Original Research

Modelling Peatland Hydrology: Three Cases from Northern Europe

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Abstract

Many of the peatlands that used to extend over large parts of Northern Europe have been reclaimed for agriculture. Human influence continues to have a major impact on the hydrology of those that remain, affecting river flow and groundwater levels. In order to understand this hydrology it is necessary to analyze and assess the groundwater and surface water system as a whole. The SIMGRO model was developed for such situations: it simulates groundwater flow in the saturated and unsaturated zones and also surface water flow. Being physically-based, it is suitable for application to situations with changing hydrological conditions and for practical aspects of water management in peatlands. This paper describes the application of the model to different hydrological situations in the Netherlands, Poland and Lithuania. The 3 cases deal with aspects of flooding, natural flow regime and flood storage in relation to suitable conditions for agriculture and nature. The calibration of the model for the cases was limited, but the simulation results show that the estimates of the discharges and groundwater levels were satisfactory, demonstrating that the model is an adequate tool for simulating the hydrological system, and has the potential to assess the impact of different measures. The Dutch case demonstrates that lowland basins where the groundwater has been lowered by extensive land drainage can be restored by restricting the inflow of surface water from the upper parts of the basin: peak flows are significantly reduced. For the Polish case, the damming of ditches in the valley of the Biebrza River could significantly improve the water regime in the peatlands of this floodplain. For the Lithuanian case, the flow regime for the Dovine River could be made more natural if sluice gates were replaced by overflow spill weirs. Understanding the hydrological system is crucial for sustainable land development and effective soil and nature conservation. The different measures simulated in the 3 cases illustrate SIMGRO's potential to simulate hydrological measures.

Keywords: flow regime, groundwater-surface water interaction, nature management, peatland hydrology, SIMGRO model

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Introduction

Over 50% of the area of world wetlands is comprised of peatland [1]. In the past, peatland[1] was generally regarded as wasteland rather than as any special, or even recognizable, part of the natural world. Much of the peatland that used to cover large parts of Northern Europe has been reclaimed for agriculture. As peatlands can store large amounts of water, they help maintain river flows in dry periods. They also contribute largely to the attenuation of flood peaks, thereby preventing flood damage to downstream areas [2]. Also, the high biodiversity is recognized and the storage of carbon is an important function of peatlands. The role of wetlands in floodwater retention has been reviewed by Bullock and Acreman [3]. Joosten and Clarke [4] provide a detailed background on the extent, types, functions and uses of peatlands. They also present a framework for the wise use of peatlands.

The very shallow water tables prevailing in peatlands mean that groundwater and surface water are closely interlinked. Among the key factors affecting the groundwater regime of these areas are the groundwater recharge pattern, drainage conditions and the hydraulic properties of the soil. The hydrology in the unsaturated zone interacts strongly with the phreatic groundwater and surface water locally. Also important is drainage to local depressions and to ditches. Furthermore, there is a spatial relationship with the regional groundwater. And the land-use in peatlands is also important, because evapotranspiration varies with the land cover or crop [5]. Thus any development such as drainage or afforestation, whether natural or human, may impact the groundwater regime, possibly triggering a number of subsidiary impacts such as excessive drying of the soil, soil subsidence and environmental degradation [6].

If peatland is to be conserved, its eco-hydrological functioning (groundwater flow pattern, groundwater quality and surface water conditions) must be assured [7]. It is therefore crucial to understand peatland hydrology. This entails analyzing and assessing the groundwater and surface water system as a whole, not separately, and not decoupling the unsaturated zone from the saturated groundwater system [8, 9]. To do so, an integrated modelling approach on a regional scale is required, combining both groundwater and surface water. Advances in computer technology and the reduction in computational time have made it possible to integrate the subsystems into hydrological response models, such as the well-known SHE model [10]. In order to be able to assess the suitability of hydrological measures to restore or conserve peatland, it is necessary to understand the hydrology of peatlands; this entails modelling the hydrology of the region involved [11]. Furthermore, it is important to use transient modelling [12], as this enables the effect of changes or measures in the system to be predicted on a regional scale. It was for such practical situations that the SIMGRO model was developed and refined [13-15]. Created some 20 years ago, the model simulates the flow of water in the saturated and unsaturated zones and also the flow of surface water. As it is physically-based, it is suitable for application to situations with changing hydrological conditions. The advantages and disadvantages of some models compared to SIMGRO have been described elsewhere [14].

This paper describes three case studies in which the SIMGRO model was used for practical aspects of water management in peatlands. The three case study areas (in the Netherlands, Poland and Lithuania) differed in their hydrology. The underlying premise was that for sustainable land development and effective soil and nature conservation in peatlands such as these, it is crucial to understand the groundwater system and manage it appropriately. The applications therefore investigated aspects of flooding, natural flow regime and flood storage, in order to maintain suitable conditions for nature and agriculture.

[1]Depending on the hydrological situation, peatlands are classified as mires and further defined as bogs or fens. A mire is an area that supports at least some vegetation known to form peat, and usually includes a peat deposit [1, 6]. A bog is fed exclusively by precipitation, but a fen is fed by groundwater too. When flooding from a river occurs, floodplain marshes can also be distinguished.

The Combined Surface and Groundwater Flow SIMGRO Model

In many practical applications, models are used as predictive tools to evaluate various water management measures, policies or scenarios. The SIMGRO (SIMulation of GROundwater and surface water levels) groundwater model we applied to the peatlands has two objectives: systems analysis and prediction. It is a physically-based model that simulates regional transient saturated groundwater flow, unsaturated flow, actual evapotranspiration, stream flow, groundwater and surface water levels as a response to rainfall, reference evapotranspiration, and groundwater abstraction. To model regional groundwater flow, as in SIMGRO, the system has to be schematized geographically, both horizontally and vertically. The horizontal schematization allows different land uses and soils to be input per node, to make it possible to model spatial differences in evapotranspiration and moisture content in the unsaturated zone. For the saturated zone, various subsurface layers are considered (Fig. 1). For a comprehensive description of SIMGRO, including all the model parameters, readers are referred to Van Walsum et al. [15] or Querner [14].

The SIMGRO model is used within the GIS environment Arc view. Via the user interface AlterrAqua, digital geographical information (soil map, land use, watercourses, etc.) can be input into the model. The results of the modelling are analyzed together with specific input parameters.

Groundwater Flow

In SIMGRO the finite element procedure is applied to approach the flow equation which describes transient groundwater flow in the saturated zone. A transmissivity is allocated to each node to account for the regional hydrogeology.

A number of nodes make up a subcatchment, as shown in Fig. 1. The unsaturated zone is represented by means of two reservoirs: one for the root zone and one for the underlying substrate (Fig. 1). The calculation procedure is based on a pseudo-steady state approach, generally using time steps of up to one day. If the equilibrium moisture storage for the root zone is exceeded, the excess water will percolate towards the saturated zone. If moisture storage is less than the equilibrium moisture storage, then water will flow upwards from the saturated zone (capillary rise). The depth of the phreatic surface is calculated from the water balance of the subsoil below the root zone, using a storage coefficient. The equilibrium moisture storage, capillary rise and storage coefficient are required as input data and are given for different depths to the groundwater.

Evapotranspiration is a function of the crop and moisture content in the root zone. To calculate the actual evapotranspiration, it is necessary to input the measured values for net precipitation, and the potential evapotranspiration for a reference crop (grass) and woodland. The model derives the potential evapotranspiration for other crops or vegetation types from the values for the reference crop, by converting with known crop factors [16].

Snow accumulation has been accounted for in the model: it is assumed that snow accumulation and melting is related to the daily average temperature. When the temperature is below 0°C, precipitation falls as snow and accumulates. At temperatures between 0°C and 1°C, both precipitation and snow melt occur: it is assumed that during daylight hours the precipitation falls as rain, whereas precipitation falling during the night accumulates as snow (and the melt rate is 1.5 mm water per day). When the temperature is above 1°C, the snow melts at a rate of 3 mm/day per degree Celsius.

Surface Water Flow

The surface water system in peatlands usually consists of a natural river and a network of small watercourses, lakes and pools. It is not feasible to explicitly account for all these watercourses in a regional simulation model, yet the water levels in the smaller watercourses are important for estimating the amount of drainage or subsurface irrigation, and the water flow in the major watercourses is important for the flow routing. The solution is to model the surface water system as a network of reservoirs. The inflow into one reservoir may be the discharge from the various watercourses, ditches and runoff. The outflow from one reservoir is the inflow to the next reservoir. The water level depends on surface water storage and on reservoir inflow and discharge. For each reservoir, input data are required on two relationships: "stage versus storage" and "stage versus discharge".

Drainage

Watercourses are important for the interaction between surface water and groundwater. In the model, four different categories of ditches (related to its size) are used to simulate drainage. It is assumed that three of the subsystems – ditches, tertiary watercourses and secondary watercourses – are primarily involved in the interaction between surface water and groundwater. A fourth system includes surface drainage to local depressions. The interaction between surface and groundwater is calculated for each drainage subsystem using drainage resistance and the hydraulic head between groundwater and surface water [17].

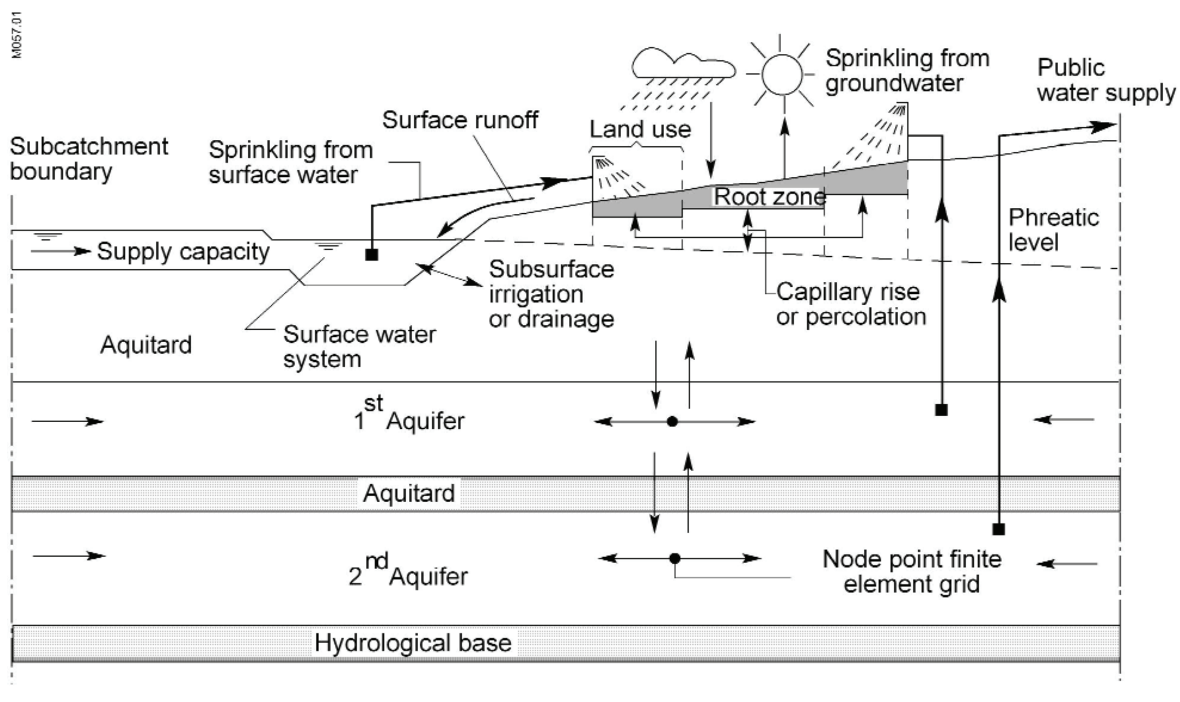

Fig. 1. Schematization of water flows in the SIMGRO model. The main feature of this model is the integration of a saturated zone, unsaturated zone and the surface water systems within a subcatchment [14].

Table 1. Change in discharges (m^3/s) for 2 sub-basins of the Drentse Aa River and the two measures as shown in Fig. 2.

Location	Scenario	Discharge for a given recurrence interval			
		10 years	5 years	1 year	15x/year
Amerdiep	Reference	13.18	9.62	5.42	2.23
	Gates	5.32	4.98	4.60	2.25
	Reduction (%)	60	49	15	-1
	Shallower streams	10.08	9.06	4.99	2.25
	Reduction (%)	24	7	8	-1
Anreeperdiep	Reference	9.12	5.81	3.38	1.47
	Gates	6.97	3.74	3.02	1.48
	Reduction (%)	24	36	8	0
	Shallower streams	8.48	5.53	3.44	1.43
	Reduction (%)	7	4	2	1

Linkage of Groundwater and Surface Water Modules

As the groundwater part of the model reacts much more slowly to changes than the surface water part, each part has its own time step. As a result, the surface water module performs several time steps during one time step of the groundwater module. The groundwater level is assumed to remain constant during that time and the flow between groundwater and surface water accumulates using the updated surface water level. The next time the groundwater module is called up, the accumulated drainage or subsurface irrigation is used to calculate a new groundwater level.

Case Studies

In common with most peatlands in Northern Europe, the three peatlands in our case studies have been affected by human influences such as drainage (which lowers the groundwater), or landuse change. Changes in river flows can further affect the peatland. If natural succession is allowed to run its course, trees, bushes and reeds will tend to encroach and their increased water consumption (evapotranspiration) may cause groundwater levels to fall. To protect the natural value of peatlands, the groundwater level must be near the ground surface throughout the year and the inflow of water of inferior quality from other regions must

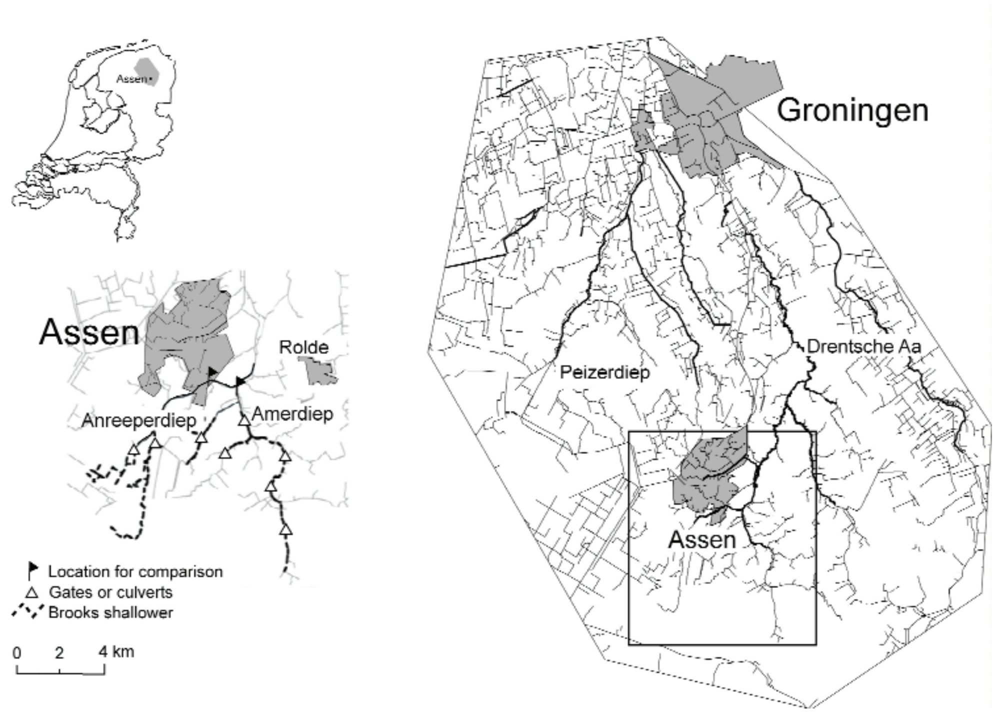

Fig. 2. Location of the Drentse Aa modelling area and the main watercourses in the northern part of the Netherlands. Detailed map shows the upper part of the basin where measures were considered.

be minimized. In our case studies, we evaluated various types of measures needed to achieve the required or optimal hydrological situation. In each case study we used digital data to model the spatially distributed features.

Case Study 1: Drentsche Aa River, the Netherlands (Flood Storage)

There was exceptionally wet weather in the Netherlands in 1993 and 1995, and the exceptionally wet autumn of 1998 resulted in areas in the north of the country being inundated and large cities being seriously at risk of flooding. A rethink of the measures to prevent flooding was clearly necessary: in particular, there was a need for more storage of flood water. A nation-wide study "Water Management in the 21st Century" was carried out [18]. Its analysis of measures designed to retain water in six basins across the Netherlands resulted in the adoption of a policy to retain more water in river basins in order to avert flooding in low-lying areas further downstream. One of the problems to be overcome as part of an integrated river basin management plan for the north of the Netherlands is how to reduce the peak discharge: specifically, how to retain more water in a basin. To this end, a project was carried out to assess the feasibility of retaining water in the upper part of two Dutch river basins [19, 20]. This project serves as the first case study described in the present paper. Below, we describe briefly the schematisation of the study area and the input data, before focuzing on the scenarios and results.

Study Area and Model Schematization

The area modelled covers 1200 km^2 and is in the northern Netherlands (Fig. 2). The area of main interest is approximately 750 km^2 and covers the basins of the Drentsche Aa River and Peizerdiep. In these basins the gradient is from 24 m above MSL in the south to about 1 m below MSL in the north. The soils of the higher-lying areas are sandy. The stream valleys and lower-lying areas include clay and peat. The land use is predominantly agriculture or forest. About 42% is under pasture, 24% is arable, 18% is woodland, 11% residential and 5% is other [19].

In order to use the SIMGRO model, the groundwater system needs to be schematized by means of a finite element network. The network is comprised of 49,050 nodes; the internodal distance was about 200 m in the area of interest and 75 m in the stream valleys. For the modelling of the surface water, the basin was subdivided into 5,625 subcatchments. Because of the height difference of about 25 m, past weirs were built to control the water level and flow. Most of the weirs are adjustable, so that in the summer the water level can be raised. The lower-lying area that is at or below sea level consists of polders; here, pumping stations are deployed to maintain the appropriate hydrological conditions for agriculture and nature.

The geology of the area is quite complex, due to influence from the Pleistocene period, permafrost, tectonic movements, peat layers and influence from wind and water [19]. A major influence on the groundwater flow patterns are the impermeable layers of boulder clay, which result in large areas with perched water tables. The groundwater system in the model consists of four aquifers alternating with three less permeable layers, the second of which is the boulder clay. The interaction between groundwater and surface water is characterized by drainage resistance that is derived from hydrological parameters and the spacing of the watercourses.

The standard SIMGRO model was unable to simulate the perched water tables on the boulder clay (model layer 2): it generated phreatic groundwater levels that were 1-3 m too low over large areas. Therefore the model was improved, using the hydraulic head below and above the boulder clay and adjusting the vertical resistance so that the flux through this clay layer would be simulated correctly. In addition, the storage coefficient above and below the clay layer was changed during the calculations, depending on whether or not a perched water table was present.

Simulations were carried out for a period of 10 years (1989-99). The results were compared with measured river discharges for nine locations; data from about 800 piezometers were used to compare groundwater levels in the different aquifers [19]. After the model had been improved to simulate perched water tables, the phreatic levels it calculated were close to the measured levels, even for the deeper aquifers. It was therefore concluded that the model was sufficiently reliable to be used to assess various possible measures for mitigating hydrological problems.

Mitigation Measures and Their Impact

Two mitigation measures to reduce the peak discharges to acceptable volumes were assessed:

- Restriction of peak discharges.

Peak flows can be restricted by installing sluice gates or culverts of such a dimension that only peaks above a certain height are reduced. In the simulations, these constructions were effective when the flow exceeded the return frequency of one day a year.

- Making the streams shallower.

Reducing the depth of the watercourse will cause water to overtop the banks sooner, resulting in more water being stored on the floodplain. As a result of the latter, the flow propagations will be reduced and thus the peak flow will also diminish.

The upstream part of the Drentsche Aa, where these measures were modelled, is shown in Fig. 2. At eight locations the flow was restricted and over a length of 29 km the streams were made shallower. Table 1 gives the results for the two sub-basins; it gives the discharge for the reference situation, the two measures and the change in flow. The measures have no influence on the low flows (column 15x/year). The flow with a return frequency of 10 years is more affected and the extreme floods are reduced the most.

Table 2. The effect of simulations on average groundwater levels in summer for the Biebrza valley.

Scenario	Area with rise in groundwater level (%)	Description
0	–	Present state used as reference
1	37	Damming ditches in Bagno Lawki (see Fig. 4)
2	30	Narrower cross-section of Biebrza River at 2 locations
3	72	Removal of all deciduous forest and replaced by intensive meadows in 44% of the valley

The first measure (restriction of peaks) has more impact than the second (shallower streams). Limiting the flow by introducing gates or culverts reduces peak flow by 25-50%. The large variation depends on local conditions and the number of structures in the stream. Limiting the flow has very little influence on groundwater levels, because the water flow is only obstructed for some days or weeks. Local flooding may occur, causing groundwater levels to rise. This small and short-lived rise, often in winter, has no apparent effect on agriculture or nature.

Making the stream shallower reduces peak discharges by 5-20% (Table 1), with the result that water levels are higher both in wet and in dry periods. The reduction in flow is mainly caused by the water overtopping the river banks and flooding the valley – which results in higher water tables adjacent to the stream. In general, these higher levels are likely to benefit nature conservation by leading to the presence of rare and protected marsh species.

If both measures are introduced, the peak flows will be reduced and the discharge will be spread over a longer time period. As an example, in Fig. 3 the flow situation is given for October and November 1998, a period when there was abnormally heavy rainfall in the northern part of the Netherlands. Fig. 3 shows the calculated discharge for the reference situation and for the scenarios with the mitigation measures. In the reference situation the duration of the high flow is about one week, but after flow restriction the maximum flow is much smaller, as it is spread over a period of 2.5 weeks. When the streams are made shallower, the maximum peak diminishes, but the flood wave looks similar to the reference situation.

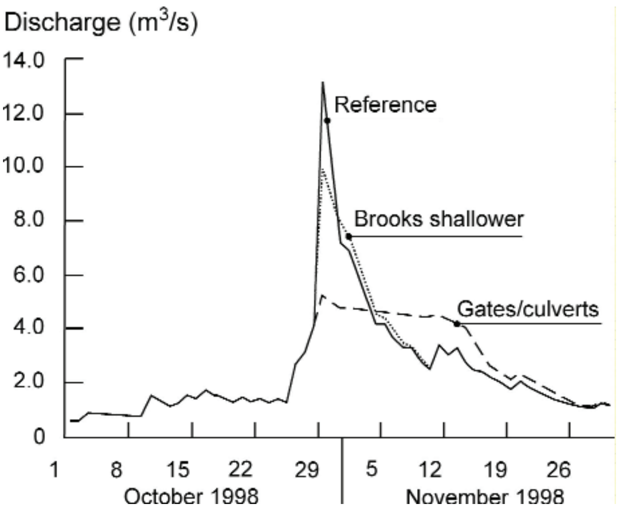

Fig. 3. Discharges for reference situation and the two measures for an extreme wet period in 1998.

Case study 2: Biebrza River, Poland (Eco-Hydrological Conditions)

This case study focused on different management measures and how they influence the hydrology of the Biebrza peatlands, Poland. One of the undesirable ecological developments in the area is excessive drying-out of the soil in response to drainage works carried out in the past; as a consequence, open areas are being rapidly encroached by scrub [21]. The solution is to reverse the effects of the drainage works. Agricultural developments in the surrounding area pose another threat, since increased nutrient input will endanger the peat-forming mesotrophic ecosystems. The flora and fauna are already degrading [7]. To counterbalance these negative effects, the aim is to restore the natural hydrological regime.

Study Area and Model Schematization

Biebrza National Park (BNP), situated in northeastern Poland (Fig. 4), is a unique environment of wetlands with very well developed zones of peat ecosystems. The Biebrza River is 165 km long, and its wide valley contains peat fens, hay meadows and woodland. The discharge of the river fluctuates during the year: almost every spring when the snow melts, the discharge increases and the valley floods.

The area modelled (1,250 km^2) was the Lower Biebrza valley and part of the adjacent upland. The gradient of the river valley slopes from about 109 m above MSL to about 101 m above MSL in the south at the confluence with the Narew River. The vegetation cover in the valley is about 51% meadow, 44% forest and 5% reedbeds [22]. For the groundwater the modelled area was schematized with 7,854 nodes spaced about 400 m apart. For the surface water the area was subdivided into 569 subcatchments. The saturated zone was divided into two layers: a peat layer overlying an aquifer comprised of sandy soil. The peat layer was considered to be an aquitard ranging in thickness 0.5-2.0 m; the underlying aquifer is 20-50 m thick and has a transmissivity of about 100-300 m²/day. The model was calibrated for the meteorological conditions of 1994-96, using measured discharges of the Biebrza River and also data on surface water levels and groundwater levels measured at different locations [23].

Mitigation Measures and Their Impact

Two types of management measures were investigated: damming drainage ditches and a change of land use. The objective was to find which measure would raise the groundwater level in the Biebrza valley [24]. Three scenarios were investigated. The first was to block the drainage ditches in the Bagno Lawki area (Fig. 4). The second scenario involved constricting the cross-section of the channel of the Biebrza River at two locations. The third scenario was to remove all the deciduous forest in the valley. Calculations for all scenarios were performed using six years of meteorological data (1990-95). Table 2 gives the results of the scenarios, presented as percentages of the area of the Lower Biebrza Valley where the groundwater level would rise in summer (Table 2). Damming all the small ditches in Bagno Lawki would raise the groundwater level over 37% of the area of the valley floor, greatly improving the soil moisture: there will be significant improvement for almost the entire area of Bagno Lawki. Fig. 5 shows the extent of this rise in groundwater level for scenario 1. The rise of groundwater can be observed during the whole year. Outside the Bagno Lawki area the rise is negligible, partly because of the schematization of the peat layer as an aquitard and the sandy layer below as an aquifer. Any rise in phreatic groundwater level influences neighbouring areas via the first aquifer. Narrowing the Biebrza River would also result in a marked rise (by 30%) of the groundwater level during summer. Both measures would also affect the extent of spring inundation.

The third scenario, the removal of all deciduous forest in the valley, would cause the groundwater level to rise over 72% of the valley floor – a much larger area than the deforested area. During the summer the water level would be about 0.45 m higher than in the reference situation. This measure would therefore be more effective than the other two measures.

During spring, the snow melts and the river valley floods. As an example, the groundwater and surface water levels for a location on the floodplain close to the Biebrza River are shown for 1993 and 1994 (Fig. 6). The location of this node (node 6633) is shown in Fig. 4. During summer, the surface water level in the Biebrza River is lower than the groundwater level of the floodplain. In spring, when the surface water level rises above ground level (101.48 m above MSL), the calculated surface and groundwater levels are the same and the model correctly simulates the storage of water on the floodplain. This situation occurred twice in spring 1993 (Fig. 6). Only a hydrological model in which surface water and groundwater are integrated is able to simulate such situations correctly.

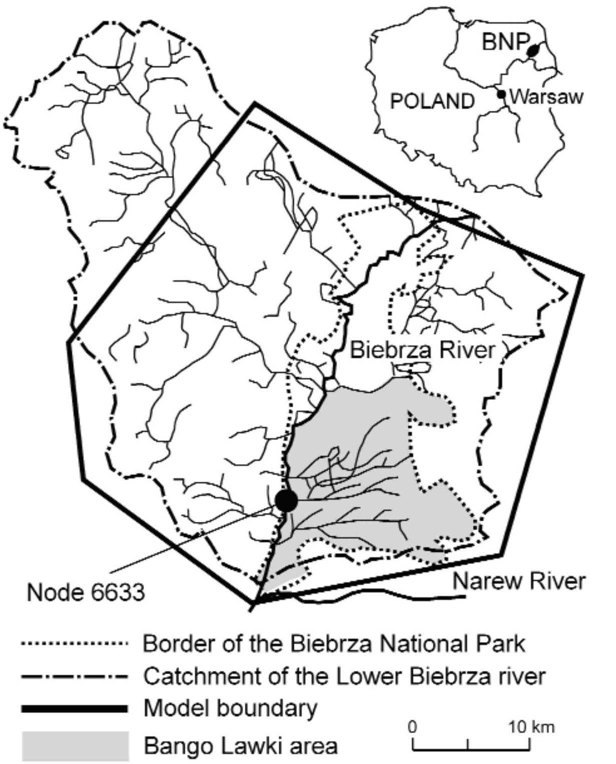

Fig. 4. The Lower Biebrza Basin in northeastern Poland.

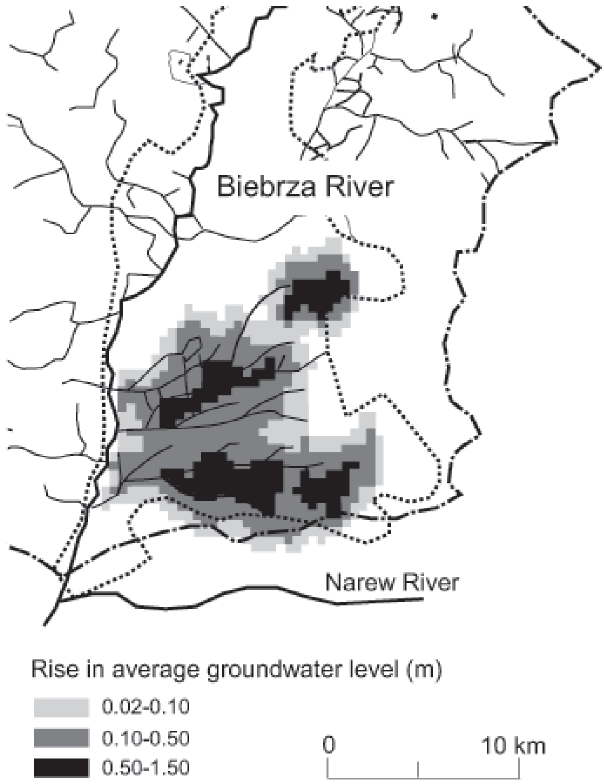

Fig. 5. Rise in average groundwater levels in summer for scenario 1 (damming ditches).

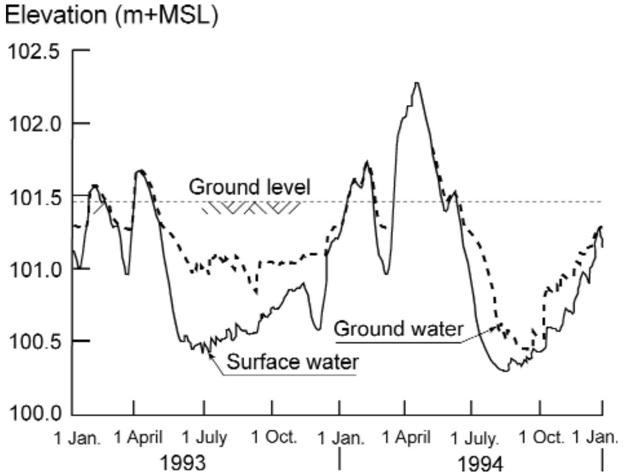

Fig. 6. Simulated groundwater and surface water levels during 1993 and 1994 for node 6633 (for location of node see Fig. 4).

Case Study 3: Dovinė River Basin, Lithuania (Natural Flow Regime)

The second half of the 20th century saw large-scale agricultural expansion on the fertile peat soils in the Dovinė River basin, Lithuania [25]. At the same time, the water regime of the river was significantly altered. Sluice-gates were built at the outlets of the lakes in the basin so that water could be retained in spring and then released in summer for irrigation. The changes in the hydrology have caused biodiversity to decline. The ongoing deterioration of the lakes and wetlands needs to be addressed. In the past, the lakes were not seen as an integrated part of the Dovinė River basin and it was not realized that solutions for the lakes have to be found at basin level. Therefore, the general objective of the research was to evaluate the impact of different water management alternatives on water regime restoration in the Dovinė River and its lakes.

Study Area and Model Schematization

The Dovinė River Basin covers an area of 588 km^2 and is located in the southern part of Lithuania (Fig. 7). The basin is the right-bank tributary of the Šešupė River and comprises a network of rivers and water bodies formed by five big lakes, a number of streams and small ponds. The Dovinė River basin contains one of the most important and most threatened nature reserves of Lithuania: the Žuvintas [26]. Adjacent to Žuvintas Lake are extensive bog and fen areas of the Amalvas wetland complex. Žuvintas lake is shallow and is rapidly shrinking in size due to massive overgrowth by aquatic plants. Land use in the basin is predominantly agricultural: about 46% is arable, 16% is pasture and meadows, 14% is natural wetlands (including wet forest), 9% is forested and 3% is built-up. The country gradient in the Dovinė basin slopes from about 185 m above MSL in the south to about 75 m above MSL at the outlet of the river.

A SIMGRO model application was built for the entire Dovinė River basin, covering an area of approximately 600 km^2 [27]. The finite element network covering the basin comprised of 4370 nodes spaced about 400 m apart. The peat layer of the Amalvas and Žuvintas bog was considered to be an aquitard with a thickness of 2-4 m and a resistance in the order of 400 days [27]. The underlying aquifer extends throughout the whole basin and has a thickness of 40-80 m and a transmissivity of 20-65 m^2/day. For the modelling of the surface water the basin was subdivided into 460 subcatchments; the schematisation also included the sluice-gates.

The SIMGRO model was calibrated with the available meteorological information and water levels measured in Dusia and Žuvintas Lakes for the period 1996-2002. The groundwater levels and the surface water level dynamics in the lakes during this period were statistically analyzed. Model verification was performed using information collected for the period 2003 to 2005. The comparison of measured and simulated discharges, groundwater levels and lake water levels revealed that there were differences. However, in spite of some inaccuracies, the SIMGRO model proved to be a useful tool to predict groundwater movement and its interactions with surface water in the Dovinė River basin. For a more detailed description on model performance, and the calibration and verification procedures, see Povilaitis and Querner [27].

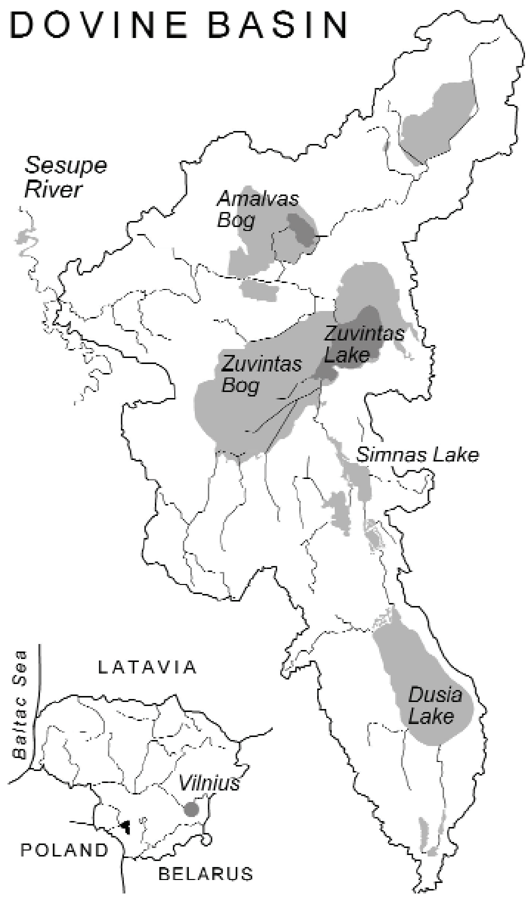

Fig. 7. Location of the Dovinė River basin and the Žuvintas Lake in the south of Lithuania.

Mitigation Measures
and Their Impact

Water management measures are focused on the entire Dovinė basin, with particular attention on Žuvintas Lake and its wetland complexes. Given the aim of making the Dovinė River runoff regime more natural, different scenarios were analyzed to ascertain the impact of changes of the river regime on the water levels in Žuvintas Lake and adjacent wetlands [27]. Model simulations were performed for the period 1994-2005.

The present situation was considered as the reference situation: it reflects the present water management practices in the Dovinė River Basin as well as their impact on surface water and groundwater characteristics. The simulation results showed that under the present conditions, the average groundwater level in the Žuvintas wetland in summer is at a depth of 0.30-1.20 m. In winter the depth of the average highest water level ranges from 0.12 to 0.25 m.

Preliminary simulations showed that it is impossible to restore the water regime in Žuvintas Lake entirely by removing the sluice-gates downstream. Such a measure would lower the water level in the lake by more than one metre and consequently destroy it. Therefore, to improve the hydrological situation along the Dovinė River, the scenario analyzed involved replacing the sluice gates by overflow weirs designed to release a minimum flow during dry periods whilst ensuring that the water level does not fall so low that large areas near the shore are too shallow. This situation was evaluated by adjusting the stage-discharge (Q-h) relationship of the lake outlet. For the case of Žuvintas Lake this was considered to be an effective measure for achieving partial naturalization of hydrological regime and for minimizing the impact of human interventions. The simulations showed that the specially designed overflow weirs would raise the water level in Žuvintas Lake by 0.05 m on average. During dry periods the rise is expected to be in the order of 0.1 m, compared to the reference scenario.

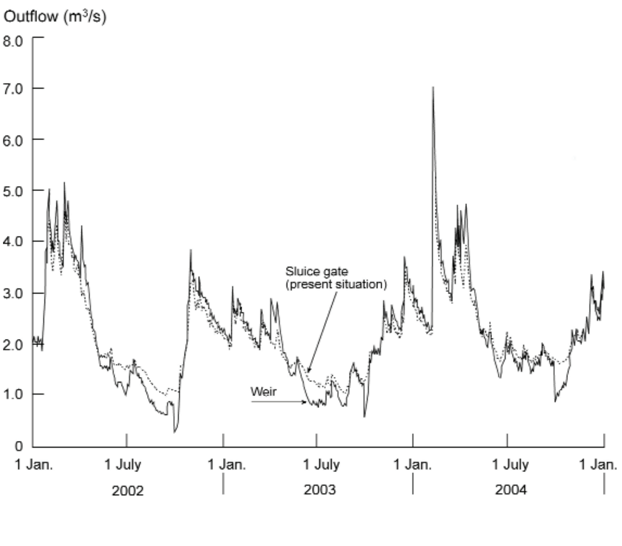

Fig. 8. Changes in outflows from Žuvintas Lake after replacing the sluice-gates (present situation) with a weir.

The groundwater level in the Žuvintas wetlands would also rise. The changes in water levels would also affect outflow. Though the average daily outflow from the lake would remain about the same (Fig. 8), the average outflow during the driest 30-day period would increase by 45%. Maximum peak outflows are expected to decrease by 10% on average. Seasonal outflow conditions would also be affected: in winter and during the spring floods, the outflows would be 6% and 10% smaller, respectively. However, during summer and autumn the outflows would increase: by 17 and 11%, respectively. It was concluded that if accompanied by agro-environmental measures in the catchment, the partial flow naturalization would be a feasible measure to improve the situation in the lake.

Discussion and Conclusions

In all three case studies, human influence has had major impacts on the peatlands: on the one hand through changes in stream flow and on the other hand through lowering of groundwater levels. In order to restore the ecosystem it is necessary to restore pristine hydrological conditions. However, many of the physical changes are irreversible and have to be taken for granted when assessing the quality of the peatlands.

The important processes included in the SIMGRO model are based on physical hydrological concepts. Beven [28] formulated various fundamental problems in the application of physically-based models on a regional scale. One problem is that the equations in such models are based on small-scale homogeneous conditions, so the model schematization must be for small-scale units. This applies particularly to parameters or processes that are non-linear in relation to other parameters, such as the flow of water in the unsaturated zone. The physically-based approach is the best way to proceed in the field of numerical simulations. Models based on this approach are the only ones that can be used in situations with changing conditions which affect the hydrological system. Examples of such changing conditions are land use, groundwater abstraction, drainage activities, discharge characteristics, etc.

The SIMGRO model, like all other models, is a simplified representation of the complex hydrological system. These simplifications of reality impose restrictions on the use of a model. In turn, there is always a temptation to increase the detail of the schematization in order to improve the results. A more detailed schematization requires more input data. Though the calibration of the SIMGRO model was limited, the simulation results show that the model gives satisfactory estimates of the hydrological situation. The fact that the model was able to simulate stream flow and groundwater levels in the three cases with different land use and climate conditions demonstrates that it is an adequate tool for simulating the hydrological system, and has the potential to assess the impact of different kinds of measures. The different measures simulated in the 3 case studies gives an idea of the possibilities of the model.

The cases reported in this paper show that in order to simulate the effect of measures in peatlands adequately, the model must be comprehensive and integrate surface water and groundwater, because the candidate measures impact significantly on surface water levels and on shallow groundwater conditions. The integration of groundwater and surface water in the model enables water to be stored intermittently as groundwater or, during wet periods, as surface water (Fig. 6). This is crucial in order to simulate the behaviour of flood plain marshes satisfactorily. If sub-models for unsaturated flow, crop evapotranspiration and surface water flow had been excluded (which is the case in groundwater models that solely consider the saturated zone) the conclusions would have been spurious.

The Drentse Aa case demonstrated that ecosystems in lowland catchments where the groundwater has been lowered as a result of extensive land drainage can be restored by restricting the inflow from the upstream areas: the peak flow is significantly delayed as a result. Limiting the flow by introducing gates or culverts produces a considerable decrease in peak flow. Making the stream shallower results in a smaller reduction of peak discharges. For extreme situations it is also possible to use measures to reduce peak flows that have a recurrence of once in 10 or 50 years: this entails explicitly tolerating local flooding in the upper parts of a catchment where most of the land is agricultural, instead of flooding the densely populated areas further downstream.

For the Biebrza case, the implementation of different kinds of measures based on damming ditches or changes in land use would significantly improve the water regime in the river valley. Damming a number of canals and ditches would produce a noticeable effect over a large area and would also improve soil moisture conditions. The area inundated in spring would also increase, opening up the possibility of conserving peat soils and conserving rare plant communities. In order to manage the wetland area appropriately, the impact of management measures that will influence the groundwater and surface water levels, such as damming canals or mowing of open meadow area, must be accurately estimated. The study revealed the great effect of land use changes on groundwater levels: if the forest is removed, groundwater will rise appreciably, especially during the summer.

In the case of the Dovinė River, the simulation revealed the impossibility of naturalizing the hydrological regime in Žuvintas Lake by removing the weirs. Such a measure would result in very shallow water levels and destroy the lake. It is clearly necessary to continue to dam the lake in order to prevent it from drying up and the water table falling too low in adjacent wetlands; the Žuvintas water regime has been modified to such a degree that the changes are irreversible. Some naturalization of the flow might be achieved by reconstructing the sluice-gates and installing a specially designed overflow spill-weir. This would raise the water level in the lake and surrounding wetlands and make outflow conditions more natural.

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