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Sensitivity and Uncertainty Analysis Applied to Water Management Problem: Upper Narew Case Study

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Abstract

The aim of this paper is to investigate the methods of maintaining desired flow conditions in the reaches of the ecologically valuable upper reaches of the River Narew taking into account the uncertainty in modelling process. The study is based on Global Sensitivity Analysis (GSA) and Generalised Likelihood Uncertainty Estimation (GLUE) techniques applied to a 1-D river flow model. We compare specified water management scenarios applied to the river and a water storage reservoir upstream. A locally conditioned GSA is used to estimate the influence of each conservation action scenario. The estimated uncertainty of model predictions is presented as a map of probability of inundation of the Narew National Park wetlands.

1. Introduction

In recent years alarming changes have been observed in the hydrologic regime of the River Narew, shown in a reduction of mean flows and shorter flooding periods. This has resulted in a serious threat to the rich wetland ecosystems. Many local management activities address this problem and a number of concepts for conservation actions have evolved. In this paper we apply Global Sensitivity Analysis (GSA), described in Archer et al. (1997), and Generalised Likelihood Uncertainty Estimation (GLUE) technique, introduced by Beven and Binley (1992), to analyse the influence of activities aimed at preserving the semi-natural state of marsh ecosystem localised downstream of the Suraż water level gauge. As far as we know, it is the first joint application of the GSA and GLUE techniques to the environmental management problem that additionally takes into account the uncertainties involved in the modelling process. The management activities have the form of water management scenarios applied to the river and a water storage reservoir upstream. The paper is a continuation of the work presented in Kiczko *et al*. (2007).

The estimation of uncertainty is a fundamental issue in hydrology and hydraulic modelling (Romanowicz and Macdonald 2005, Beven 2006, Pappenberger and Beven 2006). It is performed here using multiple Monte Carlo model simulations following the GLUE approach which was applied to flood inundation modelling by Romanowicz *et al.* (1996) and Romanowicz and Beven (2003). A computationally efficient distributed flow routing model is required for the estimation of uncertainty in flood inundation predictions used in the evaluation of the impact of water management scenarios on water conditions on the wetlands. The UNET 1D model (Barkau 1993) was chosen due to its short run times. As a result, maps showing the probability of inundation in the wetland area have been obtained.

We apply the GSA technique (Ratto *et al*. 2001) together with the GLUE approach to obtain a quantitative measure of the significance of each water management scenario. The results of the analysis are important for the future formulation of a water management system in the region.

2. Study area

The Valley of the Upper Narew is located in north-east Poland. The study area includes a 70 km long reach that begins at the Siemianówka Water Reservoir and ends at the water level gauging station in Suraż (Fig. 1). Generally, with the exception of areas close to the reservoir built in the early 1980s, this part of the river has not been modified by human activity. The valley is approximately 1-2 km wide. It has been shaped by a meandering river channel and presents a natural form of a lowland river system, with relatively small water slope values, at the level of 0.24‰. The annual river discharge varies from 5.72 to 15.50 m^3/s. In this area the river generally flows in one channel. However, due to the existence of meanders and old river beds, this river system has a rather complex structure during high flows.

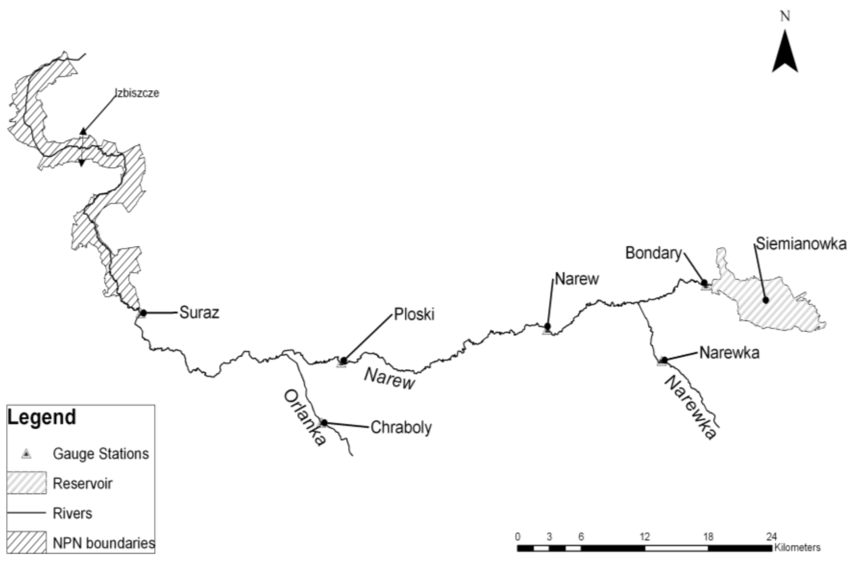

Fig. 1. Schematic map of the study area.

Almost 90% of the valley is occupied by rich wetland ecosystems, mostly marshes (55%) and peat lands (31%). Ten percents of the area is covered by postglacial mineral soils and sand dunes. Moreover, mud soils filling the old river beds play an important role in maintaining local ecosystems. Under these conditions extensive agriculture is possible only in the valley terrains. The semi-natural character and environmental conditions of the region implicate that this part of the Narew valley has great value from the ecological point of view (Dembek and Danielewska 1996).

3. Approach and methods

Wetland ecosystems depend largely on flooding (Junk *et al*. 1989). Therefore, actions aimed at preserving their quasi-natural character rely generally on the range of flooding parameters, such as flooding area, average depth and flood frequency in the wetland area (Kubrak *et al*. 2005, Okruszko *et al*. 1996). There are many different suggestions of how to improve water conditions in this region. The following approaches to this problem, aimed at affecting the chosen site through modification of river water stages, are analysed:

1. Modification of the Siemianówka reservoir releases under low flow conditions;
2. Water level control system on Narew tributaries under low flow conditions;
3. Changes in floodplain land-use under high flow conditions;
4. Changes in channel conveyance under high flow conditions.

In this paper we investigate the joint applications of GSA and GLUE techniques to assess the efficiency of the above listed management approaches when applied to the upper reaches of the River Narew. The river system is described using a One-Dimensional Unsteady Flow Through a Full Network of Open Channels model (UNET), developed by the U.S. Army Corps of Engineers, Hydrologic Engineering Center.

Irrigation of the downstream valley is one of the main purposes of the Siemianówka reservoir; therefore, it is the most suitable tool for intervention in the natural system. Following the first of approaches listed above, we investigate the impact of the generated “artificial flood pulses” (Tockner *et al*. 2000) on the chosen wetland area during summer water shortage periods. Reservoir discharges were chosen in the form of rectangular pulses, characterized by a discharge value and duration time. In the case of a low flow control system (second approach), the assumption was made for the Narew tributaries (Narewka and Orlanka) that it is possible to store water in the subcatchments during rain periods and release it during low water periods. Until now, low flow control on the River Narew has consisted of a restoration of formerly existing semi-natural river barriers, maintained by local communities for fishing purposes. The influence of such barriers on river flow was analysed through the investigation of spatial impacts caused by the modification of roughness parameters in the numerical model of the Narew reach (third approach). Changes in the floodplain land-use were considered here as a modification of terrain roughness coefficients (the fourth approach).

Because of the complexity of the problem, the study of influence of channel and floodplain conveyance (roughness coefficients) is limited to an analysis of changes of flood peak levels in the chosen wetland area. As flood area and average depth depend strongly on flood wave height, this should provide a satisfactory approximation to the influence of control variables on hydrological conditions in the area.

A sensitivity analysis was performed on locally conditioned model performance measures, which additionally allowed spatially distributed effects to be investigated. Each intervention investigation was performed in separate runs, thus it was necessary to introduce some reference factors to enable comparability of results. For this purpose, Manning roughness coefficients were used, and the other resulting sensitivity indices were normalized in relation to those indices.

The choice of parameter ranges necessary for the management scenario analysis, was achieved via a model calibration using the combined GSA and GLUE methodology. Model parameter ranges assessed in this stage of work were used in the GSA for the chosen river management scenarios. The posterior distribution of parameters obtained during the GLUE calibration stage was used to derive uncertainty of UNET model predictions in the validation stage. It has a form of varying-with-time probability distribution of water level predictions for each of the UNET model cross-sections. The quantiles of these distributions are mapped onto the digital elevation data of the studied River Narew reach to give varying-in-time maps of probability of inundation. These maps may be compared with water demands under low and high water conditions, thus helping in specifying the goals and an assessment of water management policies.

3.1 Experimental design

We performed four numerical experiments:

(i) A sensitivity analysis of model predictions at three cross-sections (Narew, Płoski and Suraż) to the following parameters: roughness coefficients, tributaries and lateral inflow correlation coefficients, lateral inflow delay, the upstream boundary condition error and the downstream water surface slope for the whole hydrologic year;

(ii) Model calibration and validation using the GLUE methodology and derivation of map of probability of maximum inundation under the natural flow conditions;

(iii) Sensitivity of model predictions at Suraż cross-section to the shape and timing of reservoir releases and controlled tributaries' outflows under low flow conditions;

(iv) Influence of modification of channel conveyance upstream and downstream of Suraż cross-section on maximum water level distribution in its vicinity.

3.2 The flow routing model

The UNET (Barkau 1993) code is a numerical implementation of the 1-D Saint Venant equation. The current version is capable of performing one-dimensional water surface profile calculation for gradually varied flow in natural or constructed channel. Subcritical, supercritical, and mixed flow regime water surface profiles can be calculated.

The River Narew reach is represented by 49 cross-sections at about 2 km intervals, obtained from a terrain survey. The model was calibrated by adjusting the Manning coefficients separately for the channel, left and right floodplains, and a water surface slope used as a downstream boundary condition. To filter out the influence of the downstream condition, an additional cross-section, 10 km downstream of the reach was included. It was assumed that the value of roughness coefficients changes linearly between cross-sections. Therefore, the variability of this parameter was described in the form of values on nodes, between which the roughness coefficient was interpolated.

The model mass balance was difficult to maintain due to a lack of data on lateral inflows, with the exception of the Narewka and Orlanka tributaries. It was possible to estimate the unobserved lateral inflows using the assumption that they are linearly correlated with observed tributary inflow and can be described using a linear regression model with a constant delay corresponding to the tributary location.

3.3 The GSA methodology

In this study, the GSA methodology (Ratto *et al*. 2001, Kiczko *et al.* 2008) was applied to determine model sensitivity to Manning coefficients and to boundary conditions. GSA also allows the significance of a particular model input to be evaluated, making it possible to investigate the effects of a particular river management action (such as discharges from Siemianówka reservoir and floodplain land-use upstream) on flow conditions downstream.

According to this approach, the variance of an output Y depending on the input set X_i can be treated as the sum of a top marginal variance and a bottom marginal variance (Ratto *et al*. 2001):

$$V(Y) = V\left[E(Y \mid X_i = x_i^*)\right] + E[V(Y \mid X_{-i} = x_{-i}^*)\big]. \tag{1}$$

where the term X_{-i} indicates all the inputs but X_i and V and E denote variance and expectation operators, respectively.

The main effect or the first order sensitivity index S_i, representing the sensitivity of output Y to the input X_i, is defined as a top marginal variance divided by the total variance:

$$S_i = \frac{V[E(Y \mid X_i = x_i^*)]}{V(Y)}. \tag{2}$$

The total sensitivity index S_{Ti} for the input X_i combines in one single term all the interactions involving X_i. It is defined as an average output variance that would remain as long as X_i stays unknown:

$$S_{Ti} = \frac{E[V(Y \mid X_{-i} = x_{-i}^*)]}{V(Y)} \tag{3}$$

where X_{-i} denotes all X input elements except X_i.

During the first application of the GSA (in the calibration stage) mean water levels at 3 gauging stations were taken as output *Y* and Manning coefficients, boundary water slope, correlation coefficients of tributaries with lateral inflows and error of upper boundary condition (inflow at Bondary) were used as input parameters *X*.

After the calibration stage, an investigation of the influence of different control variables on flood wave propagation was carried out for the maximum peak value as an output (*Y* variable) and Siemianówka reservoir, Narewka and Orlanka tributaries outflow characteristics and Manning coefficients as input parameters (*X* variables), following the experimental design outlined in Section 3.1.

3.4 The GLUE methodology

Model calibration and estimation of predictive uncertainty were carried out following the GLUE methodology. The basic assumption of this methodology (Beven and Binley 1992) is that in the case of over-parameterized environmental models, a unique solution of the inverse problem is not possible due to a lack of data (an interactive discussion of this topic is promoted by Pappenberger *et al*. 2007). There can be many different parameter sets which provide reasonable results. Therefore, calibration should consist of the estimation of the multidimensional distribution of model parameters. For such an analysis the Bayesian formula is used:

$$f(\mathbf{X}\,|\,\mathbf{z}) = \frac{f_0(\mathbf{X})L(\mathbf{z}\,|\,\mathbf{X})}{L(\mathbf{z})} \tag{4}$$

where **z** is the observation vector, $f(\mathbf{X}|\mathbf{z})$ is the posterior distribution (probability density) of the parameters conditioned on the observations $\mathbf{z}$, $f_0(\mathbf{X})$ is the prior probability density of the parameters, $L(\mathbf{z})$ is scaling factor, $L(\mathbf{z}\,|\,\mathbf{X})$ represents the likelihood measure based on the relationship between **z** and **X**. On the basis of information on the prior distribution of model parameters, which comes from knowledge of the physical structure of the modelled process and available observations of process output, it is possible to estimate the posterior distribution of parameters. In this study water levels at 3 gauging stations (Narew, Płoski and Suraż) were used as the observation vector **z**; Manning roughness coefficients, discharge estimation error and value of water slope at the end of reach were used as parameter vector **X**.

It is important to note that Eq. (4) is defined over the specified parameter space; therefore, the parameter interactions will be implicitly reflected in the calculated posterior distribution. This feature is especially important in the case of spatially distributed models, where parameters are inter-dependent. The marginal distributions for single parameter groups can be calculated by an integration of the posterior distribution over the rest of the parameters as necessary.

The essential element of the GLUE technique is a practical determination of the likelihood measure $L(\mathbf{z}|\mathbf{X})$. In this paper it was assumed that it is proportional to the Gaussian distribution function (Romanowicz and Beven 2006):

$$L(\mathbf{z}|\mathbf{X}) \approx e^{(\mathbf{z}-Y(\mathbf{X}))^2/\sigma^2} \tag{5}$$

where **z** is the observed water level, *Y* is a computed water level and σ^2 denotes the mean error variance determining the width of the distribution function. It is important to note that in the GLUE methodology a subjective choice of the distribution width is allowed. On the basis of posterior likelihood values, the distribution of simulated water levels can be evaluated and subsequently used to derive spatial probability maps of the risk of flooding or drought in the area.

The model parameter space is sampled using the Monte Carlo method. The prior distribution $f_0(\mathbf{X})$ of parameters is introduced at this stage. A number of required model realizations depend on the modality of the resulting distribution and the dimension of the parameter space.

4. Results

4.1 Calibration and validation

The UNET model calibration was performed for the observation period 23.07.1981 – 28.08.1982. At the beginning of the calibration stage, the sensitivity of model parameters was analysed using the GSA method (this constitutes the first numerical experiment from the list given in Section 3.1). The analyzed parameters are: downstream gradient, uncertainty of boundary condition in Bondary, delay periods of Orlanka and Narewka inflows, Orlanka and Narewka flow coefficients (explained at the end of Section 3.2), right and left floodplain and channel roughness coefficients. Results presented in Figs. 2 and 3 show that the channel roughness and Narewka flow coefficient for additional lateral inflow are the major sources of uncertainty. The floodplain roughness has a marginal influence, with only a minor effect on the right side of the floodplain. The downstream boundary condition does not affect flow characteristics in the study area and this parameter was fixed during the following GLUE analysis stage. According to these results, the uncertainty related to the specification of upper boundary condition can also be neglected.

As there was no *a priori* information on parameter distribution, a uniform prior distribution was assumed during the GLUE analysis stage (Beven 2001). Finally, the parameters were sampled within the following ranges: channel roughness coefficient 0.015 – 0.045, floodplain roughness coefficient 0.08 – 0.12, the error of upper boundary condition as ±7%, lateral inflow correlation coefficients 1.5 – 4.5 and delay of lateral inflow: 0 – 10 days.

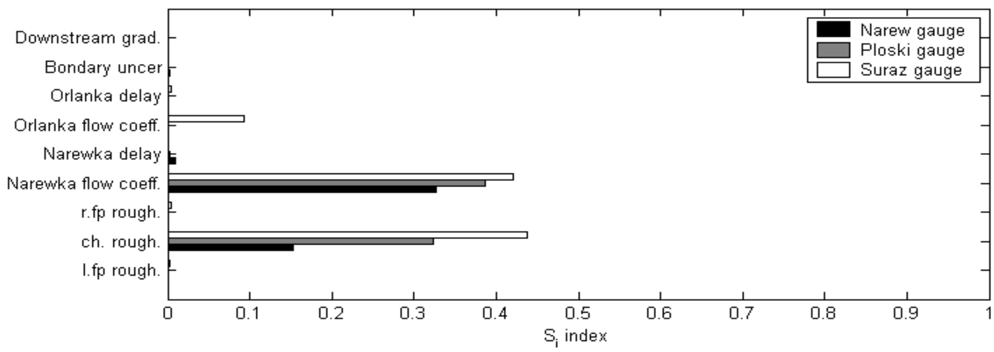

Fig. 2. First order sensitivity indices (S_i) of model input parameters listed along the *Y* axis.

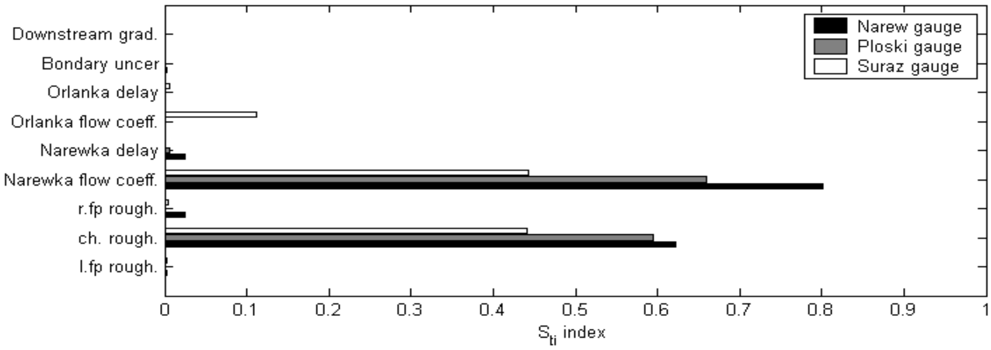

Fig. 3. Total sensitivity indices (S_{Ti}) of model input parameters listed along the *Y* axis.

The validation was performed using the observations from 3 gauging stations for the spring freshet 1981 and the period 0.5.10.1982 – 13.07.1983. Results of the model validation at Suraż are shown in Fig. 4. The observations are marked with a dotted line, thin continuous line shows the estimated water levels, and shaded area denotes 0.95 confidence bounds.

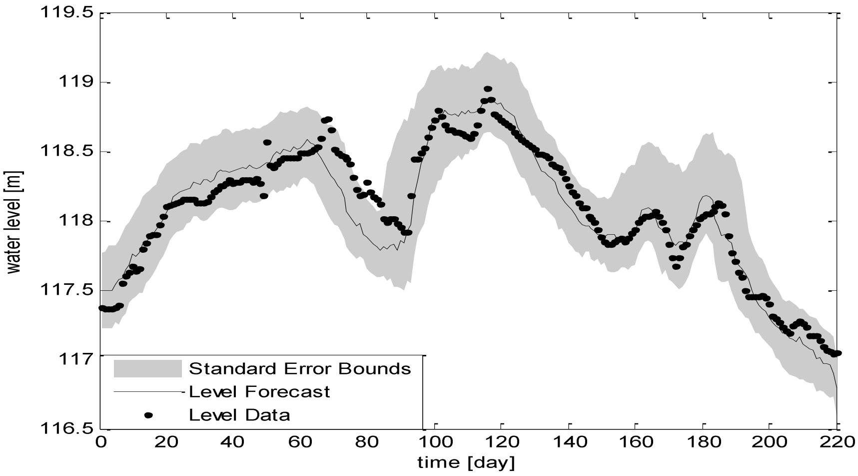

Fig. 4. Model validation for Suraż, observation period: 0.5.10.1982 – 13.07.1983, shaded areas denote 95% confidence bounds for the predictions shown by the continuous line, the observations are shown by dotted line.

The quantiles of maximum water levels along the river reach obtained during the validation stage were subsequently transformed into a map of probability of inundation shown in Fig. 5 for the spring freshet 1981.

Similar maps can be used by the water management team to assess the effects of different management scenarios on water conditions along the River Narew reach and in particular, in the Narew National Park wetland region. In this particular case, the map presents the probability of inundation under the natural conditions during the spring freshet in 1981, without the implementation of any reservoir control scheme. The detailed map of probability of inundation for the same maximum flood peak during the spring freshet in 1981 for the River Narew reach situated within the Narew National Park, downstream of Suraż (left hand corner of Fig. 5), is shown in Fig. 6.

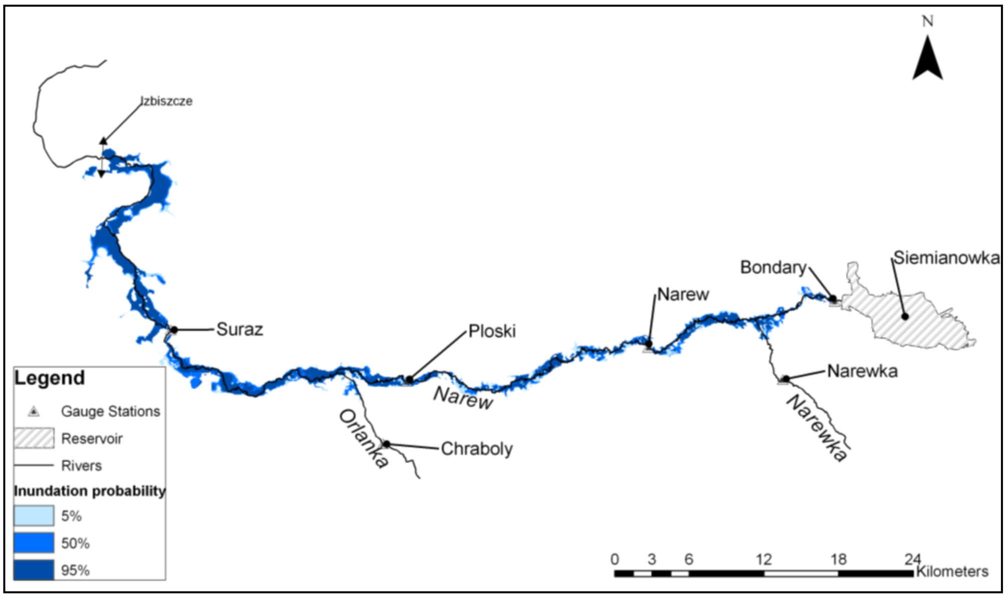

Fig. 5. Probability of inundation for maximum water levels along the Upper Narew reach during the spring freshet in 1981.

4.2 Scenario analysis

During the third numerical experiment (Section 3.1) consisting of an analysis of the impact of releases from the Siemianówka reservoir, it was assumed that 1,000,000 m^3 of water was available for control purposes during the low flow period. This value, denoting a special irrigation water reserve, was based on the present reservoir control scheme, developed by Bipromel (1999). Maximum reservoir discharges were limited by the capacity of power plant culverts to the value of 11.6 m^3/s. Storages in sub-catchments Narewka and Orlanka were assumed to be equal to 86 000 m^3, with a maximum discharge increase of 1 m^3/s. The sensitivity of the river system to the modification of channel roughness was analysed within the parameter ranges of 0.02 – 0.06, with the lower and upper ranges corresponding to a change from a straight channel to a wooded and weedy reach. The influence of floodplain roughness was neglected, as the sensitivity analysis performed during the calibration stage showed that effects caused by its variations were marginal.

The impact of the reservoir and tributaries' discharge characteristics on wetland area is presented in Table 1.

The fourth numerical experiment consisted of an analysis of the influence of channel conveyance values on water levels. Results presented in Fig. 7 show the changes of the first order and total sensitivity indices for maximum water levels at three different cross-sections situated near Suraż. The sensitivity is evaluated with respect to channel roughness variations at 6 neighbouring cross-sections indicated in Fig. 7 by stars. It should be noted that these results cannot be directly compared with the results of reservoir and tributaries' outflow impact, as they were estimated under different parameter

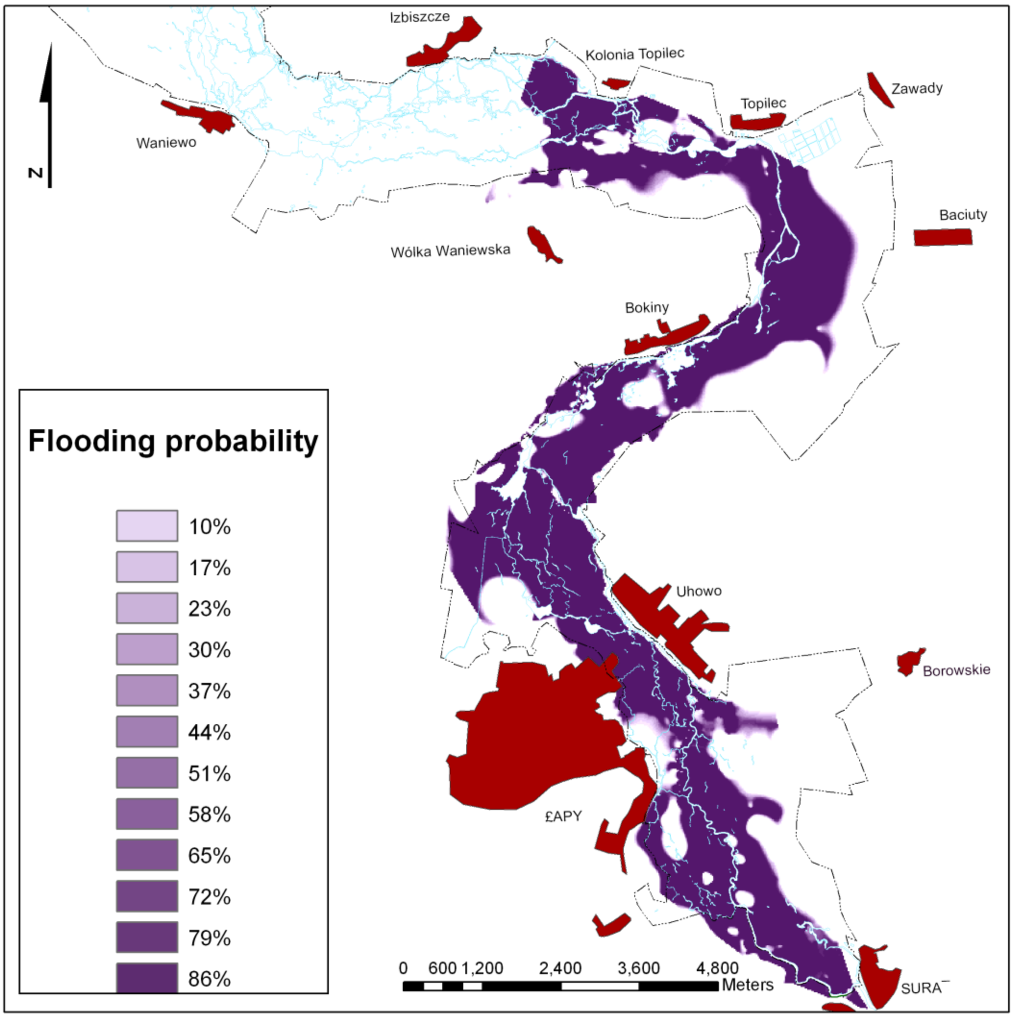

Fig. 6. Detailed map of probability of inundation for the River Narew reach situated downstream from Suraż (left hand corner of Fig. 5).

Table1

Impact of discharge characteristics on flow during the water shortage period

		Siemianówka reservoir	Narewka tributary	Orlanka tributary
Peak High	S_i	0.446	0.000	0.001
	S_{Ti}	0.510	0.011	0.009
Total discharge volume	S_i	0.446	0.000	0.002
	S_{Ti}	0.510	0.012	0.009

variations. However, as shown in Kiczko *et al.* (2007), the channel roughness has a similar impact to the modification of releases from the Siemianówka reservoir. In this experiment the range of influence varies along the river reach. In conclusion, the changes of channel roughness have an influence on the water levels within 4 km range, but the impact of these changes varies with location, probably due to some other factors, such as geometry of the channel and the floodplain.

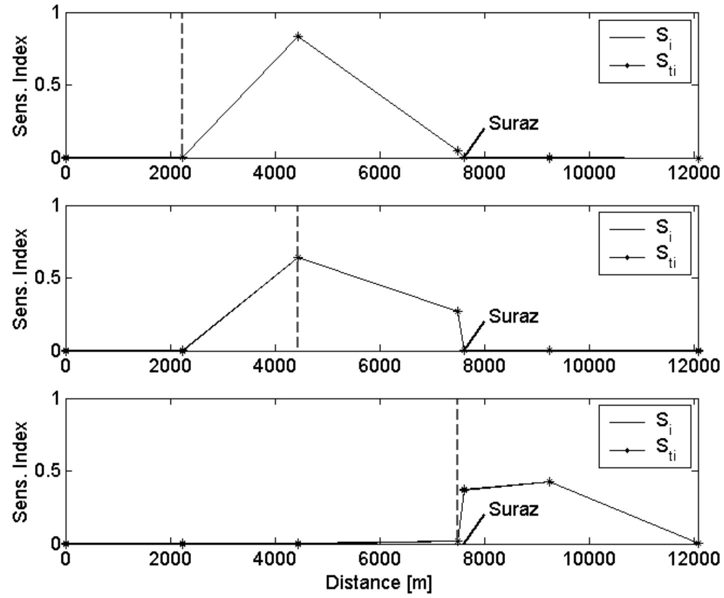

Fig. 7. Sensitivity of maximum water levels at 3 cross-sections upstream from Suraż indicated by the dashed lines (panels 1-3), to the variations in channel roughness at 6 cross-sections at the locations shown by stars.

5. Conclusions

We have reported here sensitivity and uncertainty analyses applied to water management scenarios aimed at wetland mitigation under different flow conditions. A 1D distributed flow routing model was used to derive distributed water level predictions along the Upper River Narew reach as a case study. The study included (i) a sensitivity analysis of distributed model predictions for the whole hydrologic year; (ii) model calibration and validation using GLUE and derivation of maps of probability of maximum inundations under the natural flow conditions; (iii) a sensitivity analysis of water level predictions downstream to changes of reservoir and tributary releases upstream under low flow conditions; (iv) the influence of local modifications of channel conveyance on water levels under high flow conditions. The uncertainty and sensitivity analyses were performed using GSA and GLUE techniques, which enabled a quantitative assessment of the impact.

In summary, the results show that channel roughness coefficients, Siemianówka reservoir releases and the Narewka tributary have major impacts on water conditions in the Upper Narew reach under study, whilst downstream boundary conditions and floodplain roughness coefficients have a much smaller influence. The conclusion on small influence of floodplain roughness is consistent with the results obtained by Romanowicz *et al.* (1996). Therefore, land-use along the river reach might also have a small influence. However, modification of the channel conveyance may have a large local effect on water levels in the wetland areas. The uncertainty analysis allows the maps of probability of maximum inundation along the river to be estimated. These maps can be used in the specification and assessment of the reservoir and river management scenarios.

The results show unequivocally that the river reach can be successfully controlled at the Siemianówka reservoir and the wave height can be locally increased in specific areas through the restoration of semi-natural river barriers. The results obtained should help in formulating a suitable water management policy along the selected river reach.

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