Multi-criteria Decision Support System for Siemianowka Reservoir under Uncertainties

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Approved by

Foreword

This report summarizes the research made by the author during his participation in the 2008 Young Scientists Summer Program. The research deals with the problems of reservoir management and water supply-demand under uncertainties and risks. The author formulates a novel stochastic and dynamic multi-criteria optimization model for controling the water mass balances in the area affected by the reservoir management. The model includes several criteria: wetland water requirements, agricultural, energy production, flood protection, fishery and reservoir storage. The goal of the model-based decision-making support is to achieve a desirable water management regime under defined safety levels. The author introduced the safety constraints on water supply; these are known in stochastic optimization as so-called chance constraints. In typical applications they often represent safety constraints for nuclear reactors, stability constraints in insurance business, or constraints on the Value-at-Risk in financial applications.

In dealing with the safety constraints, the author effectively used the relations between highly nonlinear, nonconvex, and often discontinuous safety constraints with minimization of convex functions and so-called Conditional Value-at-risk (CVaR) functions. This important relation allows to efficiently deal with the safety constraints by using linear programming methods.

The proposed Multiple Criteria Decision Support System for the Siemianowka reservoir management under uncertainties is a valuable tool for actual decision-makers. The proposed advanced methodology of water management integrate stochastic optimization methods with multi-criteria analysis. It incorporates diverse software and computational approaches, processing large amounts of data to be used in the solution procedures, and a proper visualization of the data and the results.

Abstract

Protection of biodiversity against climatic variations became recently one of the most important issues in water management politics. In the case of a river system it is necessary to provide desirable water conditions for protected ecosystems. This paper presents an application of a Multiple Criteria Decision Suppport System for optimal management of a reservoir located in NE Poland in the Upper Narew Basin. The proposed system allows tradeoff between different reservoir users, including protected wetland ecosystems of the Narew Nation Park to be found.

The most challenging task was to take the account of inherent uncertainties related to the model structure. It was done using stochastic formulation of the reservoir control problem. Optimisation was carried out for several criteria:wetland water requirements, agricultural, energy production, flood protection, fishery and reservoir storage. The goal was to achieve a desirable water management regime within the defined safety levels. These highly nonliniear constrains were met through the minimisation of convex functions by solving a linear programming problem within Multiple Criteria Analysis.

Acknowledgments

About the Author

Adam Kiczko undertook this research during the Young Scientist Summer Program at the International Institue for Applied Systems Analysis (IIASA) under the supervision of Yuri Ermoliev. He is currently a PhD student at the Institute of Geophysics Polish Academy of Sciences (Warsaw, Poland). His main scientific research is focused on reservoir control problems, including flood inundation modeling, model sensitivity and uncertainty estimation.

His research interests include: developing multi-criteria decision support system for reservoir management conditioned on ecological measures. Adam's past and current research includes case studies of Warsaw reach of Vistula River and the Upper Narew Basin, Poland.

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Introduction

Extreme events, such as floods or long drought periods, might become the most noticeable effects of climatic changes. Variations of a hydrological cycle could have enormous impact not only on human economy but also on present ecosystems. Therefore biodiversity protection and conservation of valuable areas become recently one of the most important issues in water management politics. In the case of river systems that manifests in a wide range of activities aimed at providing desirable water conditions at protected sites following the demands of existing ecosystems.

In many areas freshets are considered as a serious threat to humans' economy, and agriculture became an essential part of vegetation cycle, significantly increasing biodiversity of the region. Narew National Park (NNP), Poland, is such an example. Because of semi–natural character of the region, freshets do not cause losses but are necessary to preserve environmental value of the region.

This report presents a Multiple Criteria Decision Support System for optimal management of Siemianówka reservoir. The reservoir is localised on the Narew River upstream the NNP. The goal of the work is to provide decision makers with a tool that would allow to control safety of the NNP environmental requirements within the reservoir management policy to be included. Important issues concern competition among many water-dependent systems and agents, e.g., agriculture, energy, wetlands, for limited water resources. Accounting for inherent uncertainties is a challenging key task.

Here, the problem of reservoir management and water supply-demand under uncertainties and risks is formulated as a stochastic multi-criteria problem for preserving water mass balances. The management problem consists of optimizing several criteria: wetland water requirements, agricultural, energy production, flood protection, fishery and reservoir storage. The goal of optimization is to achieve a desirable water management regime with defined safety level (constraints). The connection between highly nonlinear, nonconvex and often discontinuous safety constraints with minimization of convex function was used to fulfill the safety constraints by solving the linear programming problem within a Multiple Criteria Analysis.

The first section gives the description of the Upper Narew study area followed by the formulation of the control problem. The next section describes the main source of the uncertainty introduced in the model by means of inflow forecasts and the following one states management criteria. Section 5 and 6 describe the application of the control and Multiple Criteria Analysis. Last two sections present results and general conclusions from this work.

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1 The Upper Narew case study

The Narew National Park (NNP) is situated in north-east Poland and encloses valuable water-peat ecosystems of the anastomosing Upper Narew River, 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 NNP is an important site in the European Network of Natura 2000 [1].

The river reach under consideration (Fig. 1) is a primary, semi-natural form of a lowland river system, with relatively small water slope values equal to 0.02%. The annual river discharge at Suraż is 15.50 m^3/s. At the beginning of this reach a relatively big lowland storage reservoir Siemianówka is situated, with total capacity of about 80 mln m^3.
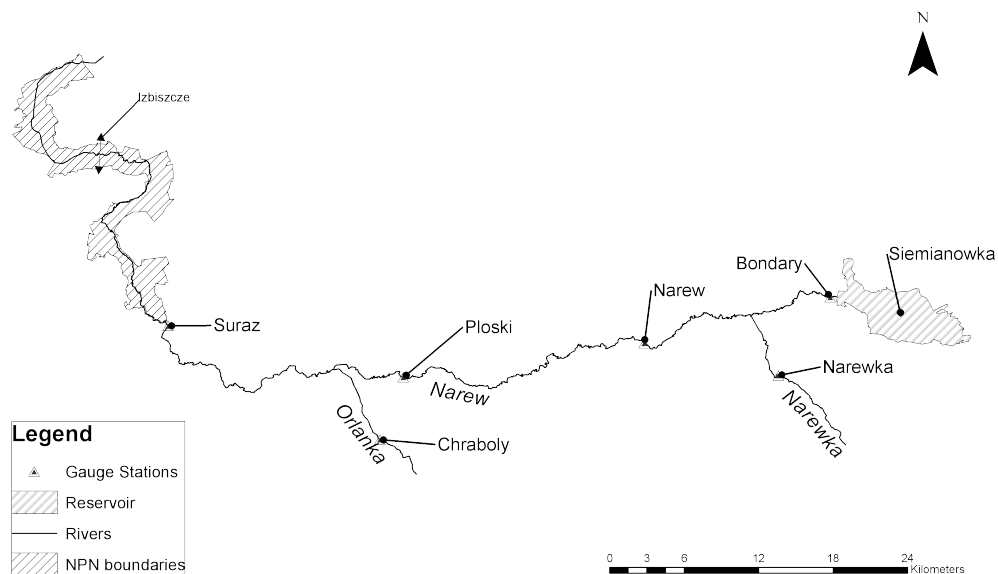
Figure 1: Schematic map of the study area.

Freshets which in most of the other regions might cause significant threat, in NNP are part of a natural hydrological cycle. Typical inundation extent for NNP is presented in Figure 2. It can be seen that the localisation of towns and villages follows the inundation zone border.

Alarming changes have been observed in the Upper Narew River hydrologic regime in recent years, manifested in a reduction of mean flows and shorter flooding periods. This results in a serious threat to rich wetland ecosystems. Local climate changes are one of causes of those 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 peaks.

As it has been showed in [3] improvement of water conditions at NNP area can be achieved through the modification of existing reservoir management rules.
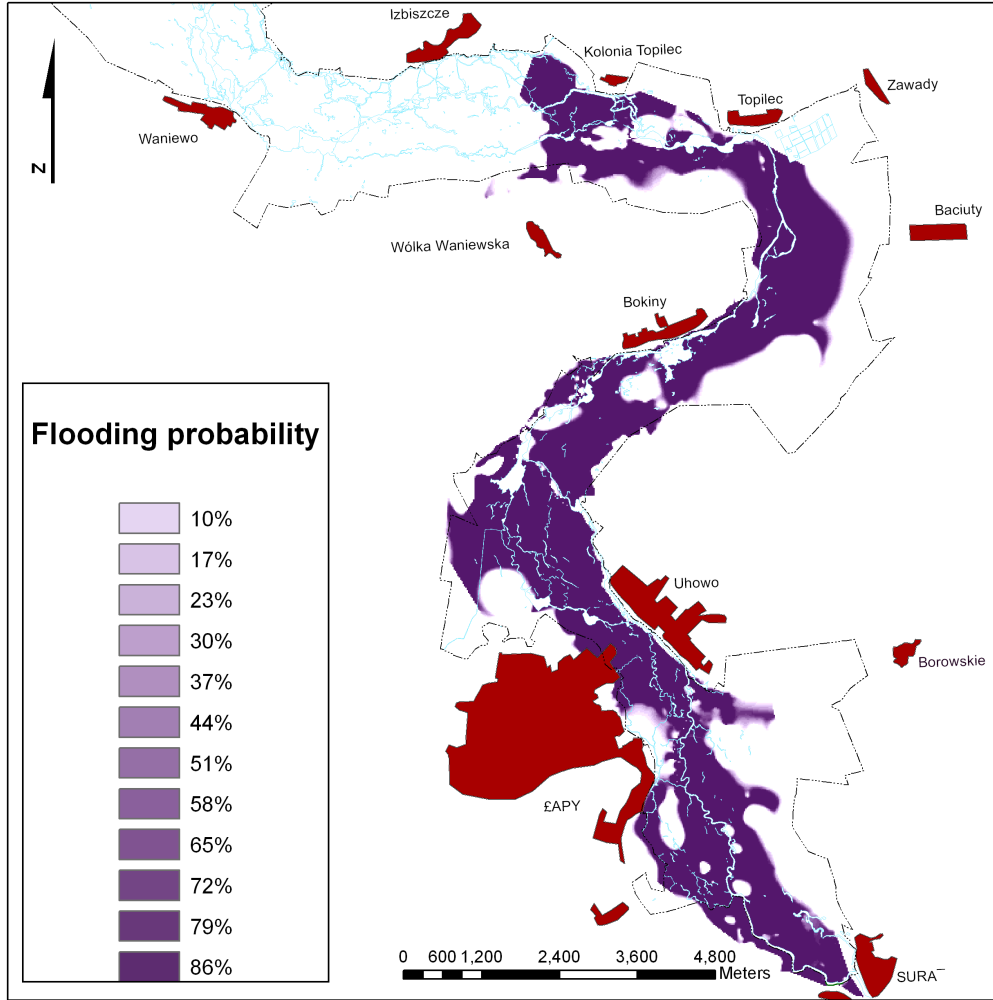
Figure 2: Detailed map of probability of inundation for the River Narew reach situated downstream from Suraż [2].

2 System description

In this work the river system (Fig. 3) is described by the balance equation for the reservoir:

$$S_{k+1} = S_k - u_k + R_k, \tag{1}$$

a Multiple Input Single Output (MISO) Transfer Function (TF) model for flow routing [4]:

$$Q_k = \frac{B\left(z^{-1}\right)}{A\left(z^{-1}\right)} u_{k-\delta_u} + \frac{C\left(z^{-1}\right)}{A\left(z^{-1}\right)} L_{k-\delta_L} \tag{2}$$

and an observation equation:

$$y_k = [S_k, Q_k]^T + \underline{e}_k \tag{3}$$

where: S_k – reservoir storage $[m^3]$ at the beginning of time k, u_k – release amount $[m^3]$ to the river at time interval $[k, k+1]$ (control variable), R_k – inflow to the reservoir $[m^3]$, Q_k – water flow $[m]$ at protected and/or agricultural sites, L_k – lateral inflow to the river system $[m^3]$, y_k – observation vector, $\underline{e}_k$ – observation noise vector with normal distribution: $\sim N\left(0, \sigma^2\right)$, z^{-1}

stands for the backshift operator, δ_u a delay associated with u_k and δ_L with L input, $A\left(z^{-1}\right)$, $B_i\left(z^{-1}\right)$, $C\left(z^{-1}\right)$ are polynomials of n_a, n_b and n_c order, respectively:

$$
\begin{aligned}
A\left(z^{-1}\right) &= 1 + a_1 z^{-1} + \ldots + a_{n_a} z^{-n_a} \\
B\left(z^{-1}\right) &= b_0 + b_1 z^{-1} + \ldots + b_{n_b} z^{-n_b} \\
C\left(z^{-1}\right) &= c_0 + c_1 z^{-1} + \ldots + c_{n_c} z^{-n_c}
\end{aligned}
\tag{4}
$$

River flow routing model, described by equation 2 was identified using *the Captian Toolbox* [5].

There are constrains on reservoir storage S_k which should not exceed minimal storage value S_{min} and maximal S_{max} for all k periods. Similar constraints are imposed on u_k, which has to be higher than u_{min} and smaller than u_{max}:

$$
\begin{aligned}
S_{min} &\leq S_k \leq S_{max} \\
u_{min} &\leq u_k \leq u_{max}
\end{aligned}
\tag{5}
$$

It is important to note that the unmeasured lateral inflows upstream of Suraż contribute up to about 30–40% of the total flow. These unmeasured inflows are incorporated into the MISO TF model by setting the model's steady state gain to 1 to adjust the mass balance.
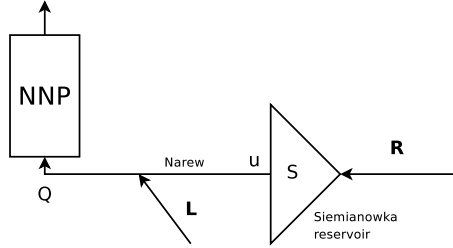
Figure 3: The model of Upper Narew River System.

3 Inflow uncertainties

All reservoir management decisions have to be based on inflow predictions R_k. Therefore the estimation of these predictions uncertainties is essential in the formulation of a management problem. Inflow forecast can be based on rainfall–runoff modelling combined with global circulation models (GCM) and downscaling techniques. Each of these modelling steps leads to highly uncertain solution and control process has to account for this uncertainty. However as this study is focused on control problem and forecast assimilation requires much more detailed investigation, the use of GCM data with downscaling and rainfall–runoff modelling is not introduced here. Instead a forecast generator is used to reflect uncertainties related to inflow predictions. Nevertheless, an application of forecast system for Upper Narew River is planned in the future research and the main features of this source of uncertainty are discussed later. The concept of a forecast generator is described in [6]. It assumes that prediction errors σ_k increase linearly with time:

$$
\sigma_k = k\tau\sigma_0
\tag{6}
$$

where σ_0 denotes base deviation, τ denotes an increase of deviation with time index k. Forecast trajectories were randomly generated within bands indicated by deviation. In this application historical observations of inflows were used as mean forecast values (nominal weather forecast). An example of generated trajectories for low water levels is shown in Figure 4.
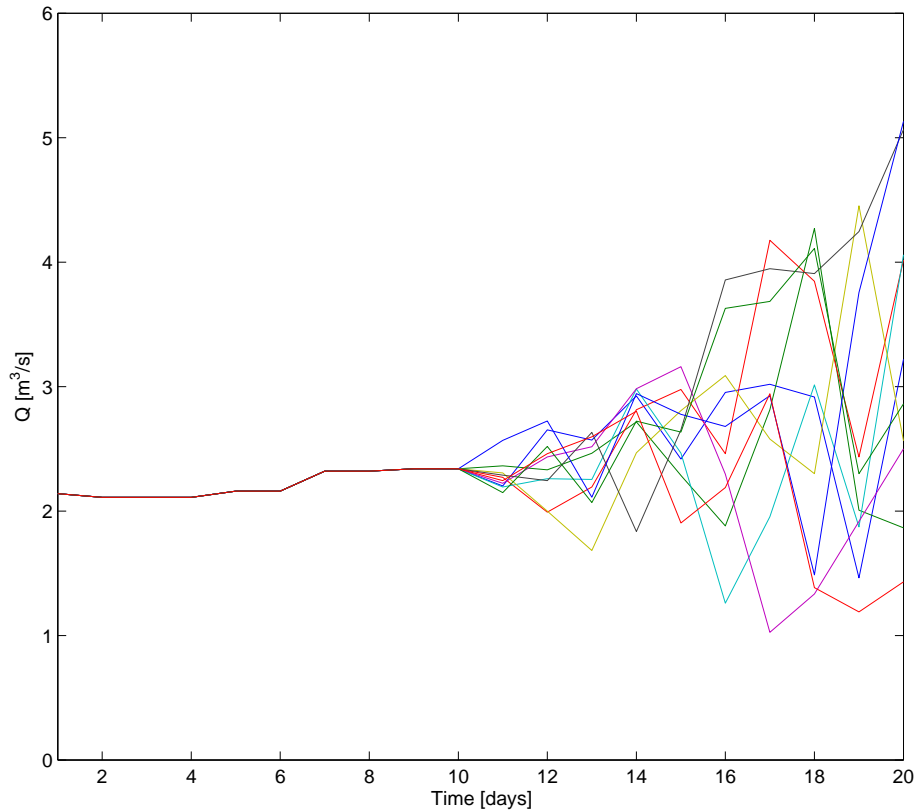
Figure 4: Example of generated forecasts trajectories for low water levels, starting form 10th day.

When the GCM data are to be applied, the precipitation forecasts will be acquired from the European Centre for Medium–Range Weather Forecasts (ECMWF). The resolution of model's computational grid is equal to $2.5° \times 2.5°$ and daily medium–range weather forecast are performed up to 15 days. To improve quality of forecasts and give more insight into the uncertainties, the Ensemble Prediction System (EPS) is added to ECMWF [7]. In that case a forecast consists of the evaluation of a number of ensemble predictions with equal chance of occurring.

In [8] ECMWF EPS's accuracy is analysed using Relative Operation Characteristic (ROC), which reflects forecasts *hit rate* i.e.. the ratio between correctly forecasted events to incorrect ones and all observed. In general, as forecast time progresses, value of ROC decreases. In the case of precipitation, there is a difference in forecasting events of different magnitude and for different seasons. Winter forecasts for precipitation below $2mm/12h$ have ROC above threshold value of 0.7, which indicates usefulness of information for about 10 days, while for summer time just 6 days. Intensive rainfalls above $10mm/12h$ are much more problematic, when useful predictions can be performed for about 7 days in advance in winter and just for 3 days in summer time [8]. Nevertheless predictions in that time scale are still highly uncertain and up to 30% of precipitation events might be incorrectly forecasted.

Downscaling of rainfall information and its final transformation into outflow from sub–basin is another significant source of uncertainty. It depends on model structure and specification of analysed area. For the Upper Narew River, the downscaling and run-off modelling will be performed using time series models [9].

4 Management criteria

Wetland ecosystems depend largely on river flow conditions, and particularly, on flooding [10, 11]. 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 [12, 13]. A formulation of straightforward criteria describing river flow conditions required by the wetland ecosystem is a difficult task. For the NNP region only qualitative information on ecologically required water levels is available. It is assumed that a maximum extent of spring flooding is the most important from the ecological point of view. During the rest of the year, a minimum admissible water flows should be maintained. On the basis of available information [14], it was possible to estimate the minimum desirable discharges for the Upper Narew River during a hydrological year with a flood period included.

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

Because of spatial heterogeneity of water demands along the river, water level criteria have to include spatial distribution. In this work water flows are controlled at representative river reaches. Optimal magnitudes of flow during the whole hydrologic year were determined for each of the chosen reaches. This type of approach should be suitable for providing a proper representation of water conditions in the Upper Narew Basin, including wetland areas of 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 mass balance in this area [15]. For the purpose of reservoir management, additional objectives concerning the physical characteristics of the reservoir, such as maximum and minimum storage and discharge have to be considered.

The management problem consists in a sense of minimising several different criteria for wetland water requirements, agricultural, energy production, flood protection, fishery and reservoir storage. Each criterion has different character and level of significance. It is possible to introduce economical measures for energy production, fishery and agriculture. However in the case of environmental goals, such as wetlands' requirements, it is difficult to quantify potential costs and benefits. Therefore criteria should reflect specific conditions that should be maintained from both economical and environmental points of view.

Because of uncertainties introduced by inflow forecasts and flow routing methods, the control problem is formulated as a stochastic optimization problem. The goal of optimisation is to achieve conditions with a specified probability (safety level) for each of the specified below criteria. This enables the evaluation of control variables that are suitable for a wide range of future states of the river system. In addition, to investigate the advantages of the proposed formulation over the commonly used approaches, also a deterministic formulation is introduced. In that formulation the optimisation objective is to find the best solution assuming that model's uncertainty might be reflected by its mean values. In this application following criteria were considered:

- Reservoir storage and fisheries,
- Wetland and agriculture,
- Energy Production,
- Flood protection.

The reservoir storage and fisheries demands criterion are essential from the reservoir management point of view. 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 flood events, the reservoir is supposed to reduce the height and extent of a peak downstream. The Reservoir storage S_k should follow a goal trajectory $\overline{S}_k$ which reflects expectations about annual inflows to the system (i.e.. spring freshet, summer droughts, etc.) and also fishery demands. In a stochastic formulation the safety criterion takes the following form:

$$P \left(\max_{k \in (T_0, T_1)} |\overline{S}_k - S_k| \leq \nu_S \right) \geq l \tag{7}$$

where $P(\cdot)$ denotes probability, T_0, T_1 are respectively the beginning and the end of a time horizon, ν_S denotes the admissible deviation from a goal trajectory and l is the safety level (admissible probability). The $max(.)$ function indicates that the criterion is focused on extreme deviations. Similarly, in the deterministic case, the objective is to minimise maximum deviation from the desired storage trajectory $\overline{S}_k$ allowing for ν_S deviation:

$$C_s = \max_{k \in (T_0, T_1)} \max \left(|\overline{S}_k - S_k| - \nu_S, 0 \right) \tag{8}$$

Wetland and agricultural demands vary during a vegetation period, henceforth these criteria have to depend on time. The required water levels should reflect trade-off between ecological and economical goals. For this region the variable in time water level demands were evaluated following the paper of [17, 18], based on the estimated probabilities of flooding of three main plant communities: *Magnocaricion*, *Carici elongatae-Alnetum* and *Pharagmition*. (see Fig. 6). Spatial distribution of those three plant types has been shown in Figure 5. As the formulation based on water levels leads to a non–linear problem, a desired water level trajectory was transformed into discharges using rating curves. The stochastic safety criterion takes a similar form to a previous one:

$$P \left(\max_{k \in (T_0, T_1)} |\overline{W}_k - W_k| \leq \nu_Q \right) \geq m \tag{9}$$

where W_k stands for flow at protected area, $\overline{W}_k$ is the required flow trajectory. Deterministic criterion can be expressed as follows:

$$C_w = \max_{k \in (T_0, T_1)} \max \left(|\overline{W}_k - W_k| - \nu_Q, 0 \right) \tag{10}$$

Energy Production demands a specific level of releases $\overline{u}_k$ from the reservoir. Bellow this level there is a "penalty for not producing" and above that level there is no additional gain as power plant works already at a full capacity. Optimisation objective is to provide safe releases that satisfy the capacity requirement with the probability (safety level) n :

$$P \left(\max_{k \in (T_0, T_1)} (u_k - \overline{u}_k) \geq 0 \right) \geq n \tag{11}$$

where $\overline{u}_k$ denotes the discharge at which the reservoir power plant works at full capacity. In deterministic case criterion will take the following form:

$$C_e = \max_{k \in (T_0, T_1)} \max \left(\overline{u}_k - u_k, 0 \right). \tag{12}$$

Flood protection consists of maintaining flows in populated areas P_k below a given value $\overline{P}_k$, above which losses occur:

$$P \left(\max_{k \in (T_0, T_1)} \left(\overline{P}_k - P_k \right) \geq 0 \right) \geq 0 \tag{13}$$
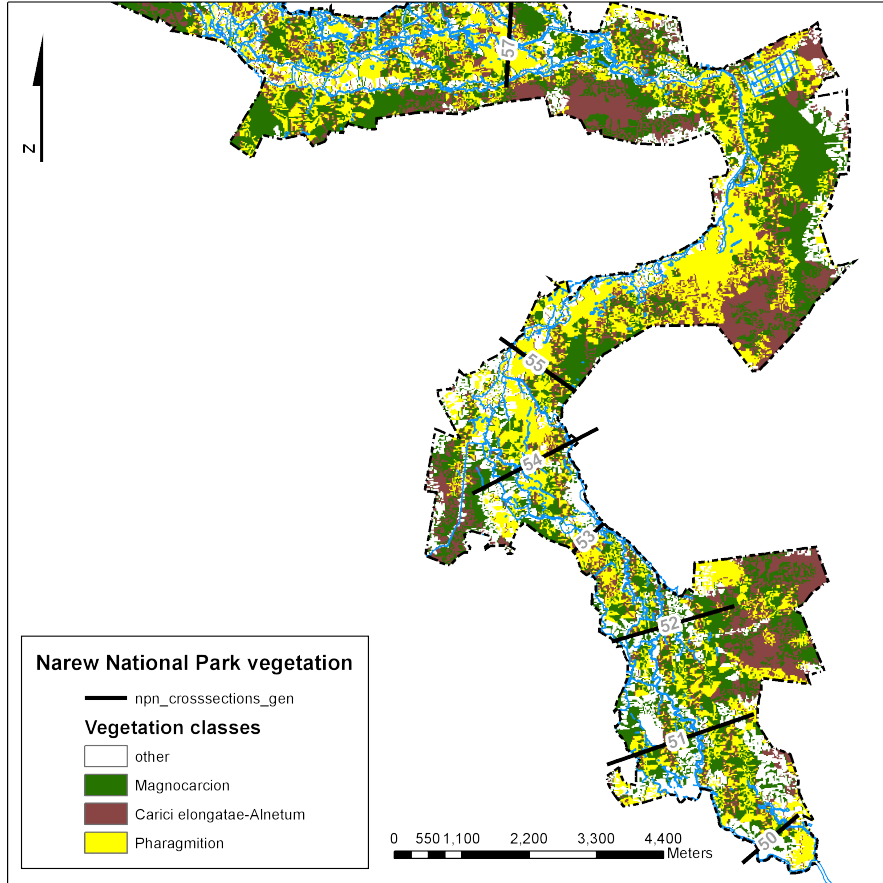
Figure 5: Three major types of vegetation in the Narew National Park [18].

Deterministic expression takes a similar to the previous form:

$$C_p = \max_{k \in (T_0, T_1)} \max\left(P_k - \overline{P}_k, 0\right) \tag{14}$$

Constraints (7), (9), (11), (13) are well known in Stochastic Optimization [19] as so called chance constraints. In applied model they are often introduced as safety constraints (e.g., nuclear reactors), stability constraints (e.g., in the insurance business), or constraints on the Value-at-Risk in financial applications.

5 Application of the control: Stochastic minimax model

Reservoir control was performed for receding time horizon (Receding Horizon Optimal Control – RHOC). This means that for each time step, values of the control variable **u** are optimised for forecasted model inputs and specified time length. As new data become available at the next time step, the process is repeated conditionally on realized situation, in particular, only a value from the previous time step is used as a reservoir release. Simulations were carried out for the whole forecast span (10 days). In addition, the sensitivity of control to the length of the time horizon was investigated. To enable the discussion about reservoir impact on wetland communities, computations were performed for the reference period 1978–1983, before the construction of the storage reservoir.
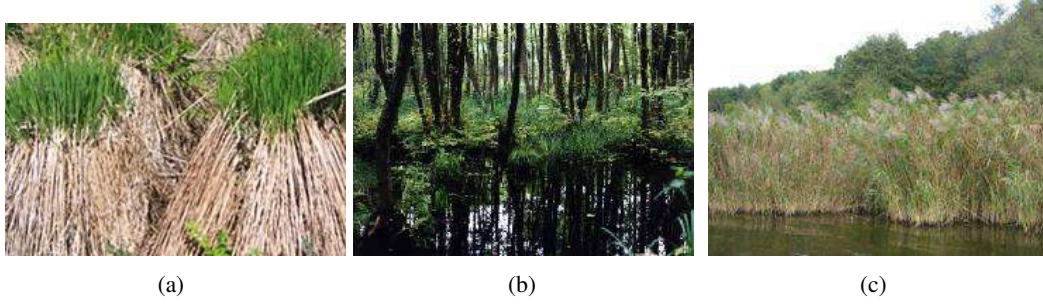
Figure 6: Pictures of three main NNP's vegetation types: (a) – *Magnocaricion*, (b) – *Carici elongatae-Alnetum* and (c) – *Pharagmition.*

Modelling of uncertainties was an important issue. It was done here on a basis of scenario simulations. At each control step, the objective was to find such value of u_k that minimises expected costs with respect to all potential scenarios of future uncertainties conditional on currently observable situation. Scenarios are generated for each of the included ensemble weather prediction combined with Monte Carlo sampling of noise elements of the river model. In a result, the number of all included scenarios was equal to $N = N_f \times N_M$, where N_f denotes the number of ensemble inflow forecast and N_M the number of Monte Carlo samples.

In the case of deterministic approach optimization was carried out according to three different concepts:

- Flood protection worst case – for maximum inflow forecast,

- Environment worst case – for minimum inflow forecast,

- Mean forecast – as trade-off between the previous two.

There are strong connections of highly nonlinear, non-convex and even often discontinuous safety constraints (7), (9), (11), (13) with minimization of stochastic convex functions [19, 20] and so-called CVaR risk measures [21]. These fundamentally important connections allow to regulate safety constraints by solving specific linear programming models. In the following, this specific LP model is formulated without proofs, which can be derived in a similar manner from general results in [19, 20, 21].

In this report we omit detailed and rather lengthy analysis. Instead, let us ilustrate only the main idea.

Consider, for example, the following convex stochastic minimax model: minimize expected value

$$G_S = E \left\{ \max \left(\alpha_S \left(\max_{k \in (T_0, T_1)} \left(\overline{S}_k - S_k \right) - \nu_S \right), \beta_S \left(\nu_S - \max_{k \in (T_0, T_1)} \left(S_k - \overline{S}_k \right) \right) \right) \right\} \quad (15)$$

with respect to $\nu_S \geq 0$. The solution of this model (under rather general assumptions) satisfy constraint (7) with any positive α, β chosen from (15). If we consider minimization, the same type of functions associated with constraints (9), (11), (13) and positive α_W, β_W, α_E, β_E, α_P, β_P, and variables y_W, y_E, y_P, then we obtain all safety constraints (7), (9), (11), and (13). Thus, the minimization of an aggregate criteria composed of G_S and other similar functions G_W, G_E, and G_P with respect to decision variables S_K, U_K, and $y = (y_S, y_W, y_E, y_P)$ would yield a solution specifying control variables S_K, U_K satisfying required safety levels. If such a solution does not exist, a multi-criteria analyzing model would allow to find a compromise solution within desirable aspiration and reservation levels.

The main methodological challenge is the optimization of a criteria composed of functions G_S, G_W, G_E, G_P. It is practically impossible to find analytically explicit form of this functions involving nonlinear transformations of uncertain variables and decisions by max operations. It is remarkable, that the stochastic optimization results allow to do this by using linear programming methods. Namely, assume that i denotes the number of a scenario (a Monte Carlo sample). Then the minimization towards criteria G_S, G_W, G_E, G_P can be substituted by minimization towards the following linear functions under constraints:

$$l = \frac{\beta_S}{\beta_S + \alpha_S} \tag{16}$$

$$m = \frac{\beta_W}{\beta_W + \alpha_W} \tag{17}$$

$$n = \frac{\beta_E}{\beta_E + \alpha_E} \tag{18}$$

$$o = \frac{\beta_P}{\beta_P + \alpha_P} \tag{19}$$

where α_S, α_W, α_E, α_P denote cost coefficients for not reaching specified levels of the reservoir storage and discharge at protected sites, respectively, β_S, β_W, β_E, β_P cost coefficients for exceeding these values. This asymmetric weighting coefficients have been also used in the deterministic approach. This allows to formulate optimization as a Linear Programing (LP) problem:

- Reservoir Storage – $\min \frac{1}{N} \sum\limits_{i=1}^{N} y_{S,i}$ subject to

$$\begin{cases} \alpha_S \left(\overline{S_k} - S_k - \nu_S \right) & \leq y_{S,i} \\ \beta_S \left(S_k - \overline{S_k} - \nu_S \right) & \leq y_{S,i} \end{cases} \tag{20}$$

- Wetland and agriculture – $\min \frac{1}{N} \sum\limits_{i=1}^{N} y_{W,i}$ subject to

$$\begin{cases} \alpha_W \left(\overline{W_k} - W_k - \nu_W \right) & \leq y_{W,i} \\ \beta_W \left(W_k - \overline{W_k} - \nu_W \right) & \leq y_{W,i} \end{cases} \tag{21}$$

- Energy production – $\min \frac{1}{N} \sum\limits_{i=1}^{N} y_{E,i}$ subject to

$$\begin{cases} \alpha_E \left(\overline{u_k} - u_k \right) & \leq y_{E,i} \\ \beta_E \left(u_k - \overline{u_k} \right) & \leq y_{E,i} \end{cases} \tag{22}$$

- Flood Protection – $\min \frac{1}{N} \sum\limits_{i=1}^{N} y_{P,i}$

$$\begin{cases} \alpha_P \left(\overline{Q_k} - Q_k \right) & \leq y_{P,i} \\ \beta_P \left(Q_k - \overline{Q_k} \right) & \leq y_{P,i} \end{cases} \tag{23}$$

where i denotes number of scenarios and $y_{S,i}$, $y_{W,i}$, $y_{E,i}$, $y_{P,i}$ are output variables for each scenario. In the case of the deterministic approach $i = 1$.

6 Multiple criteria optimisation

Most of numerical experiments presented in this work were performed using a union function, combining all four criteria:

$$F = \frac{1}{N} \sum_{i=1}^{N} (y_{S,i} + y_{W,i} + y_{E,i} + y_{P,i}) \tag{24}$$

with a possibility of using some weighting coefficients. Let us note, that the minimization of function (24) corresponds to a Multi Criteria Analysis. Henceforth, in optimization sense two first criteria $\overline{S_k}$, $\overline{W_k}$, are best possible solutions and ν_S, ν_W reflect aspiration bands. A trade–off between criteria is evaluated in-explicitly by values of these deviations and weighting coefficients: $\alpha_S, \alpha_W, \alpha_E, \alpha_P, \beta_S, \beta_W, \beta_E, \beta_P$.

However, user support system should provide possibility for direct analysis of trade–offs. At each decision step a user should be able to adjust system performance according to his knowledge. This can be achieved through introduction of the Multiple Criteria Model Analysis methodology. In this study the Aspiration Reservation Based Decision Support (ARBDS) method, developed by [22] and extended by [23], is used.

The ARBDS is based on a special criteria scaling technique using Component Achievement Function (CAF). We don't give details of this approach here since a rather comprehensive discussion can be found in [24]. In a general form, ARBDS is defined as a minimization of the following function F:

$$F_m = \min_{1 \le \kappa \le n} G_\kappa \left(q_\kappa, \overline{q_\kappa}, \underline{q_\kappa} \right) + \epsilon \sum_{\kappa=1}^{n} G_\kappa \left(q_\kappa, \overline{q_\kappa}, \underline{q_\kappa} \right) \tag{25}$$

where κ stands for a criterion number, G_κ CAF, q_κ denote criteria functions, $\overline{q_\kappa}$, $\underline{q_\kappa}$ are the aspiration and reservation levels, respectively. In this approach trade-off solutions are investigated interactively by the user at each optimisation step through adjustment of $\overline{q_\kappa}$, $\underline{q_\kappa}$ modifying CAF. In this application Interactive Specification and Analysis of Aspiration–Based Preferences (ISAAP) [24] is used.

7 Results

7.1 Identification of flow routing model

Flow routing model for Bondary–Suraż river reach was identified for flow observations from the years 1978–1981. During this period, a wide range of flow conditions was observed, therefore it could be considered as a relatively representative for the flow modeling. The autoregression polynominal A was estimated as 2-order, with $n_b = 2$, $n_c = 2$ and time delays $\delta_u, \delta_L = 0$ days. Verification was carried out for the years 1981–1983 (Fig. 7). Mean model error was estimated as 2.9 m^3/s and linear regression coefficient as 0.91. It is seen that the largest error is related to unobserved inflows.

7.2 Reservoir management scenarios

At first, the influence of forecast length to control performance was investigated. In this case the numerical experiment consists of the evaluation of the control for reference period for different lengths of ensemble forecasts. As a performance measure goal function (24) was used. Results are presented in Figure 8. It is seen that for the forecast generator model performance increases up to the 8 day forecast and then remains stable.
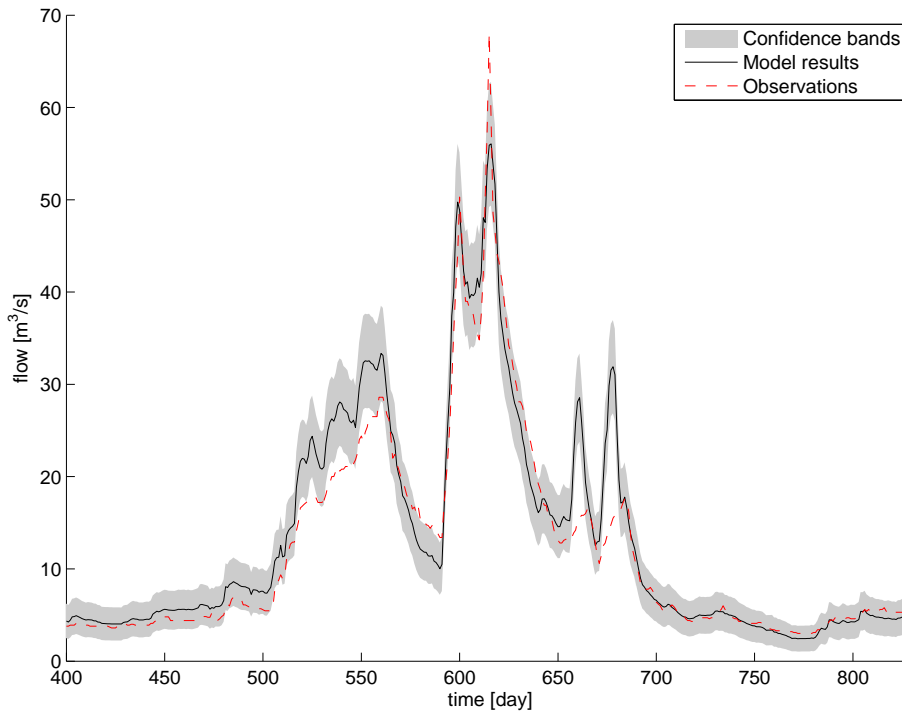
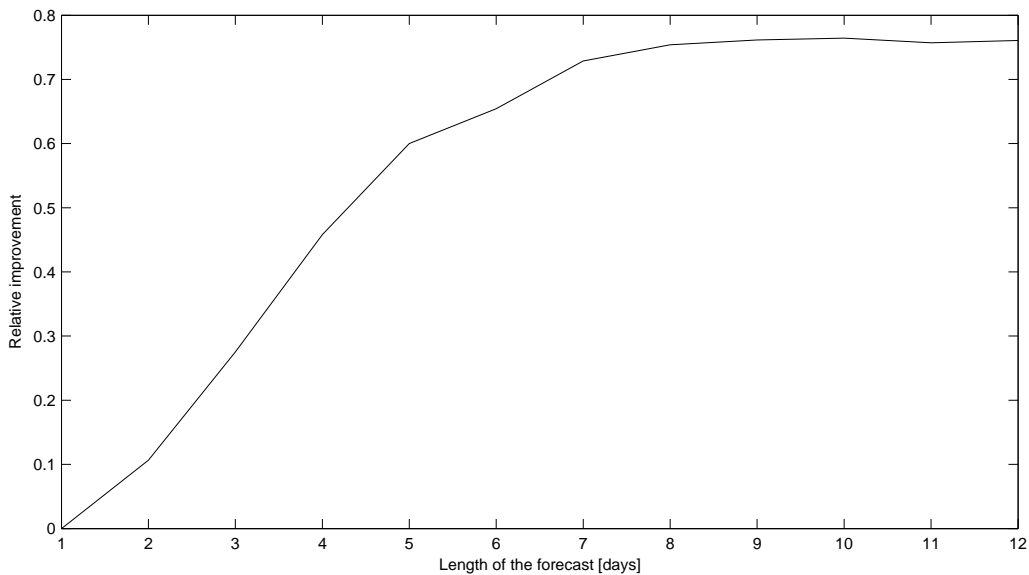Figure 7: Verification of TF flow routing model for Suraż cross-section.

Figure 8: Improvement of the objective function 24 with the length of the forecast in relation to 1 day forecast; *1978 spring freshet*.

Figures 9 and 10 show an application of the control model to the historical scenario. Simulations were carried out for 100 ensemble artificial inflow forecasts, 6 day long. Model uncertainty was neglected ($\underline{e}_k = 0$). The results show that the model reduces magnitude of spring peak and then extends its duration. In addition, control provides ecological discharges during low water periods. In the case of the reservoir storage, it is important to note that the controlled path exceeded the bands of the goal trajectory because of the other existing criteria (a compromised solution).

To compare stochastic and deterministic approaches, control simulations were performed for
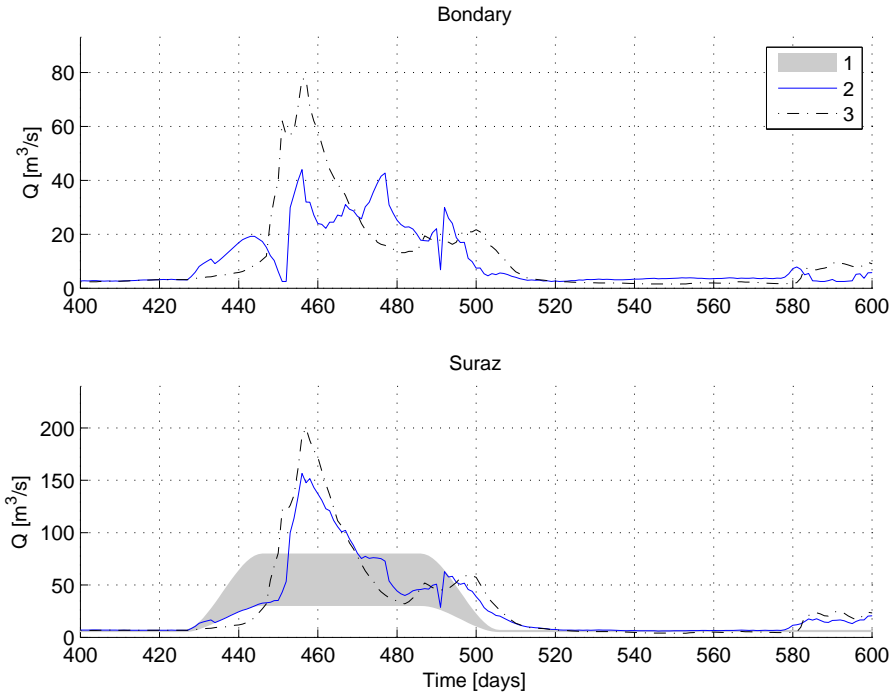
Figure 9: Reservoir control for 1979 hydrologic year – river discharges at Bondary and Suraż cross–sections; 1 – Wetland and agricultural goal, 2 – optimised flows, 3 – flows in no control case.
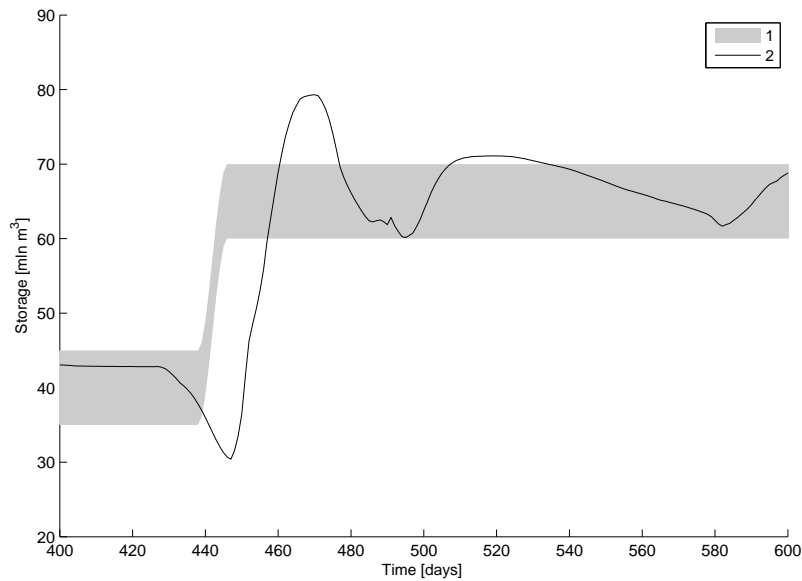
Figure 10: Reservoir control for 1979 hydrologic year – reservoir storage; 1 – reservoir storage goal, 2 – optimised storage.

the reference period 1978-1983. In addition, the results were compared with the observed flow reflecting conditions without reservoir control applied.

Differences between different control approaches were presented in Figure 11. In the first panel also inflows to the reservoir are shown presenting the hydrological background. Differences

Table 1: MCMA for one of reservoir decision steps. Utopia denotes the best possible solution for each criterion, Nadir, the worst one.

Solution no.	Storage	Wetland	Energy	Flood Prot.
Utopia	0	3.12	-0.01	-0.01
Nadir	15.9	81.2	0.42	0
1	3.86	3.58	0.01	-0.01
2	1.76	8.54	0	-0.01
3	3.61	4.18	0	-0.01
4	3.45	4.55	0	-0.01
5	3.61	4.18	0	-0.01
6	3.06	5.47	0	-0.01
7	4.05	3.13	0.41	-0.01

between stochastic and three different deterministic formulations and no control scenario are presented in the lower panels. Obviously, the largest differences are seen during the spring period. The largest differences occur in the case of the deterministic approach and results for maximum and mean forecasts are relatively similar to the stochastic approach. In the minimum case it is seen that control provides significantly higher flows at protected sites during the water shortage periods. These calculations also show that with more heterogeneous scenarios including "surprising" shifts in floods occurrences and their durations there will be more significant differences in solutions of stochastic optimization model with all there deterministic solutions (optimistic, pessimistic, and expected floods).

More comprehensive Multi Criteria Analysis is planned as a forthcoming task. A preliminary illustrative example is presented in Table 1. Each solution provides optimal criteria values. It this case it is seen that the trade-off solution is developed only between Storage, Wetland/Agricultural and Energy criteria. Flood Protection was not taken into account in this problem and for all solutions the corresponding criterion values remain unchanged. It can be noticed that solution no. 2 is focused on reservoir storage, while 7 on wetland and agricultural demands.

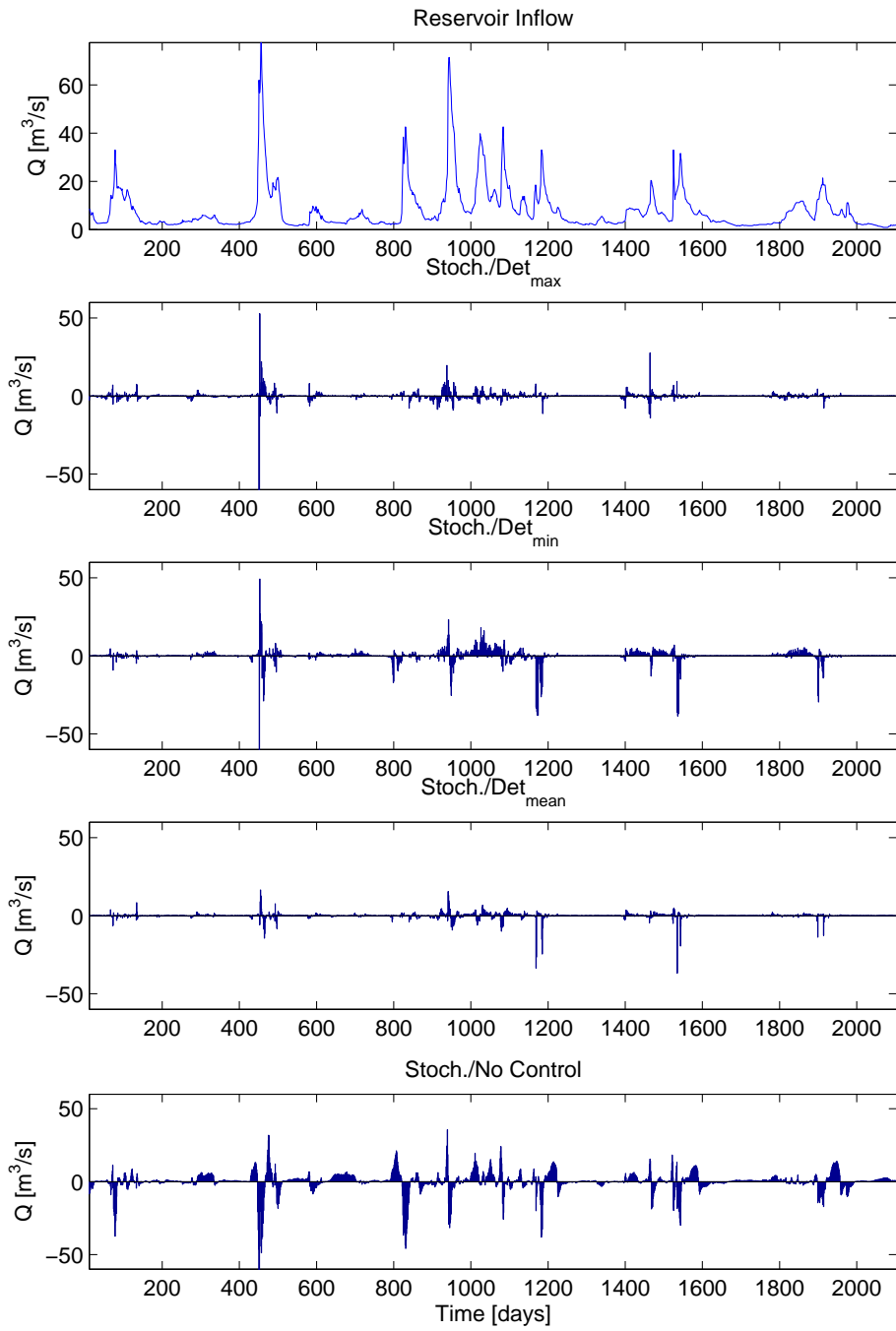Figure 11: Differences between flow through protected area evaluated according to stochastic and deterministic approaches. The first panel shows hydrological background (inflow to the reservoir), three following panels show differences between stochastic results and deterministic for maximum, minimum and mean value, respectively, and the last one shows the difference between stochastic control and no control scenario.

8 Conclusions

In this study the following issues were discussed:

1. Application of the stochastic minimax model and Multi Criteria analysis for the control under uncertainties for reservoir management with special focus on wetland demands. The evaluation of the numerically efficient flow routing model was an essential point in this task. Use of the MISO TF model for flow routing allowed this optimisation problem to be reformulated in a linear framework and therefore it was possible to use very efficient LP solvers. Results presented in Figure 9 and 10 show that the control is capable to provide improvement of water conditions at wetland sites. It is done by reduction of spring freshet magnitude and extending its duration.

2. Investigation of desired forecast length. Medium term weather forecasts are available up 15 days. However in the case of precipitation predictions, the accuracy decreases strongly with time and at some point it becomes useless from the management point of view. In this work a simple method of estimation of a desirable forecast length is proposed. For the presented case with the forecast generator, in Figure 8 it is seen that 8 day prediction is sufficient for this control problem. This assessment allows the model efficiency to be increased.

3. Comparison between stochastic and deterministic approaches. It has been shown that all deterministic approaches differ significantly form the stochastic ones. Stochastic approach seems to be the only one which provides appropriate solution for the uncertain predictions.

4. Multiple Criteria Model Analysis. Decision support system for multi–purpose reservoir should provide user with ability to choose between different, often contradictory management goals. It has been shown that it can be achieved through the MCMA. In this case model provides optimal solutions for control problem taking in account preferences of Decision Maker about control goals.

The presented study requires future investigation. Real ensemble forecast should be included in the reservoir control. In addition, the developed model does not take into account variability of natural system and therefore introduction of real time updating system should be considered. Further extension of Multi Criteria Analysis is required.

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