Batelaan, O. and Kuntohadi, T., 2002, Development and application of a groundwater model for the Upper Biebrza River basin. Annals of Warsaw Agricultural University – SGGW, Land Reclamation no. 33, p. 57- 69.

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Development and Application of a Groundwater Model for the Upper Biebrza River Basin

Abstract

A groundwater model has been developed for the Upper Biebrza Basin (Poland). The Upper Biebrza Basin contains highly ecologically valued wetlands. Purpose of the groundwater model is to explore the groundwater feeding and system of the wetlands. Important aspects of this system analysis are the determination of the location and the quantification of the groundwater discharge to the river valley. The groundwater model has been set up by using the MODFLOW interface GMS in combination with Geographical Information System analysis. A description is given of the hydrogeology of the area, the modeling tools, the conceptual model, the boundary conditions and measured and derived field data. The first results of the groundwater flow simulation are discussed. The simulated phreatic water table and areas of groundwater discharge show good agreement with respectively measured heads and occurrence of peat.

Key words: Upper Biebrza basin, wetlands, groundwater modeling, MODFLOW, baseflow, groundwater discharge.

Introduction

The unique European ecological value of the Biebrza Wetlands has been described in detail (Wassen and Okruszko, 1994ab; Wassen, 1996) as well as its possibility to be used as a reference area for nature development or restoration in similar environments (Bootsma et al., 2000). Its value is a result of a combination of the relatively extensive use of the area, the occurrence of large peat deposits and the yearly natural large flooding (up to kilometres width) that occurs in the Lower and Central Basin and moderate flooding (tens of meters width) in the Upper Basin. Almost the total valley of the Biebrza River belongs to the Biebrza National Park (BNP). The values of the wetlands are threatened by degradation of the peatlands due to a changing water management (Okruszko, 1990) and eutrophication due to effluent waste-water discharge (van de Perk, 1994).

Pajnowska et al. (1984) realised the importance of the groundwater flow as the main source of wetness of the Biebrza valley: Groundwaters of all water-bearing beds flow from a plateau towards the Biebrza River. The underground feeding and very slow outflow are the main reason for a constant excessive wetness of the Biebrza ice-marginal valley. Observations at measuring stations proved that the Biebrza and its tributaries drain the groundwater of the surrounding area. Only during spring freshets of surface waters, the underground water outflow into the streams can be stopped or the river waters can infiltrate into the alluvia. A detailed recognition of the draining, and particularly its quantitative evaluation is not possible now as the hitherto observations have not been carried out for a sufficient long time (Pajnowska et al., 1984).

Bleuten and Schermers (1994) developed a MODFLOW groundwater flow model for a part of the Middle Basin to simulate the effects of various water management scenarios for the Woznawiejski Canal on groundwater levels in the adjacent peatlands. Ślesicka and Querner (1999) describe a SIMGRO groundwater model for the entire Middle Basin of Biebrza. By way of several scenario simulations the effect of changing the surface water management was investigated.

So far, no groundwater model has been developed for the Upper Basin. The purpose of this study (Kuntohadi, 2001) is therefore a groundwater system analysis of the Upper Biebrza Basin by combining groundwater simulation with Geographical Information System analysis. Most important aspect of this system analysis is the quantification of the groundwater discharge to the river valley. In this article the set-up and first results of the groundwater flow simulation will be discussed.

Materials and Methods

The Biebrza Valley is situated in North-eastern Poland (22^{o}30’ – 23^{o}60’ E and 53^{o}30’ – 53^{o}75’ N). The Biebrza drainage basin is subdivided by morphological features into three parts, defined as the Upper, Middle and Lower Basin (Okruszko, 1990). Biebrza Basin is a vast depression, running from northeast to southwest with its very origin already from the middle polish glaciation. More recent it acted as a side valley and then as an ice-marginal valley. Most area of this valley is now occupied by a peaty flood plain (Pajnowska et al., 1984). The Upper Basin area covers 843 km^2 (Fig. 1).

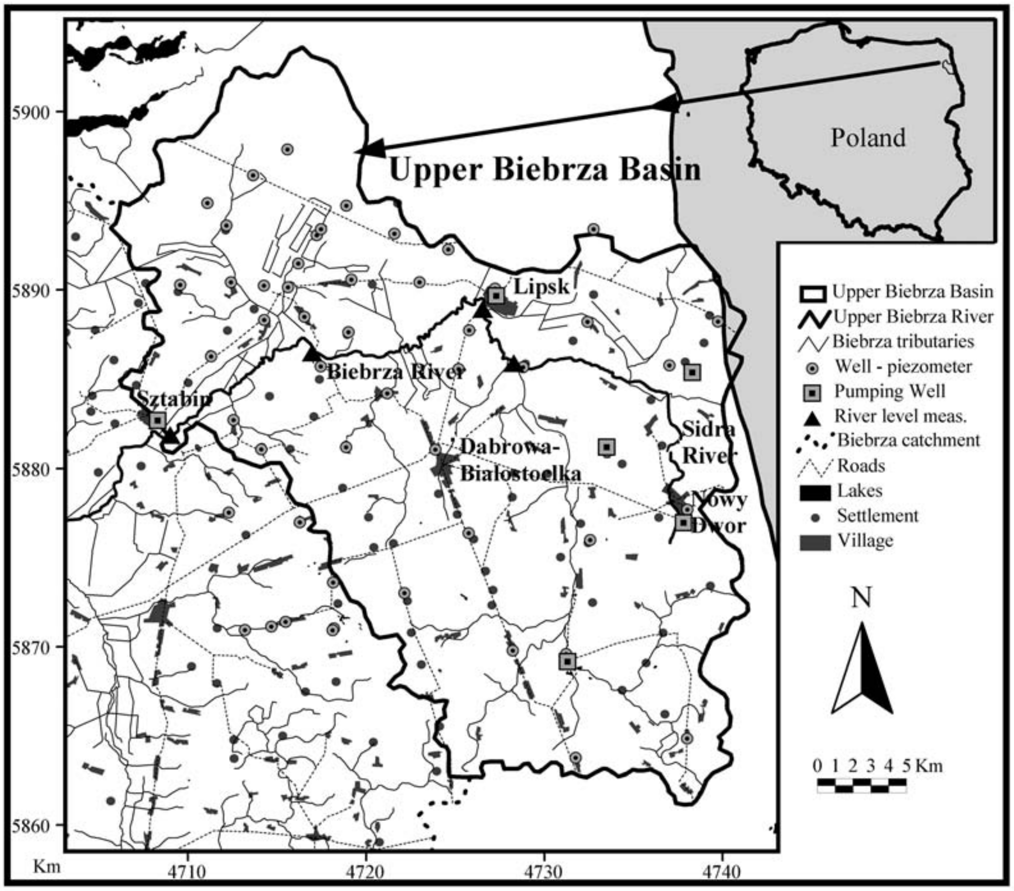

Figure 1: Upper Biebrza Basin

From an available meteorological time series of Biebrza-Pieńczykówek (Middle Basin) the mean annual temperature for the period 1991-1997 is determined as 6.9 °C, the mean annual precipitation for the period 1987-1997 is 528 mm. Kossowska-Cezak (1984) shows that for the same station the precipitation for the period 1951-1965 is 541 mm/year, while from the stations Sztabin, Dębowo and Rózanystok the precipitation for the Upper Basin for this period is around 470 mm/year. The basin is sparsely populated, agriculture is not intensive and large parts of the up-lands are still covered by forest.

Żurek (1984) describes the geomorphology and geology of the Upper Biebrza Basin. It consists of three geomorphologically different elements: the valley, outwash and morainic plateau. The valley is a relatively narrow (1-3 km) and 40 km long trough or fluvial glacial channel that widens only in its middle part near Lipsk. The flat and completely with peat covered valley bottom is situated at about 130 m at the state border and drops gradually to 116 m at the mouth of Brzozowka River. The peat valley joins, at its northern edge, with the flat sandy plain of the southern lake-less part of the Augustów outwash. The latter is a fan-like feature, 40 km wide and 10-12 km of meridional spreading. The morainic plateau is positioned 10-20 m above the valley and outwash. In the south Biebrza is delimited by the Białostocka Plateau and at the northern part of the valley, separating it from the outwash, by the Sztabińska, Jastrzębska, Nowolipska and Lipska morainic plateau islands (Żurek, 1984).

No borehole records of the study area could be obtained. Due to the scarce settlement and use of the Biebrza valley, hydrogeologic knowledge of the Biebrza valley is poor (Pajnowska et al., 1984). However, a geological map with cross-sections and some articles describing the (hydro)geology were available (Malinowski et al., 1970; Żurek, 1984; Pajnowska et al., 1984; Okruszko, 1990). Fig. 2 shows an example of a geological cross-section through the area (Malinowski et al., 1970). The wide varieties of sediments are deposited during different glacial and interglacial periods. The geological structure of the three geomorphological features are different, hence they are of different significance for the conveyance and concentration of water, resulting in varying bog development inside the basin. The morainic plateaus are composed of gravel-sands, while tills are common in lower edges of the plateau or at valley slopes. The outwash consists of more homogeneous fine, medium and coarse sands interbedded with gravels. The flood plain of the valley is entirely occupied by thick peat beds (3-6 m), partly underlain by gyttja. They both overlie up to 10 m of thickness a sandy gravel bed and form together a single water-bearing layer. Due to a considerable incision the Biebrza valley drains the mostly confined groundwater of the surrounding plateau and of the outwash. Therefore, all three described morphologic elements create a complex system, in which the highest plateau and the sloping outwash transmit their surface and groundwater to the valley (Żurek, 1984).

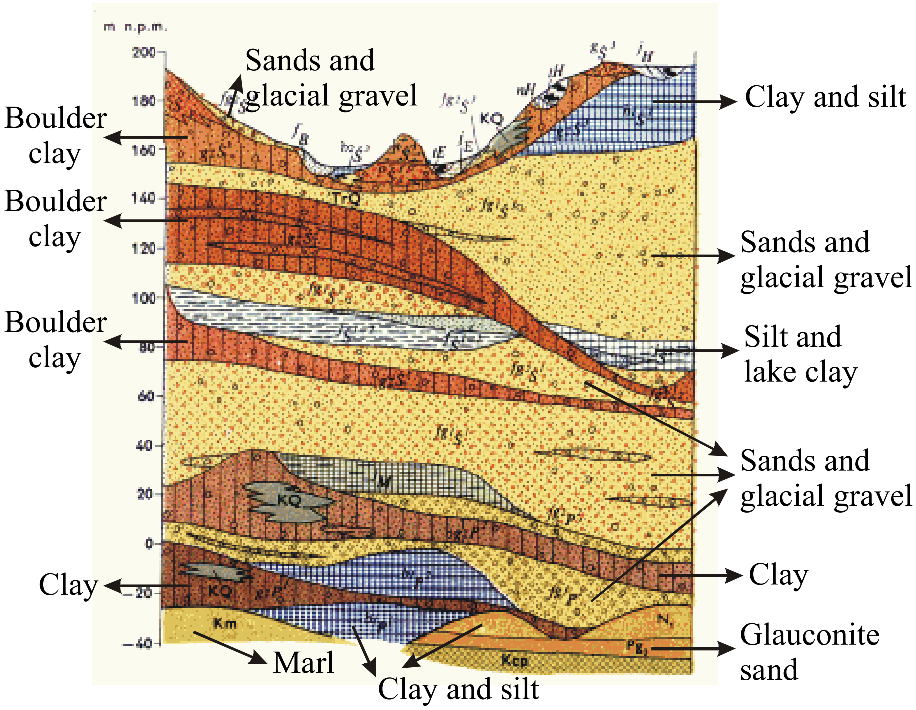

Figure 2: Geological Profile of Upper Biebrza Basin (Malinowski et al., 1970)

Groundwater level and quality measurements at 57 house wells have been performed in the field during three measurement campaigns in September 1999, May 2000 and May 2001. Topographic profiles at different locations in the Biebrza valley have been determined by total station measurements and theodolite levelling. Surface water levels and discharges have also been measured during the three measurement campaigns (Huygens et al., 2000; Chormanski, 2001).

Groundwater Modelling System (GMS) is an advanced, powerful, and comprehensive interface to different models, among others the groundwater modelling code MODFLOW (Harbaugh and McDonald, 1996). GMS offers the conceptual model approach as an efficient tool for building realistic, complex models. The conceptual model is a detailed model description by using GIS objects of sources/sinks, boundaries, recharge, evapotranspiration and layer material zones, independently of a grid or mesh. Once the conceptual model is complete, a grid or mesh is automatically constructed to fit the conceptual model, and the model data are converted from the conceptual model to the cells of the grid (Brigham Young University, 2000). MODFLOW, by using a finite difference technique, describes the groundwater flow in three dimensions, with constant density:

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)-W=S_s\frac{\partial h}{\partial t} \qquad (1)$$

Where K_{xx}, K_{yy}, K_{zz} is the hydraulic conductivity for x, y and z direction [L/T], h is the hydraulic head [L], W is the volumetric flux per unit of volume [T^{-1}], Ss is the specific storage coefficient [L^{-1}], t is time [T].

Different packages describe the stresses applied to the system by wells, rivers, drains, etc. (McDonald and Harbaugh, 1988). The purpose of River Package is to simulate the effects of the flow between surface-water features and groundwater systems. It assumed that measurable head loss between the river and the aquifer is limited to those across the streambed layer and that the underlying model cell remains fully saturated. Under these assumptions, flow between the river and the groundwater system is given by:

$$QRIV=\frac{KLW}{M}(HRIV \quad h_{i,j,k}) \text{ or } QRIV=CRIV(HRIV \quad h_{i,j,k}) \qquad (2)$$

Where QRIV is the flux between the river and the aquifer [L^3/T], HRIV is the head in the river [L], CRIV is the hydraulic conductance of the stream-aquifer interconnection [L^2/T], defined by the parameters: K, the hydraulic conductivity of the riverbed material [L/T], L and W, respectively the length and width of the river reach in the cell [L] and M the thickness of the riverbed [L]. $h_{i,j,k}$ is the head at the node in the cell underlying the river reach [L]. The Recharge Package simulates uniform or distributed recharge to the groundwater system.

The Well Package is designed to simulate features such as wells which withdraw water from the aquifer at a specified rate during a given stress period, where the rate is independent of both the cell area and the head in the cell. The Drain Package is designed to simulate the effects of features such as agricultural drains. The drain removes water from the aquifer at a rate proportional to the difference between the head in the aquifer and the level of the drain, as long as the head in the aquifer is above the drain level. The drain has no effect if the head falls below its level. The drain function is described by the equation:

$$QD_{i,j,k} = CD_{i,j,k}(h_{i,j,k} \quad d_{i,j,k}) \qquad \text{for} \qquad h_{i,j,k} > d_{i,j,k} \tag{3}$$

$$QD_{i,j,k} = 0 \qquad \text{for} \qquad h_{i,j,k} \leq d_{i,j,k} \tag{4}$$

Where QD is the discharge from the drain [L^3/T], $h_{i,j,k} - d_{i,j,k}$ is the head difference between the aquifer and the position of the drain [L], CD is a lumped conductance [L^2/T] describing head loss between the drain and the region of cell. The Drain Package can be used to simulate spatially distributed groundwater discharge in wetlands. However, Batelaan and De Smedt (1998) showed disadvantages in the use of the Drain Package and developed an alternative and more robust Seepage Package for seepage to wetlands.

For evaluation of the simulated head with the measured heads from piezometers the mean error, mean absolute error, and root mean squared error can be defined. The mean error is defined as:

$$ME = \frac{1}{n}\sum_{i=1}^{n}(h_c - h_o)_i \tag{5}$$

The mean absolute error is defined as:

$$MAE = \frac{1}{n}\sum_{i=1}^{n}\left|(h_c - h_o)\right|_i \tag{6}$$

The root mean squared error is defined as:

$$RMS = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(h_c - h_o)_i^{\,2}} \tag{7}$$

where n is the number of observations, h_c is the computed head [L], and h_o is the observed head [L].

Results and Discussion

Conceptual MODFLOW model

Model pre-processing is done with the ArcView GIS, model layers use the 1965 projection system, and map an area between X-coordinates 4705845 m and 4742645 m and Y-coordinates 5860618 m and 5903818 m. From 12 topographic maps, 1:50.000 scale, all contour lines between minimum 115 and maximum 212.5 m, with a 2.5 m contour level, have been digitised. A Digital Elevation Model (DEM) was created by a topogridtool (Arc/Info) interpolation of the contour lines together with several field measured elevation cross-sections in the valleys (Fig. 3).

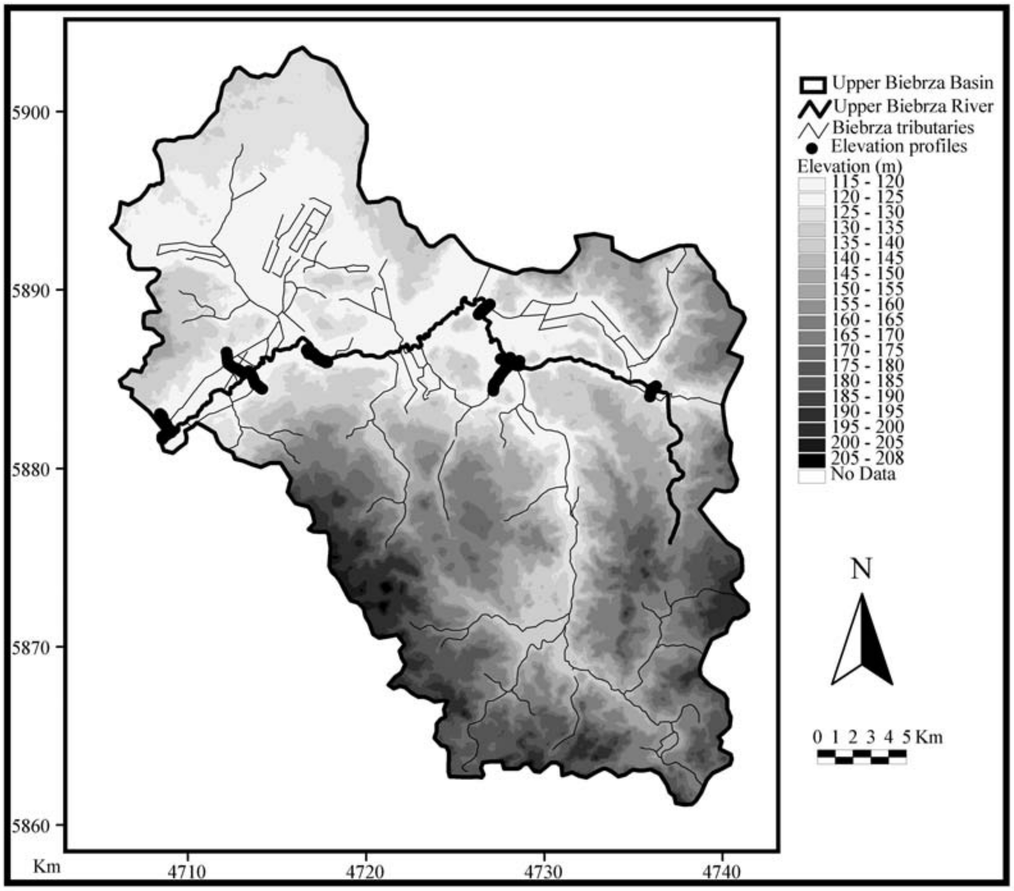

Figure 3: Digital Elevation Model of the Upper Biebrza Basin

On basis of the geological cross-sections the hydrogeology is schematised in four layers. The first layer consists of a characteristic peat soil along the Biebrza River and a sandy soil outside the river reach. The hydraulic conductivity of the peat is taken as 0.252 m/day and for sandy part as 0.15 m/day (Bleuten and Schermers, 1994). The thickness is assumed 4 m in accordance with the average thickness of the peat. Figure 4 shows that the peat occurs along the river reach and in the northern part of the basin. The second and fourth layers are (semi-)confined aquifers with a thickness of 50 m and a conductivity of 5 m/day. The third layer is a semi-confining layer with a thickness of 40 m and a conductivity of 0.15 m/day.

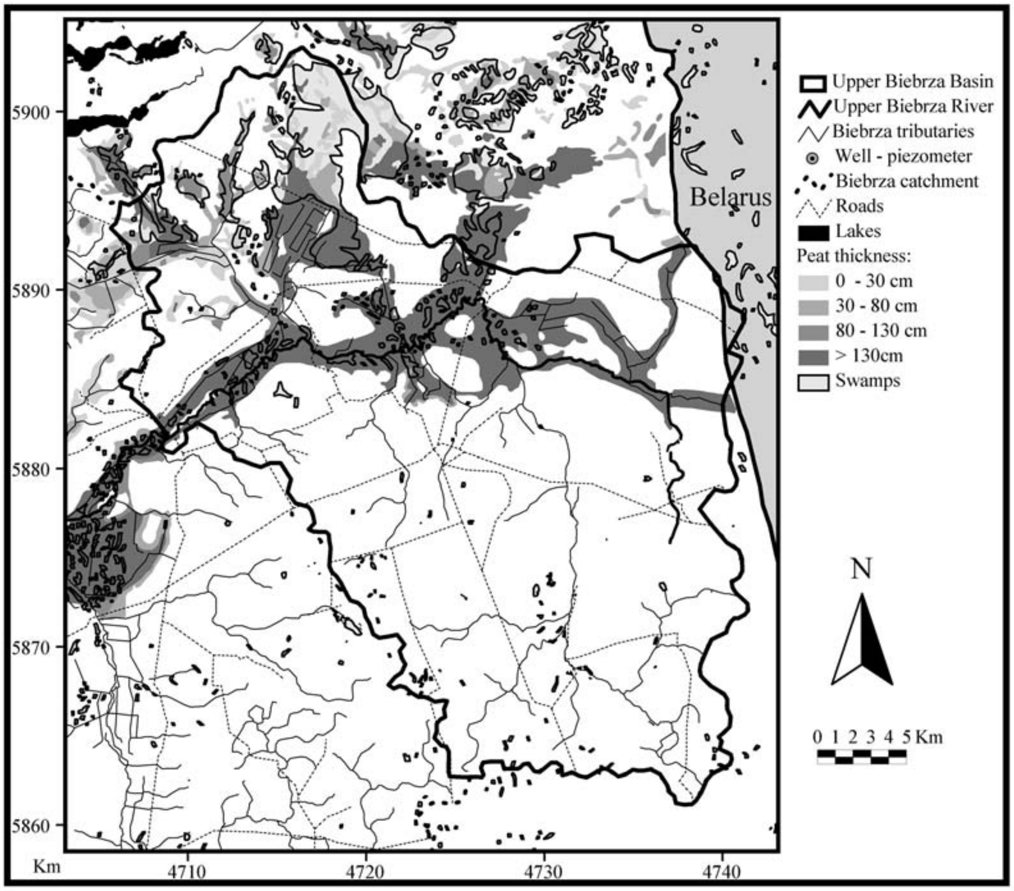

Figure 4: Peat and swamp occurrence in the Upper Biebrza Basin

Boundary conditions defined in the conceptual model are River, Drain, Well and Recharge. The River condition is assigned to the Upper Biebrza River. The calculation of the river conductance is done according to Eq. 2. However, as guidance for the parameter values it is assumed that due to the course grained subsoil in the valley (Żurek, 1984) the flow between aquifer and river occurs without major resistance. GMS requires a conductance per unit length of river, and automatically computes the appropriate cell conductance by multiplying it with the actual river arc length per grid cell. The hydraulic conductivity and effective thickness of the river bed are set to respectively 0.2 m and 1 m/day; the width of the Biebrza River is set to an average 5 m and 20 m for respectively the upstream and downstream part. The resulting conductance is 25 and 100 m^2/day/m for respectively the upstream and downstream part. The water level along the river condition was linearly interpolated along the river arcs from the measured river stages at four points during three measurement campaigns from May 1999 till May 2001 (Chormanski, 2001) (Fig.1).

The drain conductance is analogue to the Upper Biebrza River conductance defined as 25 m^2/day/m and assigned to all tributaries of the Upper Biebrza River. The drain elevation is interpolated along the drain arcs. It is equal to the average drainage level of the small ditches and tributaries in the Upper Basin. This level is assumed to be 0.5 to 1 m below the interpolated ground surface. Due to the uncertainty in the estimation, the river and drain conductance are often used as a calibration parameter to optimize the head values.

There are numerous house wells in the Upper Biebrza Basin (Fig. 1) of which the extracted volume can be neglected. Six somewhat larger pumping wells have been identified (Fig. 1) with extracted discharges from 26 to 373 m^3/d. From the depths of the wells it was determined that they extract water from the confined aquifer, the 2nd model layer.

Recharge is calculated using the HYSEP model (Sloto and Crouse, 1996). This model can be used to separate base flow and surface runoff from hydrographs. The long-term average derived baseflow of the Upper Basin can be regarded as the recharge of the basin if no bypass of groundwater flow is assumed. HYSEP analysis of the daily Biebrza River discharge at Sztabin, from 1951-1994, results in a baseflow varying between 48 and 86 % of the total discharge (Fig. 5). The baseflow shows a slight increase in time. A possible explanation is the reduction, in recent years, of precipitation in the form of snow (Oral comm., Okruszko), resulting in an increased winter recharge and/or decreased spring surface runoff. The median base flow is estimated as 3.24 m^3/s, which results in a recharge of 121 mm/year for the Upper Basin.

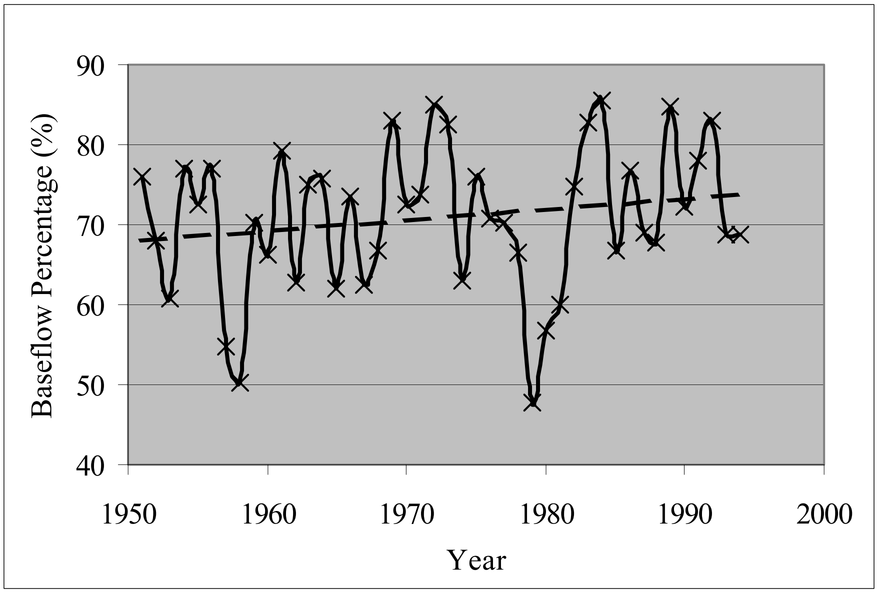

Figure 5: Yearly baseflow percentages and its trend line, of the Biebrza River discharge at Sztabin

MODFLOW simulation results

The conceptual model is translated into a finite difference MODFLOW model with cell sizes of 200 m, i.e. 184 columns and 216 rows. The PCG2, preconditioned conjugated gradient solver was used with a head and residual convergence criteria of 0.01, the model was set up as a steady state simulation. For all four layers the piezometric water level was obtained. However, in the first layer dry cells occur outside the valleys since the water table is located in the second model layer. The phreatic water table varies between 115 m and 181 m (Fig. 6). The lowest water table positions occur in the Biebrza valley. The head increases north- and southwards, with the maximum at the southern water divide. High fluxes occur near the rivers and drains, especially near the Sidra River high groundwater discharge rates occur due to the relatively steep topography.

Flooded cells are locations where the simulated groundwater level is equal or just above the topography (Fig. 7). The flooded cells occur along the Biebrza

River, in the northern part of the basin (outwash) and in the Sidra valley. These locations with a water table at or above the land surface compare in general well with the occurrence of swamps and peat in Fig. 4. In the Sidra valley groundwater discharge is calculated, however Fig. 4 does not show swamps or peat in this valley.

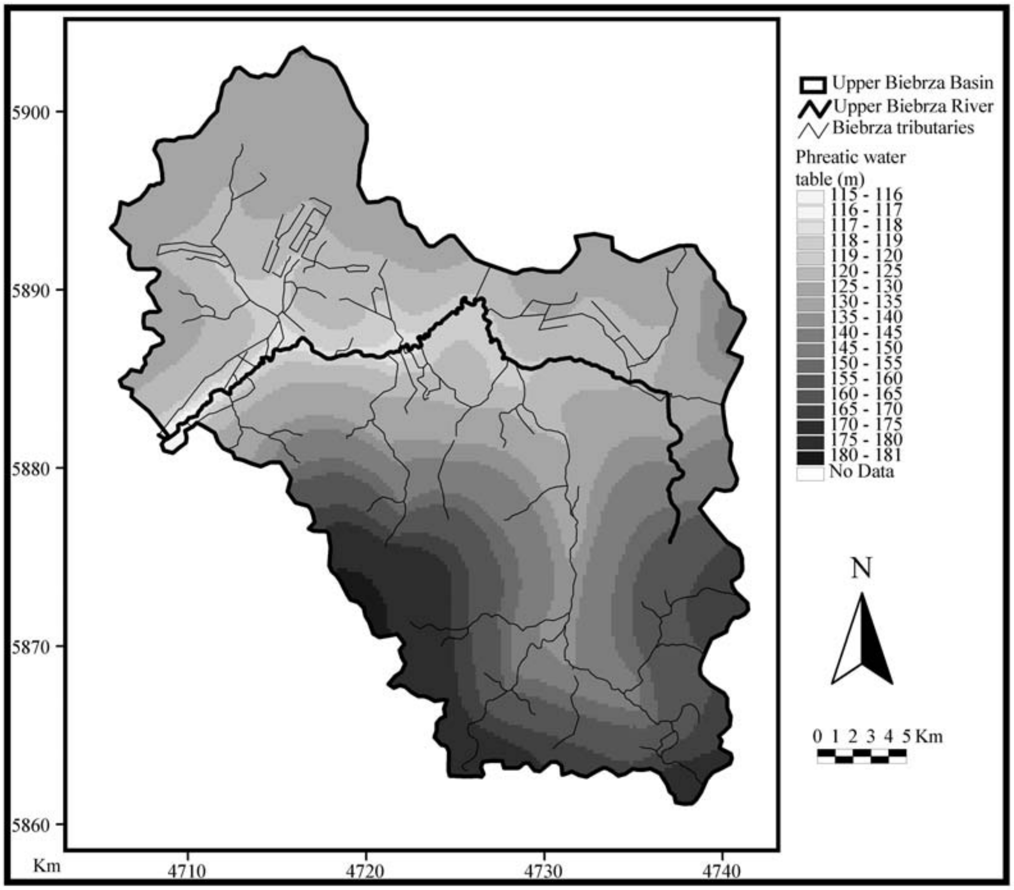

Figure 6: Simulated phreatic water table

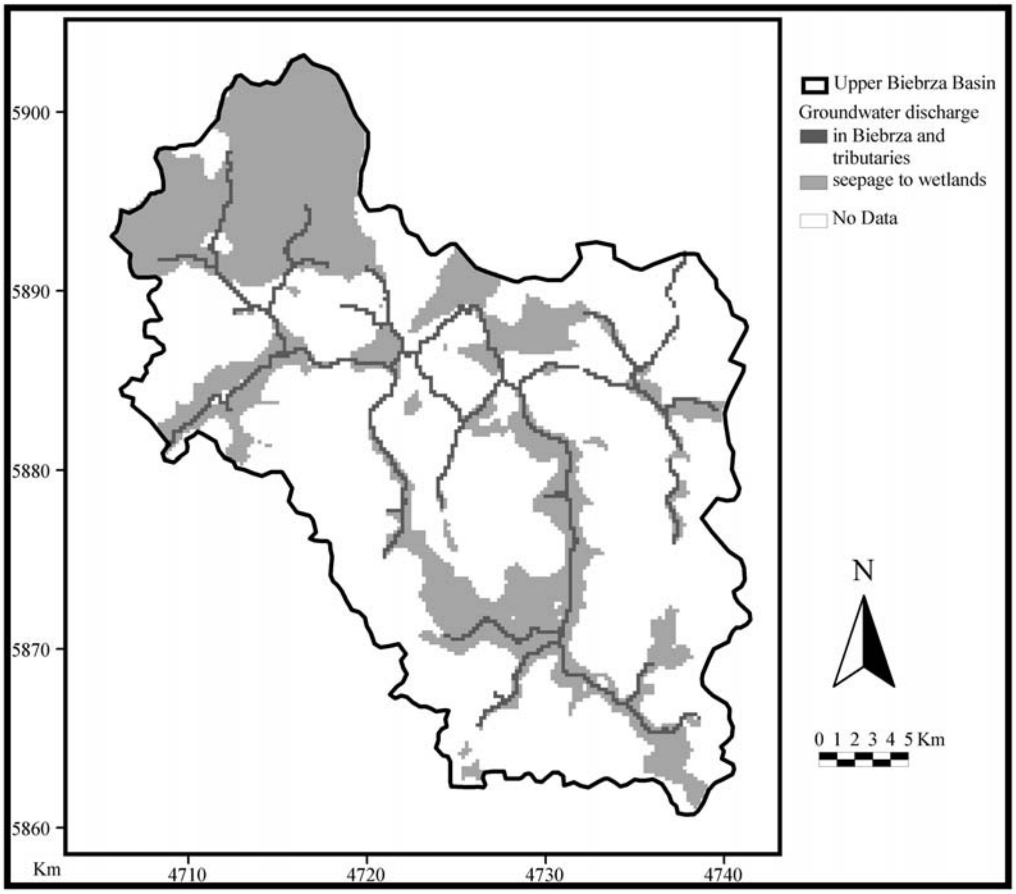

Figure 7: Simulated areas of groundwater discharge

The heads from the three piezometeric level measurement campaigns varied only little. On average the groundwater levels from September 1999 were lowest, while the levels of May 2000 and May 2001 were respectively 50 and 26 cm shallower. The average of the three measurements has been used to evaluate the simulation results. The mean error is -1.10 m, the mean absolute error is 4.99 m and the root mean square error is 7.95 m. It should be stressed here that these values indicate the model performance without calibration, and can therefore be regarded as acceptable. Trial and error or automatic calibration is able to considerably reduce these errors as Kuntohadi (2001) in a first approach showed. A structured automatic calibration, in line with the qualitative hydrogeological information, is currently part of the follow up research on this model.

The overall flow budget of the model shows a neglectable error. From this budget it emerges that 24% of the baseflow in the basin is discharged along the main course of the Biebrza, the remaining 76% is discharged in the tributaries of the Biebrza, represented in the model by drains.

Conclusions

For the first time a groundwater model has been developed for the Upper Biebrza Basin. The model allows an evaluation of the groundwater discharge to the Biebrza River valley and its tributaries. The groundwater model has been built with the GMS MODFLOW interface. GMS is one of the few simulation interfaces for groundwater flow, which allow simulation pre- and post-processing with GIS. Due to the remote position and extensive use of the Upper Biebrza Basin very little hydrogeological measurements are available. The geomorphology and geology of the Biebrza valley has been shaped by glacial activity, it is therefore likely that the subsoil is strongly heterogeneous. The hydrogeological concept of the model is therefore a simplified approximation of the reality. However, prediction of groundwater discharge locations is primarily determined by topographically driven phreatic groundwater flow. Most determining for the accuracy of the patterns is therefore the DEM. The quality of the DEM is reasonable due to the addition of valley profiles. It will be improved further in the follow-up study. The simulated phreatic water table compares reasonably with the measured piezometric levels without calibration. The first results of the model show that there is a strong correlation between the locations of groundwater discharge and the occurrence of peat and swamps in the Upper Basin. It is also concluded that about 75% of the baseflow of the Upper Biebrza basin is produced in the tributaries of the Upper Biebrza River. Presently the model is further extended, refined and calibrated.

Acknowledgements

I. Kardel, A. Mucka, A. Maksymiuk, Y. Meyus, D. Miroslaw-Swiatek, J. Severyns, A. Van Campenhout and P. van Rossum are acknowledged for the fieldwork executed in the Upper-Biebrza basin. Dr. T. Okruszko, J. Chormanski, Prof. R. Verhoeven are thanked for providing data and for the cooperation within the BIL98/87 project of the Bilateral Scientific and Technical Cooperation program between Flanders and Poland. The results here described make integral part of this project.

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