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Chapter 13

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Geoinformation Methods for Parameterization of the Hydrological Processes on the Areas of Natura 2000

1. Introduction

Temperate river floodplains are highly dynamic systems. Their hydrology is closely related to the dynamics of the river which seasonally irrigates and drains the floodplain. During peak river discharge, after snowmelt or in periods of large precipitation surplus, the river inundates the floodplain whereas in dry periods the river withdraws and groundwater tables drop. Floodplain ecosystems play an important role in the landscape. It has multiple functions: it safeguards the hinterland of flooding (Sutcliffe, Parks 1989; Large, Petts 1994), it purifies the water during floods by retaining nutrients (Olde Venterink *et al.* 2003), and it is a fertile system, due to decomposition of the organic matter that is deposited during the flood (Baldwin, Mitchell 2000), which sustains a wide variety of biodiversity and is used for agricultural purposes all over the globe.

Their protection and re-naturalization are the aim of various scientific researches and activities of environmental engineering. The specific functions of floodplain marshes in environmental processes are reflected in the Water Framework Directive (Directive 2000/60/EC 2000), concerning the protection of these ecosystems by maintaining or restoring suitable water conditions in river catchments. Main, natural floodplains in Poland are protected by Natura 2000. The habitat directive take appropriate conservation measures to maintain and restore the habitats and species for which the site has been designated to a favorable conservation status. Geoinformation can take an important role as a tool for analysis of the water conditions of the floodplain and support environmental protection process.

1.1. Research area

One of the most interesting natural floodplain with natural ecosystems is a floodplain of Biebrza River which is well known as Biebrza Wetlands. The Biebrza Wetlands have extensive floodplains and riverine marshes, and are the last big, almost unchanged river valley peatland in Central Europe. The Biebrza Wetlands are located in Northeastern Poland in an ice-marginal valley, around 195 000 ha in area; of which the wetlands occupy 116 000 ha (Fig. 1). The Biebrza National Park protects a unique diversity of plants, animals and habitats. First of all the Biebrza valley is an important place for waterfowl. Therefore in 1995 it was included on the list of the Ramsar Convention wetlands of international importance, specifically for waterfowl.

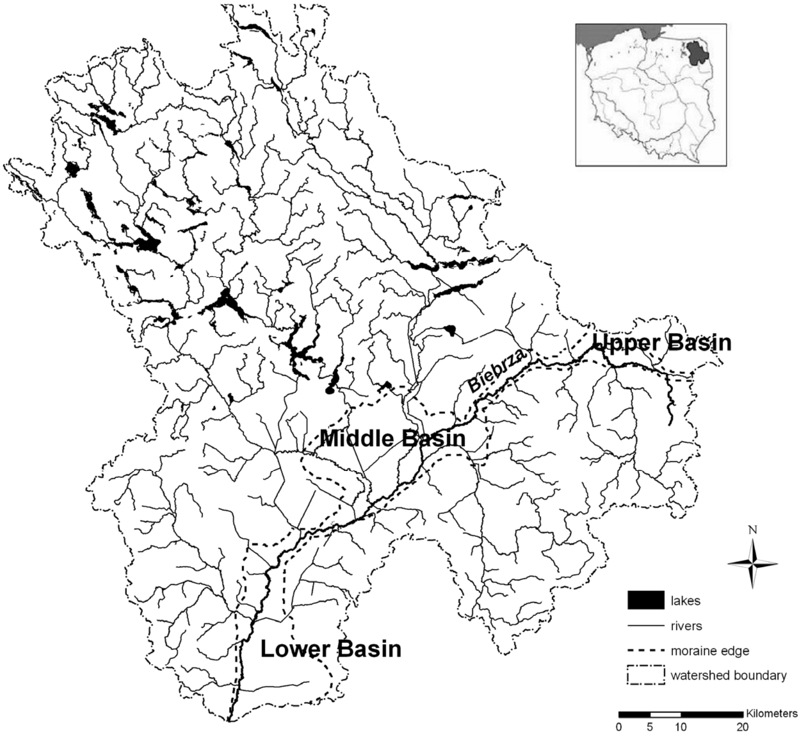

Fig. 1. Biebrza wetlands

1.2. Floodplain hydrological processes

If we talk about hydrological processes which influence ecosystems development in floodplain as Biebrza valley, we can identify three main processes:

- flooding and inundation during a spring,

- evapotranspiration during vegetation period,
- interception of natural vegetation,
- groundwater seepage.

A characteristic feature of the Biebrza River is flooding, which occurs almost every year. This paper is treats on wetland flooding and inundation, their influence on ecosystems in the valley, as well as it is description of the methodology of flood extent determination and calculation of flood statistics in ecosystem sites.

1.3. Flooding and inundation problem

The origin of floods is mostly a spring thaw (Byczkowski, Kiciński 1984). Water which inflows into the Biebrza valley is accumulated here due to the small longitudinal slopes of the basins. The high water level continues for a long time, especially in the southern part of the valley (the Lower Basin) due to the fact that here a syncline like widening of the valley is closed downstream by a morainic formation and an alluvial cone deposited by the Narew River (Żurek 1984, 1994). From the flooding point of view, this most natural part of the Biebrza Wetlands is very interesting. It plays the role of a large reservoir for surface water including the river flood, which is accumulated there and takes part in the process of filling this area with water. This floodwater from the river, which appears in river subjected areas, is accompanied in the floodplain by two other types of water such as shallow groundwater that is flowing as seepage over the surface and snow melting water in other areas. During the floods, these three main water types form one continuous water table (Okruszko 1990). Therefore, hydrologically the Lower Basin is generally described as fluviogenous along the river, and soligenous in the areas beyond the river flood zone. Generally speaking, it is a topogenous wetlands that store large amounts of surface water in spring due to small elevation difference (Okruszko 1990). The fen, which develops in the areas subject to the floods, is specified as fluviogenous fen. It means that the extent of the fen, ratio of peat accumulation and growth of peat forming plant species strongly depend on the magnitude and frequency of the floods. The fen, which has developed in the groundwater seepage-feeding zone on the wetland, is classified as the soligenous fen. The difference in water conditions, indicated by the peat deposits, is also reflected in the diversity of the communities of contemporary vegetation in the wetland, which also appears in the Lower Basin in a pattern of zones parallel to the river (Okruszko 1990, Oświt 1994). The fundamental sense of the ecological aspect of flood is formulated as a concept of flood pulse (Junk *et al.* 1989, Bayley 1991, Junk 1996). Key in the flood pulse concept is the hypothesis that during flood events habitats located further away from the river are connected to river and river marginal areas facilitating exchange of energy, matter and biota. In unmodified river floodplains, both the flood pulse concept and the river continuum concept appear to be operational, which is illustrated by the extent and spatial distribution of ecosystems in both longitudinal and transversal regularly arranged patterns (Palczynski 1984, Cellot *et al.* 1984, Wassen *et al.* 1992, Wassen, Barendregt 1992, De Mars *et al.* 1997, Casanova, Brock 2000; Lenssen *et al.* 1999).

However, these well documented patterns of vegetation zonation in floodplains are only rarely accompanied by hydrological studies. The few studies are found relate the spatial arrangement of ecosystems in floodplains to flood magnitude, frequency and/or duration (Chormanski *et al.* 2009, Okruszko, Kiczko 2008, Okruszko *et al.* 2010, Swiatek *et al.* 2008; Szporak *et al.* 2008, Stromberg *et al.* 1996, Scholz, Trepel, 2004) or they focus on biogeochemical processes after the floods (Van Oorschot *et al.* 1997, Wassen *et al.* 2002). The dynamics of the geochemistry of oxbow lakes normally mirrors the hydrology of the river (Barendregt, Wassen 1995, Glinska-Lewczuk 2009) but further away from the river this relationship is often less clear. Still, most studies implicitly assume that only river water causes the inundation of the floodplain during floods. However, palaeo-ecological studies have revealed that a distinct zonation in species composition of plant remnants occurs in river floodplains, indicating a spatial distribution of different water types (Bakker *et al.* 1976, Oswit 1994).

2. Method

A methodology for inundation and flood extent determination in the floodplain is proposed by Chormanski *et al.* (2011) and long term flood depth and frequency by Okruszko et al, 2009 and Chormanski *et al.* (2009). The Biebrza was chosen since it is an example of a natural swampy river valley. Here, it is believed a flood as river caused, and flooded as parts of floodplains influenced by river water. The first objective is to analyze the various geoinformation methods of identification of the areal inundation, whereas the second is to detect the water source, with special emphasis on the river water. Since flooding phenomena are spatially distributed in a floodplain, geo-informatic techniques widely used for flood extent determination such as GPS based measurements of flood borders (Michener, Houhoulis 1997, Chormański *et al.* 2000a), GIS analysis based 1- and 2-Dimensional modelling with use of Digital Terrain Models (Magnuszewski 2000, Oberle *et al.* 2000; Sinnakaudan *et al.* 2002, Swiatek *et al.* 2008, Chormański *et al.* 2009) and analyses of satellite images (Delemiere *et al.* 1997, Oberstadler *et al.* 1997, Pokart *et al.* 1997, Pope *et al.*, 1997, Profeti, Macintosh 1997, Ciołkosz, Bielecka 1998, Townsend, Walsh 1998, Bhanumurthy 1999, Maruyama *et al.* 1999, Chakraborti 1999, Rahman 1999, Chormanski *et al.* 2004, Swiatek, Chormański 2007, Chormański *et al.* 2011). On the other hand, the water source implicates the type of water, which can be determined and described on the basis of water chemistry (Chormanski *et al.* 2011, Hooijer 1996, Wassen 1996). Therefore, it is necessary to include the variation of water chemistry occurring in the floodplain area in geo-informatic methods.

The different geo-informatic methods such as GPS, GIS with 1D modelling and Remote Sensing were used in the Biebrza Lower Basin. The above analysis examines a possibility to use these modern methods (usually used to areal inundation mapping) for river flood distinguishing in wetland areas. To answer the fourth and fifth question it firstly needs to be analysed the chemical properties of surface water in the floodplain aiming of distinguishing different water types, and secondly, spatial visualization of the results on a map is reviewed. Answering the above questions aims at developing a new methodology for flood extent determination combining a chemical approach with geo-informatic techniques. Figure 2 shows the set up of the research and summarises the subsequent procedures applied in this research. All the four analyzed methods of flood or inundation extent determination are situated in independent columns. Next, the results of these analyses are compared and finally an integrated methodology of flood determination is developed. It is worth mentioning that the GIS is not the only integration platform for comparing the results and the new methodology development, but also the final stage of proceeding in each of the methods.

2.1. Inundation mapping by remote sensing method

Precise mapping of the extent of inundation by satellite images has been widely used, mostly for disaster monitoring or hydrodynamic model verification (Biasutti, Lombardi 1995, Blyth 1995, Smith 1997, Brivio *et al.* 2002, Islam, Sado, 2002). We applied passive sensors in the range of visible and infrared spectrum, following pioneering work on remote sensing of floods using the Multi Spectral Scanner (MSS) sensor of ERTS-1 (the first Earth Resources Technology Satellite, later renamed Landsat 1) to map the maximum flood extent along the Mississippi River (Rango, Salomonson 1974, Deutsch, Ruggles 1974, Rango, Anderson 1974). These studies found the near-infrared (IR) to be the best suited for discriminating water from dry soil and vegetated surfaces, owing to the strong absorption of water in the near-infrared range. In the Biebrza example, it is used a satellite image of Landsat ETM+ 187/ 23 from 17 March 2002. The image has been geometrically corrected by a first order polynomial transformation on the basis of 19 ground control points (GCP) based on topographic map (1:25000) with Root Mean Square Error (RMSE) about 3 m, and then. resampled to 25 m pixel size using the nearest neighbour resampling technique (Chormanski 2003). From the geometrically corrected Landsat ETM image the following ratios or transformed images were obtained: moisture ratio TM7/TM4, the Normalized Difference Vegetation Index (NDVI) and the first Principal Component (PC1). The moisture ratio 7/4 is a simple division of the TM7 (mid-IR) and TM4 (near-IR) bands. The NDVI is calculated by dividing the difference of the TM4 (near-IR) and TM3 (visible red) by the sum of the two. This index has proven to be related to the photosynthetic capacity of vegetation (Mather 2000). PC1 is the first component of the principal component analysis (PCA) of the 6 ETM bands. A PCA results in independent components of which the first component generally explains most of the variation seen in the data (Profeti, Macintosh 1997). Homogenous training regions were selected based on the information stored in the three transformed images as well as field observations, GPS measurements and landuse maps. The training regions describe unique land covers with specified vegetation type and moisture condition. Next, a supervised classification of the image by a maximum likelihood method was performed on the three transformed images, followed by a post-classification procedure of joining similar classes to improve the results of classification. The user's and producer's accuracy and Kappa index (KHAT) were calculated for statistical evaluation of the classification method (Lilesand, Kiefer 2000) and post-classification steps. The classification results were grouped into wet and dry classes in order to obtain the classified inundated area. Verification of the classification was done by measuring the inundation border with additional GPS points. The extent of the inundation was determined by manual interpolation of the measured inundation border points, with use of the contour lines of the topographic map.

2.2. Flood river extraction from inundation map by GIS and hydrochemistry

The flood zone distinguishing was done based on hydrochemical analysis. Field measurements were carried out during flood maximum and include surface water sampling with GPS association. Surface water samples were collected at a depth of less than 5 cm below the water surface in several transects. Electrical Conductivity (EC adjusted to 25°C) was measured in the field and within 8 hours after sampling acidity (pH) and alkalinity – the bicarbonate-concentration (total inorganic carbon, which consisted of HCO_3^- only) were measured in a subsample. The rest of the collected samples were preserved, and analyzed in the Laboratory of Physical Geography, Utrecht University. The concentration of the following ions were analyzed: calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+), potassium (K^+), total iron ($Fe^{2+/3+}$), total aluminium (Al^{3+}), total manganese (Mn), silicon (Si), sulphate (SO_4^{2-}), chloride (Cl^-), nitrate (NO_3^-), ammonium (NH_4^+), ortho-phosphate (PO_4^{3-}), cadmium (Cd), copper (Cu), lead (Pb) and zinc (Zn). A total number of 563 samples were collected and analyzed (Chormański 2003). Ionic balances were calculated for all samples according to Stuyfzand (1989). Samples with an ionic balance deviating more than 10% from electrical neutrality were discarded. Major variation axes in water quality were discerned by PCA after Bridgham (1998). Before performing the PCA, not normally distributed variables were standardized by log-transformation to approximate a normal distribution and next to that variables were standardized to zero mean and unit variance. In order to be able to classify all samples as belonging to one of the three water sources: river water, groundwater or rainwater/snowmelt, a K-means cluster analysis was performed on the PCA scores, and then, results were imported into GIS and linked with the geographical coordinates as measured by GPS in the field. The river water zone was determined by digitising the flood border in ArcGIS and finally verified by comparing with a vegetation map (Matuszkiewicz 2000) generalised to flood frequency classes.

2.3. Hydrodynamic modeling

Coupling of hydrodynamic model with GIS and spatial analysis determined with help of DEM on floodplain was realized in the region north-east Poland by several authors. These similar studies applied 1-D model on three wide floodplains Lower Biebrza Basin (Swiatek *et al.* 2004, 2007, 2008, Chormański *et al.* 2009) Central Biebrza Basin (Kubrak *et al.* 2002) i Narew River valley (Kubrak *et al.* 2006, Okruszko *et al.* 2008). The main application is to analyze the hydrological condition of floodplain habitats in these studies. The water level values calculated with the hydrodynamic model of flood-flow for cross-sections were used to determine the digital model of the floodwater table in the valley. Then, inundation extent maps and water depth maps were calculated for whole area of the valley by overlaying the DEM (Chormański 2003) and water table layers. Chormański *et al.* (2009) use ArcGIS Topo to Raster algorithm to interpolate floodwater table based on values of water level calculated in cross-sections by numerical model. This procedure, flood simulations with the hydrodynamic model and GIS analysis for determinations of inundation extent, was repeated for each day of the vegetation season (February-September) from 1961 until 1996. Based on calculated daily inundation maps, the flood statistics were calculated as follows:

- long-term annual mean inundation extent map;
- long-term annual maximum mean inundation extent map;
- long-term annual mean flood frequency map.

Finally, the spatial relation between the flood statistic maps and the vegetation maps (Matuszkiewicz 2000) was analyzed in ArcGIS using *Cross-Tabulation* and *Zonal Statistic* functions.

3. Results

3.1. Inundation mapping

For the training of the classification 12 different cover classes were identified. These regions encompass the main cover types of natural vegetation in the Lower Basin. The results of the classification are presented in Figure 2. The classes deep water, shallow water and inundated tall sedges and reeds were merged into one single class called open water, the dominant cover type in the Lower Basin, comprising about 50 km^2 (11%). Significant areas are covered by different types of inundated wetland vegetation like reed-shrub (ca 40 km^2 (9%)), shrub-sedge (45 km^2 (10%)) and sedge (20 km^2 (4%)). The total area of inundated classes was 215 km^2 (47%). The dominant types of "dry" classes are grasslands, and deciduous and coniferous forest, which together cover almost 80 km^2 (18%). The rest of the "dry" classes constitute less than 10 percent of the total area of dry classes. The classified image with 12 classes was verified with ground truth data for 796 locations, resulting in an error matrix. This verification yielded an overall accuracy of 88%, which shows that the classification was successful and the training regions were well defined. In general, both the user's and producer's accuracy were higher for dry classes than for wet classes; the lowest values were obtained for classes which represent different wetland vegetation types. Although a Kappa index (KHAT) (Lilesand, Kiefer 2000) of 0.86 confirmed the reasonable good result of this classification, a more generalized classification was preferred to reduce misclassification. Hence, 4 similar vegetation types (sedge, shrub-sedge, reed-shrub and moss-sedge) were joined into one class of sedges-reeds-mosses-shrubs, since these vegetation types showed most classification uncertainty. Table 2 shows the error matrix calculated for the classes after this reduction of classes. The resulting overall accuracy (Lilesand, Kiefer 2000) increased from 88% to 93%. The calculated producer's and user's accuracy for the new class sedges-reeds-mosses-shrubs was high, respectively 95 and 96%. Finally, the classified image was reclassified into two main classes of "inundated" (containing the classes deep water, shallow water, inundated tall sedges and reeds, flooded alder forest, flooded meadow, alder birch forests, reeds and shrubs, sedges, shrubs and sedges, moss-sedge communities) and "dry" (containing the classes coniferous forest, deciduous forest, grasslands, and bare soils). This 'inundated-dry' map was verified using ground truth data. i.e. an inundation map determined on the basis of GPS field measurements and topographic analysis. The 59 field observed border points between inundated and dry areas showed a correspondence of 85% with the classified 'inundated-dry' map (Fig. 3).

3.2. Flood water extraction

A cluster analysis of the PCA scores resulted in six clusters, Table 1 shows the mean values and standard deviations of each cluster. The spatial distribution of the six distinguished clusters over the inundated valley is shown in Figure 3. Clusters 1 and 2 have high HCO_3^- contents, high Ca^{2+} concentration and a slightly lower pH than river water, which are characteristics of groundwater. The enhanced values of SO_4^{2-}, Cl^-, Na^+ and K^+ in cluster 2 indicate pollution. The spatial distribution of samples belonging to cluster 2 strengthens the hypothesis of pollution by human impact in the outflow from the villages located at the edge of the valley. Clusters 3 and 6 are quite similar, having low mineral richness related to low HCO_3^- and Ca^{2+} concentrations and a low pH.

These clusters can be interpreted as water types predominated by rainwater/snowmelt, but cluster 3 also has enhanced K^+, PO_4^{2-}, SO_4^{2-}, and Cl^- suggesting a mixed type of water with human impact. Water samples belonging to clusters 3 and 6 predominate in the centre of the southern part of the Lower Basin and in several smaller isolated areas localised along the dunes, which border the valley at the eastern side.

Cluster 4 has high mean values for EC, Cl^-, K^+ and Ca^{2+}, the highest pH and SO_4^{2-} values and low values of Si, Zn, PO_4^{3-} and Mn. As discussed before, these properties are characteristic of river water, and the spatial location of samples classified as cluster 4 is indeed mostly close to the Biebrza River. The other cluster resembling river water is cluster 5, which is represented by one single sample collected from the Wissa River; a right side tributary of Biebrza. Wissa has higher nutrients (SO_4^{2-} and Cl^-) than Biebrza River, mainly due to water pollution released in the riparian villages. The boundary of the spatial distribution of clusters 4 and 5 was assumed to be the border of the river water zone and it was digitised in ArcGIS 9.x (Fig. 4), which resulted in an area of 89.2 km^2 flooded by the river.

The border of the obtained river water zone was fairly accurate; uncertainty only arose from a relatively small number of sample points in difficult-to-reach parts of the valley.

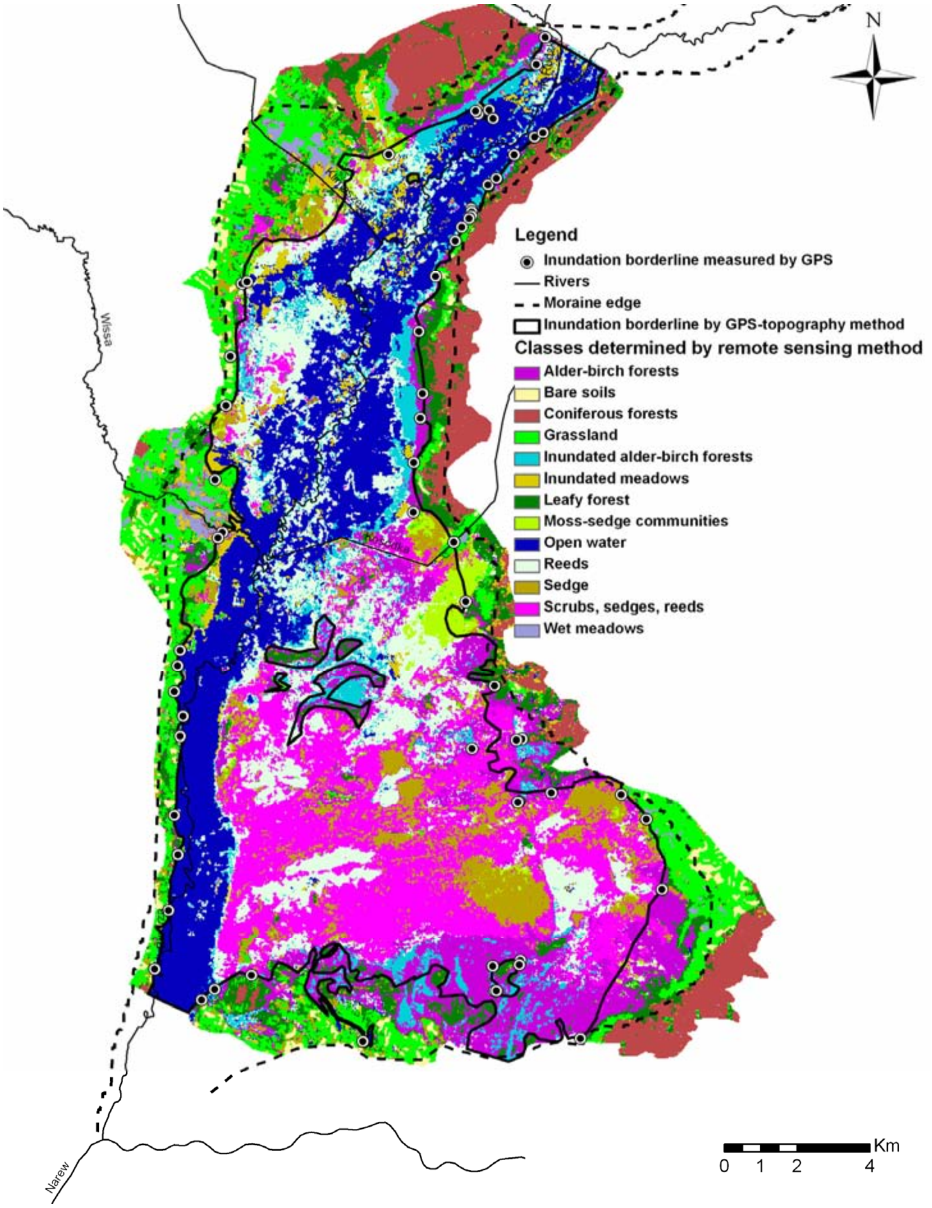

Fig. 2. Results of the supervised classification of the Landsat image for the 2002 spring flood. (Chormański *et al.* 2011)

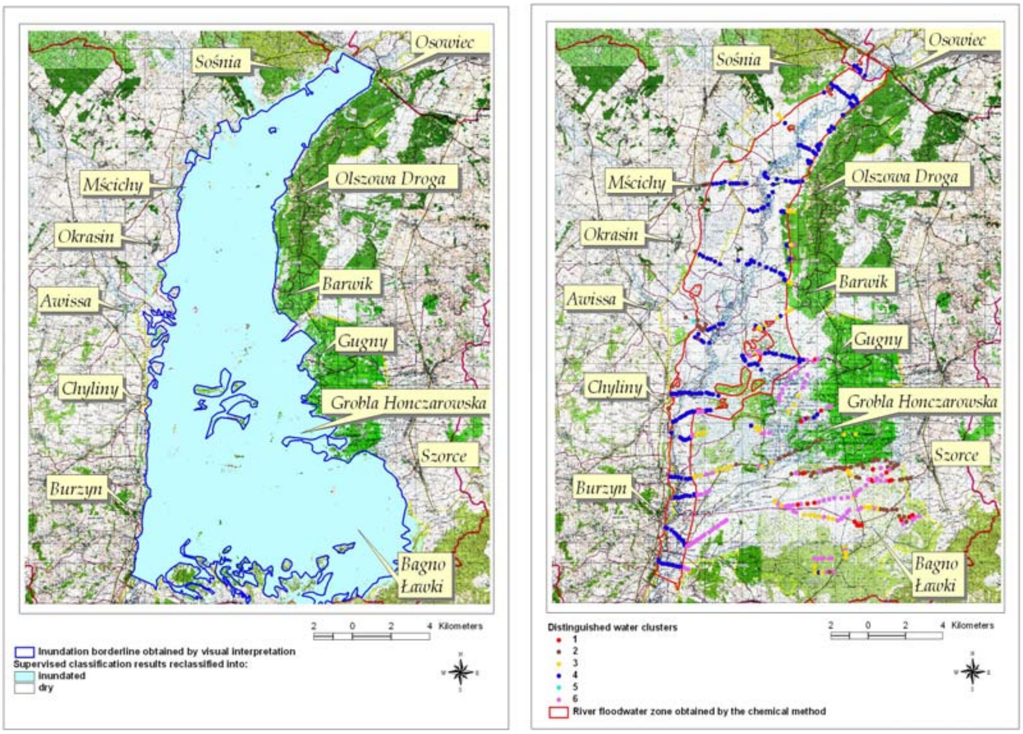

Fig. 3. Comparison of the inundation maps obtained by different methods Remote Sensing (left) and hydrochemistry (right) for the 2002 spring flood. Spatial distribution of water chemistry clusters (clusters based on scores of floodwater samples on PCA components 1, 2 and 3) (Chormański 2007)

3.3. Flood statistics

Table 3 presents the results of calculations with the model. The total calculated area of inundation for annual mean hydrological conditions is 68 sq km. This explains the magnitude of the typical extent of inundation. The water depth in the valley is mostly less than 0.5 m (more than 98% of the inundation) and is regularly distributed in three water depth classes mentioned in Table 3 as less than 0.05 m, between 0.05 – 0.15 m, and between 0.15-0.50 m (Fig. 5). Extreme water conditions calculated as the mean of yearly maximum stages is presented in the next column of this table. The total inundation extent is twice higher than in the previous one, and is 116 sq km. About 66% of the total inundated area had water depth of less than 0.5 m and 27% of area had water in the range of 0.5-1 m (Table 3). The inundation frequency explains the average duration of the flood, by the number of days with inundation during the vegetation season per year.

Table 1

Hydro-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 (Chormański 2003, Chormański e*t al.* 2011)

Variable	cluster 1		cluster 2		cluster 3		cluster 4		cluster 5	cluster 6	
	Avg.	St. Dev.	Avg.	St. Dev.	a Avg.	St. Dev.	Avg.	St. Dev.	-	Avg.	St. Dev.
EC	405.8	104.0	426.9	107.7	262.9	73.4	390.2	41.72	570.0	246.9	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
$HC0_3$	261.4	76.08	234.1	56.21	127.3	35.01	197.6	23.63	317.2	157.2	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+}	75.6	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
nb of samples	25		75		80		251		1	117	

Table 2

Flooded or inundated area determined by using particular methods, namely, GPS, Remote sensing and hydro-chemical method, in the case of flood in 2002 (Chormański et al., 2011)

Inundated/Flooded	Method		
	GPS-topography method	Remote sensing	Hydro -chemical
	Inundated	Inundated	Flooded by river
Area [sq m]	188.8	214.8	87.7

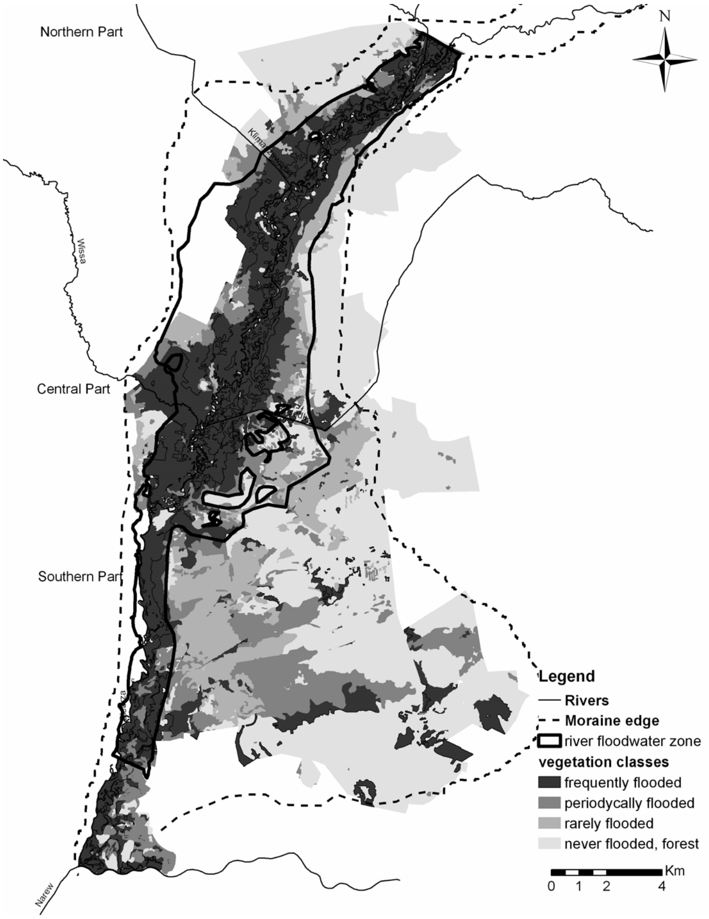

Fig. 4. River floodwater zone obtained by the hydro-chemical method compared with the generalized vegetation map. (Chormański *et al.* 2011)

Table 3

Flood statistics calculated with the hydrodynamic model and GIS for vegetation seasons in 1961-1996

Water depth	Inundated Area [sq km]		Frequency zone	Inundated Area	
	Long-term annual mean	Long-term annual			
0.01-0.05	18.09	31.25	[%]	[Sq km]	[%]
0.05-0.15	23.47	17.30	0-20	44.52	44.98
0.15-0.5	25.99	27.80	20-50	44.40	44.86
0.5-1	0.92	31.68	50-80	9.71	9.81
1-2.5	0.01	7.72	80-100	0.34	0.34
Total	68.47	115.74	Sum	98.97	100

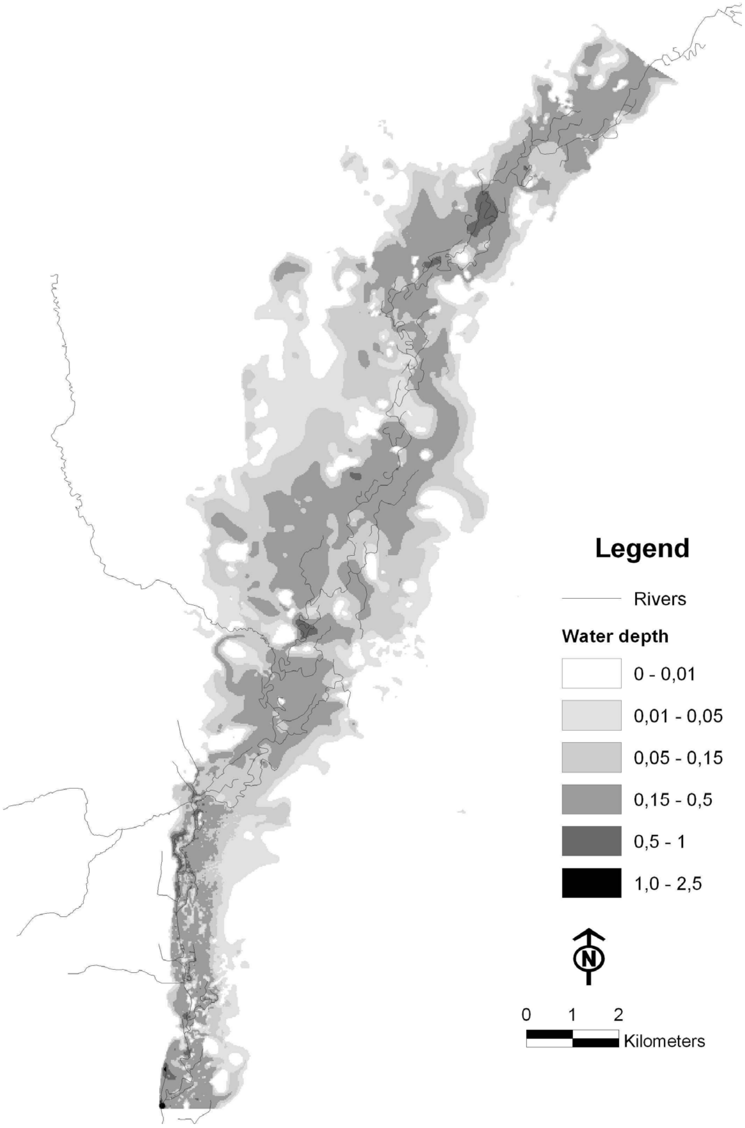

Fig. 5. Long-term annual mean inundation extent and water depth during vegetation period

This is expressed in percentage ratio of the total of 8 months, e.g. a class from 80 to 100 means from 194 to 242 days, class 50 - 80 means from 121 to 194 days, etc. This phenomena is also presented on a map (Fig. 6). The domination of classes 0-20 and 20-50, which are almost equal and cover about 45% each is clear. About 10% covers the class 50-80 while class 80-100 covers insignificant part of the inundated area (0.5%) (Table 3).

The flood statistic maps were compared by overlying them on a map of the plant communities. The map was generalized into river flood frequency dependent zones. Three of zones were described as frequently flooded, namely: *reeds typha manna grass, tall sedges*, and *sedge mire communities – long flood period* (Table 4). The long-term annual mean water depths were 0.17, 0.15, and 0.10, respectively, for these classes (Table 3). Long-term annual maximum mean water depths were 0.65, 0.60, and 0.43, respectively, for the classes mentioned above. About 60% of area of both zones, *Reeds typha manna grass* and *tall sedges*, is located in the inundation frequency zone of 20-50%.

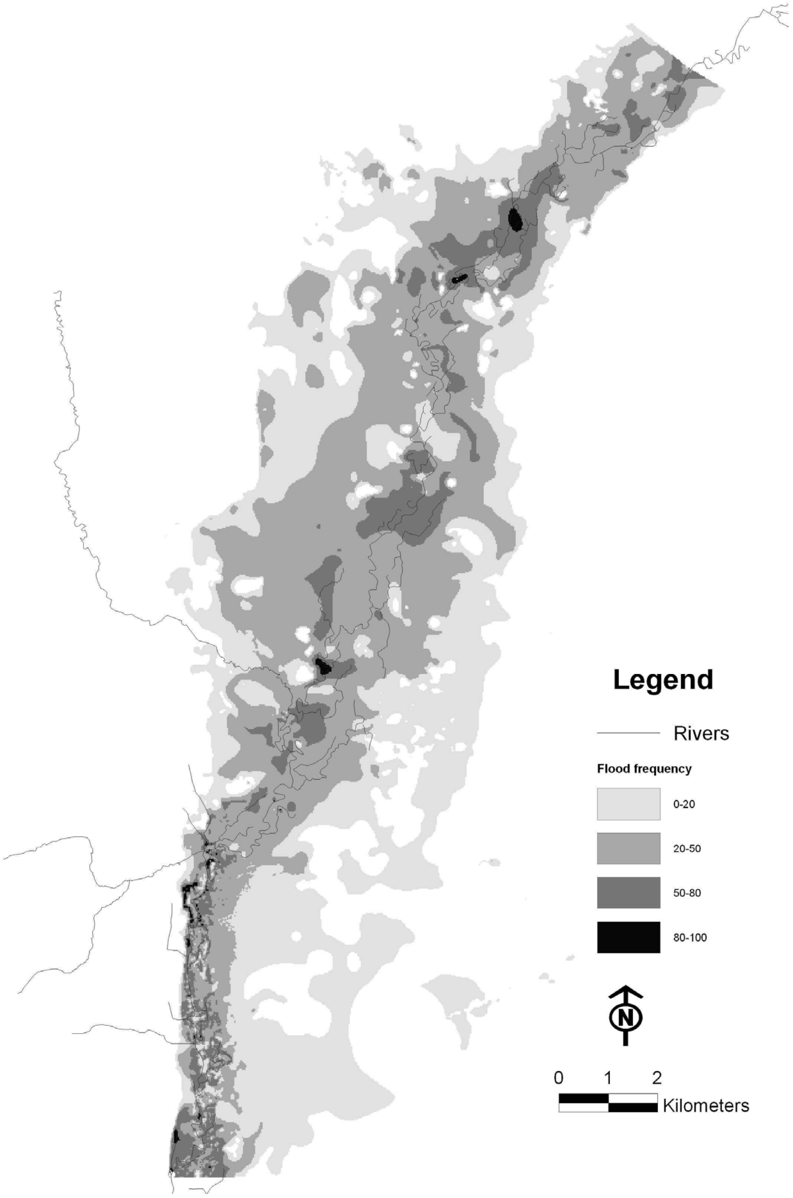

Fig. 6. Long-term flood frequency zone extent during vegetation period

It is worth noting that about 20% of these zone areas belong to the frequency zone of 50-80%. Generally, these classes were found inside the deep, long inundation duration zone. The third class, *sedge mire communities – long flood period,* was found in the inundation zone with deep water but a shorter inundation period (Table 4).

Table 4

Long-term average flood characteristics by different vegetation types (Matuszkiewicz 2000) during vegetation seasons in 1961-1996 (Chormański *et al.* 2009)

Vegetation type	Average water depth [m]		Frequency zone [%]			
	Long-term annual mean	Long-term annual maximum's mean	0-20	20-50	50-80	80-100
Reeds, typha. manna grass	0.17	0.65	12.62	64.70	21.75	0.93
Tall sedges	0.15	0.60	19.49	62.38	17.88	0.25
Sedge mire communities, long flood period	0.10	0.43	36.16	56.47	7.37	0.00
Sedge mire communities, periodically flooded	0.03	0.16	63.25	33.75	3.00	0.00
Sedge moss communities, rarely flooded	0.02	0.11	79.47	19.83	0.69	0.00
Sedge moss communities, never flooded	0.00	0.02	87.29	12.71	0.00	0.00
Wet meadows and pastures	0.03	0.15	64.32	32.93	2.71	0.05

Other plant community zones distinguished by Matuszkiewicz (2000) were described as not so strongly flood dependent, namely: *Sedge mire communities - periodically flooded; Sedge moss communities - rarely flooded; Sedge moss communities - never flooded;* and *Wet meadows and pastures*. Long-term annual mean water depths calculated for these classes prove that flooding is not a significant factor in the development of these communities. These zones are in about 80% of the total area located inside of the 0-20 inundation frequency zone, which means that inundation lasts there only for a few days (Table 4). These plant communities were never flooded for a long time, and they have never been inside the 80-100 zone.

4. Discussion

Knowledge of the range of different water zones with different origin in floodplains is important due to a number of reasons. Firstly, it has a great meaning for natural resources management in wetland ecosystems. Floodplain plays the role of a natural temporary water storage area during floods (Sutcliffe, Parks 1989, Large, Petts 1994). This function is especially important for flows at or below the 40 year returned period (Bhowmik, Demissie 1982). The higher flows also have positive role because extreme floods can "reset" floodplain ecosystems, which create new opportunities for pioneer species to regenerate (Yao Yin *et al.* 1994). Secondly, the hydrological aspect of flood zonation, especially river water extent is important. The determination of the border of river flood origin in floodplains is fundamental from the point of view of constructing hydrodynamic models. Hydrodynamic models, describing the process of water flow in a river channel and its distribution in a floodplain for high water stages, are quantitatively verified on the basis of discharge observation in gauges (Kubrak, Okruszko 2000, Kubrak *et al.* 2000, Świątek, Okruszko 2002, Soczyńska *et al.* 2002, Świątek *et al.* 2003). Trials of spatial model verification have often been undertaken, in which the calculated flood extent is compared with satellite images (Bates *et al.* 1997; De Roo *et al.* 1999, Świątek, Chormański 2003). Taking into consideration floodwater zonation, which takes place in valleys of natural rivers, the effectiveness of such an approach seems to be controversial, whereas the proper determination of a river zone becomes a fundamental aspect of hydrodynamic model calibration, what was clearly indicated in this study. The field observations with GPS resulted in an estimated inundated area of 189 km^2 (Table 2). The remote sensing supervised classification yielded a slightly larger estimate of the total inundated area (215 km^2). Figure 3 shows that the extent of the inundated area obtained by GPS and remote sensing is very similar (88% overlap). The slightly lower value of the estimated inundated area by GPS is explained by the fact that the GPS methodology strongly depends on the density of measured and easy-to-reach locations. Since the density of measuring locations was low in some difficult to reach areas, the interpolation of the extent of inundation in such areas is uncertain. This drawback of the GPS method does not apply for the remote sensing method since the extent of inundation depends merely on image classification and not on the local density of ground truth location, but rather on sufficient high quality ground truth locations. The remote sensing method is more accurate, provided that sufficient ground truth data is collected during a flood.

The hydrochemical method enabled us to estimate the extent of the river floodwater zone (88 km^2, Table 2, Fig. 3). The result is similar to the remote sensing result (about 75% of area) for the northern part of the Lower Basin in which all of the inundation was caused by river floods. However, a completely different situation appeared in the southern part of the valley where the area of the river floodwater zone was less than 20% of the inundated area: the river flood zone was only c. 2 km wide whereas the width of the inundated zone was up to 12 km

(Fig. 3). The southern part of the valley is very flat and is much wider than the northern part. In the case of the southern part of the Lower Basin, the hydrochemical method is able to separate the zone flooded by the river itself from other inundated zones.

From flooding records it is known that the Biebrza River floods, on average, once every two years, with a spatial extent similar to the one we measured in 2002. This also implies that the vegetation pattern should resemble the observed hydrochemical pattern, i.e. the flood extent described on the basis of water chemistry should be reflected in the actual vegetation map. In an attempt to verify the flood zones for the entire lower basin an available vegetation map (Matuszkiewicz 2000) is used, which was generalized into a number of vegetation types with different flood frequencies. The spatial extent of the river floodwater zone, overlain with the generalized vegetation map, and limited to the Biebrza National Park border, is shown in Figure 4. Four flood frequency vegetation classes were determined: (1) frequently flooded (including: reed typha manna grass, tall sedge, and sedge-moss communities for a long period flooded), (2) periodically flooded (sedge-moss communities periodically flooded, wet meadow and pastures), (3) rarely flooded (sedge-moss communities rarely flooded) and (4) never flooded and forest (sedge-moss communities never flooded, moist meadows, forest). Generally, the first class was found inside the river flood water zone as identified by the hydrochemical method, especially in the northern (99%) and central part (80%). However, there are some exceptions, at certain places – close to ditches, which provide surface water to these during flood events. The spatial distribution of different water types during the peak of a flood event with average frequency and duration is significantly correlated to the pattern of vegetation types in the floodplain. The river floodwater zone obtained by the hydrochemical and GIS analysis agrees very well with the vegetation map.

Assuming that flooding water determines living conditions of fluviogenous ecosystems (Junk *et al.* 1989, Okruszko 2005) the surface water modeling work performed for the Biebrza Valley was performed. It shows a strong relationships between inundation frequency maps and different water dependence classes of ecosystems. According to the works of Oświt (1991), Hoojer (1996), and Kubrak *et al.* (2005) the most important flood characteristics for riparian wetland plant communities are: inundation extent, depth and duration of flood, which are the same as those selected by the current authors. These flood characteristics calculated for long-term discharge are very important for ecosystem development. This means that the properly calibrated model could also be used as a tool for the study of relationships between flood and riparian ecosystems including the simulation of flood conditions for floodplain in general, and the prediction of the ecosystem changes due to climate change.

5. Conclusions

The remote sensing supervised classification method, which resulted in a reclassified "inundated" and "dry" map, gave satisfactory results which were verified by field sampled ground truth data.

The hydrochemical method allowed a precise determination of the river flood map in combination with GIS techniques. Its full application, which involves statistical analysis of hydrochemical features, is evaluated as the most effective tool for separating valley zones directly flooded by river water from zones inundated by groundwater or rain-snowmelt water. However, a gradual water quality gradient between areas where groundwater dominates versus rainwater/snowmelt water dominated areas and short distance spatial heterogeneity make it difficult to separate between these water sources.

Integration of different geoinformation techniques of measurement and data processing including GPS, remote sensing, GIS, and water chemistry analysis for flood extent assessment, is recommended for application in future monitoring activities. In that case, it may be valuable to monitor the extent of different zones in floodplain yearly.

Analyzing flood characteristics and plant communities together shows a satisfactory spatial relation between water zones and vegetation types.

The model that was verified based on historical data could be used for simulating the influence of long term climate changes on riparian ecosystems, which is reflected by decreasing water levels and flood duration as a consequence increasing temperature and decreasing snow cover depth. The model can answer questions on how the ecosystem would change with a different scenario of climate change. It can be used for flood characteristics calculation and then to relate temporal dynamics to hydrological variability and changes in water use, land use and climate.

The annual mean flood zone as well as long term flood frequency and flood duration could be used for projects that focus on the re-naturalization of river valleys with anthropogenic changes, for which the Lower Biebrza Basin would be treated as a reference area.

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