Recognition of Hydrological Processes
in the Upper Narew Multichannel River System
and Their Influence on Region Sustainable Development

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Abstract

The paper provides results of research related to the influence of hydrological processes on sustainable development in the Upper Narew region. They were achieved in a multi-stage process starting from the recognition of the geometry of the river system together with the adjacent floodplain areas based on the existing maps, GPS-based map, field surveys, and monitoring of two flood waves that occurred during the realization of the project. Further steps consisted in the simulations with the use of CCHE1D model and creation of respective anticipated flood area maps. This directly constitutes supplementary information and a tool for discussions with local decision makers, Board of Narew National Park, and various other stakeholders.

Key words: sustainable development, Upper Narew River, CCHE1D unsteady flow model

1. Introduction

Hydraulics of natural channels and rivers is extremely complex and despite numerous investigations it is still far from being understood in all its details. Despite the fact that the importance of the observation of the velocities in a river was recognized already in the seventeenth century, in the recent years the situation regarding the hydrometric data networks has been deteriorating rather than improving (Dooge, 2002). An astonishing fact is that there still exist rivers in which neither systematic nor episodic hydrometric surveys have been performed. One of the least known rivers in this respect is the Upper Narew in the north east of Poland. The present study is aimed at a detailed recognition of hydrological and morphometric state within the se-
lected reach of the river channel, namely, the part of the river reach connecting Suraż and Topilec villages, which constitutes the first half of the river reach within the Narew National Park. The present study is an extension of the former survey carried out in the shorter reach Suraż-Bokiny with much lower space resolution (see Rowiński et al., 2003 for details). In the case of Upper Narew, one is dealing with a multi-channel system on a floodplain. In contrast to the typical braided rivers, the Narew multi-channel system is represented by relatively small slopes. This is one of the reasons why it is suspected that the Upper Narew belongs to anastomosing type of fluvial systems despite numerous differences with other rivers of this type (Gradziński et al., 2000). Nevertheless, the general pattern of the considered reach of the Upper Narew river is similar to a braided one in the sense that the stream branches in a couple of channels which subsequently rejoin and branch again forming a structure that looks like a braid.

There are numerous studies connected to the analyses of the unique ecosystem present within the Narew National Park, and the conclusions were derived without detailed understanding of the flow regime in this highly complicated hydrographic network. No estimates have been made, for example, to see how much water outflows or (in other cases) inflows to the main river channel from (or to) various river arms and bights. Eventual modelling of the water flow routing in the area is impossible without this basic information; one needs to know whether those outflows or inflows are crucial at the achievable level of accuracy of the mathematical model utilized. Such detailed balance of the flowing volume of water is also critical for the estimates of the transport of anticipated admixtures in a given river reach. The former study surprisingly indicated relatively small supply of the main watercourse by the surface and ground inflows (Rowiński et al., 2003).

The obtained hydrometric data allows for various modelling exercises leading to scenarios of flow routing through the river system. This is a large step ahead since so far all the considerations were based on the time series from the gauge station in Suraż without any detailed knowledge of the system downstream from that site (Mioduszewski, 2002).

The considered part of the Upper Narew confirms a common opinion that watersheds with a large percentage of their area in wetlands generally have lower high-magnitude flows. In other words, wetlands can temporarily detain floodwaters and attenuate flood peaks and the Upper Narew is not specially endangered by catastrophic flood events. Nevertheless, understanding of flooding phenomenon in the area is extremely important for proper water management practices. It is known that wetlands provide essential breeding, nesting, feeding and refuge habitats for many species of birds, mammals, amphibians and reptiles. Many rare life forms, including endangered and threatened plants and animals, require wetland habitats during some portion of their life cycle. Continuation of spring floodings is therefore very important to sustain
breeding birdlife and appropriate moisture levels in the soils. On the other hand, the inundation should not menace local farms, and a compromise must be sought. Appropriate control of Siemianówka reservoir can help in achieving the right policy but a necessary step is a better understanding of the behaviour of the system, which can be achieved by means of mathematical modelling of flood routing through it. Introducing artificial floods is by no means a new concept and is recommended by many researchers—such floods should in each case vary from year to year to better mimic natural variability (Collier et al., 1997).

Even though the 3D computational models for simulating unsteady free surface turbulent flows, sediment transport and water quality models have been reported recently, water resources, hydraulic and environmental engineers, management planners, and policy makers are still demanding a reasonably accurate and a relatively "cheap" computational model. Such model would be used for better understanding of the system, for preliminary analyses and parametric trade-off studies required by planning and decision-making, for feasibility evaluations of engineering designs, for environmental assessment and other applications. Due to the pronounced environmental vulnerability of water bodies such as the multi-channel Narew River, a careful verification of the effects of any proposed modification of their equilibrium conditions is essential. Moreover, whenever an activity is planned to be carried out in the water system, it may be necessary to verify the actual feasibility of it—as long as particular physical and chemical conditions are available. Mathematical models, such as 1D channel network model CCHE1D supported by field data, are a powerful tool to investigate the effects of the proposed activities on water system and the neighbouring wetland areas for either feasibility study or environmental impact purpose and the use of this model constitutes the main objective of this study.

A number of questions at different levels of generality can be posed and discussed in the framework of this study:

- Recognition of the processes governing the momentum transport and, as a consequence in the follow up studies, fate of pollutants in the considered multi-channel river system.

- Investigations of the effects of the ongoing and proposed activities on water system and the neighbouring wetland areas for either feasibility study or environmental impact purpose by means of mathematical models supported by field data.

- Evaluation of Siemianówka Reservoir discharges leading to fluctuating flows to sustain natural habitats and other anticipated environmental values within the Narew National Park.

- Development of a framework for understanding, testing and implementing sustainable approach and various water management alternatives in the river
catchment endangered by both shortage and surplus of water as well as by affecting pollutants.

The above goals were achieved as a multi-stage process starting from the recognition of the geometry (topology, bathymetry) of the river system together with the adjacent floodplain areas based on the existing maps, field surveys and monitoring of two flood waves that occurred during the realization of the project. Further steps consisted of numerical simulations with the use of CCHE1D model and creation of respective anticipated flood area maps. This directly constitutes a tool for discussions with local decision makers, Board of Narew National Park and various other stakeholders.

2. Hydrological survey

Study area

The multichannel Narew River section extends in the marshy area from Suraż to Rzędziany villages and this part of the river constitutes the basis for the Narew National Park (see Fig. 1). Until the Rzędziany section, the river has a natural character,

![Map of the Narew River](image_url)

Fig. 1. The Upper Narew River within the Narew National Park.
since no drainage works have ever been done there (Mioduszewski, 2001). The only important unnatural factor influencing both the water quantity and quality in this area is the Siemianówka water reservoir built upstream, about 90 km from the Narew National Park. A large debate on the influence of this reservoir on the water system within NNP is carried on; nevertheless, a number of researchers emphasize its interference in the hydrological regime of the river and the decline of its water transparency (e.g. Wiśniewolski, 2001). Whatever is the case, the river system within NNP maintains its absolutely unique character with its frequently branching and rejoining streams. The Narew valley in this area is characterized by a relatively flat bottom bordered by gentle slopes of low hills built mostly of glacial clays (Gradziński et al., 2000).

The present study has been concentrated on the first half of the river within NNP starting from the bridge in Suraż and with the last measuring site at Topilec village and it extended along the main river stream over a distance of 23.6 km according to the GPS-reading (see Fig. 2).

It is worth mentioning that the detailed survey and the recognition of the actual channel network was made from a boat with the use of a Global Positioning System (GPS) unit and the relevant profiles were localized on the existing map. The GPS accuracy is related to GPS satellites’ positions in constellation. Highly favorable layout of satellites was observed during the time of measurements. This survey allowed us to validate the map and to reveal on it the channels that are really active. Most of the channels that are shown on the map can be treated as abandoned during low water conditions.

The largest tributaries to the main stream in the considered reach are the following rivers: Liza (catchment area 134.3 km²), Turosnianka (130.7 km²) and Czaplinianka (78.9 km²). The outflows from only three river branches, namely Szołajdżanka, Napiórka and Jabłonowszczyzna, were significant at the time of measurements. Detailed measurements were performed at required 44 cross-sections (see Fig. 2). They are denoted in different ways depending on what information has been obtained at a particular cross-section (HG – both cross-section geometry and velocity distributions were measured; G – cross-section geometry, HZW – velocity distributions & the water level were detected). Note that the area is not easily accessible so the difficulty of each measurement is amplified in comparison to traditional survey. However, at critical locations geometric data was obtained regardless of difficulties.

Hydrological measurements were made in the period 27.05-03.06.2003. No precipitation occurred in time of measurements; nevertheless, the changes in the water level were registered. The water level gauge station, operated by the Institute of Meteorology and Water Management, continuously controlling the changes in water levels and flow intensity, is situated near the bridge in Suraż. The water levels registered varied in the range from 152 to 135 cm. The medium stage here in 1949-1995 is
189 cm, the lowest of medium stages is 153 cm. Therefore, the water stage during measurements was lower than the lowest of medium stages, and higher than the medium of low stages, which is 116 cm in Suraż. The flow in Suraż varied in the range from $Q = 8.544 \text{ m}^3/\text{s}$ to $6.142 \text{ m}^3/\text{s}$.

Fig. 2. Recognition of the actual channel network made with the use of GPS.
Velocity profiles

Recognition of the streamwise velocity field was the main challenge for the hydrological survey. The knowledge of actual velocity distributions allowed also for the determination of the discharges at the selected cross-sections. The cross-sections and riverbed are usually quite complex in the considered case. Therefore, the flow does not always meet the assumption of one-dimensional flow. Nevertheless, this assumption is needed in order to be able to make the measurements and to interpret the data. In these kinds of applications, very often the mean velocity is determined by the average of the velocities measured at the vertical locations 20% and 80% of the water depth. If the water is shallow the mean velocity is assumed to be the same as the velocity measured at 60% of the water depth (Rantz et al., 1982). Such guidelines are based on the assumption that the river flow is basically one-dimensional and steady and the width to depth ratio is quite large (much greater than 5), so that the velocity profiles in the river cross-section are not affected by the presence of banks. Much more detailed measurements allowed us to assess how good such theoretical assumptions are.

Traditional methods that make use of current meters were utilized for the determination of point velocities. The measurements were made at all HG profiles denoted in Fig. 2. ISO standards compiled in ISO Standards Handbook 16 (ISO, 1983) were applied which assured error involved in the estimates of mean velocities not

Cross-section HG-1

![Cross-section HG-1 diagram](image)

Fig. 3. Water velocity distribution at the cross-section HG-1.
exceeding 7%. Detailed discussion of the hydrometric quality assurance systems may be found in Hudson et al. (1999).

Point velocity distribution at the selected verticals for one of the chosen cross-sections is shown in Fig. 3. Note that the number of measuring verticals depends on the width of the channel. The maximum streamwise velocities did not occur at the verticals located close to the riverbanks. The reason is that the measuring cross-sections were carried out in relatively straight river reaches in which the streamlines were parallel. In general in the areas where meandering was observed, the maximum velocities usually occurred close to the convex bank. It was verified that in many cases two measurements (at 20% and 80% depths) provide a value relatively close to the true mean velocity. However, for measurements along some verticals the error exceeded considerably 10%, reaching the value of 64% at the cross-section HG35.

Other hydraulic properties

Water surface slope along the whole river reach, slopes between measuring cross-sections, local water surface slopes, riparian (overbank parts) of riverbed profiles and ordinates of the free surface were surveyed by levelling with respect to provisional benchmarks levelled to a geodetic benchmark in Suraż, in the Kronstadt reference system. The provisional benchmarks were installed in the measurement profiles.

The velocity distribution data can be further analyzed to reveal properties of river hydraulics. Measuring river discharge is always an important task and in fact one of our key elements in balancing water outflows and inflows to the system.

The flow rate and its spatial variation during the period of measurements are shown in Table 1. Table 1 also shows other hydraulic and topographic characteristics such as the hydraulic radius, local water surface slope, Manning coefficient, Froude and Reynolds numbers for all measuring cross-sections. A discussion on the variability of these measured values has been given with respect to the former measuring campaign in (Rowiński et al., 2003) and the conclusions can also be applied to a certain extent in the present case.

3. Propensity for overbanking

A precondition for a correct and rational flood planning is the evaluation of the statistical probabilities of exceedence. In other words estimations of quantiles for given probability density functions have to be determined. There is a variety of possibilities for the choice of a probability density function for the flood frequency analysis. Empirical evidence suggests that, in the case of Upper Narew, log-normal probability density function provides a good fit to the observed time series. Log-normal PDF has been chosen from among ten PDFs fitted to the annual maxima water series.
Table 1
Measuring results in the Narew River and in its main arms and tributaries in the Suraz-Topilec reach

<table>
<thead>
<tr>
<th>Cross-section</th>
<th>River</th>
<th>Flow rate [m/s]</th>
<th>Hydraulic radius [m]</th>
<th>Local water surface slope [%/100]</th>
<th>Manning coefficient</th>
<th>Froude number</th>
<th>Reynolds number</th>
</tr>
</thead>
<tbody>
<tr>
<td>HG - 1</td>
<td>Narew</td>
<td>0.414</td>
<td>0.522</td>
<td>0.346</td>
<td>0.029</td>
<td>0.182</td>
<td>167 000</td>
</tr>
<tr>
<td>HG - 4</td>
<td>Liza</td>
<td>0.109</td>
<td>0.230</td>
<td>0.577</td>
<td>0.083</td>
<td>0.068</td>
<td>22 000</td>
</tr>
<tr>
<td>HG - 5</td>
<td>Narew</td>
<td>0.196</td>
<td>1.664</td>
<td>0.028</td>
<td>0.038</td>
<td>0.046</td>
<td>271 000</td>
</tr>
<tr>
<td>HG - 11</td>
<td>Narew</td>
<td>0.332</td>
<td>1.531</td>
<td>0.356</td>
<td>0.075</td>
<td>0.083</td>
<td>419 000</td>
</tr>
<tr>
<td>HG - 12</td>
<td>Szalajdzianka</td>
<td>0.049</td>
<td>0.503</td>
<td>0.152</td>
<td>0.159</td>
<td>0.021</td>
<td>20 000</td>
</tr>
<tr>
<td>HG - 13</td>
<td>Narew</td>
<td>0.366</td>
<td>1.255</td>
<td>0.172</td>
<td>0.042</td>
<td>0.100</td>
<td>379 000</td>
</tr>
<tr>
<td>HG - 16</td>
<td>Narew</td>
<td>0.368</td>
<td>0.950</td>
<td>0.272</td>
<td>0.043</td>
<td>0.119</td>
<td>277 000</td>
</tr>
<tr>
<td>HG - 18</td>
<td>Narew</td>
<td>0.249</td>
<td>1.000</td>
<td>0.123</td>
<td>0.045</td>
<td>0.079</td>
<td>196 000</td>
</tr>
<tr>
<td>HG - 19</td>
<td>Napiórka</td>
<td>0.133</td>
<td>0.696</td>
<td>0.365</td>
<td>0.113</td>
<td>0.047</td>
<td>83 000</td>
</tr>
<tr>
<td>HG - 20</td>
<td>Napióreczka</td>
<td>0.008</td>
<td>0.459</td>
<td>0.111</td>
<td>0.772</td>
<td>0.003</td>
<td>4 000</td>
</tr>
<tr>
<td>HG - 22</td>
<td>Narew</td>
<td>0.341</td>
<td>0.840</td>
<td>0.168</td>
<td>0.033</td>
<td>0.117</td>
<td>228 000</td>
</tr>
<tr>
<td>HG - 25</td>
<td>Awissa</td>
<td>0.062</td>
<td>0.453</td>
<td>0.183</td>
<td>0.128</td>
<td>0.027</td>
<td>25 000</td>
</tr>
<tr>
<td>HG - 26</td>
<td>Awissa</td>
<td>0.098</td>
<td>0.876</td>
<td>0.102</td>
<td>0.094</td>
<td>0.031</td>
<td>76 000</td>
</tr>
<tr>
<td>HG - 27</td>
<td>Narew</td>
<td>0.264</td>
<td>1.230</td>
<td>0.104</td>
<td>0.044</td>
<td>0.075</td>
<td>257 000</td>
</tr>
<tr>
<td>HG - 31</td>
<td>Narew</td>
<td>0.150</td>
<td>1.694</td>
<td>0.160</td>
<td>0.120</td>
<td>0.036</td>
<td>206 000</td>
</tr>
<tr>
<td>HG - 32</td>
<td>Jabłonowszczyzna</td>
<td>0.402</td>
<td>0.895</td>
<td>0.721</td>
<td>0.062</td>
<td>0.123</td>
<td>338 000</td>
</tr>
<tr>
<td>HG - 34</td>
<td>Narew</td>
<td>0.193</td>
<td>1.280</td>
<td>0.050</td>
<td>0.043</td>
<td>0.054</td>
<td>194 000</td>
</tr>
<tr>
<td>HG - 35</td>
<td>Turośnianka</td>
<td>0.070</td>
<td>0.463</td>
<td>1.094</td>
<td>0.282</td>
<td>0.032</td>
<td>27 000</td>
</tr>
<tr>
<td>HG - 37</td>
<td>Narew</td>
<td>0.183</td>
<td>1.365</td>
<td>0.113</td>
<td>0.071</td>
<td>0.049</td>
<td>200 000</td>
</tr>
<tr>
<td>HG - 38</td>
<td>Narew</td>
<td>0.284</td>
<td>1.310</td>
<td>0.162</td>
<td>0.054</td>
<td>0.077</td>
<td>307 000</td>
</tr>
<tr>
<td>HG - 39</td>
<td>Narew</td>
<td>0.257</td>
<td>1.370</td>
<td>0.105</td>
<td>0.049</td>
<td>0.068</td>
<td>285 000</td>
</tr>
<tr>
<td>HG - 40</td>
<td>Narew</td>
<td>0.357</td>
<td>1.287</td>
<td>0.249</td>
<td>0.052</td>
<td>0.096</td>
<td>385 000</td>
</tr>
<tr>
<td>HG - 41</td>
<td>Narew</td>
<td>0.303</td>
<td>1.120</td>
<td>0.100</td>
<td>0.036</td>
<td>0.090</td>
<td>266 000</td>
</tr>
<tr>
<td>HG - 42</td>
<td>Narew</td>
<td>0.166</td>
<td>1.561</td>
<td>0.291</td>
<td>0.139</td>
<td>0.041</td>
<td>208 000</td>
</tr>
<tr>
<td>HG - 44</td>
<td>Narew</td>
<td>0.193</td>
<td>1.776</td>
<td>0.080</td>
<td>0.068</td>
<td>0.045</td>
<td>284 000</td>
</tr>
</tbody>
</table>

They were: Gamma, Generalized Gamma, Inverse Gamma, General Extreme Value, Gumbel, two and three parameter log-normal, log-Pearson type 3, Pearson type 3 and Weibull (e.g. WMO, 1989; Rao and Hamed, 2000). The mentioned distributions have
been investigated as the most widely used in literature for flood frequency analysis. Some of very popular distributions like log-Gumbel and log logistic have been purposely excluded from considerations due to their constrained applicability caused by the existence of statistical moments for very limited range of parameters (Rowiński et al., 2002). The observed annual maximum discharges at Suraż gauge station are shown in Fig. 4.

![Graph](image)

**Fig. 4.** The observed annual maximum discharges at Suraż gauge station.

We do realize that the use of annual maxima series may lead to the loss of some information but it is sufficient for building the scenarios, which is one the main aims of the present study.

The further analyses assume that the fluctuations in the streamflow process arise from natural causes (randomness); the sample observations are independent from each other (independence), the sample’s observations are drawn from a common statistical population (homegeneity) and the flood series is invariant with respect to time (stationarity). Since different methods fail for different probability density functions, fitting to the observed time series was made with the use of maximum likelihood method, method of moments, and the method of probability-weighted moments. The goodness of fit was assessed by means of the standard $\chi^2$ test and Kolmogorov-Smirnov test. Mean absolute deviation index (MADI), mean square deviation index and Bayesian and Akaike information criteria were applied for evaluation of the fit (Kite, 1997; Mutua, 1994). The combination of all the criteria convinced the authors about the applicability of the log-normal probability density function.
Flood events of a given return period $T$ will be simulated further in the paper. Return period may be defined as the average of the time intervals between consecutive floods. Large floods have obviously large return periods and vice versa (Rao and Hamed, 2000). A given flood $q$ with a return period $T$ may be exceeded once in $T$ years and therefore the probability of exceedance is $P(Q_r > q) = 1/T$. Based on the observed annual maxima time series (Fig. 4), an empirical probability of exceedance may be constructed. Having assumed that $N$ is the sample size and $m$ is the rank in descending order, $T$ may be evaluated based on, for example, Weibull formula: $T = (N + 1)/m$. The computed empirical probability of exceedance is presented in Fig. 5.

![Fig. 5. Empirical probability of exceedance – Weibull formula.](image)

When we assume a given probability density function, in our case the three-parametric log normal distribution, we may say that $T$-year flood is the $(1-p)$th quantile in this distribution. Such quantiles for the considered case are given in Table 2.

<table>
<thead>
<tr>
<th>Return period [years]</th>
<th>Exceedance probability [%]</th>
<th>$Q_{\text{max}}$ [m$^3$/s]</th>
<th>Upper confidence limit [m$^3$/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>1</td>
<td>303</td>
<td>434</td>
</tr>
<tr>
<td>50</td>
<td>2</td>
<td>250</td>
<td>346</td>
</tr>
<tr>
<td>20</td>
<td>5</td>
<td>189</td>
<td>247</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
<td>148</td>
<td>186</td>
</tr>
</tbody>
</table>
Further in the paper the simulated flood waves for the return period of 100, 50, 20 and 10 years will be presented. The results will be extracted to the existing DEM and the corresponding floodplain maps will be created.

4. Digital terrain recognition and preparation of data

The key element of data preparation is the definition of solution domain. It constitutes a problem particularly when the overbank flow occurs. Then the shape of the valley cross-section has to be known. The shapes of those cross-sections need to be known with the accuracy allowing for the application of 1D model; therefore, no attention has to be paid to the detailed structure of a cross-section. Therefore, the cross-sections of the valley were extracted from the available maps. Cross-sections extend from high ground on one side of the stream valley to high ground on the opposite side. The approximate 200-year water surface elevation is used as the cross-section beginning and end mark. Cross-sections used to model channel and floodplain geometry are normally perpendicular to flow across the river valley and cross each contour line at a right angle. However, the section should be modelled to have the velocity vectors intersect each section at right angles. This requirement means that cross-sections may be curved, bent, kinked or "dog-legged" to maintain a right angle to flow. Figure 6 illustrates the layout of the cross-sections in the lower part of the actual channel network incorporating these features.

Fig. 6. Cross-section survey layout.
Large problems occurred due to low accuracy of the maps especially when bed elevation is considered. The errors encountered in many cases were as large as 0.5 m and they were caused by misinterpretation of the aerial photographs (photogrammetric data capture) due to the existence of dense vegetation. It was, however, assumed that the results of our field survey were correct and the maps were adjusted to the measured river channel cross-sections. The general procedure of the preparation of the cross-section geometry in the way allowing for further computations has been realized as follows. Firstly, the selected cross-section (including a part which was measured within a field survey) was digitized. The conversion between contour lines and grids was achieved by means of TOPOGRID model.

Contours have historically been the most common method for storage and presentation of elevation information. Unfortunately it is also the most difficult to properly utilize with general interpolation techniques. Their disadvantage lies in the under-sampling of information between contours, especially in areas of low relief which is the basic feature of the Upper Narew valley in the area under consideration. At the beginning of the interpolation process, TOPOGRID uses information inherent to the contours to build a generalized drainage model. By identifying areas of local maximum curvature in each contour, the areas of steepest slope are identified, and a network of streams and ridges created. This information is used to ensure proper hydrogeomorphic properties of the output DEM, and may also be used to verify accuracy of the output DEM. After the general morphology of the surface has been determined, contour data are also used in the interpolation of elevation values at each cell. When the contour data are used to interpolate elevation information, all contour data is read

Fig. 7. The generated cross-section and that obtained from a field survey.
in and generalized. Then a maximum of 50 data points are read from these contours within each cell. At the final resolution, only one critical point is used for each cell. For this reason, having a contour density with several contours crossing output cells is redundant. Further we have made use of a shareware Section Utility of Script X available at the web. It allows an ArcView 3.x user to create cross-sections, or profiles, of point, line, polygon, or grid themes. It aids the user in setting up a cross-section line and then offers several processing options. The utility creates profiles of point, line and polygon themes by determining their intersections with the user’s cross-section line (points are projected onto the line). It processes grids by sampling them along the cross-section line at user specified intervals. The so-generated cross-sections embrace only the dry part of cross-sections. The remaining wetted part is obtained from a field survey. In many cases, significant disagreement of both parts can be observed. An example of such situation is shown in Fig. 7.

Both parts of the valley cross-section have been adjusted assuming that the measured elevations are true. At the very end of the procedure the cross-sections are simplified as required in CCHE1D model (see Fig. 8).

![Graph](image_url)

**Fig. 8. Simplified cross-section.**

5. FLOOD WAVE ROUTING

In the presented project 1D hydrodynamic modelling allows testing of numerous policies and design scenarios thereby reducing implementation uncertainty. It is realized with the use of CCHE1D model. Due to the geometrical complexity of the
area we have clearly distinguished the cases in which water is routed through the main channel and the situations when water spreads over the floodplain. There is an ongoing debate whether 1D description is adequate in the situations when water flows over the floodplains but it is the only approach possible with the available data.

Unfortunately, the used approach pertaining to the use of the well-known Saint-Venant model requires much information concerning channel geometry and its flow resistance parameters. The needed data to run such problem has been obtained within the experimental survey described above. The problem, however, arises as to the data for calibration of the model. There is no data available for the considered reach with the registered transformation of a flood wave. We have only some fragmentary time series from the gauges in Suraž and Bokiny for eventual qualitative comparisons. Nevertheless, scenarios computations may be performed with the use of the available computer models and they may provide a reasonably accurate tool for decision makers in the region.

*Unsteady flow routing through the main channel*

There is no doubt that the prediction of flow routing under unsteady conditions is of primary importance even in the situations when the overbank flow does not occur. Flow in streams is seldom steady, yet the effects of time-varying velocity on transport in streams are poorly understood. It is therefore crucial especially for the evaluation of transport of mass (pollution, and sediment) to model the unsteady flow in the Upper Narew in a reliable way. Numerous experimental studies contributed to the increase of knowledge of the transport processes under unsteady conditions (e.g. De Sutter et al., 2001; Rowiński et al., 2000; Song and Graf, 1996). In the case of Upper Narew, preliminary studies of the transport of passive pollutants under steady state conditions have been realized (Rowiński et al., 2003) and the plans are being made to focus on time varying situations. So the first step in achieving those long term goals are realized through such modelling exercises of flood routing through the Narew channels.

For the purpose of this presentation, selected results of the simulations based on the CCHE1D model will be given. CCHE1D flow module computes one-dimensional unsteady flows in channel networks of given cross-sectional shape. It can simulate channels of compound cross-sections, differentiating between flows through the main channel and floodplain areas, using either the diffusive wave model or the dynamic wave model (Vieira and Wu, 2002). Flood wave routing in the described case considers the situations when the river water is conveyed within the channel; the case with an overbank flow needs more work and will be described in the next section. Besides, a simplifying assumption that the main channel of the Narew river carries most of the water will be made in order to allow a direct application of CCHE1D model without any additional operations. The main limitation is the non-inclusion of
the bifurcations existing in nature. However the main channel carrying more than 90% of the entire water volume is always clearly visible and the calculations are made as if this is the only active channel.

Channel flow routing provides information on the movement of flood wave as it travels downstream. Since only actual data for the described situation were recorded in spring 2004, the simulations were performed for artificially created flood-waves at the first cross-section in Suraž. Those time–discharge curves were generated based on the expression

$$Q(t) = Q_b + Q_0 \exp\left(-\left(\frac{t - T_p}{T_g - T_p}\right)\left(t / T_p\right)^{T_g / (T_g - T_p)}\right)$$

where $Q_b$ is the base flow, $T_p$ the time to peak, and $T_g$ the time to gravity centre of the curve.

Computations of 1D unsteady flow were performed for a number of parameter sets in the above function, with the use of both the dynamic wave model (full Saint Venant equations) and the diffusive wave model. The obtained results for dynamic and diffusive waves were close to each other and they seem to be qualitatively reasonable. One of the obtained results for the synthetic hydrographs is given in Fig. 9, and that for the 2004 input hydrograph in Fig. 10.

![Dynamic wave model for synthetic hydrograph.](image-url)
Unsteady flow routing of overbank flows

There are numerous modelling approaches aimed at analysing anticipated flood events and preventing their disastrous effects that meet both pre-flood aims and operational flood-management objectives (Napiórkowski and Rowiński, 2003). In our case the main output will be the risk maps built based on the probability of occurrence of high water and the simulation results with the use of CCHE1D model. The inundation areas shown in dependence on the expected flood waves facilitate the landscape planning and the management practices. As mentioned previously, the Upper Narew Valley is an agricultural watershed with the protected areas representing special, outstanding environmental values (e.g. marshy valleys characterized by extreme biodiversity with perfect conditions for birds nesting). This valley is loaded with important hydrological problems in many cases caused by the existing Siemianówka reservoir upstream. Downstream of the reservoir, water levels are lowered and traditional flooding of the riverbanks is very different. The associated impacts tend to be rather on the negative side: loss of wetlands and their associated environmental service and loss of productivity of the riverbanks associated with the reduction of vegetation diversity. This in turn may reduce the ability of the river valley to serve as a corridor for wildlife, resulting in a reduction of diversity among animal species. The most common result is a drop in species diversity and fish productivity.

Siemianówka Reservoir usually causes the reduction in natural flooding. The adverse impacts include drastic reduction of recession cultivation implying a heavy reliance on costly irrigation production, decline in the quality of pasture and in the
number of stock that can graze during the dry season, a reduction in fish harvesting, and a transformation of a natural floodplain, reducing its capacity to support migratory birds and other wildlife.

Much more understanding on the sustainable use of water must be gained. Activities allowing for the controlled spring floodings (for the benefit of "nature") and relatively limited flooded areas (not to decrease the quality of life of local population) have to be taken into account.

Going along this line, as a starting point, simulations of the flood wave routing with the use of historical flood waves have been performed (see Fig. 11) in order to gain some basic understanding of the behaviour of the system.

Before that task, some simple calibration and verification based on the data from two gages in Suraż and Bokiny have been performed. The only time series available for model calibration and verification are the recorded water elevations at Bokiny village cross-section (see Fig. 12) – one of those time series was recorded within the activities of the present project.

The computations were realized for an open downstream boundary condition and for the given upstream condition taken from a rating curve in Suraż. Computations were realized for different sets of Manning coefficients (realistic for the considered case). Only qualitative agreement between computed and measured values has been achieved but the results obtained are of sufficient quality for warranting further computations with other scenarios. Examples of the solutions for two cases (for \( n = 0.06 \) in the main channel, 0.08 on floodplains; and \( n = 0.03, 0.08 \)) are shown in Fig. 13.

![Graph](image)

**Fig. 11.** Recorded historical floods (1978, 1979, 1980 and 1981) at the Suraż cross-section.
Fig. 12. Recorded and simulated water elevations at Bokiny village cross-section.

Fig. 13. Discharges recorded at Suraż and that simulated at Bokiny village cross-section. Solutions for $n = 0.06$ in the main channel and for $n = 0.03, 0.08$ in floodplains.

Figs. 14 a, b, and c show the maximum water levels (profiles of the flooded area) at the chosen cross-sections (HG1, G14, HG39) for the flood waves depicted in Fig. 11 (the upstream boundary conditions) routed in the Upper Narew by means of the CCHE-1D model.

The next two figures show flooded area maps for the typical flood wave recorded in 1978 (Fig. 15) and the biggest observed in 1979, respectively (Fig. 16).
Fig. 14a. Maximum water levels at the cross-sections HG1.

Fig. 14b. Maximum water levels at the cross-sections G14.

It is worth mentioning that no data exist for comparing computational results with the true extent of the flooded areas during these events. The only way of verification was talking with the eyewitnesses of those events, and those people qualitatively
confirmed the achieved results. Information obtained from the eyewitneses was also used to set topography of the area in a more efficient way.

Note that the flood event in the natural river valley plays a fundamental role for the riparian ecosystem development. Hence the tools for the assessment of inundation limits are important for the river-fed wetland ecosystem protection and/or rehabilitation. Identification of the flooded areas in a marsh valley is constrained due to the dense plant cover of the natural vegetation.

The tested flood waves were reconstructed from the time period when the Siemianówka Reservoir was not operating yet. Data from that period (except the inflowing wave) is not available from the region under consideration so we may only rely on computational results.

The above simulations can, and hopefully will, assist the ongoing discussions concerning whether the liquidation of the reservoir (from the point of view on nature protection) is reasonable. Such discussions are currently led by politicians, decision makers, media, NGOs, etc.

Further computations were performed to achieve typical flood risk maps. All the computations were performed for flood waves for the return periods of 100, 50, 20 and 10 years as obtained in the way described in the previous section. Examples of the results are given in Figure 17.
Fig. 15. Flooded area map for the typical flood wave recorded in 1978.
Fig. 16. Flooded area map for the biggest flood wave observed in 1979.
Fig. 16. Flooded area map for the biggest flood wave observed in 1979.
Fig. 17. Flooded area map for the return periods of 10 and 100 years.
6. Implications of the project results

The main challenge of the current project is the aid to develop integrated approaches balancing ecologically beneficial and socially undesirable aspects of floodings. Discussions of the presented results show that significant opportunities exist for participation of interdisciplinary teams in developing new, holistic approaches to flood management in the protected area of the Upper Narew valley. An important part of the entire discussion is the mathematical modelling required for evaluating the impact of a variety of scenarios. The presented results may, and hopefully will, provoke the attempts to restore a more natural hydrologic regime in portions of the Narew river. Hopefully an iterative planning, implementation and monitoring will result from this and alike studies. Planning is being made for continuation of this project in order to elaborate optimal strategies for controlling the Siemianówka Reservoir.

The results of the ongoing research are also a kind of response to a real need of a clear determination and communication to the public, managers and policymakers the importance of the landscape connections between river and stream channels and their floodplains. Discussions with the local stakeholders based on the obtained results clearly show that manipulating water levels within portions of the floodplains and modifying the operation of the Siemianówka Reservoir to mimic more closely presettlement flood regimes may impact the sustainability in the considered area.

A by-product of the project is the new information gained on the Upper Narew river system which used to be kind of a black-box area.

Common to all the topics that have been and will be considered in the series of projects related to the Upper Narew Valley is the use of models of the reality, which are fed by different amounts of input data. Frequently, the results from one model affect the parameterisation and calibration of another one. Given the wide scope of all the projects (related to recognition of hydrologic regime, flood routing, optimisation of control strategies and water quality dynamics) and the flexible and integrated nature of their structure, they offer a unique opportunity for project participants working at different scales and parts of a catchment to exchange data and expertise. However before such communication can be made possible, it is necessary to create an information communication infrastructure based on a service-based architecture; and this is something that we continuously work on. This infrastructure should allow diverse groups involved to fully benefit from their membership to the project. The expertise of the participants in this group is the provision of high level services.

The current project aims to provide the local decision makers with the scientific and technological capacity to be able to plan and implement sustainable long term and short term development plans to be able to account for the impacts of the Narew River whilst maintaining the equilibrium of existing ecosystems. Key to achieving this aim is integrating knowledge and expertise from physical, social, economic and
environmental scientists with technologists and end users at a meaningful spatial scale which in our case comprises the Upper Narew River valley.

Each study within the mentioned projects addresses one or more of the specific objectives listed below:

- To identify and address key gaps in modelling at a river network scale to quantify the impacts of various activities on the state of environment and the society.

- To study selected aspects of the water cycle, at a river scale, in order to provide the scientific knowledge necessary to assess its behaviour. This new knowledge hopefully will deliver the basis for a new generation of management tools to allow decision makers to mitigate various impacts. Aspects will include ecological reactions to flooding, drought, biodiversity, transport of pollutants and hazardous substances.

- To develop new, more advanced methods for risk assessment and quantifying environmental quality and diversity to enable robust risk based decision-support tools to be provided to decision makers to allow effective mitigation plans to be developed and their benefits to be clearly demonstrated to all stakeholders.

Another important issue is a kind of feedback received by project participants from the local stakeholders. A key example is a hot discussion resulting in the creation of the artificial border on the map that sets out the zone susceptible to flooding - it has been created based on observations and the memory of the stakeholders - no objective data in this respect exists in the area.

The main objective of exploitation and dissemination is to exchange the produced information, technologies and methodologies to the user communities. It should lead to create awareness of generated knowledge beyond the project participants, and in particular the communication with stakeholders including among others: policy and decision makers, scientific community (students, scientists and professionals) and the general public. Meetings allowing to achieve this goal have been led throughout the project course.

7. Discussion and conclusions

The applied measurement procedures are labour intensive and in the extreme conditions of the Upper Narew expose field technicians to various hazards. Hence, computational efforts are of crucial importance and economically more efficient. Therefore, with some gained knowledge on the properties of the system in the future a lot of information may be just gained from the computational efforts. It has been also shown that the estimation of the extent of the surface area to be flooded as well as of
its socio-economical consequences in the marshy valley of the Upper Narew River requires a considerable amount of work starting with detailed surveys, "definition of the geometry", hydraulic modelling, land-use assessment. In this respect, the discussed study may be treated as a pilot one revealing directions for future research. The transferred computational technologies of NCCHE (in this case 1D flood routing model) facilitated the achievement of the project goals.

Our modelling exercise can assist in prioritising management options. However, political actors can question the validity of the models and view the models as predictive but before obtaining much larger data set they cannot be treated as such. In this respect, the obtained results can be treated as clearing the way through the current ignorance.

The presented results will affect the planned activities that will target some environmental degradation issues. This degradation includes mostly the deterioration in agricultural land and/or the quality of the rural environment, by dispersion of sediment and pollutants stored on floodplains or resulting from flooding of a chemical site. These environmental accidents cause the greatest ecological damage and human-health effects. Tangible outcomes of this and related projects will include recommendations for the management and recovery of river guidelines based on the diversity of the present risk management.

We believe that the recognition of hydrologic processes in the Upper Narew River through in situ measurements and computational efforts will constitute a basis for incoming institutional arrangements. Following Smith and Boyd (1998) those institutional arrangements can be treated as encompassing a mix of administrative, social, legal and financial tools such as policies, guidelines, regulations, by-laws, legal agreements and cultural beliefs and attitudes which provide the forum for public-decision making. By linking the results of the presented study with other ongoing and planned projects as well as with the results of the team of Kubrak et al. (2004) realizing their investigations in the preceding river reach (downstream of Siemianówka Reservoir) and closing at the Suraż gage station, the impact on those institutional arrangements becomes much stronger.

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