Climate Variability and Change—Hydrological Impacts (Proceedings of the Fifth FRIEND World Conference held at Havana, Cuba, November 2006), IAHS Publ. 308, 2006.

Interaction between surface and groundwater in the flooding of riparian wetlands: Biebrza wetlands case study

TOMASZ OKRUSZKO, JAROSŁAW CHORMAŃSKI & DOROTA ŚWIĄTEK

Department of Hydraulic Engineering and Environmental Restoration, Warsaw Agricultural University, Nowoursynowska 159, 02-776 Warsaw, Poland

t.okruszko@levis.sggw.pl

Abstract The Biebrza Wetlands is located in a marginal-ice valley in north-eastern Poland and covers some 195 000 hectares in area. The most characteristic feature of the Biebrza River is flooding, which appears there almost every year. In the period 1999–2002, investigation of the flooding phenomena was carried out in order to understand the main processes involved in the inundation of the river valley and to combine them with characteristic vegetation patterns. The investigation used Landsat images, a hydrodynamic 1-D model of river and flood plain flow, and chemical analysis of flood waters. It was shown that river water is responsible for inundation of part of the valley only. Other parts of the valley were inundated by groundwater seepage or *in situ* snow melt. These observations agree with qualitative descriptions of water sources for the particular plant communities.

Key words Biebrza wetlands; flooding; RS; hydrological models

INTRODUCTION

The Biebrza wetlands occupy 195 000 ha of a marginal-ice valley in north-eastern Poland. It forms one of the last extensive, fairly undisturbed river-margin peatlands in Europe and contains endangered plant and animal species in a large variety of fully developed ecosystems.

The Biebrza valley is also a large reservoir for surface and shallow groundwater. Water which flows into Biebrza valley is accumulated here due to the small longitudinal slopes of the basins as well as the fact that valley is closed downstream by the moraine formation. As the flooding phenomena is vital for protection of wetland ecosystems, changes in inundation extent as well as the role of different sources of water were investigated.

DATA

Hydrological and topographical data

Hydrological data were obtained form the Polish Weather Service which has operated three gauges controlling the flows in the Lower Basin since 1951. Floods during the investigation years (1999–2002) were close to the 50-years maximum average except for the flood of 2001. In this year, the maximum flood water level reached bank full only.

Two types of data were analysed to describe the topography of the Lower Biebrza basin: (a) 13 river and valley cross-sections, which were gathered during the measurement campaigns; and (b) a Digital Elevation Model (DEM) representing the topography of the valley (Fig. 1).

The river bed elevations were measured by manual sounding. Near the river, valley cross-sections were measured on both sides of the river channel by coupling the traditional levelling survey with Differential GPS (DGPS) techniques. The cross-sections were then extended to the edge of the valley by capturing elevation every 100 m from the DEM (Chormański *et al*., 2002).

Remote sensing

One satellite images from each year of a flood event were analysed. The floods in 1999 and 2001 were registered on Landsat TM images, while sensors of Landsat ETM+ captured the floods in 2000 and 2002. The Lower Basin area was located on Landsat images 187/23 in 1999, 2001 and 2002, and on image 188/24 in 2000. These images captured peak flows.

Hydro-chemical survey

Surface water samples were collected in several transects during peak flows in 2001 and 2002 at a depth of less than 5 cm below the water surface. The EC (adjusted to 25°C) values of all samples

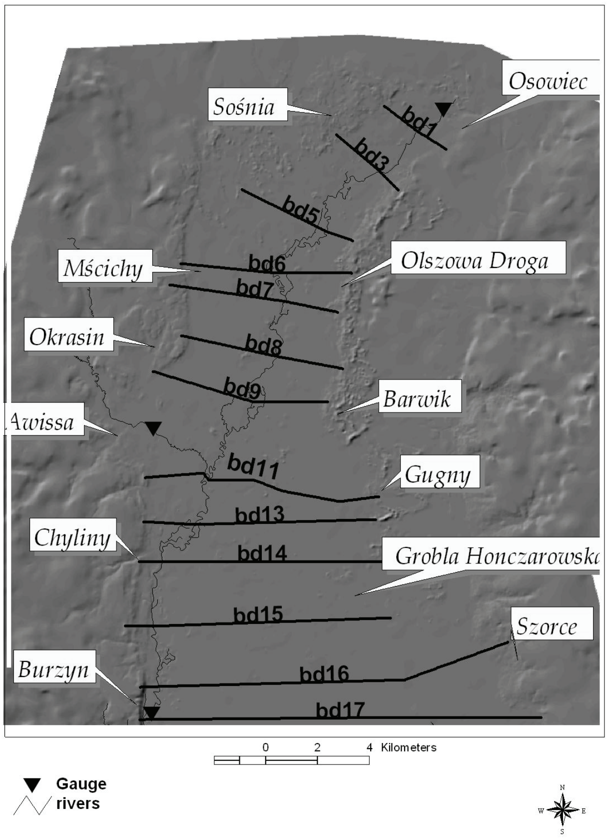

Fig. 1 Digital Elevation Model of the Lower Biebrza Basin and cross sections location.

were measured in the field. Within eight hours after sampling the acidity (pH) and alkalinity of the water samples were measured. The other analyses were performed using Inductively Coupled Plasma Atomic Emission Spectrometry techniques and colorimetrically on a continuous flow autoanalyser at the laboratory of the University of Utrecht. The concentrations of the followed ions were analysed: Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, $Fe^{2+/3+}$, Al^{3+}, Mn, Si, SO_4^{2-}, Cl^{-}, NH_4^{+}, PO_4^{3-}.Cd, Cu, Pb, Zn. In total 233 samples were collected in 2001 and 563 in 2002. For all the samples, the ionic balance was calculated according to the Stuyfzand (1989) method. This kind of reliability test allows decision making about including the particular samples in the next analysis. Samples with an ionic balance deviating more than 10% from electro neutrality (30 samples of 2001 and 14 samples of 2002) were eliminated from statistical analysis (Chormański, 2003).

METHODS

Remote sensing

The ratio TM7/TM4, Normalized Difference Vegetation Index (NDVI) and PC1 were used for pre-processing of the Landsat satellite images. The results of these three transformations were stored in new bands, and then, were used for class determination and the development of training regions. In all, 14 generalized classes, containing different cover types, were developed. The homogenous training regions were based on field observation and GPS measurements as well as analysing the land-use map. Next, a supervised classification using the maximum likelihood method was performed. Using the flood of 2002 and 796 points with known cover type, a high classification accuracy of 88% was obtained. Finally, the classified images were reclassified into two classes “inundated” and “dry”. The inundated class included deep water, shallow water, inundated tall sedges and reeds, flooded alder forest, flooded meadow, alder birch forest, reeds and shrubs, sedges, shrubs and sedges, and moss-sedge communities. The dry class included coniferous forest, leafy forest, grasslands, and bare soil. This procedure was applied for determination of the total inundation area of the floods in 1999–2002.

Statistical analysis of the hydro-chemical patterns

Samples obtained from hydro-chemical transects were statistically analysed using a PCA procedure following Verhoeven *et al*. (1996) and Bridgham (1998). The variables that were not normally distributed were standardized by log-transformation to approximate the normal distribution. They were then standardized to have a zero mean and unit variance.

The results of the statistical analysis were imported to the ArcView GIS system and linked with geographical sample location measured by GPS to create a map of the spatial distribution of the first three components. To get a better impression of the variation in ionic composition of the flood water, an iterative process was used to find the cluster centre of the scores of the three components. The *K*-means cluster analysis method was performed establishing six clusters, which finally were interpreted as three different water sources: river, groundwater and snowmelt.

Table 1 shows values of water properties calculated as the mean and standard deviation for each group. Cluster 4 is predominant in the river water and is characterized by: high EC, Cl, K and Ca values, the highest pH and SO_4 values and low values of Si, Zn, PO_4, Mn. The spatial location of samples classified as cluster 4 is close to the Biebrza River. The second cluster, which characterized the river water, is cluster 5. This group is only represented by one sample collected from the Wissa River, which flows through urban areas. Clusters 3 and 6 are similar and both have low mineral richness related to low HCO_3 content and Ca concentrations that are associated with low pH. These clusters can be interpreted as rain/snowmelt dominated water types. However, cluster 3 has properties, like very high concentrations of K, PO_4 and Cl, that are similar to other types of water such as river or groundwater and suggests that the cluster represents a mixed type of water. In cluster 1 and 2, groundwater predominates. Such properties like very high HCO_3 contents and Ca concentration, and pH smaller than in river water are characteristic of groundwater flux. The increase of Cl, Na, K in cluster 2 could be an indicator of human related pollution influences.

Table 1 Chemical properties presented as average values and standard deviation calculated for each water cluster determined for water samples collected during flood event in year 2002.

Variable	Cluster 1		Cluster 2		Cluster 3		Cluster 4		Cluster 5	cluster 6	
	Average	Std.	Average	Std.	Average	Std.	Average	Std.		average	Std.
EC	405.80	104.01	426.93	107.74	262.86	73.35	390.25	41.72	570.00	246.87	55.61
pH	7.09	0.29	7.20	0.49	6.95	0.30	7.90	0.37	7.80	7.09	0.30
$HC0_3$	261.45	76.08	234.14	56.21	127.34	35.01	197.55	23.63	317.20	157.19	34.74
Al^{3+}	0.00	0.01	0.01	0.01	0.02	0.06	0.00	0.01	0.00	0.00	0.01
Ca^{2+}	75.60	20.69	74.52	21.06	42.42	13.15	65.08	6.95	96.77	39.99	12.40
Cd	0.01	0.00	0.01	0.00	0.00	0.00	0.01	0.00	0.01	0.00	0.00
Cu	0.02	0.04	0.01	0.01	0.01	0.00	0.01	0.00	0.01	0.01	0.00
$Fe^{2+/3+}$	0.96	1.51	0.36	0.51	0.48	1.82	0.08	0.04	0.31	0.21	0.32
K^+	0.52	0.42	2.33	1.80	2.65	3.63	2.33	0.75	79.37	0.67	0.54
Mg^{2+}	13.49	3.77	14.37	3.69	7.46	1.98	11.07	1.28	15.67	7.54	2.01
Mn	0.17	0.20	0.20	0.66	0.06	0.20	0.00	0.01	0.06	0.02	0.06
Na^+	4.88	1.14	6.08	2.11	5.23	1.29	5.95	0.70	7.79	4.65	1.31
Pb	0.04	0.00	0.04	0.01	0.04	0.02	0.04	0.00	0.04	0.04	0.00
PO_4^{3-}	0.24	0.31	0.33	0.42	0.45	1.19	0.09	0.06	0.25	0.12	0.07
Si	7.40	1.80	6.66	2.39	3.94	1.75	1.25	1.28	6.33	4.24	1.91
SO_4^{2-}	4.64	3.12	25.13	20.06	22.24	16.88	33.23	7.25	42.42	6.72	6.33
Zn	0.05	0.05	0.08	0.13	0.04	0.03	0.03	0.02	0.03	0.03	0.02
NH_4^+	0.13	0.00	0.14	0.06	0.19	0.25	0.13	0.02	0.13	0.26	1.43
Cl^-	6.47	2.97	12.37	4.39	9.72	3.98	9.84	1.81	80.82	6.09	1.69
No. of samples	25		75		80		251		1	117	

Numerical model of Lower Biebrza River Flow

In order to simulate flood flow in the Lower Biebrza basin a one-dimensional unsteady model flow was applied. This model solves an unsteady one-dimensional open channel flow, based on the St Venant equations (Liggett & Cunge, 1975). The Lower Biebrza River is represented as a 1-D single channel starting from the Osowiec gauge (BD1) and terminating at Burzyn gauge, BD17 (Fig. 1). The Wissa River is treated as a point of lateral inflow located 8 km upstream of Burzyn and is described by the flow hydrograph at the Czachy gauge (Q_C). A flow hydrograph forms the upstream boundary condition and the rating curve is used as a downstream boundary condition at Burzyn gauge. The uniform lateral inflow is imposed along the river section according to the large lateral inflow from subcatchment during the flood event. The field monitoring in the Lower Biebrza Basin shows that during flood periods, the river valley consists of areas which mainly act as storage for flood water and areas that are effective in water transport. The 1-D model is capable of describing flood conditions using the appropriate geometry of cross-sections, which are limited to the flow-active zones. In developing the model, the location of each cross-section was identified according to the water source distribution determined by chemical transects and topography according to the DEM.

The calculated and observed discharge hydrographs at cross-section BD17 were compared in the model validation process using RMSE computation (Table 2). However, the good congruence of the model results with discharge rates at the downstream boundary condition does not necessarily mean that the developed model correctly reproduces water levels upstream from the Burzyn gauge.

Table 2 The RMSE calculated for different flood events.

Year	Peak flow ($m^3 s^{-1}$)	RMSE ($m^3 s^{-1}$)
1999	184	10.4
2000	80,3	3.24
2002	168	6.98

RESULTS

Flood extent and source of water

The total inundation maps prepared by the remote sensing technique for 2001 and 2002 floods were analysed to determine the different water sources. On the basis of statistical analysis and classification of water samples, three types of water were determined and attached to every sampling point. The zones representing different types of water were drawn (Fig. 2(b)). The area flooded by river water (active part of the valley) usually covered less than a half of the total inundation area (Table 3).

Table 3 Inundation area and volume of water stored in active and non-active part of the valley.

Year of event	Total inundation area (km^2)	Area of the active part of the valley (km^2)	Area of the non-active part of valley (km^2)	Volume of the non-active part of valley (m^3)	Volume of the active part of valley (m^3)	Calculated maximum daily outflow volume at Burzyn gauge (m^3)
1999	180.7	72.0	108.7	32 610 000	43 410 000	16 830 000
2000	192.7	68.3	124.4	24 884 000	27 140 000	6 580 000
2001	113.5	56.1	57.4	8 610 000	–	–
2002	188.8	77.5	111.3	33 390 000	44 520 000	14 730 000

Hydraulic model result vs Remote Sensing (RS) method and vegetation zones

Water stages calculated by hydrodynamic modelling at cross-sections were mapped across the entire flood plain using the DEM in ArcView GIS. Comparison of the inundated area generated by the hydraulic model and obtained by the remote sensing method (Fig. 2 (b)) show large differences in the downstream part of the valley. However they are in good agreement with the border between the active and non-active zones. The volume of water stored in both zones (Table 3) is similar, varying from 24×10^6 m^3 to 44×10^6 m^3 for the floods that were investigated. Comparing those volumes with volume of daily discharges during the peak flow shows that the storage capacity of each zone is equal to between two to five days of flow.

There is a very good match between the flooding area coming from the river during average flood conditions and the vegetation zones of reeds, tall sedges and sedges (Fig. 3). Those types of vegetations are normally associated with fluvial types of hydrological feeding. The groundwater

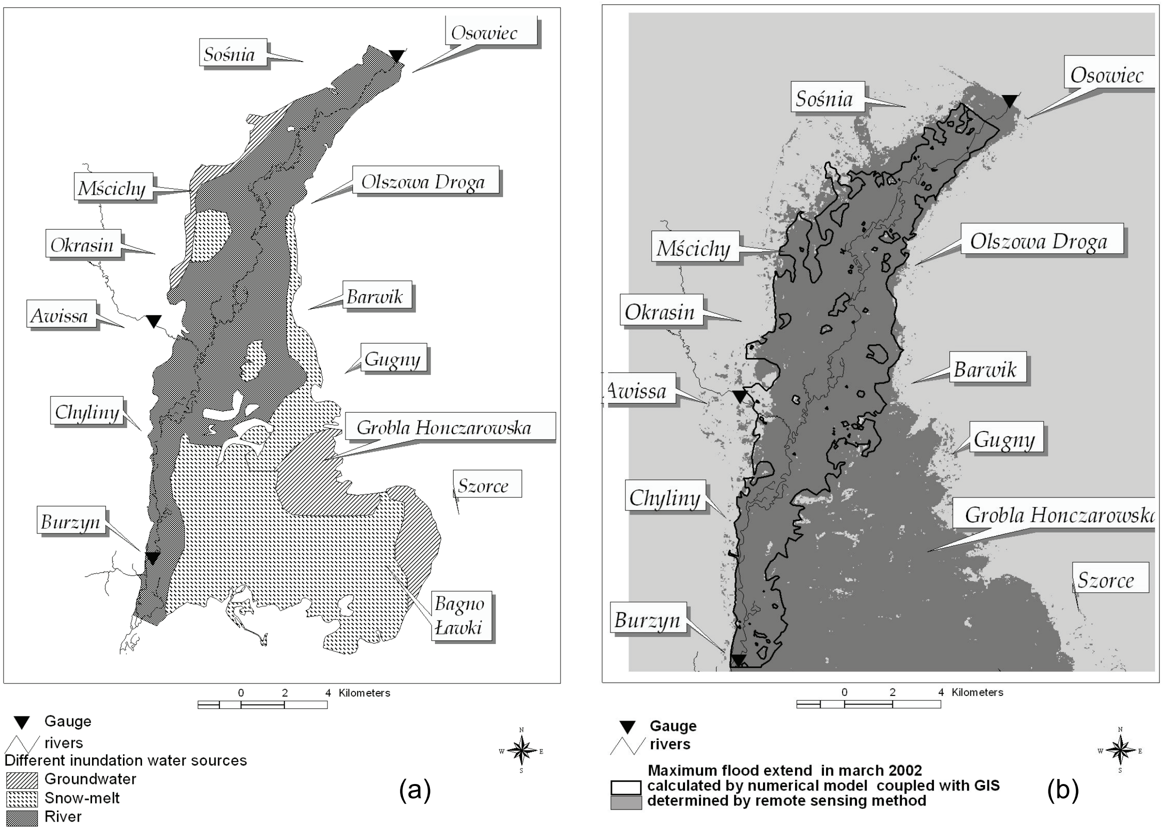

Fig. 2 (a) Inundation of river valley with water of different sources in 2002. (b) Comparison of the inundated area extent obtained by the remote sensing method and hydraulic model in 2002.

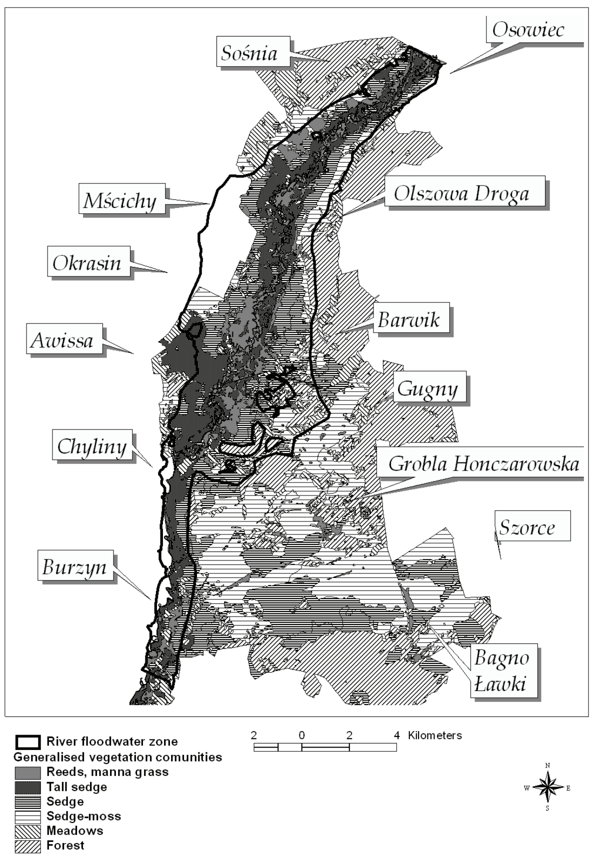

Fig. 3 Comparison of average river flood with major plant vegetation zones of Biebrza wetlands.

fed ecosystem of sedge-moss vegetation is also clearly visible outside the active zone. The lack of detailed observation of flood events of bigger magnitude (floods of 2003 and 2004 were also close to average) made investigation of the interplay between indicated water sources during such events impossible.

CONCLUSIONS

As results of our study we came to the following conclusions:

1. Inundation of the Biebrza Wetlands results from the interaction of water coming from three different sources: flooded river water, exfiltrated groundwater as well as water coming from *in situ* snow melt. The most accurate information on the sources of water was obtained from chemical transects.
2. There is a good match between the flood extent obtained as a result of this hydrological study and generalized vegetation map. It indicates that natural vegetation can be a good indicator for estimation of average flood extend.
3. A one dimensional hydrodynamic model can be effectively use in this type of river valleys when the water conveying parts of the valley are identified. The location of the water conveying parts of the valley depend on the magnitude of the flood event, and can be detected during the flood event using surveys of water chemistry or velocity. However, identifying the conveying parts of the valley for historical floods using gauge records only is difficult.
4. The exclusion of water storage areas from the inundation model leads to significant errors in the estimation of flood extend. In the case of flood event of average magnitude more then 60 % of the inundated area in the Biebrza comes from sources other then water river sources. This error has limited impact on accuracy of storage efficiency of the river valley, as it is only a few days storage of the peak flows. However, it is a major factor constituting the wetlands habitat in a river valley of this type.
5. In the case of ecological studies aiming on conservation/restoration of habitat conditions of riparian wetlands, there is a need for coupling regional ground water models with the hydrodynamical models for predicting the flood extend.

REFERENCES

Bridgham S. D., Updegraff K. & Pastor, J. (1998) Carbon, nitrogen and phosphorus mineralization in northern wetlands. *Ecology* **79**, 1545–1561.

Chormański, J., Okruszko, T., Wassen, M. J. & Skąpski, J. (2002) Surface water system analysis. Flood extent measurements and topography of the valley. In: *Hydrological System Analysis in the Valley of Biebrza River* (ed. by W. Mioduszewski & E. P. Querner). 39–57. IMUZ Press, Falenty, Poland.

Chormański J. (2003) Methodology for the flood extent determination in the Lower Biebrza Basin. PhD Thesis. Warsaw Agricultural University, Poland.

Liggett, J. A. & Cunge, J. A. (1975) *Numerical Methods of Solution of the Unsteady Flow Equations*, vol. 1, Chapter 4. Water Resources Publications, Fort. Collins, Colorado, USA.

Lilesand, T. M & R. W. Kiefer (2000) *Remote Sensing and Image Interpretation*. John Wiley, New York, USA.

Profeti, G. & Macintosh, H. (1997) Flood management through Landsat TM and ERS SAR data: a case study. *Hydrol. Processes* **11**, 1397–1408.

Townsend, P. A. & Walsh, S. J. (1998) Modeling floodplain inundation using integrated GIS with radar and optical remote sensing. *Geomorphology* **21**, 295–312.

Stuyfzand, P. J. (1989) A new chemical classification of water types. In: *Regional Characterization of Water Quality.* (ed. by S. Ragme), 89–98. IAHS Publ 182. IAHS Press, Wallingford, UK.

Verhoeven, J. T. A., Keuter, A., van Logtestijn, R., van Kerkhoven, M. B. & Wassen, M. J. (1996) Control of local nutrient dynamics in mires by regional and climatic factors: a comparison of Dutch and Polish sites. *J. Ecol.* **84**, 647–656.