

A Study of Flow Conditions Aimed at Preserving Valuable Wetland Areas in the Upper Narew Valley Using GSA-GLUE Methodology

Adam Kiczko¹, Renata J. Romanowicz², Jarosław J. Napiórkowski¹

Abstract

The aim of this paper is to investigate the possibilities of reaching desired flow conditions in the reaches of the ecologically valuable Upper Narew river using specified river management and training (or engineering) techniques. The study is based on Global Sensitivity Analysis (GSA) and Generalised Likelihood Uncertainty Estimation (GLUE) techniques applied to a 1-D river flow model. The locally conditioned GSA is used to estimate the influence of each conservation action scenario.

1. Introduction

In recent years alarming changes have been observed in the Narew river hydrologic regime, manifesting in the reduction of mean flows and shorter flooding periods. This results in a serious threat to the rich wetland ecosystems. Many local management activities refer to this problem and there is a number of concepts of conservation actions. The goal of this paper is to analyse the influence of these activities aiming to preserve the semi-natural state of the largest area of marsh ecosystem in the study, which is localised along the Ploski-Suraż reach.

We apply the General Sensitivity Analysis (GSA) technique together with Generalised Likelihood Uncertainty Estimation (GLUE) approach to obtain a quantitative measure of significance of each inference in the river system. The results of the analysis are important for a 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 outflow and ends at the water level gauging station in Suraż (Figure 2.1). Generally, with the exception of areas close to the reservoir, built in the early 1980-ties, this part of the river is not modified by human activity. The valley is approximately 1–2 km wide and 7–10 m deep. It has been shaped by a meandering river channel and presents a natural form of 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 m³/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.

Almost 90% of the valley is occupied by rich wetland ecosystems, mostly by marshes (55%) and peatlands (31%). The remaining 10% 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. In

these conditions only extensive agriculture is possible in the valley terrains. This semi-natural character and environmental conditions of the region indicate that this part of the Narew valley has a great value from the ecological point of view (Dembek and Danielewska, 1996).

¹ Institute of Geophysics of the Polish Academy of Sciences

² Environmental Science Department Lancaster University

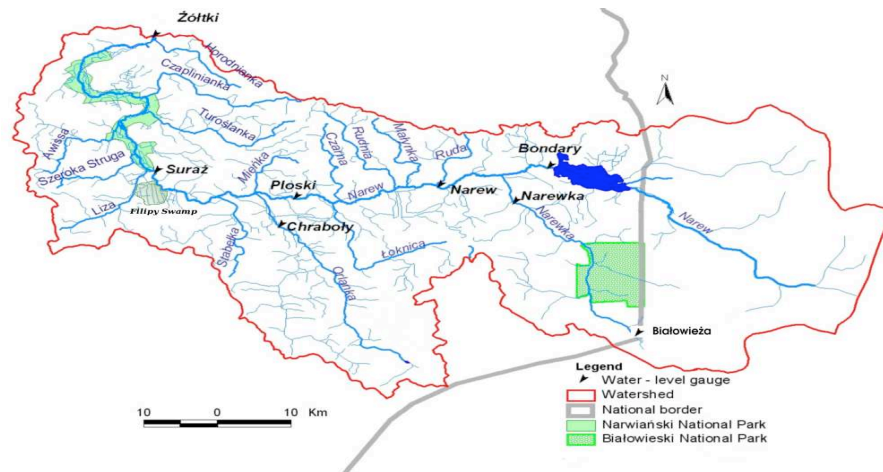


Figure 2.1: Schematic map of a study area modified from Kubrak et al. (2005)

3. Approach and Methods

Wetland ecosystems depend largely on the phenomena of flooding (Junk et al., 1989). Therefore, actions aiming to preserve 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, aiming to affect the chosen site through modification of river water stages, are analysed:

- Modification of the Siemianówka reservoir outflows
- Low flow control system on Narew and tributaries
- Changes in floodplain land use.

The river system is described using the One-Dimensional Unsteady Flow Through a Full Network of Open Channels model (UNET), developed by the U.S. Army Corps of Engineers Hydrologic Engineering Centers. The irrigation of the downstream valley is one of the main aims of the Siemianówka reservoir. Therefore it is the most suitable source of inference in the natural system. The impact of generated "artificial flood pulses" on the chosen wetland area during summer water shortage periods was investigated. The outflow peaks were chosen in the form of rectangle pulses, characterized by a discharge and a duration time. In the case of a low flow control system the assumption was made for the Narew tributaries (Narewka and Orłanka) that it is possible to store water in the subcatchments during rain periods, in this way increasing the flow in Narew during low waters periods. Until now, low flow control on the Narew consisted of a restoration of formerly existing semi-natural river barriers, maintained by local communities for fishing purposes. This influence of forming such barriers on river flow was analysed through the investigation of spatial impacts caused by the modification of roughness parameters and geometry of a channel in the numerical model of the Narew reach. Changes in the floodplain land use were considered here as a modification of terrain roughness coefficients.

Because of the complexity of the problem, this study is limited to an analysis of the influence of inference in a river system on a flood peak height in the chosen wetland area. As flood area and average depth

depend strongly on flood peak height, this should provide a satisfactory approximation of 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 inference investigation was performed in separated runs, thus it was necessary to introduce some reference factors to enable a comparability of results. For this purpose Manning roughness coefficients were used, and other resulting sensitivity indexes were normalized in accordance.

The choice of parameter distribution, necessary for the GSA technique, was achieved via a model calibration using the GLUE methodology. Model parameter ranges assessed in this stage of work were used in the GSA for the chosen river management scenarios.

3.1 The flow routing model

The UNET (Barkau, 1993) code is a numerical implementation of 1-D Saint Venant equation in the following form:

$$\frac{\partial Q}{\partial t} + \frac{\partial(\Phi^2 Q^2 A_C^{-1})}{\partial x_c} + \frac{\partial[(1-\Phi)^2 Q^2 A_f^{-1}]}{\partial x_f} + gA_C \left(\frac{\partial Z}{\partial x_c} + S_{fc} \right) + gA_f \left(\frac{\partial Z}{\partial x_f} + S_{ff} \right) = 0 \quad (3.1.1)$$

$$\frac{\partial A}{\partial t} + \frac{\partial(\Phi Q)}{\partial x_c} + \frac{\partial[(1-\Phi)Q]}{\partial x_f} = 0 \quad (3.1.2)$$

where: A_c A_f – flow area, respectively for channel (c) and floodplain (f), Q – flow discharge, Z – water level, x_c – channel length, x_f – floodplain length, S_{fc} – floodplain friction slope, S_{ff} – channel friction slope, Φ – correction coefficient for momentum due to nonuniformity of velocity distribution at cross-section.

The river reach is represented by 49 cross-sections at 2 km interval, obtained from the terrain survey. To filter out the influence of the downstream condition, an additional cross-section 10 km downstream of the reach was included. The model was calibrated by adjusting the Manning coefficients separately for the channel, left and right floodplain and a water surface slope used as a downstream boundary condition. 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 a problematic issue because of the lack of data on lateral inflows, with the exception of the Narewka and Orlanka tributaries. It was possible to estimate lateral inflows under the assumption that inflows are uniformly distributed along the river gauging stations:

$$Q_{sub}(t) = Q_{i+1}(t + \Delta t) - Q_i^*(t) \quad (3.1.3)$$

where: $Q_{sub}(t)$ – lateral inflow between river gauge stations i and $i+1$, $Q_{i+1}(t + \Delta t)$ – observed discharge at river gauge station $i+1$ at time $t + \Delta t$, $Q_i^*(t)$ discharge at river gauge i at time t added to known inflows from tributaries (Narewka and Orlanka), i – river gauge station index (Bondary, Suraz, Narew, Ploski, Suraz), t – time and Δt – time lag.

3.2 The GSA methodology

Sensitivity analysis plays a very important role in modelling practice (Romanowicz and Macdonald, 2006). In the case of an over-parameterised model it provides a reasonable reduction of parameter space.

Therefore, the GSA-GLUE methodology (Ratto et al., 2005) was applied) to determine the model's sensitivity on Manning coefficients and on boundary conditions. GSA also allows the significance of a particular model element to be evaluated making it possible to investigate the effects of a particular river management action. After the calibration stage, GSA was applied to examine and compare the possible influence of various control variables such as: the discharges of the Siemianówka and Narew tributaries, Narew channel flow conditions and floodplain land use on flow conditions downstream.

Generally, the sensitivity analysis consists of an evaluation of the relation between input and output variations. In this assessment we have used the variance based Global Sensitive Analysis approach introduced by Archer et al. (1997). According to this method, the whole set of model parameters acquired from the Monte Carlo sampling is analysed simultaneously and there is no restriction on the monotonicity or additivity of the model. Therefore this approach is suitable for over-parameterized, nonlinear, spatially distributed models.

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

$$V(Y) = V[E(Y|X_i = x_i^*)] + E[V(Y|X_{-i} = x_{-i}^*)] \quad (3.2.1)$$

where $V[E(Y|X_i = x_i^*)]$ is the variance of estimated Y output, where x_i parameters are fully fixed and others are normally varying and $E[V(Y|X_{-i} = x_{-i}^*)]$ is estimated variance in the case when all parameters are fixed, except x_i which is varying.

The direct sensitivity of output Y to the input X_i , represents the first order sensitivity index S_i which takes the following form:

$$S_i = \frac{V[E(Y|X_i = x_i^*)]}{V(Y)} \quad (3.2.2)$$

The model's sensitivity to the interactions among subsets of factors, so called higher order effects are investigated with the use of total sensitivity indices: S_{Ti} . They represent the whole range of interactions which involve x_i and are defined as:

$$S_{Ti} = \frac{E[V(Y|X_{-i} = x_{-i}^*)]}{V(Y)} \quad (3.2.3)$$

The use of total sensitivity indices is advantageous, because there is no need for the evaluation of a single indicator for every possible parameter combination. On the basis of these two indicators, S_i and S_{Ti} , it is possible to trace the significance of each model parameter in an efficient way. In this study, the estimation of sensitivity indexes S_i and S_{Ti} is carried out using the Sobol method (Archer et al., 1997).

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 and boundary water slope were used as parameters X . Following the calibration, the investigations on the influence of different control variables on flood wave propagation were carried out for the maximum peak value as the Y variable and Siemianówka reservoir, Narewka and Orlanka tributaries outflow characteristics, Manning coefficients and value of geometry change as the X variable.

3.3 The GLUE methodology

The model calibration was carried out according to the GLUE methodology. The basic assumption of this methodology (Beven and Binley, 1992) is that in a case of over-parameterized environmental models, a unique solution of the inverse problem is not possible due to of lack of data (an interactive discussion on this topic is promoted by Pappenberger et al, 2006). 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 analysis the Bayesian formula is used:

$$f(X|Z) = \frac{f(X)L(Z|X)}{L(Z)} \quad (3.3.1)$$

where Z is the observation vector, $f(X|Z)$ is the posterior distribution (probability density) of the parameters conditioned on the data, $f(X)$ is the prior probability density of the parameters $L(Z)$ is scaling factor $L(Z|X)$ 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 the 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, Ploski and Suraz were used as observation vector Z , Manning roughness coefficients, discharge estimation error and value of water slope at the end of reach were used as vector X . It is important to note that equation (3.3.1) 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 $L(Z|X)$ In this paper it was assumed that it is proportional to the Gaussian distribution function (Romanowicz and Beven, 2006):

$$L(Z|X) \approx \exp\left(-\sum_{t=1}^T (Z_t - Y_t(X))^2 / 2\sigma^2\right) \quad (3.3.2)$$

where Z is the observed water level, Y is a computed water level, t is a simulation time step 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 control 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 risk of flooding in the area.

The model parameter space is sampled using the Monte Carlo method. The prior distribution $f(X)$ 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

At the beginning of the calibration stage the sensitivity of model parameters was analysed using the GSA method (Table 4.1.1). The results show that the channel roughness is the major source of uncertainty while the floodplain roughness has a minor influence.

Table 4.1.1: Global Sensitivity Analysis for the flow routing model

		S_i	S_{T_i}
Manning roughness coefficient	Channel	0.880	0.945
	Left floodplain	0.076	0.026
	Right floodplain	0.043	0.029
Downstream water slope		0.000	0.000

The downstream boundary condition does not affect flow characteristics in the study area and this parameter was fixed during the following simulations. During the initial simulation runs, parameter ranges were adjusted and it became apparent that the river inflow uncertainty must be included. As there was no a priori information on the parameter distribution, a uniform prior distribution was assumed (Beven, 2001). Finally parameters were sampled within the following ranges: channel roughness coefficient 0.02 – 0.06, floodplain roughness coefficient 0.06 – 0.1, discharge uncertainty 30%.

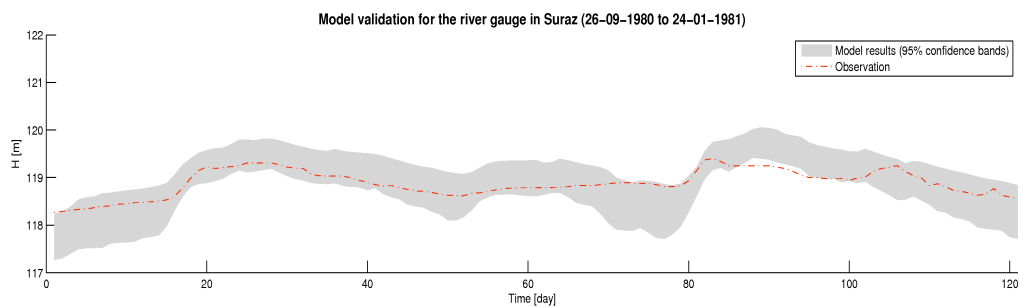


Figure 4.1.1: Model validation for 3 river gauges: Narew, Ploski and Suraz, observation period: 28-09-1980 – 24-01-1981, shaded areas denote estimated 95% confidence bands for the predictions shown by the red dashed line.

The calibration was performed using the observations from 3 gauging stations for a freshet in June 1980. The freshet from November 1980 was used as a reference event for the validation stage. Results of the model validation are shown in Figure 4.1.1.

4.2 Scenario analysis

When analysing the impact of Siemianówka reservoir outflows, it was assumed that 1 000 000 m³ of water was available for control purposes during the low flow period. This value, denoting a special irrigation water reserve, was taken from the present reservoir control scheme, developed by Bipromel (Bipromel, 1999). Maximum water outflows were limited by the capacity of power plant culverts to the value of 11.6 m³/s. Storages in subcatchments Narewka and Orłanka were assumed to be equal to 86 000 m³, with a maximum discharge increase of 1 m³/s. The sensitivity of the river system to the modification of channel roughness was analysed within the parameter ranges used in the GLUE analysis (0.02 - 0.06). The geometry was assumed to vary within ±0.2 m. The floodplain roughness was sampled, similarly to the channel roughness, within the ranges assessed in the GLUE stage: 0.06 - 0.1, with lower and upper ranges corresponding to changes in the land use (grasslands areas and density tree formations respectively). The impact of the reservoir and tributaries' discharge characteristics on wetland area is shown in Table 4.2.1.

Table 4.2.1:
Impact of discharge characteristics on flow conditions 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

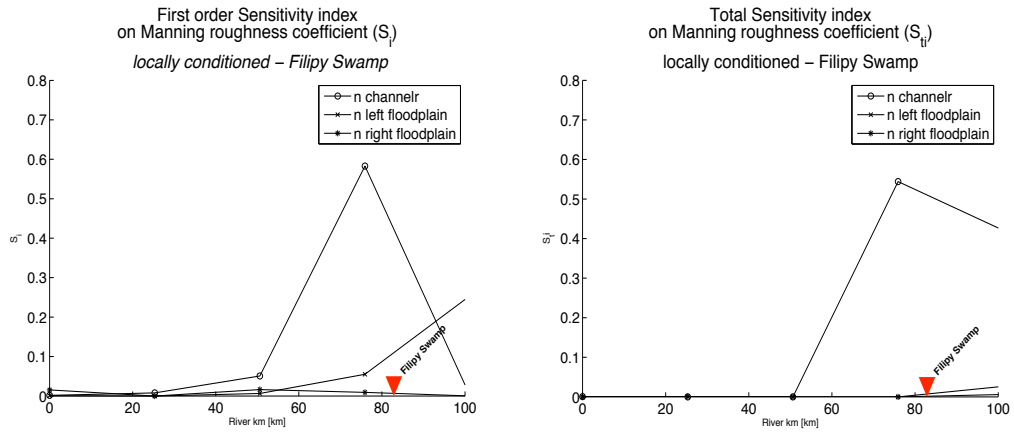


Figure 4.2.1: Spatial influence of roughness modification on flow conditions at Filipy Swamp

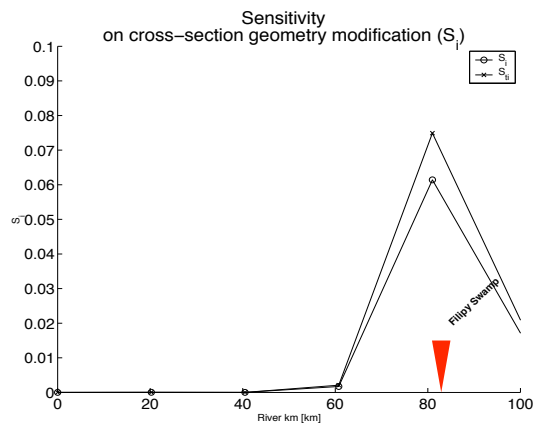


Figure 4.2.2: Spatial influence of geometry modification on flow conditions at Filipy Swamp

An analysis of channel geometry variation influence on flow conditions, shown in Figure 4.2.2, indicates that geometry has a relatively smaller impact on flows than the channel roughness coefficient, shown in Figure 4.2.1 (the value of sensitivity index is 10 times smaller). The channel roughness coefficient has a major influence on the flow at Filipy Swamp, as illustrated in Figure 4.2.1.

5. Conclusions

In conclusion, the combination of GSA and GLUE techniques applied in the analysis of the water level control scenarios enabled a quantitative assessment of the impact of flood pulse control. The results show that Siemianówka reservoir has a major impact on the water conditions in the chosen reach of the River Narew, while the inflows from the tributaries have a much smaller influence on the flows in the River Narew downstream. We have also evaluated the influence of roughness coefficients of the channel and floodplains. This analysis indicates that the floodplain roughness coefficients have a small influence on flow, which is consistent with the results obtained by Romanowicz et al., (1996). Therefore, the land use along the river reach also has a small influence. The geometry was shown to have a much smaller influence on flow than the roughness coefficients, however, this result may be affected by small geometry variations assumed during the scenario analysis which were justified by low flow conditions.

The results show unequivocally that river reach can be successfully controlled through 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 suitable water management policy along the chosen river reach.

Acknowledgements

This work was supported in part by grant 2 P04D 009 29 from the Ministry of Higher Education and Science.

Bibliography

- Archer, G., Saltelli, A., and Sobol, I.M., (1997): Sensitivity measures, Anova-like techniques and the use of bootstrap. *Journal of Statistical Computation and Simulation*, 58: 99-120
- Barkau, R.L. (1993): UNET, one-dimensional flow through a full network of open channels, user's manual version 2.1. Publication CPD-66, U.S. Army Corps of Engineers, Davis, CA, Hydrologic Engineering Center
- Bipromel (1999): Siemianówka reservoir – Water management rules (in Polish), Warsaw.
- Beven, K. and A. Binley (1992): The future of distributed models: model calibration and uncertainty prediction. *Hydrol. Process*, 6:279–298,
- Dembek, W. and Danielewska, A., (1996): Habitat diversity in the Upper Narew valley from the Siemianówka reservoir to Suraz. (in Polish) *Zeszyty Problemowe Postępów Nauk Rolniczych*, 428
- Junk, W.J., Bayley, P.B. and Sparks, R.E..(1989): The flood pulse concept in river floodplain systems. In: D.P. Dodge (ed.), "Large River"; *Proc. Intern. Sym. Journal of Canadian Fisheries and Aquatic Sciences*, 11: 106-107
- Kubrak, J., Okruszko, T., Mirosława-Świątek, D. and Kardel, I. (2005): Recognition of hydraulic conditions in the Upper Narew River System and their influence on the wetland habitats in the river valley. In: *Publications of the Institute of Geophysics, Polish Academy of Sciences*, 387: 209-237.
- Okruszko, T., Tyszewski, S., and Pusłowska, D. (1996): Water management in the Upper Narew valley. (in Polish) *Zeszyty Prob. Post. Nauk Rol.*, 428

- Pappenberger, F., Beven, K., Frodsham, K., Romanowicz, R., Matgen, P. (2006): Grasping the unavoidable subjectivity in calibration of flood inundation models: A vulnerability weighted approach *Journal of Hydrology*, In Press, Corrected Proof, Available online 9 November 2006,
- Ratto, M., Tarantola, S., and Saltelli, A., (2001): Sensitivity analysis in model calibration: GSA-GLUE approach. *Computer Physics Communications*, 136:212–224
- Romanowicz, R., Beven, K. and Tawn, J. (1996): Bayesian calibration of flood inundation models. *Floodplain Processes*, pp. 336-360.
- Romanowicz, R. J. and K. Beven (2006): Comments on Generalised Likelihood Uncertainty Estimation, *Reliability Engineering and System Safety*, DOI: 10.1016/j.res.2005.11.030.
- Romanowicz, R.J. and R. Macdonald (2005): Modelling Uncertainty and Variability in Environmental Systems, *Acta Geophysica Polonica*, 53: 401-417
- Young, P.C. (2000): Stochastic, dynamic modelling and signal processing: time variable and state dependent parameter estimation. In: *Nonstationary and nonlinear signal processing*, (W.J. Fitzgerald, A. Walden, R. Smith & P.C. Young eds.), pp 74-114. Cambridge: Cambridge University Press.