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Integration of Reservoir Management and Flow Routing Model – Upper Narew Case Study

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Abstract

This paper analyses the possibilities of reaching required flow conditions in the reaches of an ecologically valuable river, using reservoir management techniques. The study utilizes a one-dimensional flow routing model and a global optimisation procedure, with a special focus on ecological criteria. The methodology is applied to the valley of the Upper Narew, in north-east Poland. The work is focused on improving water conditions in the Narew National Park, which encloses one of the most valuable swamp ecosystems in Europe. The study area includes a 100 km long reach that begins at the outflow of the Siemianówka Water Reservoir and ends at the National Park. The reach of the River Narew studied has a rather complex anastomosic structure. An analysis is carried out on several historical scenarios. In each case the outflow from the reservoir is optimised to provide ecologically required flow conditions. The results point to the need for a reconsideration of the management of the Siemianówka reservoir.

1. Introduction

The aim of this paper is to analyse the possibility of reaching required water conditions at ecologically valuable wetland sites through reservoir management. After a presentation of the study area, control objectives conditioned on ecological and economical issues are formulated and subsequently the applied methods are presented. Then an investigation of optimal management scenarios against the observed river states is made, followed by a discussion of the effectiveness of a reservoir situated upstream in the mitigation of undesired changes in the river regime. Finally, a sensitivity analysis of the objective function evaluating the obtained management scenarios to the violation of some of the assumptions applied during the analysis is described.

In natural rivers, water conditions vary spatially along the floodplain and therefore a distributed approach to flow modelling is required where both ecological and economic issues are addressed. In this study, river flow is described using a One-

Dimensional Unsteady Flow Through a Full Network of Open Channels model (UNET) (Barkau 1993). Optimization of river roughness coefficients required by UNET and reservoir management is performed using the Differential Evolution Algorithm technique (Storn and Price 1995). In addition, a sensitivity analysis of reservoir management reaction time on desirable objectives is performed following Global Sensitivity Analysis (GSA) (Archer *et al.* 1997).

2. Case study

The Narew National Park (NNP) (Fig. 1) is situated in north-east Poland and encloses valuable water-peat ecosystems of the anastomosing upper River Narew, making this region unique in Europe. The NNP's flora consists of more than 600 species of vascular plants, including many protected varieties. Park wetland areas provide habitats for about 200 bird species, being one of the most important stop-over points for migrating birds. Due to its unique features, the NPN is an important site in the European Network of Natura 2000 (Dembek and Danielewska 1996, IWOR 2002).

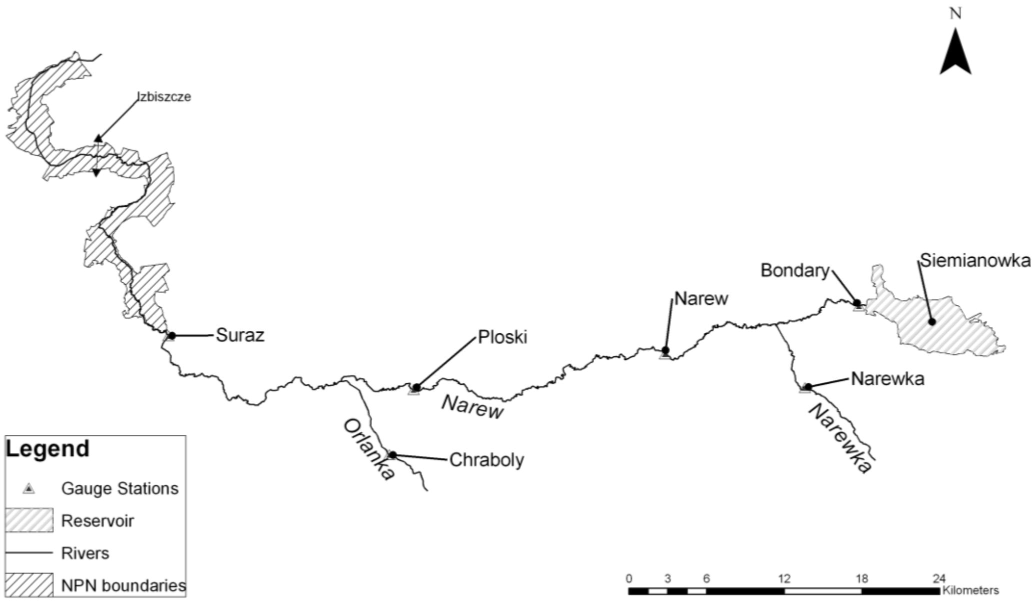

Fig. 1. Schematic map of study area.

The river reach under consideration is a primary, semi-natural form of a lowland river system, with relatively small water slope values, at the level of 0.2‰. The annual river discharge at Suraż is 15.5 m^3/s. The river reach is represented by 57 cross-sections at 2 km intervals obtained from a terrain survey.

Alarming changes have been observed in the Upper River Narew hydrologic regime in recent years, manifested in a reduction of mean flows and shorter flooding periods. This results in a serious threat to the rich wetland ecosystems. On one hand it is caused by local climate changes. Mild winters combined with a reduction in annual rain levels have resulted in a reduction of the valley's groundwater resources. However, recent human activities also have had a significant influence on the deterioration of wetlands water conditions. River regulation work performed in the lower river reach has lowered water levels. Additionally, a water storage reservoir constructed upstream of the NNP has had an important impact on water conditions, causing a reduction in flood wave peaks.

3. Methodology

3.1 Statement of reservoir management problem

Wetland ecosystems depend largely on river flow conditions, especially on flooding (Junk *et al*. 1989). Therefore, actions aimed at preserving the Park's quasi-natural character rely generally on an improvement of the river's water levels and flooding characteristics, such as flooding area, average depth and flood frequency in the wetland area (Kubrak *et al*. 2005, Okruszko *et al*. 1996).

A statement of straightforward criteria for the river flow conditions required by the wetland ecosystem is a difficult task. For the NNP region only qualitative information on ecologically demanded water levels is available. Providing a maximal extent of spring flooding is most important from the ecological point of view. During the rest of the year, a minimum admissible water level should also be maintained. On the basis of available information (IWOR 2002), it was possible to estimate the minimum desirable water levels for the Upper Narew during a hydrological year with a flood period included.

However, in order to meet socio-economical criteria, maximum admissible water levels also have to be specified to protect farmland and urban areas from flooding. The Narew valley is used for extensive agricultural production and the water demand for crops varies in time, depending on the stage of the growing season.

Because of spatial heterogeneity in water demand along the river, water level criteria have to be spatially distributed. In this paper water levels were controlled at discrete representative cross-sections. Optimal water level ranges during the whole hydrologic year were determined for each of the chosen cross-sections. This type of approach should provide a proper representation of water conditions in the wetland area at the NNP.

In this application, Siemianówka reservoir discharges are used as control variables. Although the reservoir is located nearly 100 km upstream from the NNP, it has a significant impact on water levels in this area (Kiczko *et al*. 2007). For reservoir management, additional objectives concerning the physical characteristics of the reservoir, such as maximum and minimum storage and discharge and hydro-power plant effectiveness, have to be considered.

Control performance of the reservoir system depends on river water levels H and reservoir storage V and is evaluated using "fuzzy-like" measures (Romanowicz and Beven 2003) assuming a knowledge of desirable conditions for both variables. The first measure $M(H, \mathbf{g}_H)$ is shown in Fig. 2. Vector $\mathbf{g}_H = [g_{H1}, g_{H2}, g_{H3}, g_{H4}]$ of the desirable water levels depends on time and location of the cross-section along the river. Note that the measure function is 0 if H meets the evaluation criteria on $H \in [g_{H2}, g_{H3}]$ and increases to 1 following a parabolic function when the water levels are outside the specified ranges.

The second measure $M(V, \mathbf{g}_V)$ has a similar shape to that depicted in Fig. 2 and is responsible for the appropriate reservoir water content during the assumed time horizon.

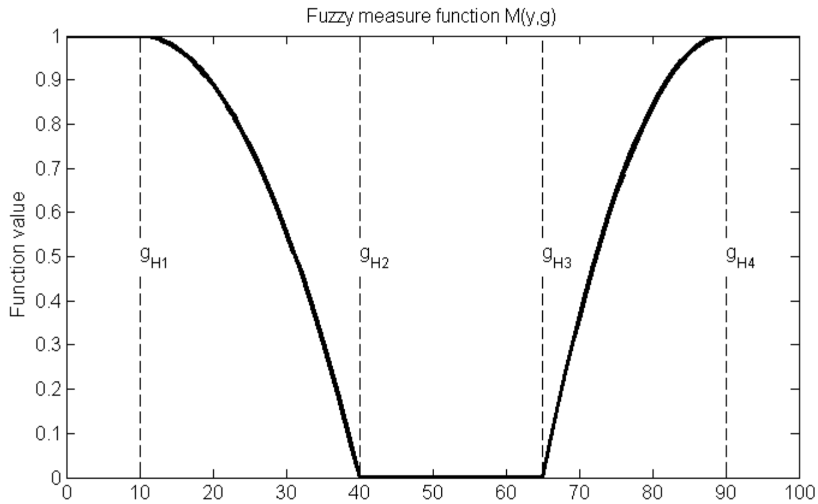

Fig. 2. Fuzzy measure function, where g_{H1} – minimum water level, g_{H2} – lower bound of acceptable water level values, g_{H3} – upper bound of acceptable values, g_{H4} – maximum water level.

At present, the reservoir management is based on "Reservoir Siemianówka management instructions" written by BIPROMEL (1999). This document focuses on the reservoir's operational requirements and the agricultural demands for water levels during a year. During flooding events, the reservoir is supposed to reduce the height and extent of a flood wave downstream. From a wetland ecosystem mitigation point of view, it is an unfortunate demand (IWOR 2002). In this work, criteria for water levels were adjusted to preserve and extend the duration of the spring freshet, according to the recommendations for improving water condition at wetland areas. However, agricultural water demands were also included. Requirements for reservoir water storage values were taken directly from the reservoir management instructions. The fuzzy objective function for water levels applied here changes in time (Fig. 3).

All considered criteria were merged into a unique objective function, discretised in time and space, in the following manner:

$$J(H,V) = \sum_{k=1}^{T} W_{H,k} \left(\frac{1}{N_c} \sum_{j=1}^{N_c} M(H_{kj}, \mathbf{g}_{H,kj}) \right) + W_V \sum_{k=1}^{T} \left(M(V_k, \mathbf{g}_{V,k}) \right) \tag{1}$$

where: T is the number of time steps, N_c is the number of controlled cross-sections, H_{kj} is the water level at time k at cross-sections j, V_k is the reservoir storage at time k,

$\mathbf{g}_{H,kj}$ is a vector of desirable water levels at time k and cross-section j, $\mathbf{g}_{V,k}$ is a vector of desirable reservoir storages at time k, $W_{H,k}$ is the weighting coefficient for water levels, W_V is the weighting coefficient for reservoir storage.

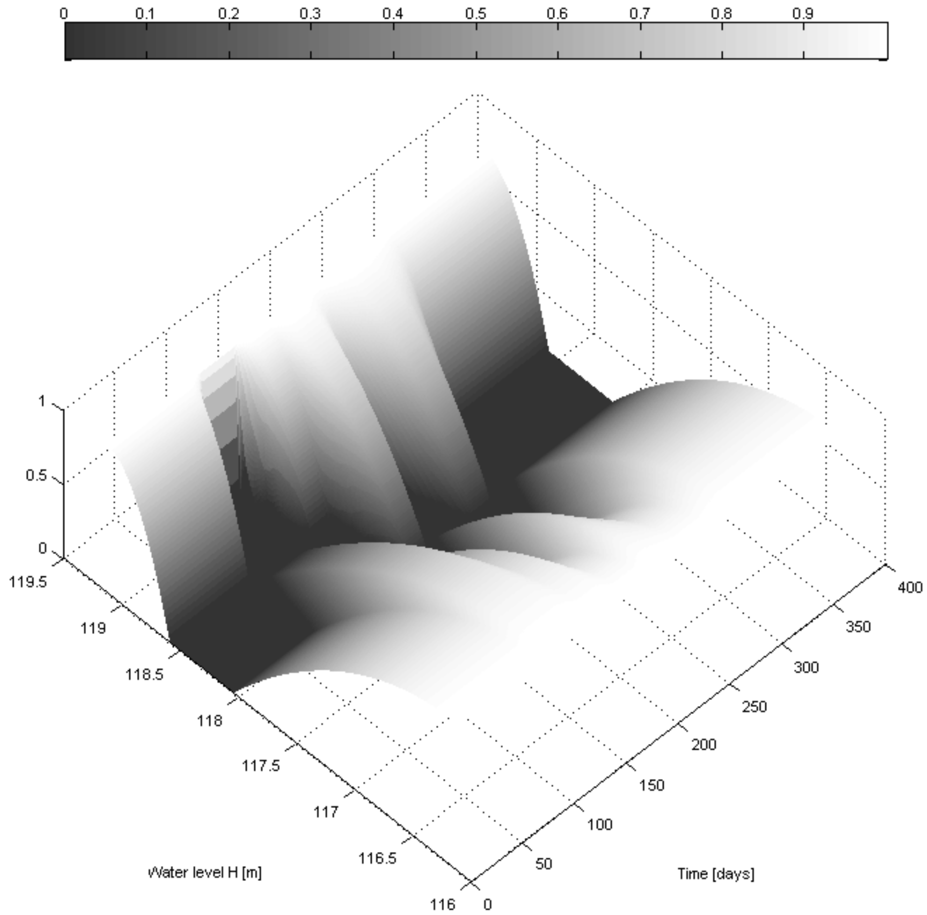

Fig. 3. Response surface of a "fuzzy-like" objective function for water levels at cross-section 51 for a one-year period.

A higher value of the weighting coefficient $W_{H,k}$ is introduced in the objective function during flood periods in order to increase the significance of spring flooding to a wetland area and to maintain the required status of riverine wetlands.

As the optimization criteria have a distributed character, a distributed flow routing model is required.

3.2 Flow routing model

The UNET (Barkau 1993) model is applied to describe flow routing in the Upper River Narew system. This code is a numerical implementation of a 1-D Saint Venant equation in the following form:

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

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

where A_c and A_f are flow areas, respectively, for channel and floodplain; Q is the flow, H is the water level, g is the gravitational acceleration, x_c is the distance along the channel, x_f is the distance along the floodplain, S_{fc} is the floodplain friction slope, S_{ff} is the channel friction slope, Φ is the correction coefficient for momentum due to non-uniformity of velocity distribution at cross-section.

The model was calibrated by adjusting the Manning coefficients separately for the main channel and left and right floodplains. Water surface slope was used as a downstream boundary condition. Water level observations from only three river gauges were available for the whole river reach; therefore it was assumed that roughness coefficients do not change spatially between the gauges.

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 assumed that unmeasured lateral inflows are linearly correlated with two known tributaries and can be described using a linear regression model.

Therefore, calibration was carried out for 14 parameters, 12 roughness coefficients and 2 linear correlation coefficients for unobserved inflows. The sum of squared errors between simulated and observed water levels at controlled gauging stations: Narew, Płoski and Suraż was used as an objective function for roughness coefficients calibration.

3.3 Differential Evolution Optimization Algorithm

In this paper there are two separate optimization problems to be solved. The first is the calibration of roughness coefficients in the UNET model, the second – finding the optimal discharges from Siemianówka reservoir. Please note that the notation used in this section is not linked directly to a particular optimization problem.

Both optimization problems are solved by means of the same Differential Evolution Algorithm described below. This methodology was introduced by Storn and Price (1995) and is currently considered to be one of the most promising global optimization algorithms.

The algorithm used in the present paper works as follows. In each step of the procedure, the population of N individuals [$\mathbf{x}_{1,G}$, $\mathbf{x}_{2,G}$, ..., $\mathbf{x}_{N,G}$] searches for an optimum in D-dimensional space ($\dim(\mathbf{x})=D$), where G denotes the generation number, in order to find the minimum value of the objective function $f(\mathbf{x})$.

At each generation, for each individual $\boldsymbol{x}_{i,G}$ (i=1,…,N) three different population members are randomly chosen ($\boldsymbol{x}_{r1,G}$, $\boldsymbol{x}_{r2,G}$ and $\boldsymbol{x}_{r3,G}$). On this basis the ancestor ($\boldsymbol{v}_{i,G+1}$) is generated:

$$\mathbf{v}_{i,G+1} = \mathbf{x}_{r1,G} + F(\mathbf{x}_{r2,G} - \mathbf{x}_{r3,G}) \tag{3}$$

where F is a parameter, fixed here at a value of 0.8 (Storn and Price 1995). Then, each element of vectors $\boldsymbol{x}_{i,G}$ and $\boldsymbol{v}_{i,G+1}$ is recombined, yielding the final offspring $\boldsymbol{u}_{i,G+1}$:

$$u_{i,j,G+1} = \begin{cases} v_{i,j,G+1} & \text{if} \quad U_{i,j} \le CR \quad \text{or} \quad j = I \\ x_{i,j,G} & \text{if} \quad U_{i,j} > CR \quad \text{and} \quad j \ne I \end{cases} \qquad j = 1, ..., D \tag{4}$$

where $U_{i,j}$ is a random value, I is a random integer. In this application, as is usually the case, the crossover probability CR is equal to 0.9.

The selection is performed on the basis of objective function value $f(\boldsymbol{u}_{i,G+1})$, in the following manner:

$$\mathbf{x}_{\mathrm{i,G+1}} = \begin{cases} \mathbf{u}_{i,G+1} & \text{if} \quad f(\mathbf{u}_{i,G+1}) \le f(\mathbf{x}_{i,G}) \\ \mathbf{x}_{i,G} & \text{if} \quad f(\mathbf{u}_{i,G+1}) > f(\mathbf{u}_{i,G}) \end{cases} \tag{5}$$

3.4 Global Sensitivity Analysis

Sensitivity Analysis plays a very important role in modelling practice (Romanowicz and Macdonald 2005). In the case of an over-parameterized model it provides a reasonable reduction of parameter space.

Generally, the Sensitivity Analysis consists of an evaluation of the relationship 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 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.

Following this methodology, the variance of an output Y depending on the variable input set X_i, i = 1, …, D, can be treated as a sum of the top marginal variance and the bottom marginal variance (Ratto *et al*. 2001):

$$V(Y) = V\left[E(Y|U)\right] + E\left[V(Y|U)\right] \tag{6}$$

where U is a group of one or more elements X_i. The top marginal variance from U is the expected reduction of the variance of Y in case U becomes fully known and is fixed at nominal values, whereas other inputs are normally varying. The bottom marginal variance form U is defined in the case where all parameters but U become fully known, U remaining a variable as before.

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

$$S_i = \frac{V[E(Y \mid X_i = x_i^*)]}{V(Y)}, \tag{7}$$

where x_i^* is fixed value.

The model sensitivity to the interactions among subsets of factors, the so-called higher order effects, is investigated using total sensitivity indices: S_{Ti}. They represent the whole range of interactions which involve X_i and are defined as:

$$S_{Ti} = \frac{E[V(Y \mid X_{-i} = x_{-i}^*)]}{V(Y)}, \tag{8}$$

where the term X_{-i} indicates all the factors but X_i.

The use of total sensitivity indices is advantageous, because there is no need to evaluate 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 efficiently. In this study, the estimation of sensitivity indexes S_i and S_{Ti} is carried out using the Sobol method (Archer *et al*. 1997).

There are two different sensitivity problems studied, following from the two optimisation problems stated. One is related to the calibration of roughness parameters in the flow routing model and the other one to reservoir management. Therefore the model output Y is understood either as a criterion of calibration or reservoir management result, depending on the problem under consideration.

4. Results

4.1 Upper Narew flow model calibration and verification results

A sensitivity analysis of parameters was carried out before the calibration stage of the model. The results show (Table 1) that channel roughness coefficients have the major influence on the model results, while floodplain roughness has a minor effect. In this case parameters interactions play a significant role.

Table 1

Global Sensitivity Analysis for the flow routing model

		S_i	S_{Ti}
Manning roughness coefficient	Channel	0.016	0.267
	Left floodplain	0.000	0.026
	Right floodplain	0.003	0.104

In this application, the annual variations of roughness coefficients due to vegetation and variable winter events are difficult to estimate. In order to minimise the number of unknown parameters, it was assumed that roughness coefficients are constant during the hydrologic year. The model calibration was carried out for nearly 13 month period (10.03.1980 – 14.04.1981) including winter months and spring freshet, as well as summer freshets (Fig. 4).

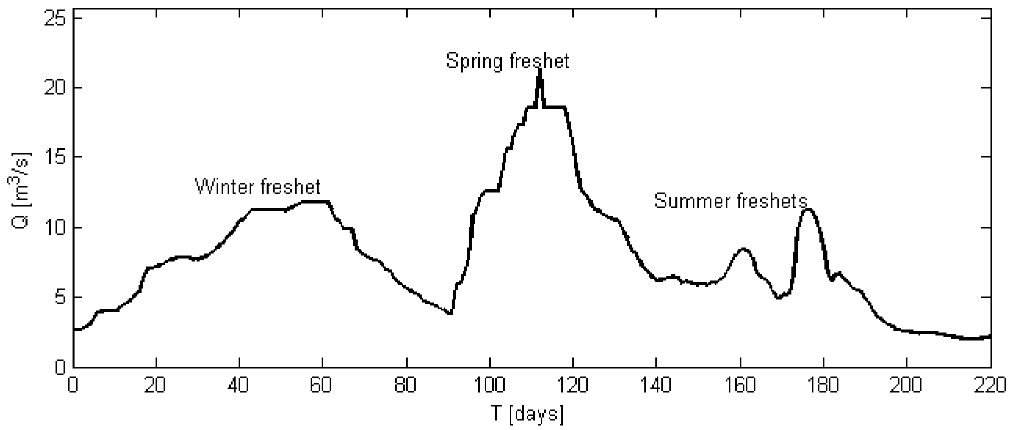

Fig. 4. Discharges at Bondary water level gauge (1980-1981): the upstream boundary condition for the model calibration.

Channel and floodplain (left and right) roughness coefficients for four separate reaches between gauging stations and downstream boundary condition were used as the model parameters. As mentioned above, optimization was carried using the DE algorithm. Verification was done for the period 27.08.1982 – 23.07.1983, giving a good fit with a mean standard deviation less than 0.14 m for each gauging station (Fig. 5).

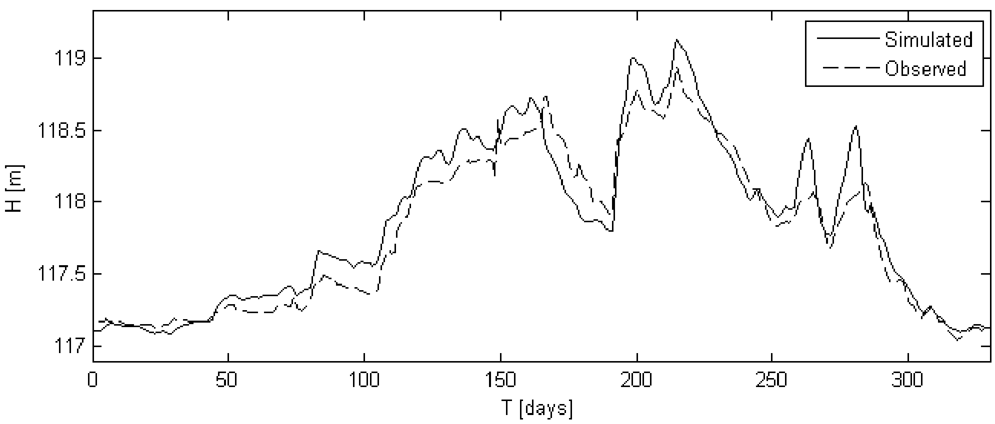

Fig. 5. Model verification at Suraż river gauge for 27.08.1982 – 23.07.1983 period; solid line denotes simulations, dashed line observations.

4.2 Optimization of discharges from Siemianówka reservoir (control stage)

The Siemianówka water reservoir was described using a simple discrete balance model:

$$V_{k+1} = V_k + Q_k^{in} - Q_k^{out}, \qquad k = 1, ..., N_t \tag{9}$$

where V_k is the reservoir capacity in time instant k, Q_k^{in} is the reservoir inflow, Q_k^{out} is the reservoir outflow. Reservoir outflows are represented as the sum of rectangular pulses represented in continuous time t as:

$$Q_{out}(t) = Q_{base} + \sum_{j=1}^{NP} P_j(t, t_j, dt_j, q_j) \tag{10}$$

where Q_{base} is the minimum flow (a minimum allowed discharge from the reservoir), t_j is the time middle point of j-th pulse, dt_j is the pulse duration time, q_j is the discharge and NP is the number of considered pulses.

The j-th rectangular is defined as a

$$P_j(t, t_j, dt_j, q_j) = \begin{cases} 0 & \text{for} \quad t \in \left\langle t_0, t_j - 0.5dt_j \right) \\ q_j & \text{for} \quad t \in \left\langle t_j - 0.5dt_j, t_j + 0.5dt_j \right\rangle \\ 0 & \text{for} \quad t \in \left(t_j - 0.5dt_j, t_k) \right\rangle \end{cases} \tag{11}$$

where t_0 is the initial time and t_k is the optimization horizon.

Historical observations of discharges at the Bondary river gauge before the time when the reservoir was built were used as an inflow to the reservoir. Currently, the reservoir outflow is located in that place. This is a relatively simple approach but it is sufficient for this application, where focus is placed on the reservoir's management abilities to improve water conditions, rather than on a classical control problem.

Initial reservoir storage was set to the recommended value for a chosen control period. Additionally it was assumed that each of the goals included in the global objective function (1) has the same significance. Therefore the weighting coefficients for the reservoir storage and water levels were set to 1, except for flood periods where the weights for water levels were doubled.

Analysis was performed for three different management scenarios:

Scenario A

20.03.1980 – 08.06.1980 – wet period of a maximum discharge in Suraż at 101 m^3/s level, 0.28 probability of exceedance during a year (Rowiński *et al*. 2005);

Scenario B

23.02.1981 – 11.10.1981 – also wet period of a maximum discharge in Suraż at 111 m^3/s level, 0.22 probability of exceedance during a year;

Scenario C

05.10.1982 – 13.07.1983 – rather dry period, of a maximum discharge in Suraż at 68 m^3/s level, 0.53 probability of exceedance during a year.

The periods were chosen from the time before the Siemianówka reservoir was built in the early 1990s. Thus the impact of the reservoir on observed water levels was excluded, which allowed the reservoir's ability to mitigate water conditions at ecologically valuable sites to be investigated. This makes it possible to answer the elementary question of whether a reservoir can improve the water conditions in a natural river system.

In each case, optimization was carried out for 30 parameters, i.e., 3 parameters of $NP = 10$ rectangular pulses. Numerical investigations showed that higher values of NP did not improve solutions significantly for the scenarios considered and they made the optimization process computationally ineffective. The optimization procedure for each scenario was evaluated many times for different starting points in order to ensure finding a value close to the global optimum.

In Table 2, the objective function values acquired for optimal management solution for each scenario are compared with the values for historical water levels not affected by the reservoir.

Table 2

Comparison of objective functions for optimal management scenarios and natural conditions; $J(H,V)$ – objective function as defined by Eq. (1), $J(H)$ – the first part of objective function related to the water levels along the river (without reservoir storage part); $J_n(H)$ – objective function for natural conditions; A, B, C – analyzed scenarios

	Management solution		Observation	Improve
	$J(H,V)$	$J(H)$	$J_n(H)$	
A	0.383	0.345	0.388	12%
B	0.679	0.494	0.533	8%
C	0.708	0.456	0.544	19%

Figure 6 presents a comparison of estimated optimal discharges from the Siemianówka reservoir and observed flows for the third scenario (05.10.1982 – 13.07.1983).

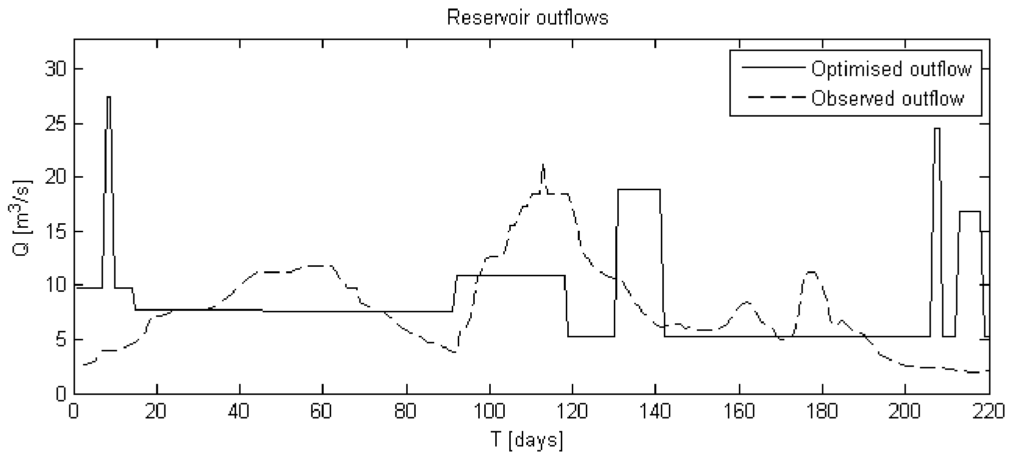

Fig. 6. Evaluated optimal discharges from the Siemianówka reservoir and observed flows (scenario: 05.10.1982 – 13.07.1983).

Figure 7 presents the variation with time of the estimated reservoir storage, with the values of objective function shown in the background as a gradually varying shaded area. At the beginning of, in this case the winter period (0-100 days), the reservoir storage is kept slightly above desired levels. However it allows the achievement of optimal storage during freshet (100-150 days) and following periods (150-220 days).

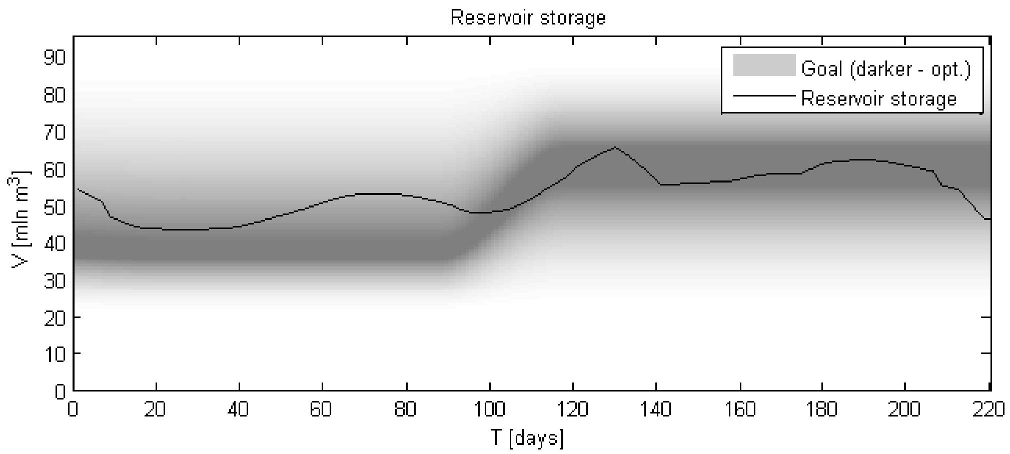

Fig. 7. Computed reservoir storage for the optimal management scenario; the values of goal function are shown as the gradually changing shaded background, demands are shown in dark grey (scenario: 05.10.1982 – 13.07.1983).

Figure 8 presents a comparison of the historical and controlled water levels at cross-section 51 for the third scenario (05.10.1982 – 13.07.1983) with the values of objective function shown as a shaded background.

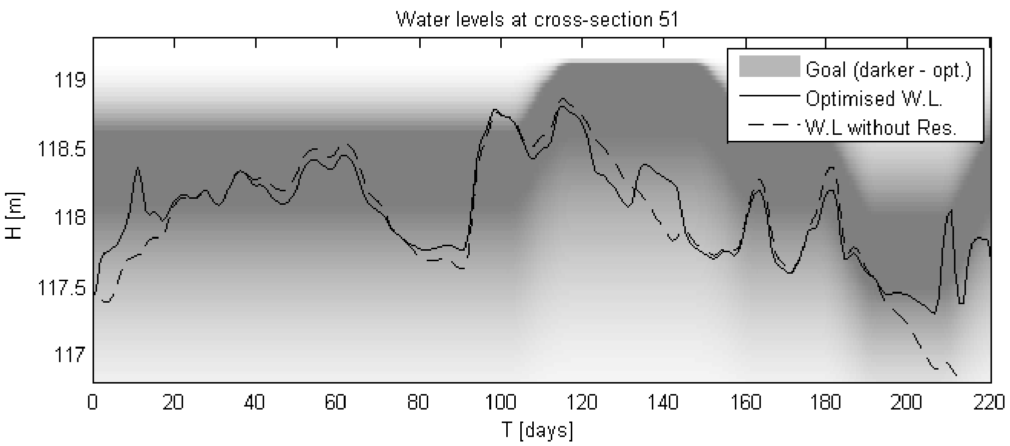

Fig. 8. Water levels at cross-section 51 and observed data; the values of goal function are shown as gradually changing shaded background, demands are shown in the darkest gray (scenario: 05.10.1982 – 13.07.1983).

4.3 Sensitivity analysis of water management scenario

The solutions for management presented in the previous section are obtained for the case of an “unlimited prediction” condition. In other words, all the management decisions presented were carried out assuming a full knowledge of present and future river inflows. Obviously, such a situation does not take place under real management conditions, where all decisions have to be carried out using short-term, uncertain predictions.

In this section we investigate the significance of a delay in reservoir management operation, by the analysis of sensitivity of the objective function to the varying delay in the reservoir discharge t_{sh}. The sensitivity was measured for three different values of pulse delay (1, 2, 3 and 4 days), that allowed to estimate an acceptable threshold for which the objective function is not seriously affected. Different sensitivity indexes of a pulse delay are compared with reference to the sensitivity index of pulse duration time t_d equal to 3 days.

The sensitivity to delays increases linearly (Table 3). A delay equal to 3 days introduces about 23% of the prediction error, whilst a 4 day delay causes a 30% error in the model response (pulse duration).

Table 3

Sensitivity profile of optimal management (scenario: 20.03.1980 – 08.06.1980) sensitivity to pulse delay; Sensitivity to pulse duration was used as reference

Sensitivity to pulse delay			Sensitivity to pulse duration (3 days)	
Delay [day]	S_i	S_{Ti}	S_i	S_{Ti}
1	0.000	0.056	0.444	0.503
2	0.027	0.107	0.392	0.503
3	0.078	0.150	0.342	0.431
4	0.109	0.200	0.290	0.400

5. Conclusions

This paper presents the development of a sustainable water management system for a lowland river. The system consists of a storage reservoir situated upstream of the river, a river channel and wetlands which have to be maintained due to their ecological value. The proposed approach is illustrated using the Upper Narew catchment, with the Siemianówka reservoir situated upstream of the Narew National Park. The formulation of control objectives conditioned on the ecological and economical issues is one of the major issues discussed in the paper. Due to the distributed nature of the ecological objectives, the distributed 1-D model UNET is applied to describe the flow routing process through the channel and the surrounding wetland areas. Optimal discharges from the reservoir are obtained using the DE optimisation algorithm under the assumption of a perfect knowledge of the inflows to the reservoir. A comparison of optimal management scenarios with observed historical river levels from the time before the reservoir was built shows that properly scheduled discharges from the reservoir situated upstream are suitable for the mitigation of undesirable changes in the river flow regime. An analysis of the sensitivity of the objective function to variation in timing of the optimal discharge shows that errors in timing of up to 3 days are acceptable from the point of view of management performance. Further analysis is required to evaluate the influence of inflow and model uncertainty on the behaviour of the management system.

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