ECOLOGICAL MODELLING 200 (2007) 475–492

available at www.sciencedirect.com

ScienceDirect

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

Modelling the impacts of land-use and drainage density on the water balance of a lowland–floodplain landscape in northeast Germany

Stefan Krause[a,*], *Jörg Jacobs*[b], *Axel Bronstert*[c]

[a] *Centre for Sustainable Water Management, Lancaster Environment Centre, Lancaster LA1 4YQ, UK*
[b] *Potsdam University, Institute for Geo-ecology, Potsdam University, Germany*
[c] *Potsdam University, Institute for Geo-ecology, Dept. Hydrology & Climatology, Potsdam University, Germany*

ARTICLE INFO

Article history:
Received 9 August 2005
Received in revised form
7 August 2006
Accepted 24 August 2006
Published on line 27 October 2006

Keywords:
Floodplain
Water balance
Modelling
Land-use change
Drainage
Scenario
Lowland

ABSTRACT

This study presents the modelling approach and impact assessment of different strategies for managing wetland water resources and groundwater dynamics of landscapes which are characterised by the hydrological interactions of floodplains and the adjacent lowlands. The assessment of such impacts is based on the analysis of simulation results of complex scenarios of land-use changes and changes of the density of the drainage-network. The method has been applied to the 198 km^2 Lower Havel River catchment as a typical example of a lowland–floodplain landscape. The model used consists of a coupled soil water and groundwater model, where the latter one is additionally coupled to the surface channel network. Thus, the hydrological processes of the variable saturated soil zone as well as lateral groundwater flow and the interactions between surface water and groundwater are simulated in an integrated manner. The model was validated for several years of significantly different meteorological conditions. The comparison of lateral and vertical water balance components showed the dominance of lateral flow processes and the importance of the interactions between surface water and groundwater for the overall water balance and the hydrological state of that type of landscape.

The simulation of land-use change scenarios showed only minor effects of land-use change on the water balance and groundwater recharge. Changes of groundwater recharge were particularly small within the wetland areas being part of the floodplain where interactions between surface water and groundwater are most pronounced. Alterations in vertical groundwater recharge were counter-balanced by the lateral interaction between groundwater and surface water. More significant deviations in groundwater recharge and storage were observed in the more peripheral areas towards the catchment boundaries which are characterised by greater groundwater distance from the surface and less intense of ground water–surface water interactions.

However, the simulation results assuming a coarsening of the drainage network density showed the importance of drainage structure and geometry for the water balance: The removal of the artificial draining ditches in the floodplain would result in significant alterations of total groundwater recharge, i.e., less recharge from winter to early summer and an increase of groundwater recharge during summer and autumn. Furthermore the different effects of groundwater recharge alterations on the dynamics of groundwater stages within the wetland areas close to the floodplains compared to the more peripheral areas could be

* *Corresponding author*. Tel.: +44 1524 595861; fax: +44 1524 510217.
E-mail address: s.krause@lancaster.ac.uk (S. Krause).
0304-3800/$ – see front matter
doi:10.1016/j.ecolmodel.2006.08.015

quantified. Finally, it will be discussed that a well-adjusted co-ordination of different management measures is required to reach a sustainable water resources management of such lowland–floodplain landscapes.

1. Introduction: the role of floodplains and adjacent lowlands for the conditions of lowland rivers

The European Water Framework Directive (WFD) demands the good status of surface waters and groundwater to be accomplished until 2015 (article 4 a ii and b ii, WFD). This predefined status considers qualitative as well as quantitative issues of the river and other water bodies. However, ecological and hydrological characteristics of a lowland river depend on both the conditions and processes within the river itself but also on the influences of the floodplain corresponding with the river (Krause and Bronstert, 2005, 2006; Vidon and Hill, 2004; Sophocleous, 2002; Bullock and Acreman, 2003; Lasserre et al., 1999; Hayashi and Rosenberry, 2002). Hydrological conditions and nutrient dynamics of lowland river systems and the adjacent floodplains and wetlands are strongly controlled by the tight interactions between surface water and the groundwater of the floodplain (Hayashi et al., 1998; Vidon and Hill, 2004; Lasserre et al., 1999; Osman and Bruen, 2002; Sophocleous and Perkins, 2000; Sophocleous, 2002; Krause and Bronstert, 2004, 2005, 2006; Joris and Fejen, 2003). The WFD furthermore emphasises the importance of natural regulation functions of lowland catchments regarding water balance, nutrient dynamics and subsequently floodplain ecology (Bullock and Acreman, 2003; Prescott and Tsanis, 1997; Hayashi and Rosenberry, 2002; Sophocleous, 2002; Sanchez-Perez et al., 2003). These natural regulatory functions of lowland floodplains concern the quality of surface water and groundwater due to transformation and transport of nutrients and pollutants on the one hand (Burt et al., 1999; Vidon and Hill, 2004; Andersen, 2004; Hayashi and Rosenberry, 2002; Hill, 1990; Devito and Dillon, 1993; Sanchez-Perez et al., 2003), on the other hand also the control of the dynamics of water balance and water availability, flood frequencies, flood extends and retention capacity (Bullock and Acreman, 2003; Hayashi and Rosenberry, 2002; Sophocleous, 2002; Krause, 2006; Andersen, 2004; Osman and Bruen, 2002; Wurster et al., 2003).

The water resources management of the wetlands and floodplains within the lowlands of Northeast Germany is confronted with conflicting demands of different stakeholders and land users. These contrary requirements concern the temporal variations of water demand (e.g., for crop production, or sustaining ecological functions for nature protection areas and wildlife) as well as different intentions for the temporally and spatially distribution of saturated areas in the floodplain and the control of groundwater levels tailored for particular land-use types. Due to intensive changes in agricultural and ecological policies within the last years, the promotion of floodplain functions and of sustainable floodplain management has become more important (Acreman et al., 2003; Bullock and Acreman, 2003; Garcia-Linares et al., 2003; Gasca-Tucker and Acreman, 2000).

Although agriculture (farming, animal production) in the lowlands has been performed in a more sustainable manner within the last 15 years (such as reduction of fertilisers and groundwater drainage, reduced numbers of cattle and cows), remarkable contrasts between the requirements of agricultural land-use and nature conservation do persist. e.g., for an optimal agricultural use of the lowland floodplains the groundwater depths have to be controlled in such a way that they are low enough in spring to enable the ploughing of the arable land but not to low in summer to prevent the risk of droughts. In consequence of these demands an intensive drainage management was carried out until recently. In contrast, for nature conservation and wetland restoration as well as for soil conservation of the peat lands a periodically flushing of the floodplain is essential. These contrasting demands on the water balance within the same catchment at the same time create conflicts between the different stakeholders. These conflicts might be aggravated by insufficient knowledge about the efficiency of different impacts and management strategies for the floodplain water resources.

This study aims at assessing the effects of different strategies for water resources management of the floodplains and wetlands within the lowland landscape. Therefore, several land-use change and a drainage density scenarios were setup and their effects on water balance and groundwater dynamics analysed. The study area is the Lower Havel River catchment as a typical example of a ground water–surface water influenced lowland–floodplain landscape. The study focuses on quantitative water balance aspects of such a lowland–floodplain system as a pre-requisite of quantifying water quality and other ecological aspects. Thus, the results of the water balance analyses carried out in this work represent an important link to eco-hydrological wetland models which can be used to quantify the impact of a changing floodplain water balance on its ecological functions and characteristics. However, specific modelling or assessment of water quality or floodplain ecology is not part of this paper.

2. Hydrological characteristics of lowland–floodplain landscapes

2.1. *General features*

During the last years several studies that focused on lowland river catchments pointed out that for a sustainable management of floodplains it is necessary to improve the water quality as well as to enhance the eco-hydrological and water balance controlling functions of the floodplains and their interconnected lowlands (Sophocleous, 2002; Sophocleous and Perkins, 2000; Hayashi and Rosenberry, 2002; Osman and Bruen, 2002). The influence of groundwater–surface water interactions was identified as very important for floodplain water balance in several studies (Heidemann et al., 2001; Wurster et al., 2003; Devito et al., 1996; Krause and Bronstert, 2005, 2006). Previous studies have shown that the water balance dynamics of floodplains are controlled by vertical, meteorological driven processes as well as by lateral processes which are controlled by the tight interaction between groundwater and surface waters (Krause and Bronstert, 2005, 2006; Sophocleous, 2002).

For the Lower Havel River basin a major importance of the interaction processes between groundwater and surface water for floodplain water balance could be proved by field experiments and observations (Krause and Bronstert, 2004, 2006). Quantitative analyses based on model simulations with the IWAN model have shown how the tight interactions between groundwater and surface waters cause a major control of the temporal and spatial dynamics on the floodplain water balance at several subcatchments of the Havel River (Krause and Bronstert, 2004, 2006). The temporal and spatial pattern of the intensity of these interactions and the efficiency of its impact on the floodplain water balance is mainly controlled by pressure head gradients as well as by the transmissivity of the soils and sediments (Krause and Bronstert, 2006).

2.2. Study area

The Havel River has a length of 325 km and its catchment is located in the glacially formed north-eastern German Lowlands and covers an area of about 24,000 km^2 before the Havel River runs into the Elbe River. The catchment of the Lower Havel River (Fig. 1) is a typical example for floodplain dominated lowland landscape. It covers an area of 198 km^2 and is located about 20 km upstream of the Havel River confluence with the Elbe River. The area is characterised by a wide floodplain with a mean altitude of 25–28 m asl in the central part of the catchment surrounded by relatively small plates which consist of pleistocene moraines reaching heights of up to 120 m asl. The floodplain, together with the Lower Havel River, form one of the largest inland wetlands of central Europe, which is of high ecological value, in particular for bird populations as waders, cranes and different goose-species (Mühle et al., 1998; BirdLife, 2005). Wide areas of the floodplain are protected by German and European nature conservation laws and belong to natural reserves of different status as nature protection areas or Flora–Fauna-Habitat Directive- and RAMSAR sites.

Mean precipitation in that area is 540 mm/a with a bit higher overall rainfall in autumn and spring and higher rainfall intensities in the westerly hillslope areas caused by local thunderstorms in summer. Hydraulic conductivities of the floodplain soils (2.3×10^7 to 2.1×10^6 ms^{-1}) are lower than of the sandy soils of the moraines areas (1.2–4.2×10^{-4} ms^{-1}) but always high enough to infiltrate all rainfall and to inhibit infiltration excess overland flow, also during summer thunderstorms.

For centuries, the catchment has been characterised by periodic inundation of large parts of the floodplain. Such inundations can be caused by both high discharge of the Havel River itself and – more frequently – by high water levels in the Elbe River and a successive backwater into the Havel River. Since many decades, the landscape has been equipped with a more and more dense and cross-linked drainage network in order to enable and to improve the agricultural use of that area. The water balance of the floodplain, especially the temporal and spatial availability of water, control the ecological conditions and wetland functions. Thus, the abundance of wildfowl (Mühle et al., 1998), plant societies and biodiversity patterns (Ward, 1998) are strongly determined by plant water availability or flooding cycles.

Similar also spatial patterns of land-use within the Lower Havel River catchment are strongly determined by the hydrological conditions. Thus, the hillslope areas are characterised by mixed and coniferous forests caused by to high groundwater depths whereas extensive pasture and heathland dominates within the central floodplain parts due to wet conditions

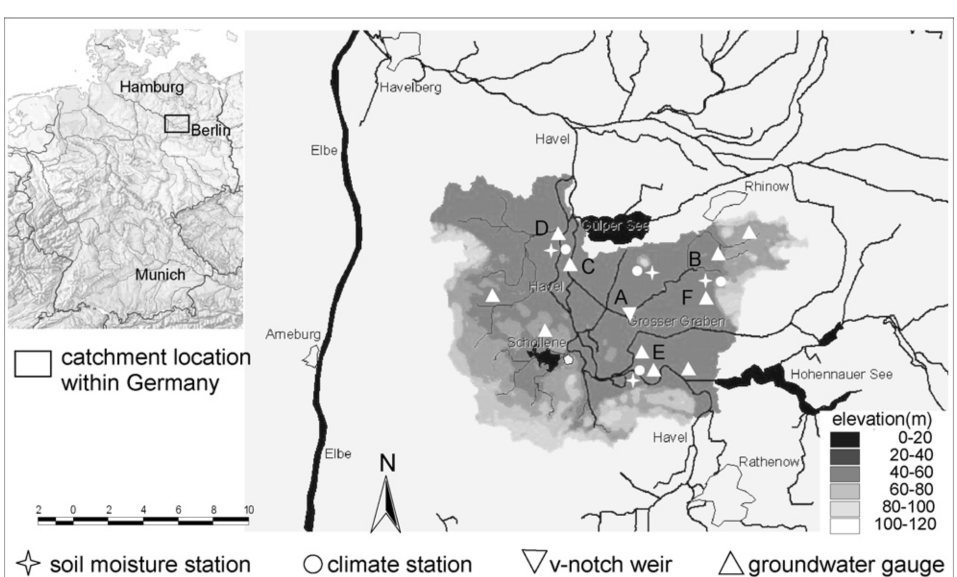

Fig. 1 – Topography and location of the "Lower Havel River Basin" research area within Germany, river network and location of the experimental setup including position of the groundwater observation gauges.

from autumn to spring. More peripheral lowland parts of the catchment which are characterised by a higher distance to the surface waters and moderate groundwater depths are intensively used by agriculture. In the research area, meteorology, groundwater conditions and surface water dynamics as well as soil moisture are observed at several locations which are presented in Fig. 1.

2.3. *Model requirements and state of the art*

For a sustainable management of a typical lowland catchment like the Lower Havel River basin it is essential to quantify the impacts of certain management strategies on the overall water balance, on groundwater dynamics and on soil water dynamics. Considering that within floodplains the management of soil water and of groundwater cannot be separated (Sophocleous and Perkins, 2000; Sophocleous, 2002; Hughes, 2004) and acknowledging the need for an integrated water balance modelling (Sophocleous, 2002; Krause and Bronstert, 2006), the development of a coupled soil water–groundwater–surface water model system became necessary.

Some exemplary numerical experiments about the spatial variability and varying extent of groundwater–surface water interaction have been accomplished by detailed two-dimensional, vertical-plain simulations of exemplary transects of rivers beds connected with the adjacent floodplains and lowlands by using numerical unsaturated-saturated soil water models, e.g., HYDRUS-2D (Simunek et al., 1994; Joris and Fejen, 2003). These simulations refer to the field scale.

At the mesoscale, several models have been developed and applied for water balance simulations of lowland–floodplain landscapes, which account for groundwater–surface water interactions in different manner. Some of these models are based on more conceptual approaches for soil and groundwater, e.g., by considering data of groundwater gradient or surface water distances (HECNAR, Jayatilaka and Gillham, 1996; Jayatilaka et al., 1996), or on a combination of a vertical soil water simulation with a simplified representation of groundwater flows towards the main drainage direction (SWATRE, Spieksma and Schouwenaars, 1997), but also on fully three-dimensional physically based numerical approaches for both soil moisture and groundwater (VanderKwaak, 1999; VanderKwaak and Sudicky, 1999; Sudicky et al., 2000; Weng et al., 2003). Other approaches couple physically based groundwater models (two-dimensional horizontal-plain, or full three-dimensional) with a more conceptual model for the hydrological processes in the unsaturated zone and at the soil surface (SWAT – MODFLOW, AGRIFLUX–MODFLOW Lasserre et al., 1999).

Most of the models mentioned above perform important simplifications: e.g., the spatial extent of the interactions between groundwater and surface water is assumed to be constant, or spatially and temporally transient changes of processes are considered in a rudimentary manner only. However, the "most-physically" approach – a full three-dimensional numerical solution of saturated-unsaturated zone processes (in both the soil and ground water domain) – encounters limitations for mesoscale applications, because of its high computational demands and problems with changing type or boundary conditions (e.g., varying saturation areas in space and time), and insufficient knowledge concerning representative parameters of the soil hydraulic properties for such models.

The groundwater–surface water interactions between floodplains and surface waters are represented in most of these models. However, the influence of the areas, which are adjacent to the lowland–floodplain landscapes (i.e., their hydrologic conditions at the non-surface-water boundary) are not taken into account by most models (Hayashi et al., 1998; Krause and Bronstert, 2005, 2006).

Summarising the requirements to simulate the water balance in such kind of inter-connected surface water–floodplain–lowland landscape, one can say that an appropriate model has to be able to cope with:

- temporal and spatial dynamics of runoff generation processes, including the surface runoff from saturated areas of a temporally variable spatial extend,
- soil water dynamics within horizontally and vertically variable soil properties and extension of the unsaturated soil zone,
- groundwater flow in the saturated soil zone of variable spatial extend,
- the direct interaction between groundwater and surface water including the resulting processes of surface water infiltration and groundwater exfiltration, including the representation of their variations in time and space.

3. Methods

3.1. *A coupled model approach for different compartments of the hydrological cycle in lowlands*

3.1.1. *Model summary*

For simulation of the water balance in the study area we used the model-system IWAN (Integrated Modelling of Water Balance and Nutrient Dynamics), (Krause and Bronstert, 2005, 2006). The IWAN model is a coupled model system considering vertical processes of the soil surface (interception, evapotranspiration, runoff generation) and of the soil water dynamics (percolation, soil water storage, groundwater uptake, vertical groundwater recharge) as well as lateral processes of the groundwater in interaction with the surface water (groundwater flows, exchange fluxes between groundwater and surface water) (Fig. 2). The model dynamics are controlled by an atmospheric boundary condition, by the predefined surface water stages as well as by the geographical settings, physical soil characteristics and plant parameter (Fig. 2) (Krause and Bronstert, 2006). The main deliverables of the model simulations are temporal and spatial information about the soil water contents and plant water availability, vertical groundwater recharge, exchange fluxes between groundwater and surface water and the water balance of the floodplain catchment (Fig. 2). Apart from the eco-hydrological dynamics investigated in this work, the model results provide valuable information for wetland ecology and water quality modelling. Ecological wetland models which are linked with hydrological models for instance, mainly focus on systems and processes at the land surface, soil and groundwater or on interactions

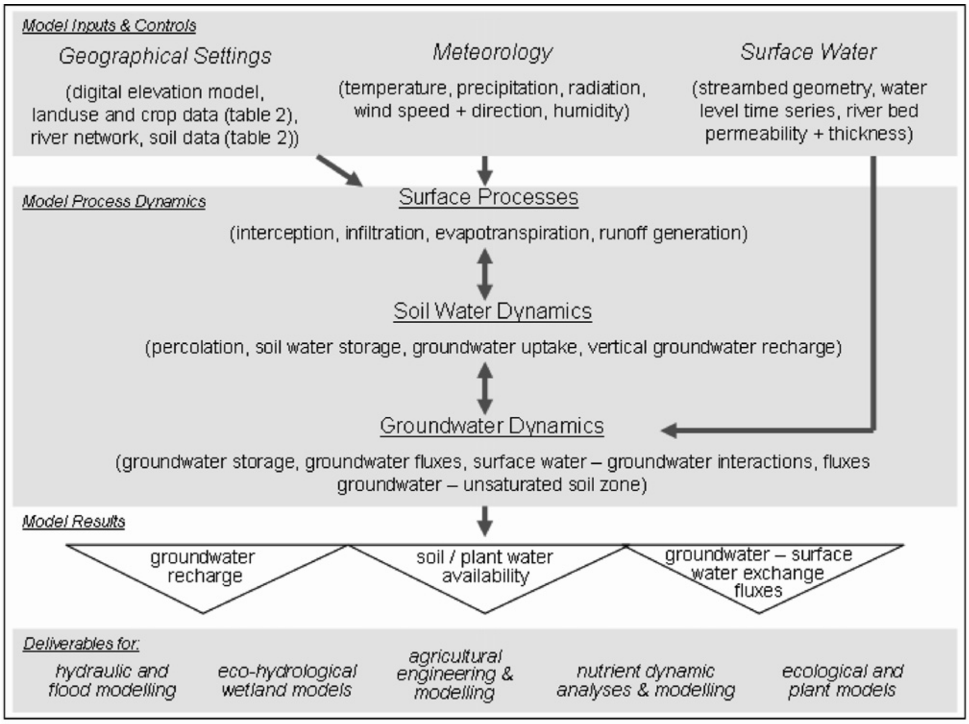

Fig. 2 – Considered processes, inputs and forcing functions, outputs and deliverables of the IWAN model as well as linkages to other modelling disciplines.

between land surface and surface waters (Toner and Keddy, 1996; Cline and Swain, 2002). Due to the incorporation of the results of a coupled model like IWAN (Fig. 2), e.g., exchange fluxes between groundwater and surface waters or groundwater recharge and water availability the process dynamics in wetlands as an interface between terrestrial and aquatic systems can be described more adequately and some of the general assumptions ecological wetland models base on can be tested. Similarly, the consideration of the model results (especially groundwater–surface water exchange fluxes) add valuable information to ecological wetland models which focus on wetland water quality and nutrient dynamics (Li et al., 2003; Martin and Reddy, 1997; Doerge, 1994; Wang and Mitsch, 2000). The incorporation of the knowledge about exchange fluxes between ground- and surface water can help to improve the understanding of flow paths and sources which effect the nutrient turnover and natural attenuation in wetlands. Finally the IWAN model results as the soil water availability provide an important link to combined ecological and economic models in agricultural used areas (Muenier et al., 2004).

The IWAN model is composed of two major components (Fig. 3), which have been coupled in a two-way mode, i.e., feedback effects are taken into account in both directions:

1. runoff generation and vertical soil water dynamics are simulated by using the respective routines of the deterministic, spatially distributed hydrological model WASIM-ETH-I (Schulla, 1997; Schulla and Jasper, 1999),
2. the flow in the saturated zone and its interactions with the channel systems is modelled by using the three-dimensional finite element based numerical groundwater model MODLFOW (Harbaugh and Mc Donald, 1996a,b), respectively Processing MODFLOW (Chiang and Kinzelbach, 1993, 2001).

The development of this coupled approach enables the adequate simulation of floodplain water balance for landscape

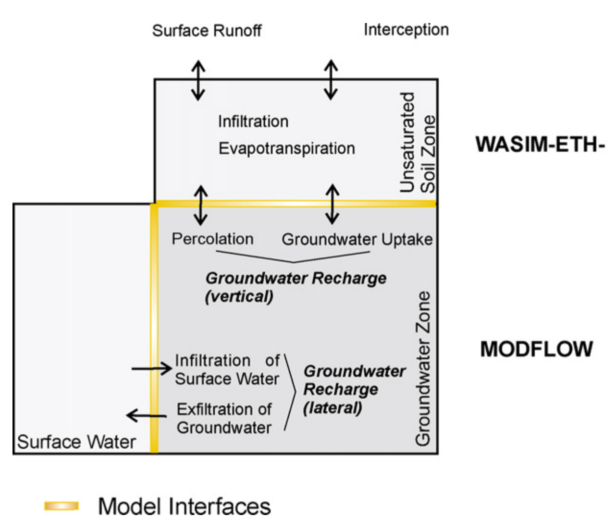

Fig. 3 – The coupling approach and interfaces of the IWAN model components (integrated modelling of water balance and nutrient dynamics) incorporating WASIM-ETH-I for the simulation of the runoff generation and water balance of the unsaturated soil zone and MODLFOW for the groundwater dynamics and interactions to the surface water.

types as described above, considering the direct influences of groundwater dynamics as well as of surface water interactions on the water balance of the whole lowland–floodplain system.

The approach for the simulation of vertical soil water dynamics of the WASIM-ETH-I model (Fig. 3) was derived using an adjusted version of the soil-routine of TOPMODEL (Beven and Kirkby, 1979). Soil water movement is being approximated by a system of storages with inter-linked dynamics and predefined depletion and refilling algorithms (Schulla, 1997). In the presented simulations, an extended version of the WASIM-ETH-I model, which accounts for macropore flow, was used (Niehoff et al., 2002). The saturated zone in WASIM-ETH-I is represented by a baseflow- and groundwater-storage.

Lateral groundwater flows as well as the temporally and spatially variable interactions between groundwater and surface water were calculated in MODLFOW (Fig. 3). The exchange between surface water and groundwater (Fig. 3) is approximated in the model-environment of Processing MODFLOW by using the "River Routine" (Prudic, 1988; Rembe and Wenske, 1998). Hereby the exchange rate is calculated by a leakage-approach (Eq. (1)). The leakage factor controlling the fluxes above the river-boundary-condition is calculated by:

$$C_{RIV} = K_{RIV} L \frac{W_{RIV}}{M_{RIV}} \quad (1)$$

with: C_{RIV} = leakage factor ($L^2 T^{-1}$); K_{RIV} = hydraulic permeability of riverbed ($L T^{-1}$); L = river length (L); W_{RIV} = effective river width (L); M_{RIV} = thickness of hyporheic zone (L).

This approach enables to consider the temporal and spatial variable intensity of the interactions between groundwater and surface water within in the model.

The coupling of runoff generation and vertical soil water dynamics of the unsaturated zone modelled in WASIM-ETH-I and of the lateral flows and exchange processes with surface waters simulated in MODFLOW (Fig. 3) is realised by transmitting the outflows and inflows from the WASIM-ETH-I groundwater storage as groundwater generation or losses to MODFLOW and vice versa (Fig. 3) (Krause and Bronstert, 2003, 2004, 2006).

The boundary conditions at the river boundary are determined by the pressure heads of the river cells (given by the interpolation of local river stage measurements). These are based on observed data at 7 observation gauges along the river network. Datasets of two climate stations and four rain gauges (Fig. 1) were used for the definition of the upper atmospheric boundary condition of the soil water routines in WASIM-ETH-I. Because river boundary conditions as well as atmospheric boundary conditions are unsteady, the model has to handle with transient conditions. The geophysical conditions of soils and aquifer (hydraulic conductivity, aquifer thickness, storage capacity, effective porosity) were derived from already existing datasets for boreholes (Krause and Bronstert, 2004, 2006).

In order to simplify transfer of simulated fluxes at the module boundaries both models were run with same time steps. An overview of simulation time periods and time steps as well as of the model areas used for the different simulations is given by Table 1.

3.1.2. *Model calibration and validation*

Calibration and validation of the IWAN model are comprehensively described in Krause and Bronstert, 2006. They are based on the comparison of simulated and observed values of groundwater stages at several observation gauges where groundwater stages were measured at non-uniform time steps. River discharge was not used as a criteria for the evaluation of the model efficiency as the water level dynamics in the river are mainly controlled at weirs and a free discharge does not occur. Furthermore, at this stage IWAN does not consider the modelling of runoff concentration and stream discharge (Fig. 2). However, with the information about groundwater level at observation boreholes distributed over the research area, a spatially and temporally variable criteria has been used for the model validation. Thus, the information about the model efficiency within the floodplain based on compared groundwater stages is an adequate criteria to test the model appropriateness which has the advantage that it is based on spatially distributed data in contrast to discharge-based validations which deliver an integral measure of the model fit.

The calibration and validation was carried out for the coupled routines of the IWAN model together. Hence, for instance the resulting groundwater stages are determined by vertical groundwater recharge simulated in the soil water balance part as well as by the groundwater simulations in interaction to the surface water.

The IWAN model was calibrated for two subcatchments (Table 1) of the Lower Havel River (Krause and Bronstert, 2006). The most sensitive parameter was the leakage factor C_{RIV} of the hyporheic zone (Eq. (1)) which controls the fluxes between groundwater and surface water in the groundwater modelling part of IWAN (Krause and Bronstert, 2004, 2006). Since river length (L_{RIV}) and river width (W_{RIV}) of Eq. (1) can be identified for each model cell but there is a lack of spatially detailed knowledge about the riverbed thickness (M_{RIV}) and the hydraulic permeability (K_{RIV}) of the riverbed calibration was carried out by alteration of the K_{RIV}/M_{RIV} ratio from 1:100

Table 1 – Simulation time periods, time steps and model areas used for different simulations of the IWAN model

	Simulation period	Simulation time step	Area (km^2)
Calibration	01.09.01–31.12.01	1 h	1.4, 25
Validation	01.10.01–30.09.02 01.10.02–30.10.03	1 day	198.1
Water balance simulation	01.10.01–30.09.02	1 day	198.1
Scenario simulation (1 year)	01.10.01–30.09.02	1 day	198.1
Scenario simulation (13 years)	01.01.88–31.12.00	1 day	198.1

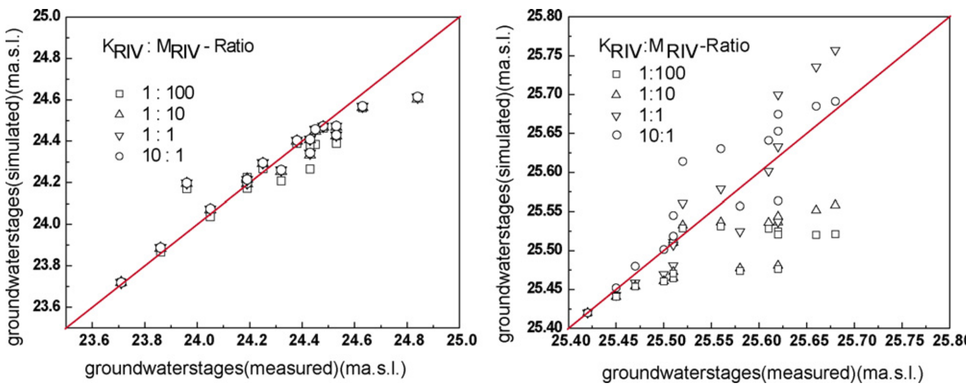

Fig. 4 – Calibration of the IWAN model for different catchments of the Lower Havel River basin: comparison of observed and simulated groundwater stages for different K_{RIV}/M_{RIV} ratios at the two observation points C and D (Fig. 1) for the "Guelper Insel" (left, NSE: 1:100 = 0.75; 1:10 = 0.96; 1:1 = 0.97; 10:1 = 0.97) and two observation points A and B (Fig. 1) for the "Muehlengraben" catchment (right, NSE: 1:100 = 0.18; 1:10 = 0.11; 1:1 = 0.5; 10:1 = 0.68).

[1/s] to 10:1 [1/s]. Fig. 4 shows that the best congruence of measured and simulated groundwater stages could be obtained for ratios between 1: 1 and 10: 1 (mean Nash & Sutcliff index, NSE, of 0.82).

Consequently, the travel time through the river bed can be assumed to be in the range of 1 s which seems to be surprisingly low. However, if the high transmissivity of the mainly artificial river bed water (blocks of ca. 10 cm diameter) is taken into account, the range becomes more reasonable.

The model was successfully validated for the entire Lower Havel River basin for different singular years which were characterised by significantly different hydrological and climatologic boundary conditions (Krause and Bronstert, 2006). The catchment used for validation covers the central floodplain as well as the surrounding hillslope areas (Fig. 1). Validation results based on a comparison of the temporal dynamics of simulated and observed groundwater stages at 14 observation points all over the Lower Havel catchment were satisfactory with an average NSE of 0.78 (Krause and Bronstert, 2004, 2006). A comparison of simulated and measured groundwater stages for two exemplary single points is given in Fig. 5. For evaluation of systematic over- or under estimation additionally the BIAS—fraction of the mean square error (MSE) was analysed.

For MSE ≠ 0 the BIAS fraction is calculated by:

$$\mathrm{BIAS} = \frac{(\bar{O}_i - \bar{P}_i)^2}{\mathrm{MSE}} \tag{2}$$

with: O = observed value, P = simulated value.

It was shown, that a systematic failure was limited to minor underestimation mainly in the peripheral regions at the catchment boundary although a systematic offset occasionally occured even at observation points with a good fit of the simulated and observed dynamics (high NSE) (Krause and Bronstert, 2006).

Generally it can be concluded that the overall simulation goodness characterised by the dynamical and systematic model errors is satisfactory and enables to use the IWAN model for scenario analyses.

3.2. *Scenario generation for different land-uses*

The scenarios for different land-use and management developments were generated in order to be used as different possible future conditions of the landscape surface for the simulation of both water quantity and water quality issues (latter

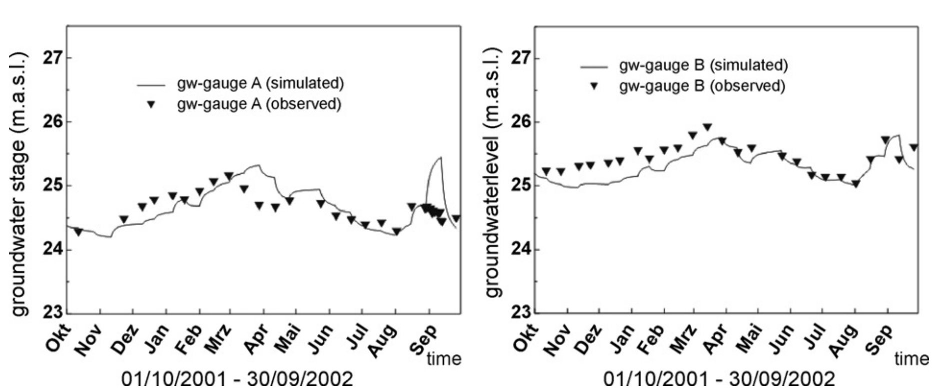

Fig. 5 – Validation of the IWAN model for the entire Lower Havel River catchment: time series of observed and simulated groundwater stages for two selected observation points A and B (Fig. 1) of the floodplain (simulation period 10/2001–09/2002).

is not considered in this article). They also account for specific features of nature conservation areas concerning water quality and quantity.

To accomplish its *specific objectives* each scenario considers a complex matrix of different *management strategies*. The land-use change and management scenarios considered here are based on the analysis of the potential natural functions, characteristics and capabilities of the different landscape units in consideration of the specific predefined scenario objectives (Jacobs and Jessel, 2004). For the implementation of the scenario objectives as well as for the development of adequate management strategies, information about specific, spatially detailed management requirements were analysed. Therefore, nature protection and landscape conservation acts, infrastructure development plans as well as stakeholder interviews have been considered (Jacobs and Jessel, 2004).

The scenarios derived here consider a change in agricultural land-use or the related management practices (scenarios 1–4) and on the coarsening of the drainage channel system of the landscape (scenarios 5).

3.2.1. *Land-use change scenarios (scenarios 1–4)*

These management strategies implement *changes of land-use types* as well as the *alteration of cropping methods*, e.g., the additional cultivation of intercrops, conversion of forest types, crop rotation, or crop extensification. Such changes are related with the alteration of vegetation features such as vegetation height or density, plant phenology as well as the timing of plugging and harvesting.

The implementation of the specific scenario objectives is expressed by modified land-use and vegetation cover maps considered in the soil water balance part of the IWAN model as well as by the alteration of different soil and vegetation parameter sets as root depth, plant height, leaf area index, soil cover index. The different parameters influence the process simulation of soil water fluxes, evapotranspiration, infiltration, root water uptake, and groundwater recharge, or capillary rise. Parameter values were estimated in consideration of the WASIM parameter databases (Schulla, 1997) as well as by using the plant parameter database 'PlaPaDa' (Breuer et al., 2003; Breuer and Frede, 2003). Table 2 lists the IWAN model parameters which were affected by the different scenarios including their range and seasonal variations.

The management strategies were bundled to four alternative scenarios considering agricultural land-use changes termed:

Scenario 1 'Best Nature Conservation',
Scenario 2 'Actual Trend',
Scenario 3 'Best Water Quality', and
Scenario 4 'Best Management Practice'.

The different assumptions the certain scenarios are based on are given below as well as their specific water balance objectives:

Scenario 1—'Best nature conservation': For this scenario management strategies which lead to an advancement of nature protection (e.g., wetland and groundwater protection, erosion control, nature conservation) are considered. The technical feasibility and the acceptance of the management strategies are not considered.

Scenario 2—'Actual trend': Supposing the further existence of the actual political framework conditions and of their development the continuity of the actual land-use conditions is assumed.

Scenario 3—'Best water quality': All management strategies are focussed on maximal improvement of the surface water and groundwater quality. Allocation rules were derived from different legal and technical documents, e.g., LAWA (2002), Frielinghaus and Winnige (2000), LUA (1997) and MELF/MUNR-Steuergruppe (1996).

Scenario 4—'Best management practice': This scenario implies land-use management according to existing national and European law in agriculture and forestry. Thus, compliance with the good practice in agriculture and forestry is required. In nature conservation areas land-use activities are furthermore optimised according to specific protection and soil conservation objectives.

Additionally influences of external tendencies (expansion of urban areas and infrastructure) were assumed for every scenario. Appropriate information has been gained from the development plans of the federal state of Brandenburg (Jacobs and Jessel, 2004).

The spatial pattern of land-use under scenario conditions, finally accomplished due to the implementation of the management strategies are shown in the maps of Fig. 6 in comparison to the actual land-use conditions.

Table 3 shows the distribution of specific land-use fractions for actual land-use conditions in comparison with the assumed scenario land-use changes.

Table 2 – Model parameter which are affected by the different scenarios including their range and seasonal variations

Parameter	Values	Inner annual parameter variability
Albedo (%)	5–25%	Year round
Canopy resistance (time/length)	20–100 m	Monthly
Vegetation period (time)	Julian days	Four vegetation periods (0–3, 4–6, 7–9, 10–12)
Leaf area index (%)	5–13%	Four vegetation periods (0–3, 4–6, 7–9, 10–12)
Vegetation height (length)	0.1–10 m	Four vegetation periods (0–3, 4–6, 7–9, 10–12)
Vegetation cover (%)	10–90%	Four vegetation periods (0–3, 4–6, 7–9, 10–12)
Root depth (length)	0.1–1.5 m	Four vegetation periods (0–3, 4–6, 7–9, 10–12)
Macro pores (length)	0–1.2 m	Year round
Macro pores (vol.%)	0–1.2%	Year round

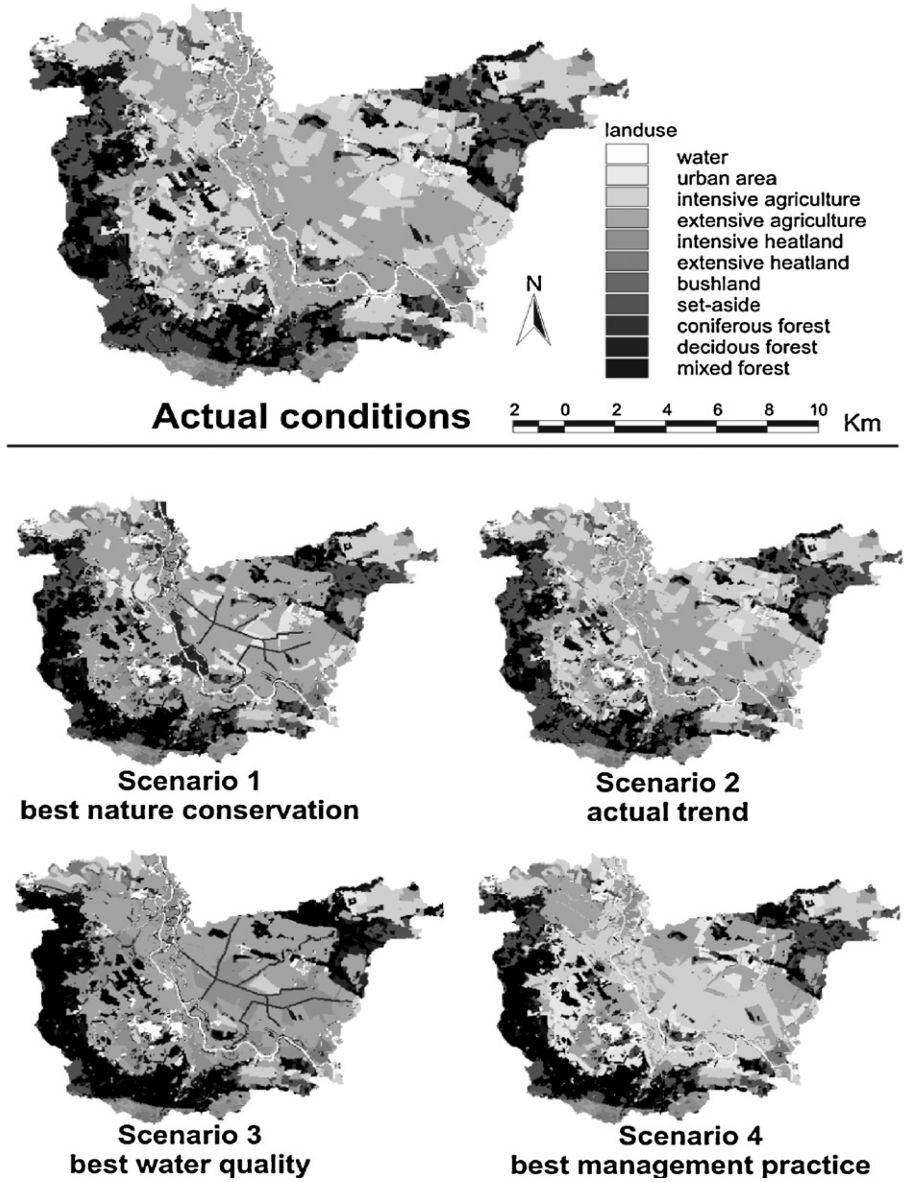

Fig. 6 – Actual land-use conditions in comparison to the changed land-use conditions for the scenarios: (1) 'best nature conservation', (2) 'actual trend', (3) 'best water quality' and (4) 'best management practice'.

Table 3 – Classification of land cover for actual conditions and conditions of the land-use change scenarios (1–4)—distribution of landcover fractions in m^2 and percentage deviation of scenario conditions from actual conditions

Land-use	Actual conditions	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Surface water	4.44	4.18 (93.93%)	4.14 (93.14%)	4.18 (93.93%)	4.14 (93.14%)
Urban areas	4.09	4.12 (100.73%)	4.12 (100.73%)	4.12 (100.73%)	4.12 (100.73%)
Decidous forest	8.36	15.19 (181.64%)	8.39 (100.29%)	16.06 (192.05%)	8.39 (100.29%)
Coniferous forest	36.53	21.05 (57.61%)	30.61 (83.76%)	5.51 (15.08%)	18.62 (50.95%)
Mixed forest	15.87	31.47 (198.24%)	21.86 (137.71%)	44.38 (279.59%)	33.85 (213.23%)
Extensive agriculture	4.72	24.51 (519.16%)	1.55 (32.87%)	13.83 (293.01%)	17.35 (367.44%)
Intensive agricultue	48.92	12.66 (25.87%)	44.92 (91.82%)	10.47 (21.40%)	48.46 (99.06%)
Intensive heathland	32.87	46.59 (141.73%)	53.77 (163.57%)	53.94 (164.06%)	21.51 (65.43%)
Extensive heathland	21.58	2.99 (13.84%)	2.99 (13.84%)	2.99 (13.84%)	2.99 (13.84%)
Bushland	10.11	15.61 (145.34%)	9.24 (91.32%)	30.75 (304.08%)	12.6 (124.60%)
Set-aside	0.74	9.89 (1341.02%)	6.68 (905.08%)	2.03 (275.59%)	16.23 (2201.1%)

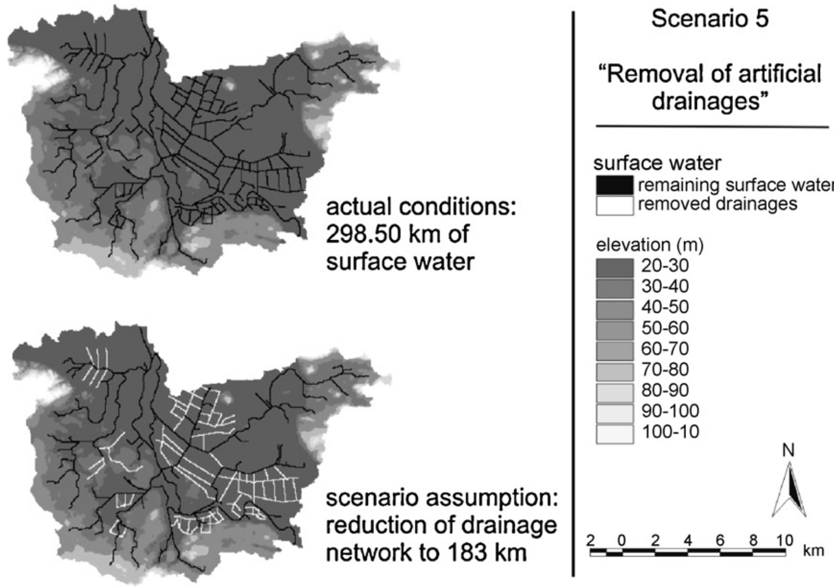

Fig. 7 – Scenario 5 (drainage density reduction scenario) assuming the removal of all artificial ditches. This would cause a decrease of the total river length of about 40%. Only the major drainages are depicted in this figure.

3.2.2. *Drainage density reduction scenario (scenario 5)*

To analyse the impact of the density of the drainage channel network on water balance and groundwater recharge an integrated scenario was applied that assumes a reduction of river length (Fig. 7). It furthermore takes into account the land-use conditions of scenario 4, the so-called 'best management practice' (Fig. 6). In addition to the Havel River, the research area is currently drained rather efficiently by a dense network of artificial (man-made) small, interconnected ditches. Most of these ditches have been constructed during the last 50 years with the aim to drain the floodplain during winter and spring in order to enable agricultural management with heavy machinery. Today, the operation of the pumping stations and the maintenance of the ditches are not always considered economical. Thus, scenario 5 assumes the removal of all artificial ditches, and only natural or at least semi-natural surface waters would remain. This would cause a reduction of total river length from 298.5 km to 183 km (Fig. 7).

4. Results

4.1. *Water balance modelling*

The model was applied for simulation of water balance and groundwater recharge of the Lower Havel River basin for several years. Analysis of the simulation results proved that the temporal distribution of groundwater discharge and recharge periods was strongly controlled by both precipitation and by the fluxes to/from the surface water system (Fig. 8).

Groundwater recharge is caused by both percolation below the unsaturated zone (triggered by infiltrating precipitation) as well as by lateral surface water infiltration (in case of relatively high river water level). Groundwater discharge appears due to root water uptake as well as groundwater exfiltration into the river (in case of relatively low river water level). The simulated dynamic of groundwater discharge and recharge differ significantly depending on the actual importance of the mentioned processes. Comparing the simulated vertical groundwater recharge (given by the ratio of percolation and groundwater uptake) and the total groundwater recharge (including the lateral interactions between groundwater and surface water) significant differences were observed (Fig. 8).

These results show that total groundwater recharge is strongly affected by the groundwater surface water interactions. For most of the simulation period the vertical groundwater recharge dynamics is clearly superimposed by such lateral interactions, i.e., lateral groundwater flow–surface water interactions are of major importance for the water balance of the lowland- floodplain landscape of the Lower Havel area.

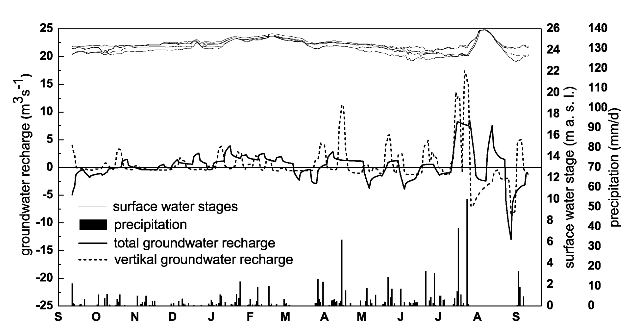

Fig. 8 – Comparison of vertical and total groundwater recharge (taking into account also the interactions between groundwater and surface water) in dependence of surface water stage dynamics and precipitation for the time period 10/2001–09/2002.

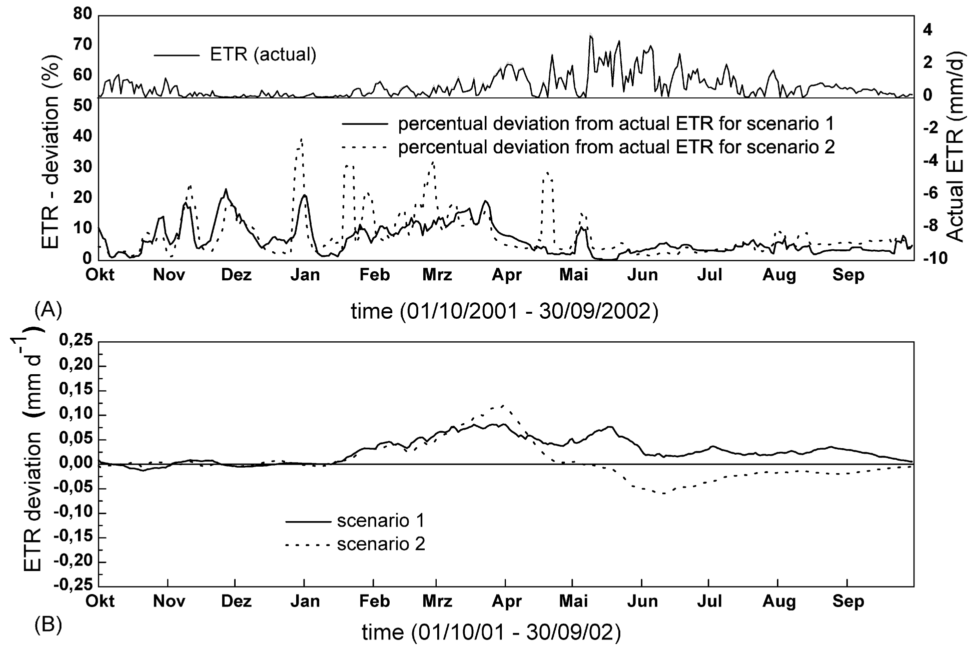

Fig. 9 – Simulated time series of ETR for actual conditions and percentage deviation of simulated ETR for scenario 1 and scenario 2 (A) and simulated total deviation of ETR from actual conditions for scenario 1 and scenario 2 (B).

4.2. Scenario analysis

4.2.1. Simulation results for the land-use change scenarios

For the simulation of land-use change effects on floodplain water balance the four land-use change scenarios 1–4 (Fig. 6) were used to prescribe the conditions of the land surface. The water balance was simulated by the IWAN model system for the time period from 1988–2000 with the observed meteorological and river level boundary conditions of that period. In addition, to analyse the sensitivity of the vertical groundwater fluxes to land-use changes the time period of 10/2001–09/2002 was simulated.

4.2.1.1. Effects on the vertical groundwater recharge. At first, a simulation of the vertical groundwater recharge was performed to test the sensitivity of the model results concerning the water balance to alterations of land cover and the related effects to vertical soil hydrological processes like root water uptake and evapotranspiration (ETR), infiltration and percolation. Therefore scenario 1 and scenario 2 were simulated for the period from 10/2001 to 09/2002 with an hourly simulation time step (Table 1). Fig. 9a shows the simulated ETR for the actual conditions and the percentage deviation of the simulated ETR of the two scenarios from the simulated actual conditions.

The scenario conditions show some notable changes in the annual dynamics of ETR. The relative change is high during winter; however, this is the season when the ETR is low anyway. As Fig. 9b shows, the total change is highest in spring and early summer, which is the vegetation growing period, and therefore changes in land-cover have an higher impact on evaporation. Table 4 summarises the subsequent changes of the simulated vertical groundwater recharge that are caused by the alteration of ETR and the vertical water fluxes in the unsaturated soil zone.

To analyse the spatial distribution of these changes, the catchment was divided into four zones (Fig. 10) which were classified based on the specific conditions of the landscape compartments, such as landscape morphology, hydrogeology, and drainage network density. These zones are: the westerly moraine hillslopes, the central moraines, the easterly hillslope area and the floodplain.

The comparison of simulated vertical groundwater recharge for actual conditions and scenario conditions indicated some distinct alterations due to land-use changes. In both cases the vertical groundwater recharge was decreased,

Table 4 – Simulated vertical groundwater recharge for the current conditions (simulation time period (10/2001–09/2002) and for conditions of scenario 1 and scenario 2 in mm a^{-1} for four parts of the Lower Havel River catchment, percentage deviation of scenario groundwater recharge from actual conditions (cursive)

Scenario	Westerly moraine hillslopes (A)	Central moraines (B)	Easterly hillslopes (C)	Floodplain (D)	Total
Current land-use	233	191	71	64	0.559
Scenario 1	221 (94.8%)	177 (92.7%)	52 (73.2%)	7 (10.9%)	0.457 (81.6%)
Scenario 2	211 (90.6%)	180 (94.2%)	65 (91.5%)	46 (71.9%)	0.502 (89.8%)

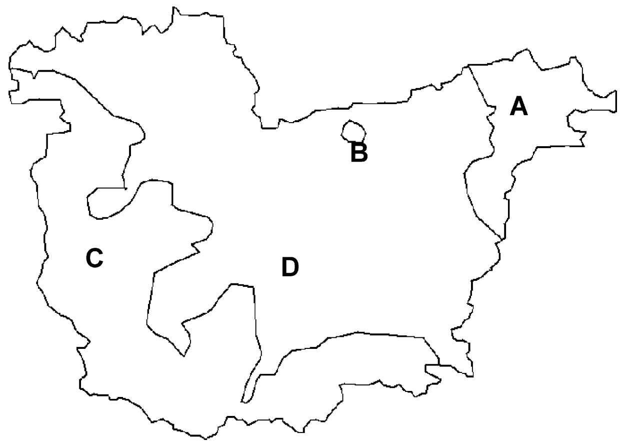

Fig. 10 – Four zones for quantification of simulated vertical groundwater recharge: westerly moraine hillslopes (A), central moraines (B), easterly hillslope area (C), floodplain (D).

by 18.4% for scenario 1 and by 10.2% for scenario 2. The simulation results indicate that the strongest impacts are within the floodplain part of the catchment (zone D), where the vertical groundwater recharge is only 10.9% of the current conditions for scenario 1 and 71.9% for scenario 2. These results point out the sensitivity of percolation and vertical groundwater recharge for land-use changes especially within the central parts of the floodplain which are characterised by low groundwater depths.

4.2.1.2. *Effects on the total groundwater recharge.* For the analysis of land-use change effects on the total groundwater recharge of the Lower Havel River basin the water balance for actual conditions as well as for the four scenarios was simulated continuously. The meteorological and river stage observations of the period from 1988 to 2000 were used for the definition of the boundary conditions. Fig. 11a shows the simulated total groundwater recharge for the land-use change scenarios in comparison with the simulated groundwater recharge for actual conditions. No significant differences were observed during the entire simulation period for the dynamics of scenario and actual groundwater recharge time series.

An analysis of the mean annual groundwater recharge averaged over the simulated 13 years period (Fig. 11b) showed, that generally from winter to the early summer a recharge period characterised by a mean groundwater recharge of $0.2\,m^3\,s^{-1}$ occurs.

In this period groundwater recharge is caused by infiltration of precipitation water and percolation on the one hand as well as by surface water infiltration from the river and the ditches (where water levels are usually higher than the groundwater levels at this time) on the other hand. During summer the groundwater dynamics turn into groundwater discharges which occur until approximately late autumn when groundwater recharge starts again. These characteristic

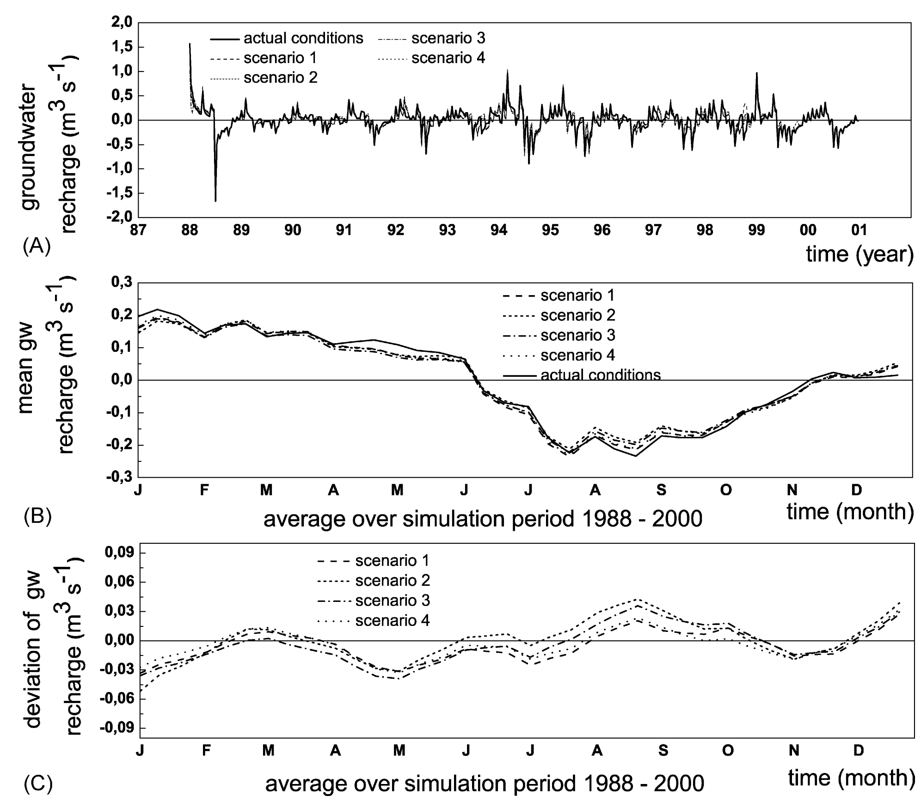

Fig. 11 – Simulated groundwater recharge of the Lower Havel catchment for actual conditions and for land-use change scenarios (1–4) for the simulation period 1988–2000 (A), simulated mean groundwater recharge (averaged for 1988–2000) for actual and for scenario conditions (B), deviation of simulated scenario groundwater recharge from groundwater recharge of actual conditions (C).

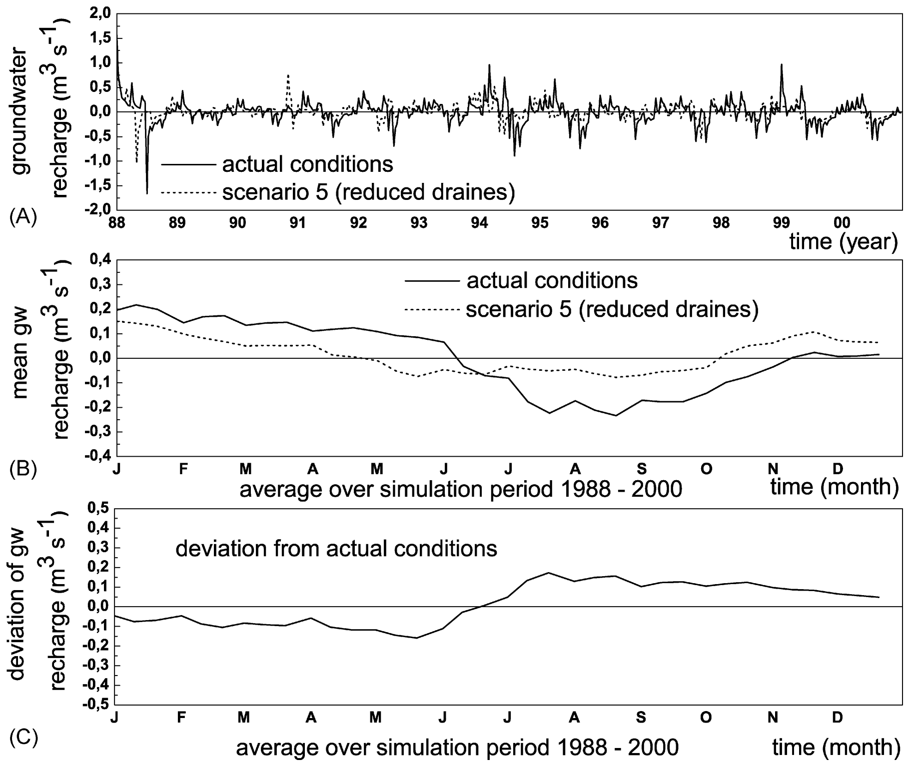

Fig. 12 – Simulated groundwater recharge of the Lower Havel catchment for actual conditions and for drainage density reduction (scenario 5) for the simulation period 1988–2000 (A), simulated mean annual dynamics of groundwater recharge (averaged for 1988–2000) for actual and for scenario conditions (B), differences of simulated mean annual dynamics (scenario conditions—actual conditions) (C).

losses of groundwater storage during summer are caused by the fact that during that season root water uptake is higher than rainfall infiltration as well as by groundwater discharge into the ditches which are usually filled marginally only during summer. Only minor deviations (less than 10% on average) were observed between the mean total annual groundwater recharge for scenario and actual conditions (Fig. 11c).

Taking into account the observed effects for the simulated vertical groundwater recharge (Table 4) substantial differences between vertical groundwater recharge and total groundwater recharge become obvious. The alterations of vertical groundwater recharge induced by land-use changes are almost completely counter balanced by the lateral fluxes of the groundwater. If the groundwater table rises due by vertical groundwater recharge (percolation below the unsaturated zone), the lateral groundwater runoff into the river system increases subsequently. Otherwise, if the root water uptake is higher then the rainfall infiltration (resulting in a subsequent decrease of groundwater tables), the infiltration of surface water from the river and drainage network into the groundwater storage will increase. In both cases, the effects of vertical groundwater recharge seem to be counter balanced by the lateral groundwater reaction. Thus, the impacts of changes in land-use are widely buffered due to lateral groundwater flows and the interaction to surface waters. This leads to the conclusion, that in groundwater dominated lowland–floodplain landscapes, possible changes in land-use may only results in rather insignificant changes of groundwater recharge and groundwater stage, as long as the supply by surface water is not constrained.

4.2.2. *Simulation results for the drainage density reduction scenario*

Scenario 5 assumes a reduction of drainage density. The same 13 years from 1988 to 2000 were chosen for simulation period. Fig. 12a shows the simulated total groundwater recharge for scenario 5 in comparison with the simulated dynamics for actual conditions. The simulated groundwater recharge differs significantly for actual and scenario conditions, both to be seen for the time series of the whole 13 years and for the mean annual dynamics (Fig. 12b and c).

Generally the scenario conditions seem to lead to a smoothed annual groundwater recharge dynamics. The reduction of the drainage network would cause less groundwater recharge during winter and spring due to less surface water infiltration from the ditches. On the other hand, during the groundwater abstraction period from summer to autumn, the groundwater losses would be smaller, caused mainly by a reduced groundwater exfiltration into the drainage system.

The effect of the changes of groundwater recharge on the dynamics of groundwater levels is presented in Fig. 13, where time series of the simulated groundwater tables for two representative groundwater observation wells (Fig. 1) are plotted for the 13 years period.

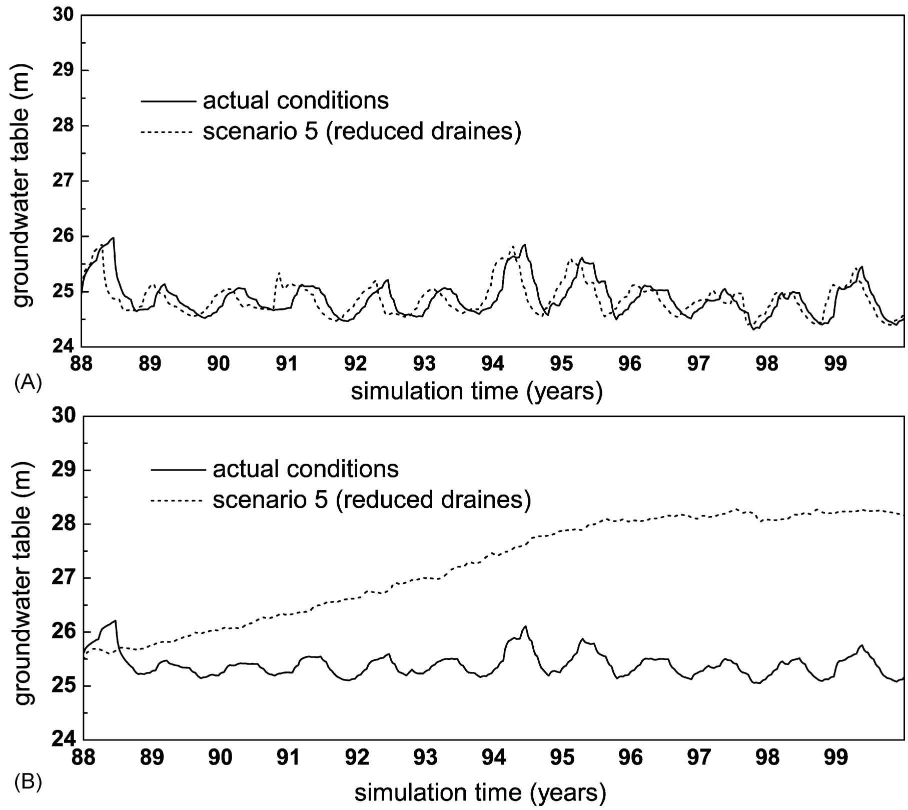

Fig. 13 – Comparison of simulated groundwater levels for actual conditions and for conditions of scenario 5, for (A) an observation well in immediate neighbourhood to surface water (0.8 km) (observation well E in Fig. 1) and for (B) an observation well in a larger distance of the main river (2.4 km to surface water) (observation well F in Fig. 1).

This figure shows two locations of different distance to the remaining surface waters, which have been analysed for the dependency of their changes in groundwater dynamics on their distance from the river. The observation point E (Fig. 13a) is located in a relatively short distance to the next channel. At this point, the groundwater dynamics show a slightly smoothed and shifted pattern, which is caused by less recharge in winter and spring and less abstraction in summer and autumn. Nevertheless, the groundwater–surface water interactions remain effective. Under current conditions ('actual conditions'), also the second observation point F (Fig. 13b), is located close to a drainage channel. Under scenario conditions, this drainage channel would no longer exist, i.e., this point would have a larger distance to the next surface water. Fig. 13b shows a transient increase of the groundwater table for this observation point of about 4 m. It is furthermore shown that the seasonal dynamics of groundwater tables would almost disappear, because the influences of the surface water seasonality does not reach these locations. According to these simulation results, the time until a new more or less steady state of the groundwater dynamics can be observed is about 6 years (assuming the removing of the ditches is accomplished at the 1st year).

The characteristic influence of surface water (drainage network density) on the groundwater dynamics is representative, i.e., a similar behaviour has been observed for all simulated groundwater wells, depending on their location (distance to the channel) within the research area. To assess the spatial distribution of the dependence of the water balance on the surface water conditions the simulation results for the entire lowland–floodplain area have been analysed. The spatial differences of the seasonal dynamics of groundwater table between actual and the scenario conditions for the Summer and the Winter period are given in Fig. 14.

Summarising the results regarding the effects of drainage network density, two different types of specific spatial characteristics can be identified:

1. General, long-term effects occur in the areas which are hydraulically disconnected from the channel system (e.g., groundwater increase all over in that areas).
2. Specific seasonal effects of water stage deviations occur in the areas which are directly linked to the channel system. These effects are less severe than the previous one, and thus are less important.

In winter within the entire central floodplain part of the catchment area would be drier, caused by the removal of the artificial ditches whereupon the remaining, non-artificial drainages would not drain the floodplain as efficiently as before. This effect lasts until early summer. In summer, most of the formerly intensively drained areas would be wetter as a result of reduced groundwater losses.

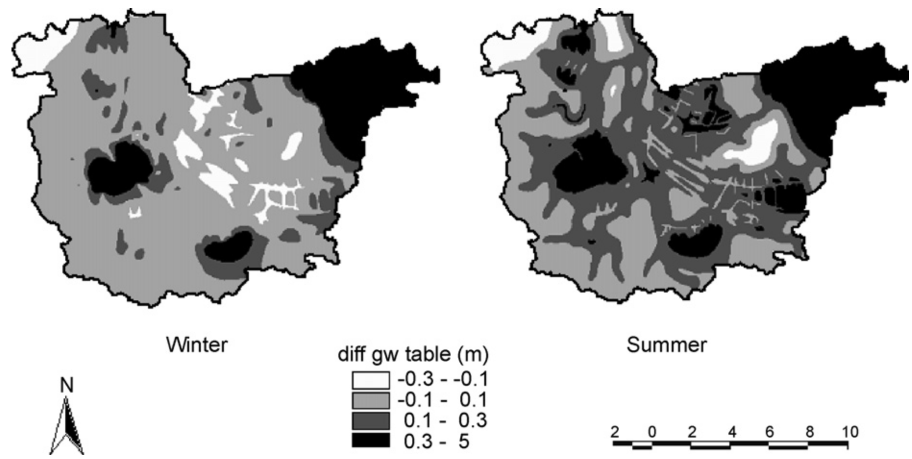

Fig. 14 – Differences of simulated groundwater tables for conditions of scenario 5 compared to actual conditions for average summer and winter seasons (positive values signify higher groundwater tables = wetter conditions for scenario assumptions, negative values signify lower groundwater stages).

4.3. *Comparison of management effects on groundwater recharge*

In this section we contrast the effects of the four different land-use management scenarios with the ones of the drainage reduction scenario. In Fig. 15, the effects of the four different land-use change scenarios (scenarios 1–4) and of the drainage density reduction (scenario 5) on groundwater recharge of this particular landscape type are compared.

Based on this comparison, one can conclude that the presented land-use change scenarios cause only marginal effects on groundwater recharge and groundwater stage dynamics within the floodplain. However, this statement is valid only as long as the supply of surface water (by the channel network) can be considered to be similar to the current conditions. On the other hand, the reduction of the drainage density results in much more significant changes as seen for scenario 5. The removal of ditches within the floodplain would cause less groundwater recharge, effecting lower groundwater stages in the usually wet period from winter to the end of spring. These altered characteristics would mostly affect the more peripheral regions located in a larger distance to the river. i.e., the parts of the floodplain which are characterised by both direct hydraulic connections to the channel system and shallow groundwater depths below the ground surface will hardly be affected. These areas, usually among the wettest of the region, are the ones which are of major concern for nature conservation objectives, e.g., of high relevance for bird habitats and bird migration. On the other hand, the more peripheral areas (larger distance to the drainage system and larger groundwater depths) are of higher importance for the agriculture and less for nature conservation. In these parts of the landscape an increase of groundwater stages could be achieved, which would be beneficial for agriculture, in particular in dry summer periods. This effect would also be welcomed for nature conservation objectives.

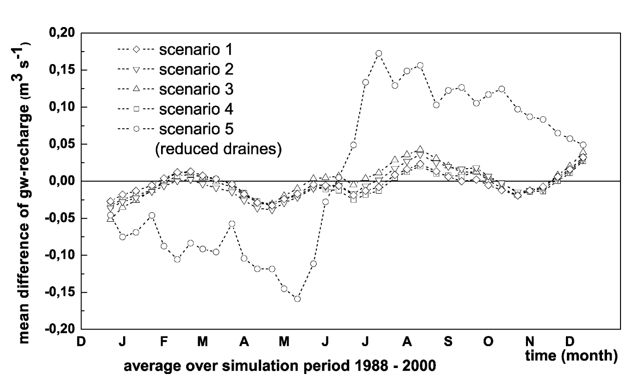

Fig. 15 – Comparison of the simulation results of the land-use change and drainage density reduction scenarios concerning changes of the groundwater (mean annual dynamics for the period 1988–2000).

5. Conclusions

The presented coupled model approach, considering soil water balance modelling, groundwater modelling, and the interactions to surface waters, has been successfully applied for the lowland–floodplain landscape of the Lower Havel River region.

Four land-use change scenarios have been developed to test the impacts of changing land-use conditions on the water balance of the floodplain. While simulating floodplain water balance for these land-use change scenarios it was demonstrated how alteration of the landscape cover effects changes in evapotranspiration and vertical groundwater recharge. It was furthermore shown by simulation of the scenario water balance, how these changes in vertical groundwater recharge are counter balanced by both lateral groundwater flow and the tight interactions between groundwater and surface waters. Thus, it can be concluded that the assumed alterations of land-use characteristics would cause only marginal effects on overall groundwater recharge and floodplain water balance. With this scenario simulation we could demonstrate the minor importance of changes in vertical groundwater recharge processes for floodplain water balance. As a major reason for this it could be detected that changes in the vertical groundwater recharge/discharge are counter balanced by an increase/decrease of the lateral fluxes, i.e., the lateral groundwater recharge/discharge from/to the surface water system. The applications of the model to several subcatchments of the Havel River region, with different geo-morphological features, show similar response characteristics. Thus, we conclude that the achieved results of the importance of surface water interactions and the major importance of lateral groundwater flows are rather typical for floodplains of glacially formed lowlands.

To analyse the impact of the design and structure of the drainage network, a scenario was developed which assumed the total removal of the artificial ditches of the floodplain, hence a dismantling of about 40% of the whole channel system. In contrast to the effects of the land-use change scenario, this scenario showed significant deviations of the simulated groundwater recharge dynamics in comparison to the simulated actual conditions. It was shown that due to the dismantling of the artificial drainage channels:

1. In parts of the landscape with shallow groundwater depths and direct interactions with the remaining channel network, less groundwater recharge and subsequently lower groundwater stages during the wet winter period and higher groundwater stages caused by less groundwater discharge to the river in the dry summer period could be reached.
2. In the parts of the landscape with a higher distance to the remaining channel network and with a larger groundwater depth a significant, long-term increase of groundwater levels can be expected, mainly due to the prevention of groundwater discharge into the drainage channels in summer.

Taking into account the spatial and temporal variability of the distribution of groundwater stage changes, it occurs to be promising to test whether these altered conditions could be a compromise between different land users with agricultural objectives on one side and nature conservation activities on the other side.

Generally the results of the scenario simulations emphasise the necessity of integrated approaches, which combine land-use management as well as the layout of river/drainage channel network (including the design of the cross sections), to reach the desired impacts and improvements of the water balance dynamics of the floodplain. Removal of artificial ditches is only one possible option to achieve the favoured conditions. A change of the overall discharge regulation practice of the weirs and other control structures is another opportunity.

Obviously, there are limitations concerning the overall validity of the model concept which are stated in the following:

An important prerequisite is given by the assumption of predefined pressure heads at the river boundaries for all of the scenarios which were not affected by the simulation results nor included into the scenarios. This assumption is valid only if groundwater–surface water interactions have only negligible impacts on river discharge and subsequent surface water stages. This assumption is valid for the Havel River and the drainage network, where the water level is controlled by weirs. However, in case of non-controlled, free running rivers the assumption of a stable water level in the river, non-dependent of the interactions with the groundwater of the surrounding landscape has to be questioned. In that case the river water dynamics may need to be included into the model system. This can be achieved for instance due to the simulation of the hydrodynamic St.-Venant equations.

Finally, the simulation results for current and scenario water balances, groundwater recharge and exchange fluxes represent important information for ecological wetland and water quality analyses and models. They may help to improve the understanding of the impact of vegetation cover and drainage intensity on wetland water balances and subsequent wetland (ground) water chemistry and ecology. The consideration of the knowledge gained in this study will furthermore add valuable information to wetland management and land-use planning in floodplains.

Acknowledgements

This work has been supported by the German Federal Ministry of Education and Research (BMBF). We thank Andreas Bauer and Markus Morgner for extensive fieldwork, data processing, and technical assistance. The authors wish to thank the referees and editor for their valuable comments.

REFERENCES

Acreman, M.C., Riddington, R., Booker, D.J., 2003. Hydrological impacts of floodplain restoration: a case study of the River Cherwell, UK. Hydrol. Earth Syst. Sci. 7, 75–86.

Andersen, H.E., 2004. Hydrology and nitrogen balance of a seasonally inundated Danish floodplain wetland. Hydrol. Processes 18 (3), 415–434.

Beven, K.J., Kirkby, M.J., 1979. A physically based variable contributing area model of basin hydrology. Hydrol. Sci. Bull. 24 (1), 43–69.

BirdLife International, 2005. BirdLife's Online World Bird Database: the Site for Bird Conservation, Version 2.0. BirdLife International, Cambridge, UK. Available: http://www.birdlife.org (accessed 16/2/2006).

Breuer, L., Eckhardt, K., Frede, H.-G., 2003. Plant parameter values for models in temperate climates. Ecol. Model. 169, 237–293.

Breuer, L., Frede, H., 2003. PlaPaDa—an online plant parameter data drill for eco-hydrological modelling approaches. http://www.uni-giessen.de/~gh1461/plapada/plapada.html.

Bullock, A., Acreman, M., 2003. The role of wetlands in the hydrological cycle. Hydrol. Earth Syst. Sci. 7, 358–389.

Burt, T.P., Matchett, L.S., Goulding, K.W.T., Webster, C.P., Haycock, N.E., 1999. Denitrification in riparian buffer zones: the role of floodplain hydrology. Hydrol. Processes 13, 1451–1463.

Chiang, W.H., Kinzelbach, W., 1993. Processing Modflow (PM), Pre- and Postprocessors for the Simulation of Flow an Contaminant Transport in Groundwater Systems with MODFLOW, MODPATH, and MT3D. Distributed by Scientific Software Group, Washington, DC.

Chiang, W.H., Kinzelbach, W., 2001. 3D-Groundwater Modeling with PMWIN—A Simulation System for Modeling

Groundwater Flow and Pollution. Springer-Verlag, Berlin, Heidelberg, New York.
Cline, J.C., Swain, E.D., 2002. Linkage of hydrologic and ecological models: SICS and ALFISHES. In: Second Federal Interagency Hydrologic Modelling Conference, Las Vegas, Nevada.
Devito, K.J., Hill, A.R., Roulet, N., 1996. Groundwater–surface water interactions in headwater forested wetlands of the Canadian shield. J. Hydrol. 181, 127–147.
Devito, K.J., Dillon, P.J., 1993. The influence of hydrologic conditions and peat oxia on the phosphorus and nitrogen dynamics of a conifer swamp. Water Resources Res. 29, 2675–2685.
Doerge, J., 1994. Modelling nitrogen transformations in freshwater wetlands. Estimating nitrogen retention and removal in natural wetlands in relation to their hydrology and nutrient loadings. Ecol. Model. 75–76, 409–420.
Frielinghaus, M., Winnige, B., 2000. Maßstäbe bodenschonender landwirtschaftlicher Bodennutzung. UBA-Texte 43. Bonn—Bad Godesberg (in German).
Garcia-Linares, C., Martinez-Bilbao, M., Sanchez-Perez, J.M., Antiguedad, I., 2003. Wetland restoration and nitrate reduction: the example of the peri-urban wetland of Victoria-Gasteiz (Basque Country, North Spain). Hydrol. Earth Syst. Sci. 7, 109–123.
Gasca-Tucker, L.G., Acreman, M.A., 2000. Modelling ditch water levels on the Pevensey Levels wetland, a lowland wet grassland wetland in East Sussex, UK. Phys. Chem. Earth Part B—Hydrol. Oceans Atmos. 25, 593–597.
Harbaugh, A.W., Mc Donald, M.G., 1996. User's documentation for MODFLOW-96, an update to the U.S. Geological Survey modular finite-difference groundwater flow model: USGS Open-File Report 96-485.
Harbaugh, A.W., Mc Donald, M.G., 1996. Programmer's documentation for MODFLOW 96, an update to the U.S. Geological Survey modular finite-difference ground-water flow model: USGS Open-File Report 96-486.
Hayashi, M., van der Kamp, G., Rudolph, D.L., 1998. Water and solute transfer between a prairie wetland and adjacent uplands. 1. Water balance. J. Hydrol. 207, 42–55.
Hayashi, M., Rosenberry, D.O., 2002. Effects of ground water exchange on the hydrology and ecology of surface water. Ground Water 40, 309–316.
Heidemann, L.J., Christensen, S., Rasmussen, K.R., 2001. Scale dependent hydraulic variability of a stream bed on an outwash plain. In: Proceedings of the Sixth IAHS Scientific Assembly on Impact of Human Activity on Groundwater Dynamics, Maastricht, IAHS Publ. No. 269.
Hill, B.R., 1990. Groundwater discharge to a headwater valley, northwestern Nevada, USA. J. Hydrol. 113, 265–283.
Hughes, D.A., 2004. Incorporating groundwater recharge and discharge functions into an existing monthly rainfall-runoff model. Hydrol. Sci. J. 49, 297–311.
Jacobs, J., Jessel, B., 2004. Landnutzungsszenarien zur Entscheidungsunterstützung—Ein Beispiel aus dem Einzugsgebiet der Havel. In: Möltgen, J., Petry, D. (Eds.), (Hrsg.) Interdisziplinäre Methoden des Flussgebietsmanagements. IfGI prints Bd. 21, Schriftenreihe des Instituts für Geoinformatik der Westfälischen Wilhelm-Universität, Münster, pp. 261–267 (in German).
Jayatilaka, C.J., Gillham, R.W., 1996. A deterministic-empirical model of the effect of the capillary fringe on near-stream area runoff. 1. Description of the model. J. Hydrol. 184, 299–315.
Jayatilaka, C.J., Gillham, R.W., Blowes, D.W., Nathan, R.J., 1996. A deterministic-empirical model of the effect of the capillary fringe on near-stream area runoff. 2. Testing and application. J. Hydrol. 184, 317–336.
Joris, I., Fejen, J., 2003. Modeling water flow and seasonal soil moisture dynamics in an alluvial groundwater-fed wetland. Hydrol. Earth Syst. Sci. 7 (1), 57–66.
Krause, S.M., Bronstert, A., 2003. Beschreibung des Wasserhaushalts an der Unteren Havel als Voraussetzung für ein nachhaltiges Flussgebietsmanagement—Modellierung der Grundwasser—Oberflächenwasser Interaktionen mittels Modellkopplung. Forum für Hydrologie und Wasserbewirtschaftung, 04 (2) (in German).
Krause, S., Bronstert, A., 2004. Approximation of groundwater–surface water interactions in a mesoscale lowland river catchment. Hydrol.: Sci. Practice 21st Century, Br. Hydrol. Soc. 2, 408–415.
Krause, S., Bronstert, A., 2005. An advanced approach for catchment delineation and water balance modelling within wetlands and floodplains. Adv. Geosci. 5, 1–5.
Krause, S., Bronstert, A., 2006. Water balance simulations and groundwater–surface water interactions in a mesoscale lowland river catchment. Hydrol. Processes, published online 24.05.07, doi:10.1002/hyp.6182.
Lasserre, F., Razack, M., Banton, O., 1999. A GIS-linked model for the assessment of nitrate contamination in groundwater. J. Hydrol. 224, 81–90.
Länderarbeitsgemeinschaft Wasser (LAWA), 2002. Gemeinsamer Bericht von LAWA und LABO zu Anforderungen an eine nachhaltige Landwirtschaft aus Sicht des Gewässer- und Bodenschutzes vor dem Hintergrund der Wasserrahmenrichtlinie, http://www.lawa.de/ (in German).
Li, X., Xia, D., Jongman, R.H., Harms, W.B., Bregt, A.K., 2003. Spatial modelling on the nutrient retention of an estuary wetland. Ecol. Model. 167, 33–46.
Landesumweltamt Brandenburg (LUA) (Hrsg.), 1997. Entscheidungsmatrix als Handlungshilfe für die Erhaltung und Wiederherstellung von Bodenfunktionen in Niedermooren. Fachbeiträge des Landesumweltamtes No. 27, Potsdam (in German).
Martin, J.F., Reddy, K.R., 1997. Interaction and spatial distribution of wetland nitrogen processes. Ecol. Model. 105, 1–21.
MELF/MUNR-Steuergruppe, 1996. Leitlinien der ordnungsgemäßen landwirtschaftlichen Bodennutzung. In: Landesumweltamt Brandenburg (LUA) (Hrsg.) (1997): Entscheidungsmatrix als Handlungshilfe für die Erhaltung und Wiederherstellung von Bodenfunktionen in Niedermooren. Fachbeiträge des Landesumweltamtes No. 27, Potsdam (in German).
Mühle, R.U., Burkart, M., Pötsch, J., 1998. On the importance of flooded grassland at the RAMSAR site of the lower Havel River valley for waterfowl. Gibier Faune Savage Game Wildl. 15 (3), 963–972.
Muenier, B., Birr-Pedersen, K., Schou, J.S., 2004. Combined ecological and economic modelling in agricultural land-use scenarios. Ecol. Model. 174, 5–18.
Niehoff, D., Fritsch, U., Bronstert, A., 2002. Land-use impacts on storm-runoff generation: Scenarios of land-use change and simulation of hydrological response in a meso-scale catchment in SW-Germany. J. Hydrol. 267 (1–2), 80–93.
Osman, Y.Z., Bruen, M.P., 2002. Modelling stream-aquifer seepage in an alluvial aquifer: an improved loosing-stream package for MODFLOW. J. Hydrol. 264, 69–86.
Prescott, K.L., Tsanis, I.K., 1997. Mass balance modelling and wetland restoration. Ecol. Eng. 9, 1–18.
Prudic, D.E., 1988. Documentation of a computer program to simulate stream-aquifer relations using a modular, finite-difference, ground-water flow model. U.S. Geological Survey, Open-File Report 88-729, Carson City, Nevada, 119 pp.
Rembe, M., Wenske, D., 1998. The Lake Package—An Additional Boundary Condition For The Modular Three-Dimensional Finite-Difference Ground-Water Flow Model MODFLOW, MODFLOW '98. Colorado School of Mines.

Sanchez-Perez, J.M., Vervier, P., Garabetian, F., Sauvage, S., Loubet, M., Rols, J.L., Bariac, T., Weng, P., 2003. Nitrogen dynamics in the shallow groundwater of a riparian wetland zone of the Garonne, SW France: nitrate inputs, bacterial densities, organic matter supply and denitrification measurements. Hydrol. Earth Syst. Sci. 7, 97–107.
Simunek, J., Vogel, T., van Genuchten, M., 1994. The SWMS-2D Code for Simulating Water Flow and Solute Transport in Two-Dimensional Variably Saturated Media Version 1.2 Research Report No. 132. Department of Agriculture, U.S. Salinity Laboratory, Riverside, California.
Spieksma, J.F.M., Schouwenaars, J.M., 1997. A simple procedure to model water level fluctuations in partially inundated wetlands. J. Hydrol. 196, 324–335.
Sudicky, E., Jones, J., Brunner, D., McLaren, R., VanderKwaak, J., 2000. A fully-coupled model of surface and subsurface water flow: model overview and application to the Laurel Creek watershed. In: Bentley, L., Sykes, J., Brebbia, C., Gray, W., Pinder, G. (Eds.), Proceedings of the XIII International Conference on Computational Methods in Water Resources. Calgary, Alberta, July 26–29, 2000. A.A. Balkema, Rotterdam, pp. 1093–1099.
Schulla, J., 1997. Hydrologische Modellierung von Flussgebieten zur Abschätzung von Folgen der Klimaänderung. Züricher Geographische Schriften, Heft 69.
Schulla, J., Jasper, K., 1999. Modellbeschreibung WASIM-ETH, Zürich.
Sophocleous, M., Perkins, S.P., 2000. Methodology and application of combined watershed and ground-water models in Kansas. J. Hydrol. 236, 185–201.
Sophocleous, M., 2002. Interactions between groundwater and surface water: the state of science. Hydrogeol. J. 10, 52–67.
Toner, M., Keddy, P., 1996. River Hydrology and riparian wetlands: a predictive model for ecological assembly. Ecol. Appl. 7 (1), 236–246.
VanderKwaak, J.E., 1999. Numerical simulation of flow and chemical transport in integrated surface-subsurface hydrologic systems. Ph.D. thesis, University of Waterloo Canada, Deparment of Earth Sciences.
VanderKwaak, J.E., Sudicky, E., 1999. Application of a physically-based numerical model of surface and subsurface water flow and solute transport. In: ModelCARE 99 Conference. IAHS, 265, pp. 515–523.
Vidon, P.G.F., Hill, A.R., 2004. Landscape controls on the hydrology of stream riparian zones. J. Hydrol. 292, 210–228.
Wang, N., Mitsch, W.J., 2000. A detailed ecosystem model of phosphorus dynamics in created riparian wetlands. Ecol. Model. 126, 101–130.
Ward, J.V., 1998. Riverine landscapes: biodiversity patterns, disturbance regimes and aquatic conservation. Biological Conservation 83, 269–278.
Weng, P., Giraud, F., Fleury, P., Chevallier, C., 2003. Characterising and modeling groundwater discharge in an agricultural wetland on the French Atlantic coast. Hydrol. Earth Syst. Sci. 7, 33–42.
Wurster, F.C., Cooper, D.J., Sanford, W.E., 2003. Stream/aquifer interactions at Great Sand Dunes National Monument, Colorado: influences on interdunal wetland disappearance. J. Hydrol. 271, 77–100.