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Modelling flood plain vegetation based on long-term simulations of daily river–groundwater dynamics

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Abstract The quantitative prediction of ecological patterns in flood plain areas is a complex task. Variabilities and interactions of hydromorphological and biotic components stand against model limitations concerning input data and process representation. With respect to uncertainties, the coupling of abiotic and biotic data and models, a prerequisite for sustainable management, is a scientific challenge. In this paper, the coupling of models is investigated using a GIS and a digital elevation model in a flood plain area of the German Elbe River. Initially, the habitat suitability for a specific flood plain vegetation type was calculated based on reconstructed daily river and groundwater levels (period 1964–1995), with good agreement compared to a map of observed vegetation types. Subsequently, the calculation was repeated based on stochastic simulations of daily river flow (30 series of 32 years). The results reveal the sensitivity of the predicted habitat suitability against long-term hydrological variability, pointing out important components of the predictive uncertainty.

Key words Elbe River; flood plain vegetation; habitat model; hydrological variability; long-term simulation; predictive uncertainty; river–groundwater interaction

INTRODUCTION

Biologists and hydrologists are both challenged by substantial variabilities of environmental parameters and processes, asking for an interdisciplinary approach to estimate uncertainty components. In this context, uncertainty due to the biotic and hydrological variability in time and space poses a common problem (e.g. for the quantification of ecological patterns in flood plain areas). The problem becomes increasingly complex with data scarcity and coupling of models from different origins. However, the integration of models is a prerequisite for a better system understanding, for the identification of critical parameters and processes (e.g. endangered areas, floods/droughts), for impact analyses (e.g. long-term effects of river engineering measures or climate change) and thus for sustainable management. Finally, the dynamic behaviour of ecosystem components must be considered as inherent part and important source of predictive uncertainty, especially in flood plain areas.

Although a sharp delineation between variability and uncertainty is difficult, these terms are used here according to the definition suggested by Vose (2000): “Variability is the effect of chance and is a function of system. Uncertainty is the assessor's lack of knowledge (level of ignorance) about the parameters that characterize the physical system that is being modelled". Vose points out that the total uncertainty of a model result is a combination and interaction of variability and uncertainty. Following the discussions of the IAHS Decade on Predictions in Ungauged Basins (PUB, Sivapalan *et al.*, 2003), hydrological predictions are afflicted with two major types of uncertainties. One type is the uncertainty inherent to the estimation of model parameters associated with landscape properties and climatic inputs. This type of uncertainty propagates through a given model and contributes to an aggregated uncertainty of the final result. The uncertainty associated with parameter estimation might be reduced by higher quantity and quality of observational data. The second type of uncertainty arises from the imperfectness of the model structure. This type of uncertainty can only be addressed by comparing model results with observed data in the specific study area, aiming at an improved understanding and representation of dominant processes at different time/space scales.

The present study responds to the research focus of PUB, to estimate and subsequently to reduce the predictive uncertainty by developing appropriate model approaches. The goal is to learn more about the uncertainty associated with the coupling of biotic and abiotic model components. Their coupled application is realized within the framework of an integrated model concept, which additionally supports the estimation of the uncertainty associated with the long-term dynamics of hydrological parameters. Special interest is directed to the response of species composition in flood plains of large river systems to long-term changes of habitat conditions. The data and model components used were created from independent studies carried out within the framework of the research programme "Elbe Ecology", a cooperative project with more than 30 interdisciplinary sub-projects funded by the German Ministry of Education and Research between 1996 and 2005. Regarding the hydrological and hydraulic models used in this study, the two projects described earlier by Nestmann & Büchele (2002) and Köngeter *et al.* (2001) have to be pointed out. A synopsis of the extensive biological research activities in the flood plains is given in Scholz *et al.* (2005).

MODEL CONCEPT (STOCHASTIC APPROACH)

To quantify the habitat suitability in a flood plain area, the following model concept is used which integrates different deterministic and stochastic model components (overview, see Fig. 1). The habitat suitability at a specific site is interpreted as the output (response) of a time-variant system. The input (driving force) of this system consists of the hydrological dynamics, defined by the long-term flow process of the river basin. The flow process is transformed into local habitat conditions in the flood plain by means of morphological and hydraulic parameters and processes. For example, relief, soil structure, surface and groundwater levels, etc. are essential for the habitat suitability.

In the present study, a habitat model for the vegetation type "flood meadow" is taken as an example for specific habitat requirements in flood plain areas along the Elbe River (see Model Base section). According to this model, the occurrence of flood meadows mainly depends on the surface and groundwater levels. The relevant

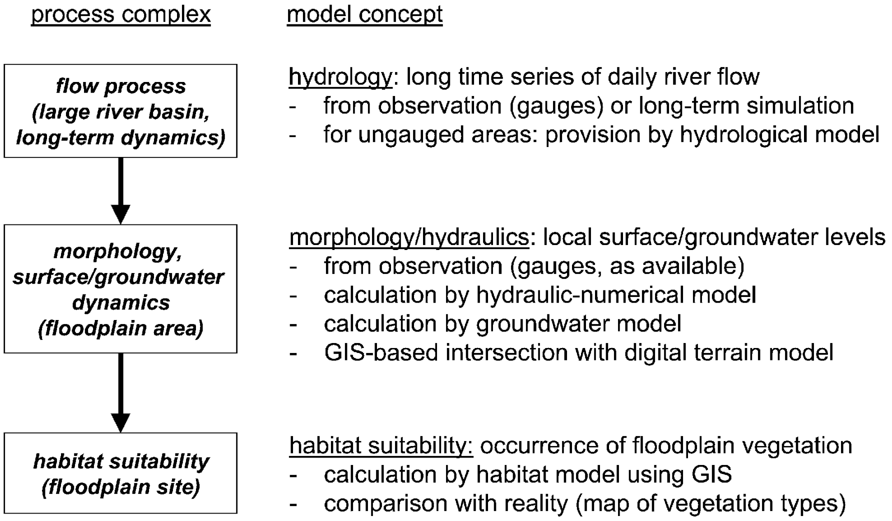

Fig. 1 Sketch of the model concept.

parameters are obtained from a hydraulic–numerical model for the Elbe River and a connected groundwater model which also allows scenarios of changed habitat conditions (e.g. decrease of water levels) to be considered. The hydrological input of the system is specified by time series of daily flow of the Elbe River from either observed or simulated periods.

STUDY AREA AND DATA

The study area is a flood plain area of about 1 km^2 at the Middle Elbe River near the village of Sandau (52.48°N, 12.03°E, Fig. 2). It is located in northeast Germany between Berlin and Hamburg in close vicinity to the tributary mouth of the Havel River. At the gauge Sandau, the Elbe River is covering a catchment area of 98 322 km^2 with a mean flow (MQ) of 580 m^3 s^{-1} and mean annual maximum flow (MHQ) of 1740 m^3 s^{-1} (reconstructed flow series 1964–1995). The mean annual precipitation is about 530 mm (climate station Havelberg). The active flood plain areas of the Elbe River are constrained by dykes, which are typical for the flood protection along the whole Middle Elbe River. The Havel River near the study area is regulated by a system of weirs installed in the 1950s specially to protect the Havel lowlands from Elbe floods. The Havel River has a catchment area of 24 037 km^2 (gauge Havelberg-City) and the following characteristics: MQ = 118 m^3 s^{-1} and MHQ = 229 m^3 s^{-1} (flow series 1964–1995). However, due to backwater effects, an important influence of Elbe floods on the water levels along the lower Havel River and thus on the given flow values may be noted.

The region is part of the Northern German Lowlands formed during the glaciations of the Pleistocene. The hydrogeological processes are mainly affected by the immediate hydraulic connection between the permeable sandy river beds of the Elbe, the Havel and the aquifer. Hence, the groundwater level is closely related to the water level of both rivers up to several kilometres behind the dykes. The flood plains are characterized by an inhomogeneous and anisotropic structure of the subsoil reflecting

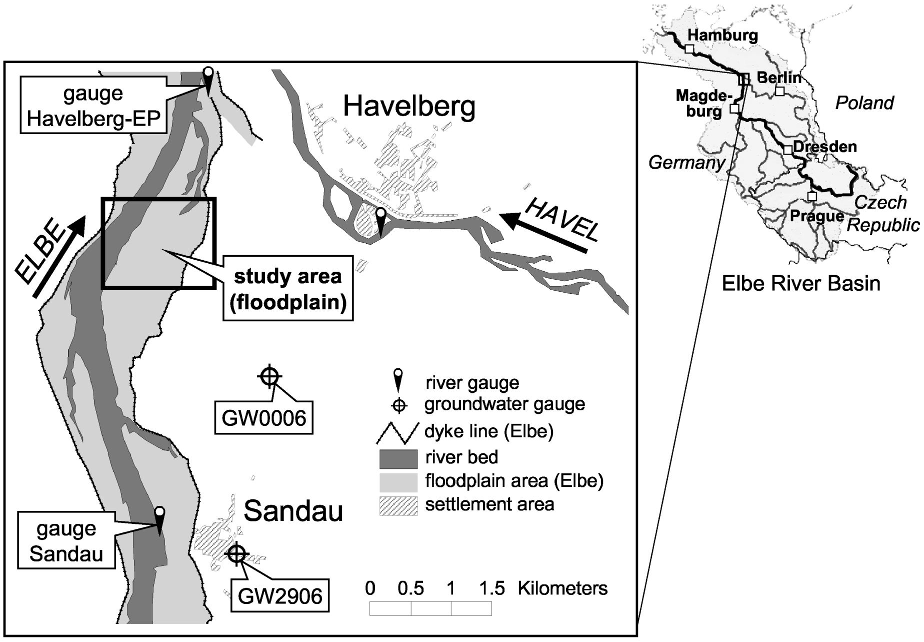

Fig. 2 Flood plain study area at the Elbe River.

the fluvial processes in the past. And so, the aquifer shows unconfined, semi-confined and confined conditions depending on the local subsoil situation and the actual piezometric head (= groundwater level for unconfined conditions). Drainage systems behind the dykes have further relevance for the land use in areas or periods characterized by high groundwater levels.

The study area (Fig. 2) is used as pasture land since as an active flood plain, it is not suitable for intensive agriculture. Depending on the end of the yearly flooding period, the grazing season normally starts in the late spring. The vegetation is dominated by various grassland types, structured by trees. The relief of the area is shaped by the Elbe River with higher sandy banks and flat gullies, which regularly run dry from early summer to autumn. The elevations vary between 23 m a.s.l. in depressions and 30 m a.s.l. on the banks. Accordingly, the vegetation is separated along this elevation gradient from higher areas with poor sandy pastures, extended grasslands dominated by *Alopecurus pratensis* to the summer-dry gullies and water holes with special flood plain grassland mostly dominated by *Alopecurus geniculatus* (for details see Baufeld, 2005). The latter species is tolerant of a longer flooding period every year and is positively affected by grazing.

In the present study, the following data sets were used.

Hydrology Water levels in daily and weekly time steps, respectively, are given at the river and groundwater gauges indicated in Fig. 2. The available record periods vary among gauges during 1900–1998 (gauge Havelberg-City, Havel River), 1964–1999 (Havelberg-EP, Elbe River), 1984–1999 (gauge Sandau, Elbe), 1957–1999 (groundwater gauge GW2906) and 1977–1999 (groundwater gauge GW0006). Furthermore, the daily flow series 1900–1998 of the Elbe River at gauge Barby near Magdeburg was employed (compare Fig. 2; about 120 km upstream of the study area, 94 060 km^2, MQ = 576 $m^3 s^{-1}$ for period 1964–1995).

Topography A digital elevation model (DEM) for the active flood plain was provided by the Federal Institute of Hydrology, Koblenz. The DEM is based on an airborne Laserscanner survey from 2003 and has a spatial resolution of 2 m × 2 m. Actually, the high resolution of the DEM promises low data uncertainty related to this crucial spatial data set.

Vegetation For the habitat model, grassland vegetation data were collected over a river stretch of 80 km around, but not within the study area (see below). For the study area, a digital map of vegetation types is available (Baufeld *et al.*, 2001).

MODEL BASE

In the scope of the present study, the following model components, developed in independent research projects, have been coupled.

Habitat model for the flood plain vegetation type "flood meadow"

The habitat model for flood meadows is chosen here to exemplify a species composition which depends on dynamic hydrological conditions. Characterizing species are, e.g. *Alopecurus geniculatus*, *Agrostis stolonifera* and *Carex vulpina*. The model is based on field data of Leyer (2002). Data on the presence and absence of the vegetation type flood meadow have been collected at 206 sites along an Elbe River stretch of 80 km upstream and downstream of the study area. Near the sampling sites, water-level wells were installed and observed weekly during the period 11/1996 to 02/1999. These data were transformed into daily water level depths below surface at each site using regression (for details see Leyer 2004, 2005). Subsequently, for each site the two parameters "mean water level depth below surface" (M) and the corresponding "standard deviation" (SD) were calculated. The latter served as an indicator for water-level fluctuations. These two parameters strongly affect grassland species composition at the Elbe River (Leyer, 2004, 2005).

The habitat model for flood meadows was developed by logistic regression, which describes the probability of occurrence of this vegetation type (p) as a function of one or more environmental variables (ter Braak & Looman 1986). The general form of this habitat model is widely known as:

$$p(X) = \frac{\exp(X)}{1 + \exp(X)} \tag{1}$$

where X is a vector defined by the environmental variables. For the particular case of flood meadow here, X is identified as an empirical function of M and SD:

$$X = -3.859 + 8.390 \cdot M - 15.088 \cdot M^2 + 6.087 \cdot SD + 9.546 \cdot M^2 \cdot SD \tag{2}$$

with M and SD in unit m. Thus, the best fit could be achieved with an unimodal model of M and a linear model of SD. The last term in equation (2), the interaction term, was included in the function to account for the interaction of both environmental parameters (Leyer, 2005). For a better understanding, the model consisting of the equations (1) and (2) is plotted for selected values in Fig. 3: an optimum of p regarding M as well as an increasing p for increasing SD can be observed.

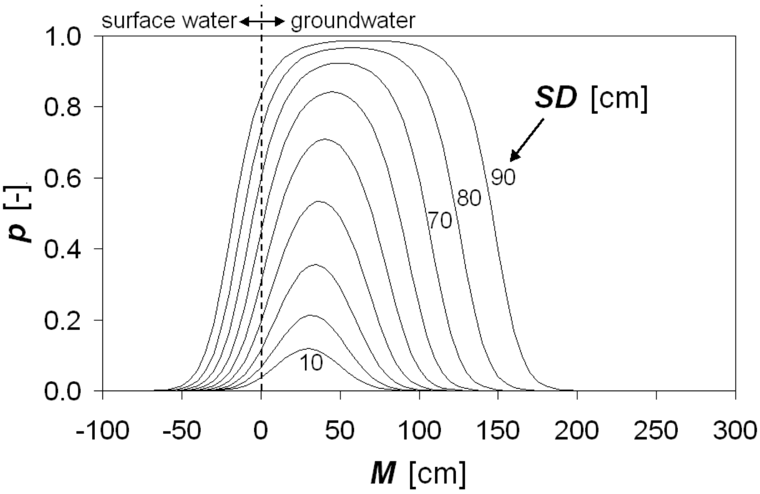

Fig. 3 Habitat model: probability of occurrence for the vegetation type flood meadow *p* as a function of *M* and *SD* (mean and standard deviation of water level depths, see text).

The quality of the model fit to the observed data was assessed:

(1) By the explained deviance, which is defined as –2 times the difference in log likelihood between the current model and a saturated model (i.e. a model that fits the data perfectly; Crawley, 2002). The model explained 43.5% of the total deviance on a high level of significance (error probability <0.001).

(2) By comparing the predicted values with the observed data from which the model was derived. Using the numbers of correct and false predicted occurrences and absences, performance criteria can be described such as sensitivity and specificity and the correct classification rate (Fielding & Bell, 1997). Here, a threshold value (p_{fair}) was selected at which sensitivity and specificity are the same (Schröder & Richter, 1999). The G-test (log-likelihood ratio test; Sokal & Rohlf, 1995) was used to test the null-hypothesis that suitable habitats (prognosis: presence) and unsuitable habitats (prognosis: absence) are occupied proportionally. The model generated highly significant results with 84.5% correctly predicted presences and absences (error probability <0.001).

Model for surface water levels (Elbe)

According to the requirements of the given habitat model, major attention has to be given to the surface water levels, either as flooding condition or as hydraulic potential for the groundwater. For the study area, the Elbe water levels were computed using the results of a two-dimensional stationary hydraulic-numerical model (Köngeter *et al.*, 2001). In particular, daily time series of local water levels were obtained using 18 stationary simulations from low flow to extreme flood conditions (principle of spatially distributed rating curves). On this basis, scenarios of potential water level changes can be derived; e.g. water level may change due to river engineering measures or bed erosion.

Model for river–groundwater interaction

Simultaneously to the surface water levels, the spatial and temporal variability of the groundwater level must be described by a model. To reach statements founded on the dynamics, long time series have to be analysed. Moreover, the model should allow the assessment of the impact of changed boundary conditions on the groundwater level. In view of these requirements and the computing time for long time series, Burek (2003) proposed and implemented a model concept that is based on a simplified physical approach and integrates the three main process groups: the hydraulic interaction between the river and the aquifer, the infiltration upon flooding, and the infiltration and capillary rise due to precipitation and evapotranspiration.

The implemented model structure consists of two modules coupled on daily base via the piecometric head. The first module is representing the river–aquifer interaction by an analytical solution for the linearized Boussinesq equation for unsteady conditions. The formal approach is given by:

$$T\frac{\partial^2 h}{\partial x^2} = S\frac{\partial h}{\partial t} - R \tag{3}$$

where h is the piezometric head, T the transmissivity of the aquifer, S the storage coefficient (= porosity for unconfined conditions) and R the groundwater recharge resulting from the infiltration and evaporation processes at the surface. Thus, the piecometric head at time t is calculated as function of the distance from the river as first boundary condition (see Fig. 4). The reasoning for this concept is described by Wald *et al.* (1986) and Workman *et al.* (1997).

The second module is a soil water model for R realised as one-dimensional storage model of the root-zone (for details see Burek 2003).

Burek (2003) relates the calibration procedure for the area around Sandau following a multi-objective generative calibration method (MOCOM-UA) proposed by Gupta *et al.* (1998). Hence, the groundwater model is calibrated for a total area of 55.6 km^2; thereby, data from 19 groundwater gauges with observation periods between 7 and 30 years were taken into account. The first boundary condition is the Elbe water level, the second is derived from the Havel water level and three neighbouring groundwater gauges. Due to the analytical solution, the calculation of long time series of daily groundwater levels is realized for the model area (55.6 km^2, represented by 409 nodes)

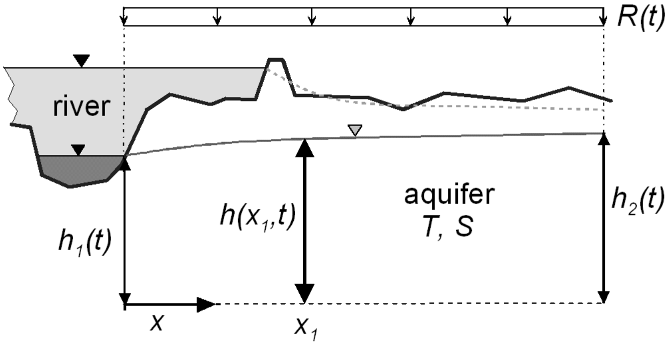

Fig. 4 Model concept for the river–groundwater interaction.

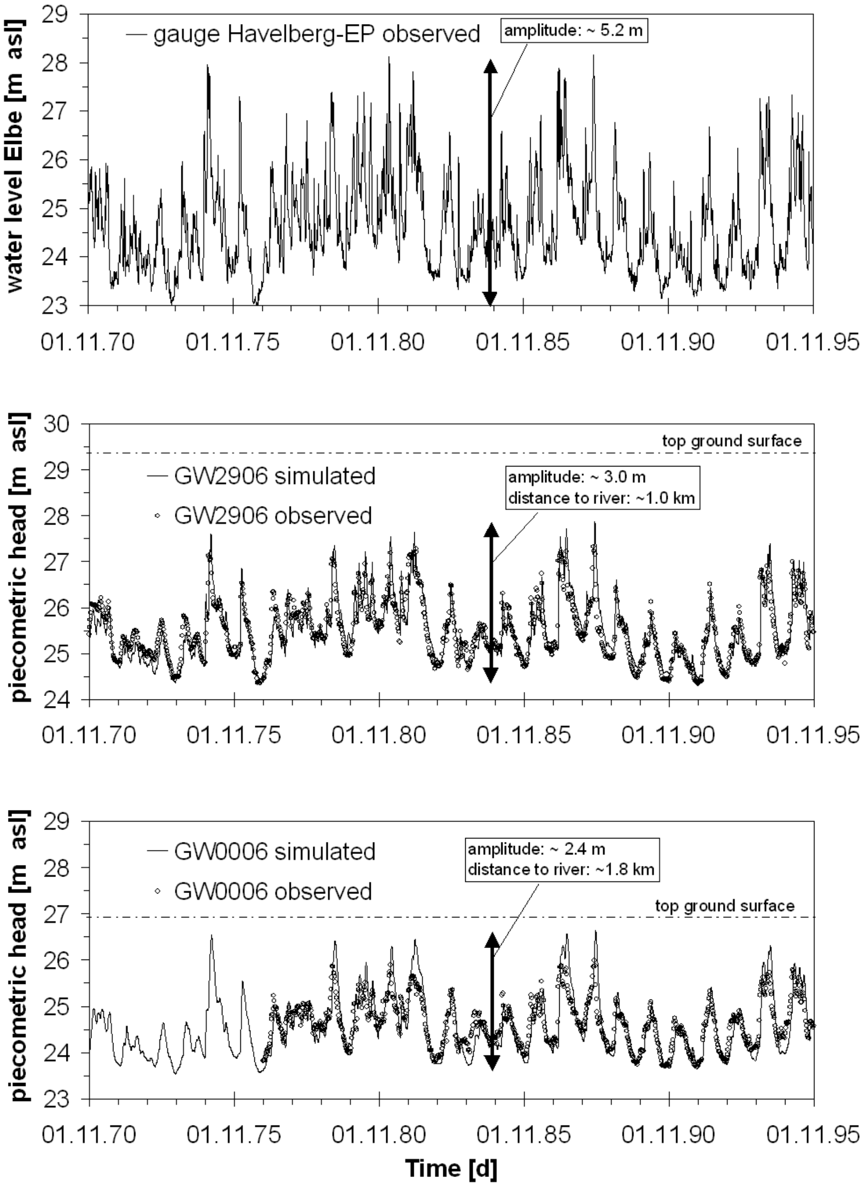

Fig. 5 Daily water levels 1970–1995 at the gauges Havelberg-EP (Elbe: observed), GW2906 and GW0006 (groundwater: simulated compared to observed).

Table 1 Comparison of observed and simulated *M* and *SD* at GW2906 and GW0006.

Gauge	Period	Relevance of period	*M* obs. (m)	*M* sim. (m)	*SD* obs. (m)	*SD* sim. (m)
GW2906	11/1970–10/1995	*)	3.86	3.85	0.64	0.68
	11/1996–02/1999	**)	3.85	3.92	0.56	0.51
	11/1964–10/1995	***)	3.81	3.82	0.66	0.69
GW0006	11/1976–10/1995	*)	2.94	2.94	0.50	0.60
	11/1996–02/1999	**)	2.87	2.95	0.45	0.49
	11/1964–10/1995	***)	–	2.99	–	0.68

M: mean water level depth below surface; *SD*: standard deviation of daily water level depths; relevance of period: *) record period for groundwater model calibration/validation, **) period of data collection for habitat model, ***) hydrological reference period (present study).

within a few minutes on a standard PC. The physical base (represented by equation (3)) facilitates the spatial transfer of this model concept to the ungauged study area. A comparison of simulated and observed daily piezometric heads at two groundwater gauges at different distances from the Elbe River (period 1970–1995) reveals a good process representation in view of the dynamic behaviour of the groundwater level (Fig. 5, for more details on model validation see Burek, 2003). Groundwater gauge GW2906 is located at a distance of 1.0 km and gauge GW0006 at 1.8 km from the river Elbe (compare Fig. 2). Thus, the dynamic is decreasing with increasing distance from the river: the difference between the highest and lowest water level is varying from 5.2 m at gauge Havelberg-EP of the Elbe to 3.0 m at gauge GW2960 and 2.4 m at gauge GW0006.

With regard to the present study, this groundwater model represents the key interface between dynamics from the river-side and biological response in the flood plain (i.e. defining *M* and *SD*). Therefore, special interest may be given to the model performance in this coupling context, which is also a question of the selected reference period. A comparison of observed and simulated *M* and *SD* at the gauges GW2906 and GW0006 shows suitable agreement in different periods (Table 1; for details on periods see caption and text).

Hydrological reference period and long-term simulation of daily flows

To describe the present flow situation in a founded, although in view of the long-term dynamics approximate, way, a reference period adequate in length and stationarity of the time series is needed. The definition of the hydrological *status quo* may be achieved based on historical flow series and extended by stochastic simulations of flow data (generated series).

Regarding the variable hydrological conditions in the 20th century (climate variability and human impact due to the installation of large reservoirs in the Elbe River basin mainly before 1963), the daily flow series 1964–1995 was chosen here as relatively reliable reference for the present conditions. This leans against the analyses of the Elbe flow process provided by the study of Helms *et al.* (2002a,b). These analyses involve an extensive consistency and stationarity analysis which indicates significant changes in the flow conditions from the middle of the 19th to the end of the 20th century. Moreover, the series 1964–1995 is considered as representative for the present-day conditions for which a comprehensive hydrological analysis of the flow series including regionalization of statistical parameters has been carried out (e.g. longitudinal sections of flood parameters along the German Elbe River).

In addition, the stochastic model of Treiber (1975), an established approach for the simulation of daily flow series, is considered suitable to extend the analysis in the present study. Details about this shot-noise model are specified in Treiber (1975) and Treiber & Plate (1977). The model was calibrated earlier by Helms *et al.* (2002a) for different historical periods between 1853 and 1995 (including 1964–1995) and for different sub-catchments of the Elbe River basin. They achieved very good fits to the observed series (Nash-Sutcliffe efficiency criteria (NS) > 0.9, in particular NS = 0.92 for 1964–1995 at gauge Barby). A statistical diagnosis of generated series *vs* the corresponding observed series (e.g. annual and monthly peak flows, mean monthly flows, daily flows in monthly distributions) confirmed the good quality of the model.

Against this hydrological background, the stochastic model was applied in this study to generate 30 time series of daily flow corresponding to the reference period 1964–1995 for the catchment area upstream of gauge Barby. The 30 simulated series (each of 32 years) were routed downstream to the study area (gauge Havelberg-EP) using a flow routing model based on the diffusion analogy (for more details about this latter model see Helms *et al.*, 2002b). A rating curve was used to transform the flow series into water levels at gauge Havelberg-EP.

For an appraisal of the stochastic simulation of Elbe water levels at gauge Havelberg-EP, mean water levels and mean annual maximum water levels derived from the reference period (1964–1995) are compared to those from the simulation (30 series corresponding to 1964–1995: SIM01 to SIM30); for details see Fig. 6. The diagram reveals a plausible variation of the mean water levels and mean annual maximum water levels of the simulated series, the latter resting within the 95% confidence interval of the mean of the observed annual maxima 1964–1995.

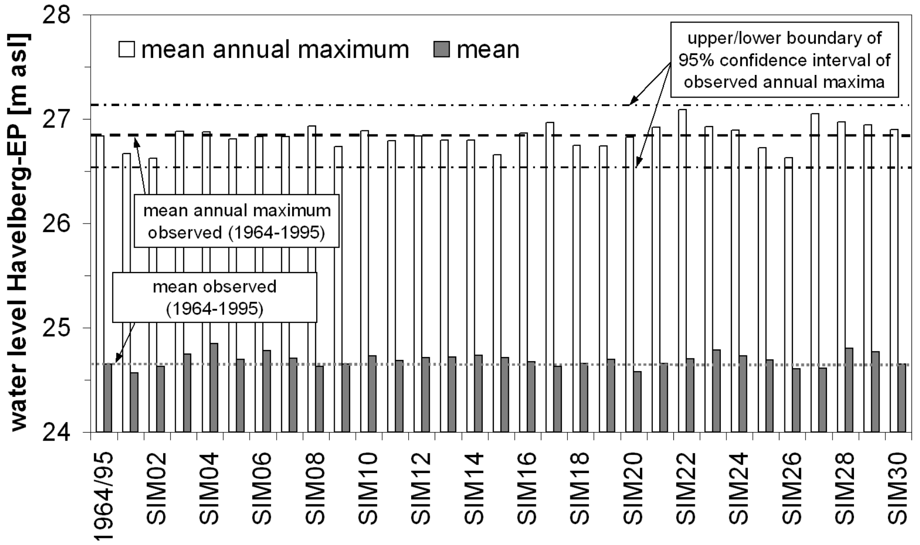

Fig. 6 Mean water level and mean annual maximum water level of the Elbe River at gauge Havelberg-EP: comparison of the reference period (1964–1995, bars on the left side) with results from stochastic simulation (30 series corresponding to 1964–1995: bars SIM01 to SIM30) (please note: dotted lines mark the observed values plus the 95% confidence interval of the mean of the observed annual maxima 1964–1995).

RESULTS AND DISCUSSION

The model application and discussion of results is divided in two parts: the first part is related to the reference period 1964–1995. In the second part, the analysis is extended by simulated series corresponding to this reference period.

GIS-based model application for the reference period 1964–1995

Initially, the GIS-based application of the model concept was tested for the present-day conditions ("status quo") represented by the hydrological reference period (1964–

1995) and the above mentioned model components. In particular, the environmental parameters M and SD were derived as spatial data sets for the study area based on the DEM and the reconstructed daily surface water and groundwater levels in the reference period.

The model results (i.e. the spatial distribution of the habitat suitability indicated by p) are compared to the areas where flood meadows occur in reality using the map of vegetation types from Baufeld *et al.* (2001, Fig. 7(a)): the predicted suitable habitats encompass a larger area than the observed occurrences of flood meadows (not all suitable habitats in the light of hydrology must be suitable in general). But as the observed occurrences (hatched in Fig. 7(a)) lie almost exactly within the predicted areas, the spatial distribution of p implies a good quality of overall model results, all the more the predicted p amount to values of 0.75 to 1.0 (dark grey in Fig. 7(a)) on 78% of the observed areas. The overestimation of the habitat suitability (in spatial terms) can be partially explained by the fact that the habitat model is applied to higher mean groundwater levels and more variable conditions compared to its calibration period (note differences of about 10 cm of M and SD between 1996–1999 and 1964–1995 in Table 1). Consequently, the predicted p must be higher and the areas must be larger than reality. So, apart from a more detailed validation of the model results with more site-specific observations (which are not yet available), the integrated model concept is substantiated in general. However, even without more observational data, a further *interdisciplinary* analysis and improvement of the modelling system is necessary.

For further improvement of the model concept, the following aspects should be taken into account. In the present case, the *status quo* conditions are primarily defined from a hydrological point of view (i.e. referring to the long-term variability of the Elbe flow process). But it is not clear whether the hydrological reference period (1964–1995) is appropriate in length and character for the prediction of the given vegetation type. In this respect, long-term observations on the occurrence of vegetation are needed (but not yet available). Furthermore, a systematic validation and improvement of the model concept requires a common definition of the reference period. And it requires uncertainty analyses, because the coupling of model components has been presented so far in a deterministic sense (i.e. the predicted p are here resulting from one specific combination of hydrological data and model components). In an extended analysis, the predictive uncertainty of p should be addressed by means of a sensitivity analysis with uncertainty estimations for individual data and model components (e.g. using Monte Carlo techniques). At the same time, the input uncertainty of the system, meaning the long-term hydrological variability associated with climate inputs and environmental processes at the river basin scale, has to be estimated via long-term simulation of the processes (for sample results see next section).

At large, the model application for this ungauged study area and the reference period seems justified. Therefore, we decided to use the model concept for changed hydromorphological conditions, i.e. to assess the impact of a hypothetical scenario of river bed erosion on the habitat suitability. It was assumed that the surface water levels may be lowered with a mean of 30 cm mainly related to low and mean flow conditions. The result for this scenario, “bed erosion”, shows a significant reduction of the predicted areas compared to the “status quo” (see Fig. 7(b) and Fig. 7(a)). The difference of p between these two scenarios reveals predominantly a decrease of p due

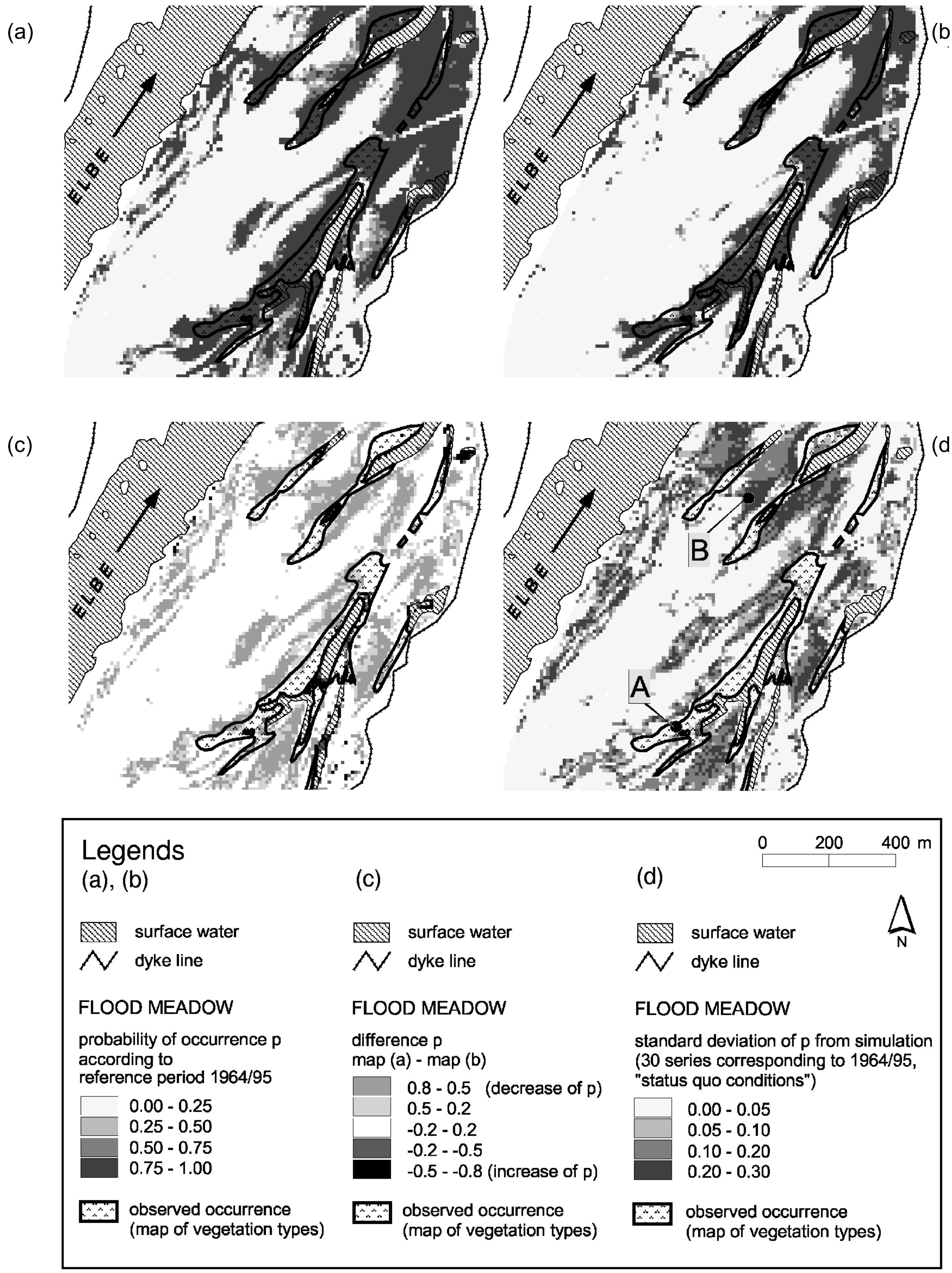

Fig. 7 Spatial distribution of predicted probability of occurrence *p* compared to observed occurrence (map of vegetation types) of vegetation type flood meadow: (a) *p* according to the reference period 1964–1995 (“status quo”), (b) *p* according to the reference period 1964–1995 (“bed erosion”), (c) difference of *p* between “status quo” (a) and “bed erosion” (b), (d) standard deviation of *p* from stochastic simulations (30 series corresponding to 1964–1995) and locations of site “A” and “B” (compare Fig. 9).

to lower water levels in the study area, but also a local increase of *p* in some water-filled depressions (note grey areas and some black pixels in Fig. 7(c)). Interestingly, the decrease of *p* is primarily predicted for the neighboured areas and not for the observed areas (grey areas mainly outside of hatched white areas, Fig. 7(c)). Thus, the habitat suitability for flood meadow is prominently affected in transition zones between depressions (high *p*) and higher elevations (low *p*).

Results from long-term simulation corresponding to reference period 1964–1995

In order to assess the influence of hydrological variability on the predicted data, the model application was repeated using the 30 series from the stochastic simulation (Fig. 6) as input of the system. No additional long-term changes of boundary conditions (i.e. DEM and model parameters for surface and groundwater levels) were assumed. A sample result from the simulation at a selected site "A", which is lying within an observed area of flood meadow (see Fig. 7(d)), is illustrated in Fig. 8: the *M* and *SD* resulting from the simulation (30 series corresponding to 1964–1995) are building a scatter plot compared to those from the reference period. Hence, the 30 simulated pairs of *M* and *SD* (each representing 32 years of daily water level fluctuations at site "A") are varying in a range from 20 to 30 cm (Fig. 8).

Subsequently, the model results for *p* derived from 30 simulated series vary likewise. As an example, the variability of the model results is plotted in Fig. 9 as frequency distributions of *p* at two selected sites "A" and "B" (location see Fig. 7(d)). For the comparison with the simulated *p*, the values for *p* from the reference period are drawn as dotted lines in Fig. 9. In addition, a map of the standard deviation of *p* from the 30 simulated series is shown in Fig. 7(d). Comparing this map with the frequency distributions of *p* (Fig. 9), the small standard deviation of *p* at site "A" (<0.05, light grey in Fig. 7(d)) and the high standard deviation of *p* at site "B" (>0.20, dark grey) can be explained. So, the areas with a high standard deviation of *p* can be identified

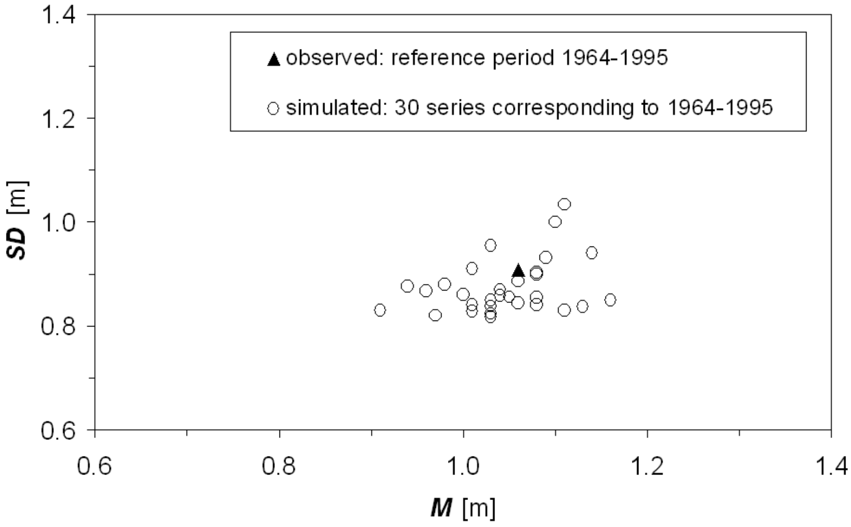

Fig. 8 Results from long-term simulation of water level fluctuations at site "A" (see Fig. 7(d)): simulated *M* and *SD* compared to those from the reference period.

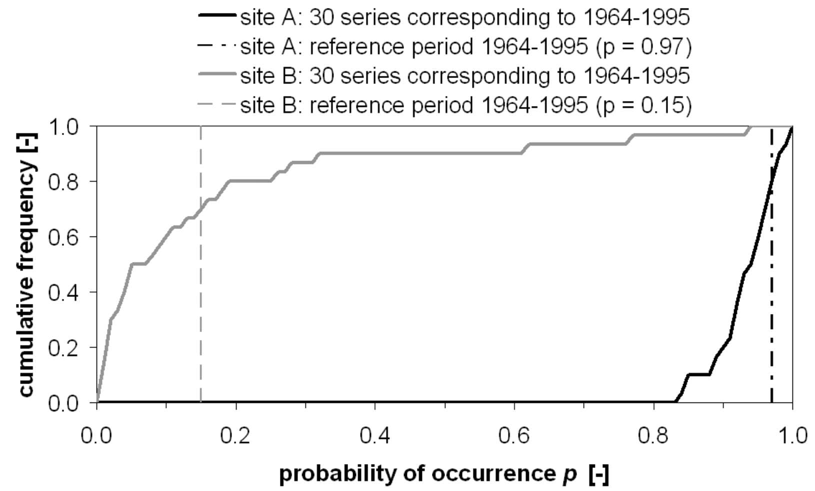

Fig. 9 Distribution for *p* from stochastic simulation (30 series corresponding to 1964–1995) at site “A” and “B” (see Fig. 7(d)) compared to those from the reference period.

and interpreted as areas where the habitat suitability is more sensitive against hydrological variability from river-side (Fig. 7(d)). In other words: the darker a habitat is coloured in Fig. 7(d), the higher is the predictive uncertainty related to the hydrological conditions. In this respect, the discussed uncertainties related to the predicted *p* for the “status quo” and the calculated changes of *p* according to the scenario “bed erosion” are conclusive, as well (see previous section, Fig. 7(a)–(d)). Finally, the results from this long-term simulation open the perspective of probabilistic analyses in such variable systems.

CONCLUSIONS AND PERSPECTIVES

The coupling of abiotic and biotic model components from different origins shows realistic results, even though biological and hydrological observation data from the study area itself were not available. In this study, the target variable was the probability of occurrence for the vegetation type “flood meadow”, which is a function of site-specific hydrological conditions. A GIS and a digital elevation model with high resolution supported the assessment of the corresponding spatial distribution. Since the model results represent a potential habitat suitability, the predicted spatial distribution of flood meadow matches very well with data for this vegetation type mapped in an independent study. The realistic character of the results for the “status quo”, which is tentatively defined from the hydrological viewpoint referring to the period 1964–1995, approve the integrated model concept. Moreover, the application of the model concept for the impact assessment of changes of habitat conditions seems justified. Finally, the uncertainty inherent to the dynamic input of the system, meaning the flow process of the river, was estimated by stochastic simulation. In this way, the hydrological variability is identified as a main source of uncertainty in the final prediction. The results of stochastic simulation explain and make relative uncertainties identified for the above mentioned results referring to the period 1964–1995. However, considerable uncertainties remain due to missing biotic data for further validation of the habitat model for long-term predictions. The definition of an appropriate reference period for the given vegetation type is therefore a challenge for further interdisciplinary research.

Further validation, extension and application of this model concept to other biotic components at the Elbe River are needed. Individual model components may be adapted, improved or replaced in order to verify whether the overall model concept can be transferred to other river systems. In short, the present study shows the perspective of a better understanding and quantitative evaluation of flood plain ecosystems considering various aspects of uncertainty. Risk assessment and founded management strategies, e.g. concerning the potential loss of river-dependent habitats due to climate change or river engineering measures, will be subject to further studies.

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