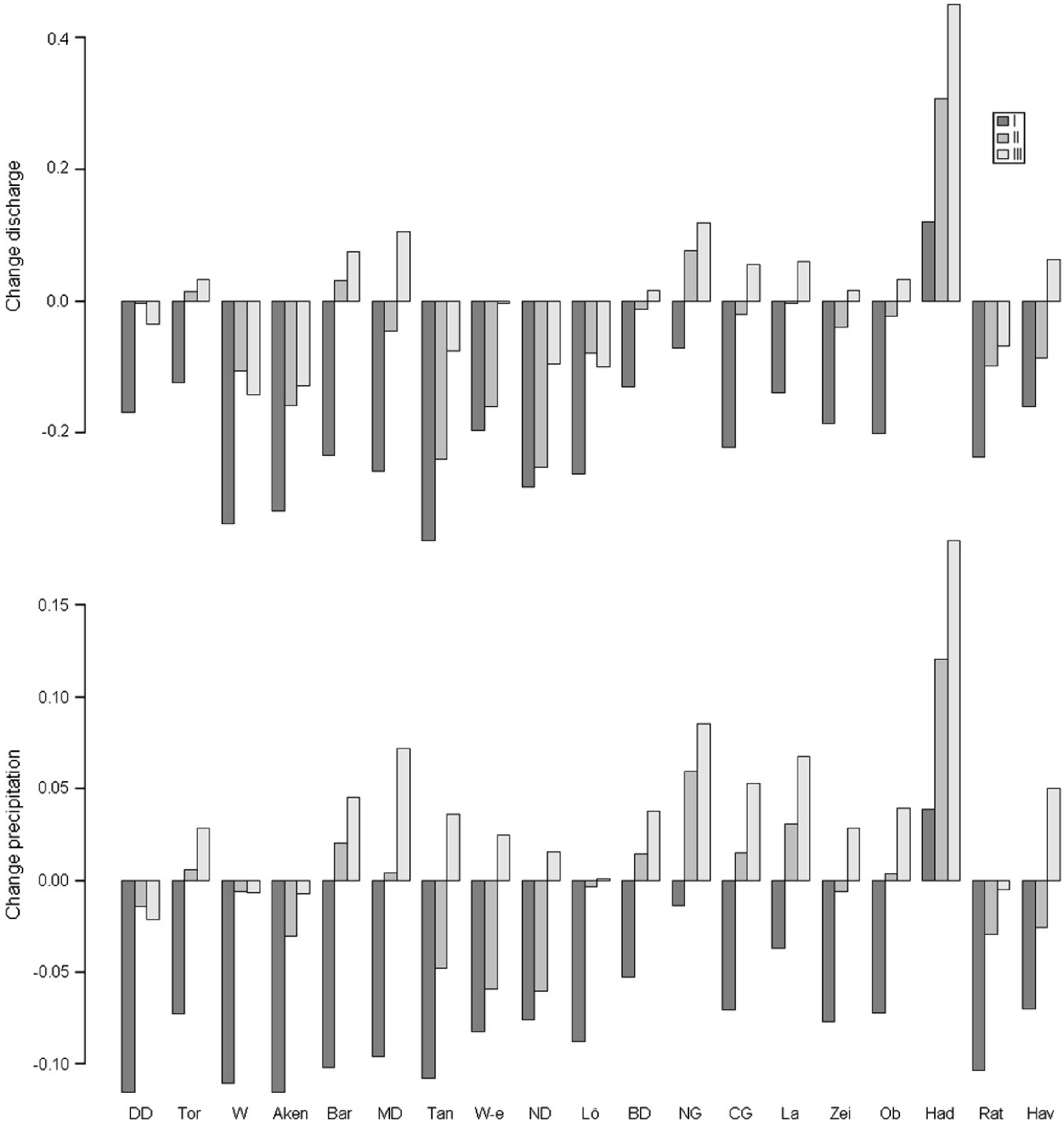

Fig. 10. Changes in mean discharge and precipitation in all 19 catchments for different climate change scenario realizations. The bar plots show the change of the period 2000–2055 relative to the reference situation 1979–2000. The discharge values are calculated on the basis of the discharge that originates inside the catchment itself, i.e. without consideration of effects in upstream catchments. The gauges are shown in the same order as in Table 3, i.e. grouped by the river they belong to. Table 3 also contains the mapping between abbreviations used here and the full names of the HBV-D catchments.

Finally, in scenario III mean precipitation increases in most catchments. In the remaining catchments, precipitation decreases only slightly. The response to this scenario is mixed. For example, in some modeled catchments mean discharge decreased despite increasing mean precipitation. In other words, the available regional climate predictions show a wide range of possible future conditions: the mean discharge can drop as far as by 34% (Aken) in scenario I or can increase up to 45% (Hadmersleben) in scenario III. Note that these results only reflect changes inside the catchments themselves. Changes in mean discharge downstream will integrate the effects of all upstream catchments. As no data for the Czech part are available, the mean discharge of the reference situation is used as input from the Czech catchment component.

Changing discharge patterns are linked to the calculation of nutrient emissions in MONERIS. Fig. 12 shows that the majority of the MONERIS catchments are characterized by decreasing diffuse phosphorus and nitrogen emissions. For all scenarios, means (22%, 18% and 15% for phosphorus and 14%, 5%, 1% for nitrogen) also show a decrease in emissions, but scenarios II and III both show an increasing number of sub-catchments with increases in nutrient emissions. This indicates that effects of climate change need to be studied in a spatially explicit way.

For the calculation of the emissions we also needed to consider trends in phosphorus accumulation in the topsoil as well as the time lag caused by long groundwater residence times (compare the discussion in the ecological-farming section). This was done under the assumption that the present nutrient surplus on agricultural land stays the same. All three scenario realizations show a decline in the number of storm events which leads to a reduction of emissions via erosion and sewage treatment plant bypasses. Taking all of these processes into account, the spatially heterogeneous pattern of emission changes becomes comprehensible. The pattern shows the strongest correlation with the pattern of changes in precipitation (results not shown). In addition to this trend, the pattern of groundwater residence times can be detected in the spatial pattern of nutrient emissions. The pattern of changes in phosphorus emissions shows an additional strong correlation with areas of higher relief energy. High relief energy is linked to high erosion potential, the most important driving force for phosphorus emissions, which is sensitive to changes in surface runoff.

The different emission paths contribute differently to the changes in diffuse nutrient emissions. Erosion leads to decreasing emissions of phosphorus and nitrogen for all scenarios, while emissions through tillage drainage results in decreasing and increasing trends for the different sub-catchments. An increasing mean trend for phosphorus and nitrogen can be detected for emissions by surface runoff under the climatic characteristics of scenario III.

Fig. 11 shows longitudinal profiles of concentration change for total phosphorus and total nitrogen resulting from changes in discharge and altered emission patterns from diffuse sources. In general, the change of the phosphorus concentration is greater than for nitrogen. Scenarios II and III show noticeable concentration reductions of nitrogen for the upstream part of the Saale. Through the confluence of the Unstrut at the Naumburg-Grochlitz gauge (for which all scenario realizations forecast an increase in nitrogen emissions) this concentration reduction is diminished. For scenario I, a concentration increase in nitrogen can be detected at the Saale despite the decline in nitrogen emissions in the contributing areas. Phosphorus concentrations show a broad decrease for all scenario realizations in the Saale. In the Havel catchment, decreasing mean discharges lead to increasing nitrogen concentrations for scenarios I and II, and to almost no effect in the case of scenario III. The sharper reduction of phosphorus emissions leads to lower concentrations for the first 350 km for scenarios II and III as well as lower concentrations on the first 180 km for scenario I. The situation in the Elbe shows a continuous increase of nitrogen concentrations for scenario I, which is boosted by the confluence of the Havel. The forecasted higher mean discharge for scenario III leads to reduced nitrogen concentrations along the main channel while scenario II has no noticeable effects for the Elbe with the exception of the decline caused by the confluence of the Saale. The higher reduction of phosphorus emissions causes a strong decline of concentrations in the main channel, which is triggered by the decline in the Saale and Vereinigte Mulde catchments. In summary, the different climate scenario realizations lead to a heterogeneous spatial pattern of concentration changes in the different parts of the catchment. This shows the benefits of a spatially explicit modeling approach.

4. Discussion

4.1. Discussion of results

Here, we have presented a set of example applications of the Elbe-DSS. The integrated model system describes runoff processes, nutrient emissions as well as nutrient concentrations for the different scenarios in a satisfactory manner. Through the coupling of the models we are able to gain insights into the relative importance of the different processes. Reforestation, for example, leads to two counteracting effects that influence nutrient concentrations in rivers: (i) decreasing discharge and (ii) decreasing emissions. Without the coupling of hydrological and emission models it would be impossible to decide which of the processes outweighs the other. The results of the integrated model indicate that the effect of decreasing emissions is stronger (compare Fig. 9); but the strength

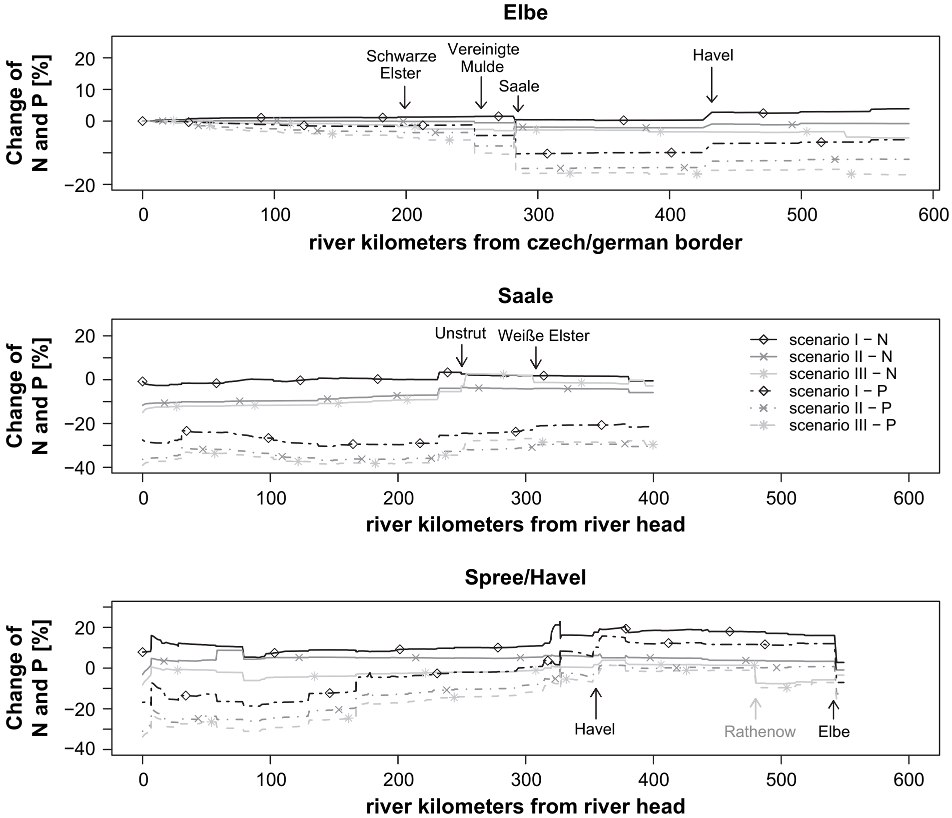

Fig. 11. Relative change of total phosphorus and nitrogen concentrations caused by climate change scenarios in selected longitudinal profiles. The change is expressed in relation to the reference situation 1979–2000. Also included are important tributaries (black) or gauging stations (gray). Climate change scenarios are only available for the German part of the catchment. Therefore, concentrations in the Elbe show no effect at the German/Czech border.

of this relationship depends on other factors which vary between sub-catchments.

The modeling results of most of the chosen scenarios show detectable differences compared to the reference situation. But the effect varies in space like Figs. 8, 9, 11 and 12 indicate. This differences of system response to scenarios need to be considered in planning river basin management actions. The Elbe-DSS allows viewing the different emission processes separately. Thereby, it is possible to illuminate some of the reason why sub-catchments respond differently to the same management action.

The spatial resolution of the catchment and the river network module is detailed enough to support the end users by the compilation of the river basin management plan according to the EU-WFD. For detailed management planning it might be necessary to apply models with finer resolution. The Elbe-DSS can be used to identify areas for further investigations. While the spatial resolution is detailed, the resolution in the time domain is rather coarse. We do not think this is a drawback since we want to support strategic decisions. Therefore, we tailor the analysis by focusing on the detection of differences between scenarios.

4.2. *Discussion of possible applications*

We presented four examples of possible applications of the Elbe-DSS. How could policy makers concerned with the requirements of the European water framework directive (EU-WFD) benefit from these applications? They could gain a deeper understanding about how diverse the system response can be and how many factors and interactions between factors need to be considered. The Elbe-DSS could also be applied to derive a set of management actions to achieve the “good ecological status” of the EU-WFD in a cost-efficient way, which would of course require additional model runs.

We anticipate that the typical end-user workflow starts with the definition of the goal: Do we want to focus on emissions or on concentrations or loads in the rivers? Which rivers are the focuses of the analysis? Most often the smaller tributaries show the highest concentrations due to their low discharge. Thus, management actions which ensure a good ecological state in the main rivers may fail to ensure this state for the smaller tributaries. Which substance is the focus? Do we want to reach our goal under consideration of future developments like different climate change realizations?

After the goal has been defined, different management options can be explored. From the examples presented here, reforestation of agricultural land is favorable for most parts of the catchment. We do get the greatest reduction of substance concentration for phosphorus as well as for nitrogen in all three longitudinal profiles considered here. But reforestation might be expected to be expensive since its effect comes from the reduction of agricultural production – farmers will lose income and will therefore claim compensation payments.[2] Therefore, it might be worth considering the second best option from the presented set of management actions, which would be erosion control for phosphorus and ecological-farming for nitrogen. Also some of the sub-catchments are especially sensitive to specific management actions, e.g. the head sub-catchment of the Saale. These sensitive locations are a good stating point for the compilation of a set cost-effective management actions. We would expect, for example, a ranked list of management actions specified on the basis of sub-catchments as the result of such an analysis.

The ranking of management options will further depend on assumptions about future developments like climate change. For example, climate change scenario I indicates increasing nitrogen concentration in the Spree/Havel. This might counteract the effects of management actions or lead to a different ranking of management actions. Changing demographic patterns might also indicate that an improvement of treatment plants is unnecessary for some regions since the population sizes drop further.

So the Elbe-DSS offers a rather large set of options to explore the future with regard to requirements of the WFD. Our close cooperation with the end users in administrative units that are engaged in the implementation of the WFD should hopefully ensure that these options cover the real needs of the decision making process. Thus, the Elbe-DSS might be a key tool for the preparation of the river catchment management plan of the WFD.

Evaluation of the integrated model with test data showed good to satisfactory model performance (see section system test). However, users of the Elbe-DSS need to consider that the system aims at comparison of scenarios and not at a complete risk assessment. Assumptions made in the design and coupling of the models as well as in the implementation of management actions and external constraints introduce uncertainty into the DSS. Model efficiency is far from perfect, the missing Czech part of the catchment is a heavy burden for the system and the spatial subdivision could be at a finer level to reflect more details of the involved processes. Since missing information about the uncertainty of several model equations inside MONERIS inhibited an uncertainty analysis of the system we are not yet able to present uncertainty ranges or confidence intervals for our model forecasts. Therefore, we restricted the DSS to scenario analysis. We expect the model system to detect differences between scenarios on a long term average and on a spatial subdivision at the scale of the MONERIS sub-catchments. Results should be interpreted as changes relative to the reference situation and not as real concentrations or loads. This limitation does, however, not prevent application of the results, since even high forecast uncertainty does not preclude effective decision support per se (Reichert and Borsuk, 2005). While a full analysis of the dependence structure of the sources of uncertainty in the Elbe-DSS is still under study, we argue that positive correlations between some of the input data of several scenarios and management actions lead to a notable reduction of uncertainty regarding the differences between the alternatives. Most scenarios presented here show a detectable general signal. By focusing on that signal instead of the noisy part of the results, a ranking of scenarios is possible, which makes the model system valuable for a decision making process.

Nevertheless, future applications of the Elbe-DSS should try to reveal the error and uncertainty propagation inside the system. Important topics for these uncertainty assessments could be the effect of the different spatial and temporal resolutions used by the models, the error propagation in the coupled system and the effect of the spatial resolution on management actions.

4.3. *Lessons learned*

Although, the Elbe-DSS was designed as a tool for the specific management objectives of the Elbe river catchment, we believe that the general approach of designing a DSS is transferable to river basins with comparable problems. Therefore, we will present some of the main lessons learned during the development of the Elbe-DSS. The main challenges during the development were: (i) involving stakeholders, (ii) overcoming the conceptual differences between the different models, (iii) separating kernel and user interface, and (iv) ensuring maintenance of the system.

We found it important to start with the requirements of the intended end users of the system instead of scanning the functionality of available models. Therefore, we involved stakeholders and policy makers early. This is in accordance with the general

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[2] The Elbe-DSS supports this selection process by providing a basic set of costs associated with specific actions – a topic which has not been discussed here.

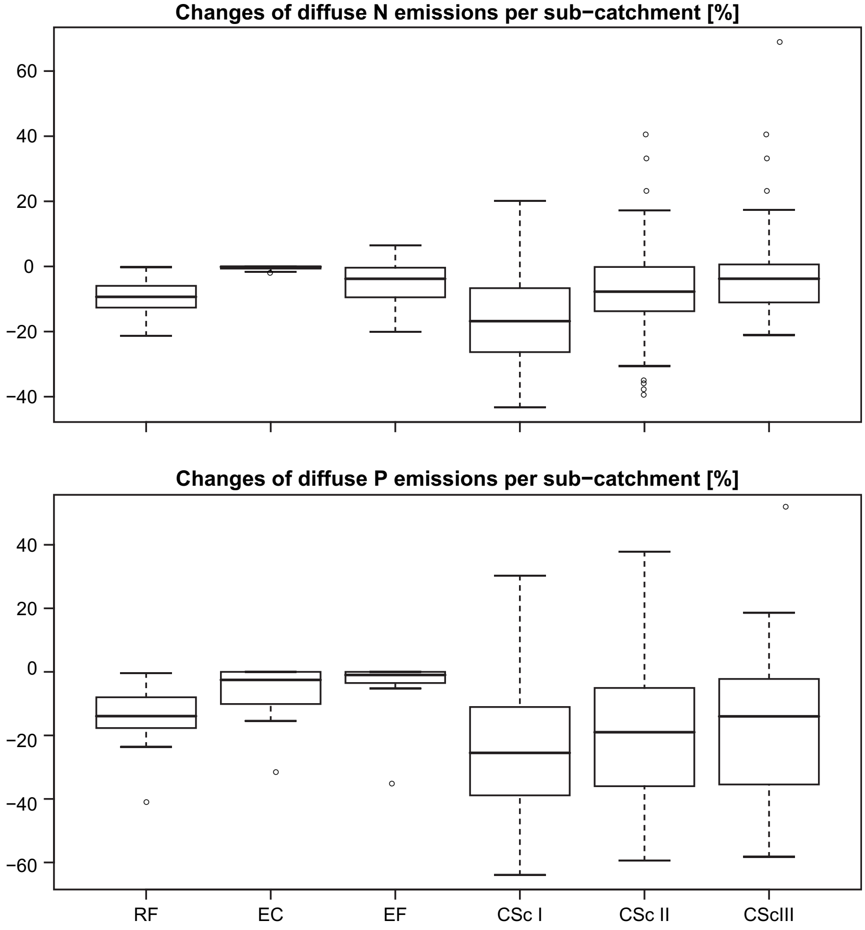

Fig. 12. Changes of diffuse nutrient emissions per catchment caused by management actions and climate change scenarios. For each scenario the change per MONERIS sub-catchment in nitrogen (top) and phosphorus (bottom) emissions relative to the reference situation is shown. Notation on the *x*-axis: RF, reforestation of 20% agricultural area without intensification on the remaining areas; RC, additional use of erosion control practice on 20% of the agricultural area; EF, increasing the agricultural area managed by eco-farming by 20% of the agricultural area; and CSc I–III, climate change scenario I–III. See text for details.

guidance rule to start each modeling process with the definition of the model purpose (Jakeman et al., 2006) and with the conclusions drawn by Newham et al. (2006). This interaction should not only involve people at the management level of the intended organization, who have knowledge about the general aims but also the people at the implementation level, who will use the system after its development. The better the DSS fits to the existing knowledge and IT structure in an organization, the better the chances of its acceptance. After the important management problems had been defined, the next step was the definition of the related spatial and temporal scales. Afterwards, a set of possible management options had to be classified together with the group of end users. The output at this stage of system development was a system diagram which was discussed again with the users. After end users and model developers agreed about the structure of the system diagram, we started to map models to the different elements of the system diagram.

Since no model was able to handle all requirements it was necessary to combine a number of models. One of the lessons learned is that conceptual problems of model integration proved to be much harder to tackle than technical problems. Since none of the models were designed to interact with other models, the interfaces between them had to be defined first, which was not a trivial process. We have presented here some of the solutions we used. Another big issue was the avoidance of model-specific details in the user interface. The users clearly stated that they wanted a monolithic user interface. This was implemented in the Elbe-DSS by consequently mapping model parameters to user friendly terms and definitions. The problem with this approach might be that real world terms and definition do not always map exactly to model parameters – we may have introduced ambiguity by doing so. On the other hand, end user feedback during the development phase clearly showed the importance of a well designed, consistent interface. They will not use dialogs which are unclear or too detailed. Our compromise was to wrap the models with easy-to-use interfaces while documenting all possible drawbacks as well as the mapping between model parameters and user interface elements in the online-library to make the simulation process transparent. Missing information about the Czech part of the Elbe as well as unspecified uncertainty ranges for some of the models limit the scope of application of the Elbe-DSS. This is reflected in the presentation of the results inside the system which focus on a comparison between different scenarios instead of forecasts of absolute concentrations and loads.

The Elbe-DSS reflects the state of the art that had been available at the start of the project. In the mean time additional knowledge in form of models and data has become available. A critical point in the use of any DSS is its ability to incorporate new knowledge and new objectives. In our case, the fact that the German hydrological institute (BfG) has taken the responsibility to host and maintain the system offers a chance that the Elbe-DSS will continuously be updated.

Our experience suggests, in accordance with (Parker et al., 2002), that not only the DSS itself but also the process of building a DSS is considered as important as the product.

5. Conclusions

The purpose of this paper has been threefold: (i) providing design and implementational details about the Elbe-DSS, (ii) demonstrating the capabilities of the system by scenario analysis, and (iii) providing some of the lessons learned during the development process. It has been shown that it is possible to build a complex DSS on existing models – but this approach has lead to problems that had to be tackled. Most problems encountered during the development of the DSS were not technical problems like reading or writing formats or calling libraries. Instead, model integration was hampered by the different conceptual design of the models, e.g. by different spatial scales or by different process descriptions. The application of the management scenarios shows the benefits of the use of a DSS: the complex spatial pattern present in the response of the system to the scenarios could not be analyzed without an integrated model system. Finally, the development of the Elbe-DSS has profited from the close cooperation with potential end users and an interdisciplinary development team.

Acknowledgements

We wish to thank the DSS development team (Sebastian Kofalk, Matthias Scholten, Bernhard Hahn, Arjan Maas, G. Engelen, Silke Reimer, Petra Jankiewic, F. Kohmann, Jean-Luc. de Kok, H. Holzhauer, Y. Huang, Koen van der Waal) for their kind and productive collaboration, the Bundesanstalt für Gewässerkunde (German Federal Institute for Hydrology) and the Federal Environmental Protection Agency for data supplying as well as the Federal Ministry for Education and Research (Project ID: 0339542A) for their financial support of the project. Additionally, we wish to thank Valentina Krysanova and Lukas Menzel from the Potsdam Institute for Climate Impact Research for the access to the HBV-D model and very important discussions about the calibration process, Koen van der Waal and Jean-Luc de Kok from Twente University for their assistance during the model calibration as well as all the stakeholders who participated in the project. Mr. Gerstengarbe and Mr. Werner from the Potsdam Institute for Climate Impact Research kindly offered the use of the climate scenarios from their STAR model and Mr. Behrend from the IGB, Germany kindly allowed including the MONERIS model in the Elbe-DSS. Likewise, we have to thank Mr. Bach and Mr. Frede, University of Giessen for implementing the LFBilanz model. Justin Calabrese and Anke Hildebrandt from the UFZ helped to improve the grammar and readability of the manuscript. Additionally, the constructive comments of two anonymous reviewers helped to improve the manuscript.

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