Flood control in Nysa Reservoir System by means on sequential optimisation and CRS method

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Abstract Decision Support System for flood control for the Nysa Klodzka Reservoir System includes modules responsible for precipitation forecast, rainfall-runoff transformation, unsteady flow routing for Nysa Klodzka and selected reach of Odra River as well as operational control. The main goal of the paper is to present a control structure and control mechanisms for the cascade of reservoirs - problems related to the last module. To improve efficiency and accuracy of the used optimisation technique we tested a sequential optimisation and suggested a particular modification of the standard controlled random search. We show that the introduced concept considerably improves the performance of the control structure by reducing the dimensionality of the sub-problems.

INTRODUCTION

The hydrological features of the upper part of the Nysa Klodzka catchment are massive rocky underground covered only by small layer and an average yearly precipitation of about 900 mm. An inability of storing water underground leads to dangerous floods. To handle this problem two reservoirs were built, and more are under construction.

The paper discusses the management of reservoirs governing the discharges in the city of Nysa, which lies just below the last reservoir. We propose the new control algorithm that makes use of characteristic features of the system and global optimisation methods. Relations resulting from the system dynamic equations allow to perform calculations separately for each particular reservoir in the cascade and to propagate the results to other system components.

In this paper we apply the global optimisation technique elaborated by Price (1983), later developed by Ali and Storey (1994) (Controlled Random Search method), and finally modified by the authors.

PROBLEM FORMULATION

The considered system that consists of N reservoirs in series is schematically shown in Fig.1.

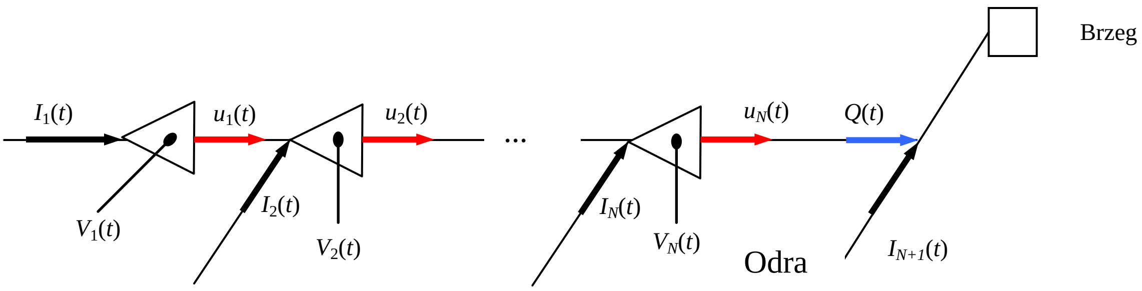

Fig.1 Schematic representation of the system

At this stage we assume that inflows *I(t)* to the system represent one of many possible scenarios taken into account by a decision maker. The scenarios considered could be based on rainfall-runoff prediction models, or recorded historical data.

Retention in each reservoir $V_j(t)$ is described by the dynamics of a simple tank, with one forecasted inflow $I_j(t)$ and one controlled output $u_j(t)$, $j=\overline{1,N}$. According to the introduced notation, the state equations for the reservoir system are:

$$\frac{dV(t)}{dt} = B * I(t) - C * u(t) \tag{1}$$

with the following constraints on the reservoir storage and releases

$$V_{\min} \le V(t) \le V_{\max} \qquad U_{\min} \le u(t) \le U_{\max} \tag{2}$$

and initial condition $V(0) = V_0$ (3)

for any $t \in [0, T_H]$, where V_{min} denotes dead storage, V_{max} denotes total storage, and T_H is optimisation time horizon.

To simplify the optimisation problem the dynamics of flow in the reach between the reservoirs is omitted and flood routing in Nysa Klodzka River below the last reservoir is described by means of so-called linear channel (pure delay) with time constant T_0, so the flow at Nysa Klodzka outlet $Q(t)$ is

$$Q(t) = u_N(t - T_0) \tag{4}$$

The main goal of this system is the protection of the user located below the cascade of reservoirs against flooding by minimizing the peak of the superposition of waves $Q(t) + I_{N+1}(t)$ on Nysa and Odra rivers, respectively. This can be achieved by desynchronization of the flow peaks via accelerating or retarding flood wave on Nysa River. The second objective is storing water for future needs after flood.

Hence the objective function of the optimisation problem under consideration can be written in the form of a penalty function:

$$\min_{u_j, j=\overline{1,N}} \left\{ \beta_1 \max_{t \in [0,T_H]} \left[Q(t) + I_{N+1}(t) \right] + \beta_2 \sum_{k=1}^{N} \left[V_k(T_H) - V_{\max k} \right]^2 \right\} \tag{5}$$

where symbols β_1 and β_2 denote appropriate weighting coefficients and T_H is the optimisation time horizon.

SEQUENTIAL OPTIMISATION

In this section we describe the application of the particular iterative optimisation procedure for N reservoirs in series. At any iteration step the water content of only one *j*-th reservoir is modified. Additionally we modify outflow from this particular reservoir and all outflows from reservoirs below this reservoir $u_k(t); \quad k = \overline{j,N}$.

The applied sequential optimisation procedure contains the following steps:

(1.) assuming zero outflows from all reservoirs, i.e.

$$u_k(t) := 0 \qquad \forall k = \overline{1,N} \text{ and } \forall t \in [0, T_H] \tag{6}$$

(2.) assuming index of the „improved" reservoir as $j := N$

(3.) solving the problem

$$\min_{u_N}\left\{\beta_1 \max_{t\in[0,T_H]}\left[Q(t)+I_{N+1}(t)\right]+\beta_2\left[V_N(T_H)-V_{\max N}\right]^2\right\} \tag{7}$$

with $Q(t)=u_N(t-T_0)$ and following constraints

$$V_{\min N} \le V_N(t) \le V_{\max N} \tag{8}$$

$$U_{\min N} \le u_N(t) \le U_{\max N} \tag{9}$$

and $$\frac{dV_N}{dt}=u_{N-1}+I_N-u_N \qquad V_N(0)=V_N^{(0)} \tag{10}$$

(4.) denoting the best solution as $B := \max_{t\in[0,T_H]}\left[Q(t)+I_{N+1}(t)\right]$

(5.) assuming index $j := j-1$

(6.) solving the problem

$$\min_{u_j}\left\{\beta_1 \max_{t\in[0,T_H]}\left[Q(t)+I_{N+1}(t)\right]+\beta_2\left[V_j(T_H)-V_{\max j}\right]^2\right\} \tag{11}$$

with $Q(t)=u_N(t-T_0)+\Delta u_j(t-T_0)$, where $\Delta u_j(t)$ is the difference between trajectories of the j-th control function of the current and the previous iteration steps; the optimisation is led under constraints

$$V_{\min j} \le V_j(t) \le V_{\max j} \tag{12}$$

$$U_{\min j} \le u_j(t) \le U_{\max j} \tag{13}$$

and $$\frac{dV_j}{dt}=u_{j-1}+I_j-u_j \qquad V_j(0)=V_j^{(0)} \tag{14}$$

or $$\frac{dV_j}{dt}=I_j-u_j \qquad V_j(0)=V_j^{(0)} \qquad \text{if } j=1 \tag{15}$$

with additional constraints: $$U_{\min k} \le \Delta u_j(t)+u_k(t) \le U_{\max k} \tag{16}$$

for $k=\overline{j+1,N}$.

(7.) assuming $u_k(t)=\Delta u_j(t)+u_k(t)$ for $k=\overline{j+1,N}$

(8.) solving the problem $A := \max_{t\in[0,T_H]}\left[Q(t)+I_{N+1}(t)\right]$

(9.) returning to (2.) if $A>B$,

(10.) returning to (5.) if $j>1$.

The above algorithm describes the consecutive steps of computation which was conducted from the reservoir N to 1. Of course the starting point for the next iteration would be step (2). If the results obtained for *j*=1 are not worse than results obtained in step *j*=2 the procedure stops. The experiments showed that the computation time for one iteration could be very long (eight hours for *N*=4 on PC Pentium III).

CONTROL RANDOM SEARCH METHOD

The functions $u_j(t),\ j=\overline{1,N}$ were represented by a train of rectangular pulses and the time horizon was divided into L unequal time intervals. The parameters to be determined were values of pulses $\hat{u}_l$ and time instances of switching the control function *u*(*t*). This type discretisation, denoted as TD-RP (Time Dependent Rectangular Pulses) was described in detail by Dysarz and Napiórkowski (2002).

The local optimisation problems for all reservoirs were solved by means of the global random search procedure, namely the following version of Controlled Random Search (CRS2) described in details in Dysarz and Napiórkowski (2002).

The CRS2 algorithm starts from the creation of the set of points, many more than $n+1$ points in n-dimensional space, selected randomly from the domain. Let us denote it as *S*. After evaluating the objective function for each of the points, the best x_L (i.e. that of the minimal value of the performance index) and the worst x_H (i.e., that of the maximal value of the performance index) points are determined and a simplex in n-space is formed with the best point x_L and n points ($x_2,..., x_{n+1}$) randomly chosen from *S*. Afterwards, the centroid x_G of points x_L, x_2 ,…, x_n is determined. The next trial point x_Q is calculated, $x_Q = 2x_G - x_{n+1}$. Then, if the last derived point x_Q is admissible and better (i.e., $Q(x_Q) \le Q(x_H)$), it replaces the worst point x_H in the set *S*. Otherwise, a new simplex is formed randomly and so on. If the stop criterion is not satisfied, the next iteration is performed. In the CRS2 version applied in the tests, the worst point of the current simplex will be the reflected point $x_Q = 2x_G - x_H$, rather than the arbitrary chosen one (Dysarz and Napiórkowski, 2002).

RESULTS OF TEST FOR HISTORICAL DATA

The described sequential optimisation was tested and verified on a number of historical and synthetic flood events. Results for two of them, namely for the historical floods in Nysa catchment in 1965 and 1997 and for existing two reservoirs, are presented in Fig.4 and Fig.5, respectively.

The floods in 1997 were caused by the most disastrous recent abundance of water in the region. During the first stage of a disaster, a rapid increase in runoff was noted after intense and long lasting rains in the 4-10 July period in the highland tributaries. Yet, a few days later, from 15 to 23 July, another series of intensive rains occurred. The highest precipitation in the Klodzko valley reached 100-200 mm. The flood virtually ruined the town of Klodzko (Kundzewicz et al., 1999), and the historic stage record was exceeded by 70 cm. During the 1985 flood, daily precipitation maxima were significantly (two to three times) lower than in 1997. Several all-time maximum stages recorded in 1985 were largely exceeded by the 1997 flood.

Fig.4a and 5a show the performance of the Otmuchow (upper) Reservoir, Fig.4b and Fig.5b show the performance of Nysa (lower) Reservoir, and Fig.4c and 5c show the flow at the cross-section below the junction of Nysa and Odra Rivers.

As one can see, by an appropriate choice of the control functions the peaks of the waves on Nysa Klodzka and Odra rivers were desynchronised and the culminations did not overlap.

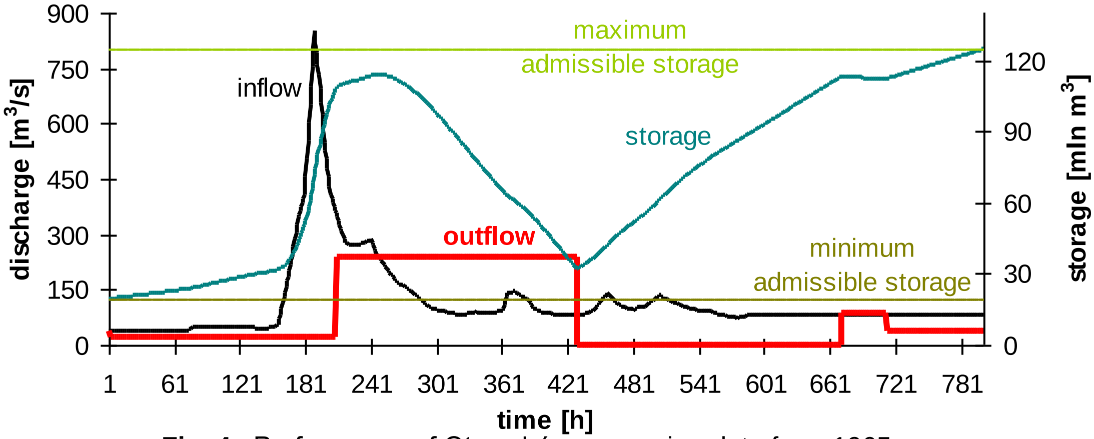

Fig. 4a Performance of Otmuchów reservoir – data from 1965

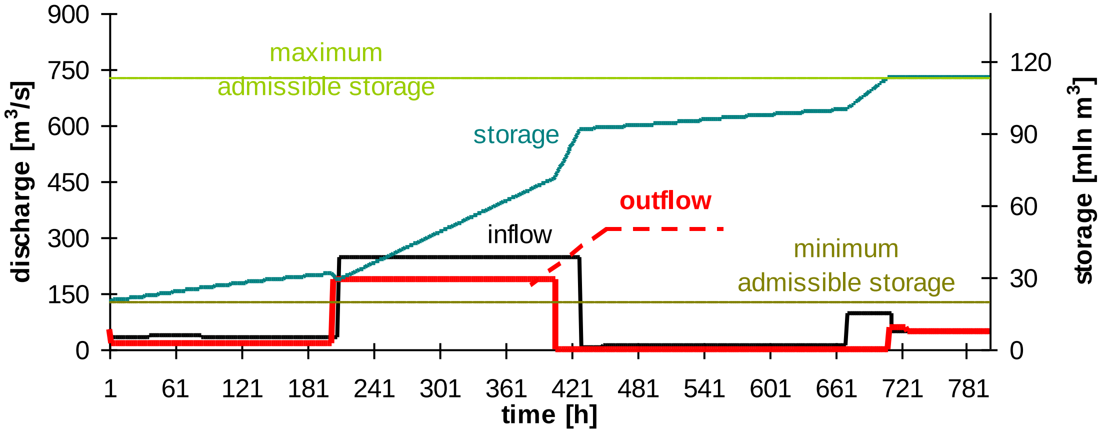

Fig. 4b Performance of Nysa reservoir – data from 1965

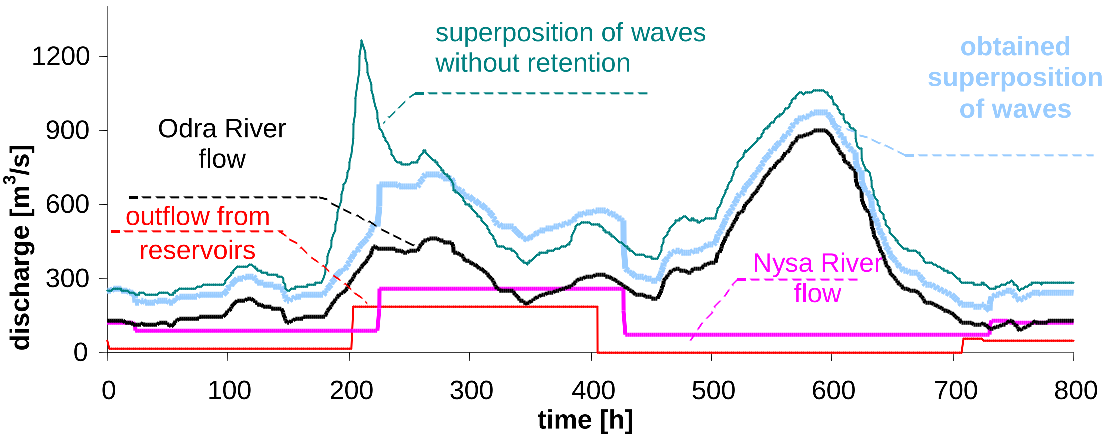

Fig. 4c Flow below the junction of Nysa and Odra Rivers –1965 data

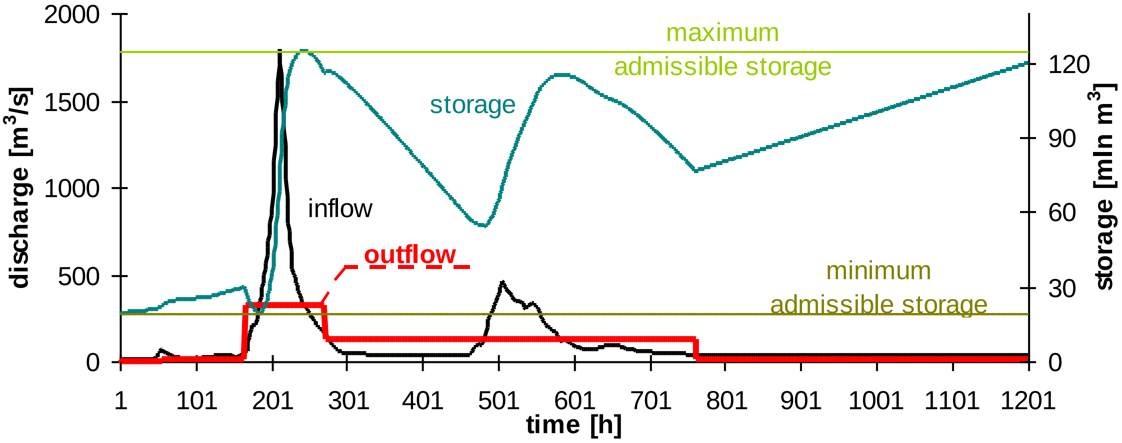

Fig. 5a Performance of Otmuchów reservoir – data from 1997

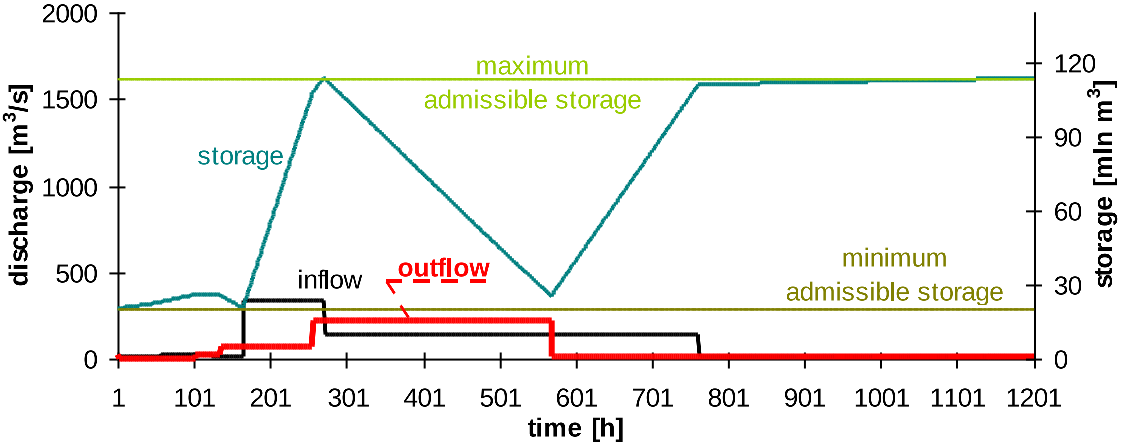

Fig. 5b Performance of Nysa reservoir – data from 1997

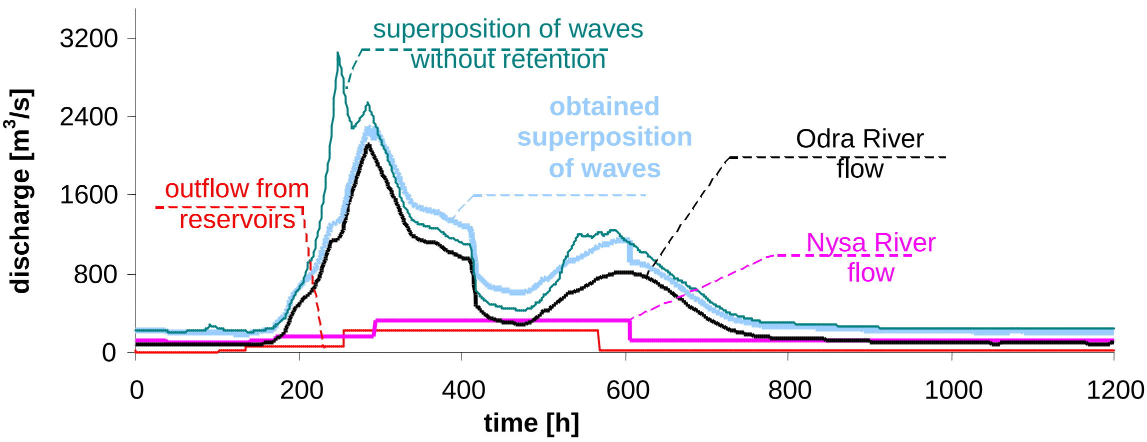

Fig. 5c Flow below the junction of Nysa and Odra Rivers –1997 data

CONCLUSIONS

It is necessary to take into account the uncertainty of the inflows forecast in operation control of reservoirs system during flood. Hence the optimisation problem has to be solved repetitively for many scenarios using actual measurements and updated forecasts. Therefore, from the decision making point of view, the access to a quick and reliable, especially designed for the particular system optimisation module, is very important.

The approach presented in the paper makes a decomposition of the general problem possible, so that computational costs grow linearly with the number of reservoirs. Hence, more complex representation, than that described by Niewiadomska-Szynkiewicz et al. (1996) and Niewiadomska-Szynkiewicz and Napiórkowski (1998), of the control functions $u_j(t)$ can be adopted.

Because of nondifferentiability of global and two local performance indices, the global optimisation technique CRS is used. The authors have not proved the convergence of the proposed method yet, however convergence was observed in all carried out tests.

The results from applications of the sequential optimisation by means of control random search methods to determine the reservoir decision rules during flooding are encouraging. Accuracy of the proposed method is satisfactory. The initiation procedure and the stop criterion were cautiously investigated, so high efficiency does not cause losses in accuracy. As a result, the described control structure of Nysa Kłodzka reservoirs system can be easly extended to include transformation by means of hydrodynamic flood routing model, because the proposed technique guarantees that the solution of the optimisation problem can be obtained in reasonable time.

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