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# CELTIC WATER IN A EUROPEAN FRAMEWORK

## POINTING THE WAY TO QUALITY

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# Application of sequential optimisation for flood control – Nysa Reservoir System case study

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**Abstract**

We present an application of the controlled random search method for real time operation of the Nysa Klodzka reservoir system in Poland. To improve efficiency and accuracy of the optimisation technique used we tested a sequential optimisation and suggest 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. This allows treatment of the optimisation problems that seemed to be unsolvable due to the so called "course of dimensionality".

**Resume**

Une application de la méthode de la recherche aléatoire commandé pour commander en temps réel d'un système des réservoirs de la rivière Nysa Klodzka en Pologne est présentée. Pour améliorer l'eficacité de la téchnique d'optimisation appliqué, l'optimisation séquentielle était testé et une modification de la méthods classic de la recherche aléatoire est proposée. Il est montré que cette amélioration changé remarquable l'eficacite, de la méthode de commande par la réduction du nombre des dimensions de sou-problèmes. Ce permettait résoudre le problème d'optimisation qu'il parait inrésoluble à cause de „l'imprécation de dimensions".

## 1 Introduction

Decision Support System for flood control for the Nysa Klodzka Reservoir System includes modules responsible for precipitation forecast for a catchment, 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 Otmuchow and Nysa reservoirs - problems related to the last module.

The catchment of the Nysa Klodzka River as shown in Fig.1 is located in the southern part of Poland.

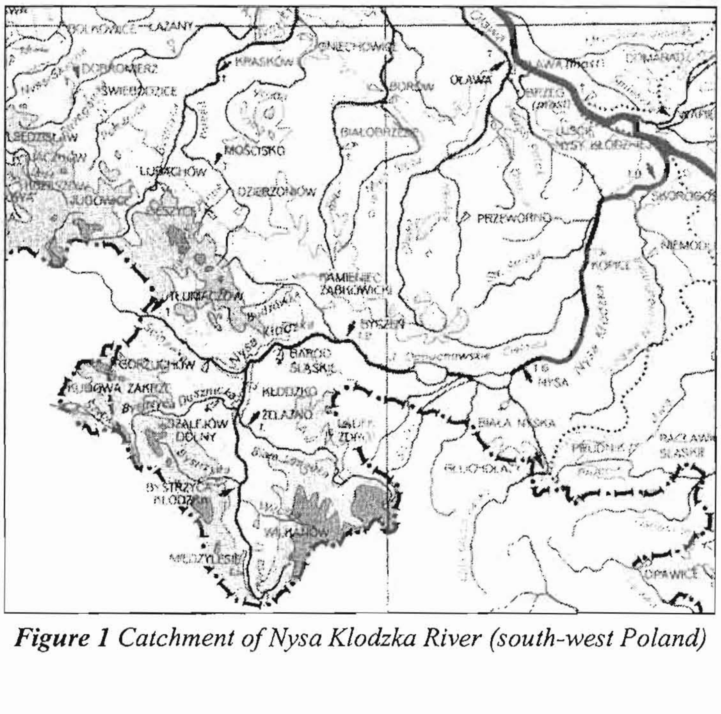

***Figure 1** Catchment of Nysa Klodzka River (south-west Poland)*

The hydrological features of the upper part of this 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 two more are under construction.

The paper discusses the management of two existing reservoirs governing the discharges in the city of Nysa, which lies just below the second 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. This decomposition makes the computational costs to depend linearly on the number of reservoirs.

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.

## 2 Problem formulation

The considered system that consists of two reservoirs in series is schematically shown in Fig.2. Management and control of flooding generally require the use of forecasting techniques. At this stage we assume that inflows $I_1(t)$ and $I_2(t)$ 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.

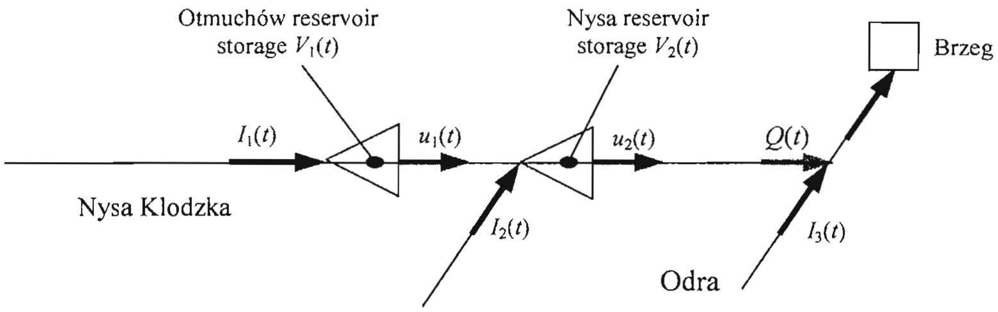


***Figure 2** Schematic representation of the system*

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 $u_j(t)$, $j = \overline{1,2}$

$$\frac{dV_1}{dt} = I_1(t) - u_1(t) \tag{2.1}$$

$$\frac{dV_2}{dt} = u_1(t) + I_2(t) - u_2(t) \tag{2.2}$$

The following constraints on the reservoir storage and releases (given in Table 1) are taken into account:

$$V_1(0) = V_{10} \qquad V_2(0) = V_{20} \text{ (initial condition)}$$

$$V_{\min j} \leq V_j(t) \leq V_{\max j} \qquad U_{\min j} \leq u_j(t) \leq U_{\max j} \tag{2.3}$$

for $j = \overline{1,2}$ and 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.

*Table 1 System parameters*

| Reservoir | $V_{min}$ [mln m$^3$] | $V_{max}$ [mln m$^3$] | $U_{min}$ [m$^3$/s] | $U_{max}$ [m$^3$/s] |
|---|---|---|---|---|
| Upper (no 1) | 19,38 | 124,66 | 0,0 | 1363,0 |
| Lower (no 2) | 20,29 | 113,60 | 0,0 | 1960,0 |

To simplify the optimisation problem the dynamics of flow in the reach between the reservoirs is omitted and flood routing in Nysa River below Nysa 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*

$$Q(t) = u_2(t - T_0) \tag{2.4}$$

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 $Q(t) + I_3(t)$ 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:

$$\min_{u_1,u_2}\left\{\beta_1 \max_{t\in[0,T_H]}\left(Q(t)+I_3(t)\right)+\beta_2\sum_{j=1}^{2}\left[V_j(T_H)-V_{\max j}\right]^2\right\} \tag{2.5}$$

where symbols $\beta_1$ and $\beta_2$ denote appropriate weighting coefficients and $T_H$ is the optimisation time horizon.

## 3 Sequential optimisation

In this section we describe the application of the particular optimisation procedure for two reservoirs in series. Let us assume that for k-th iteration step the control $u_1 = \hat{u}_1^{(k-1)}$ and the retention $V_1 = \hat{V}_1^{(k-1)}$ of the of upper reservoir are specified for any $t \in [0, T_H]$. Then one has to determine the control value $u_2 = u_2^{(k)}$ and retention value $V_2 = V_2^{(k)}$ of the lower reservoir. The optimisation problem for lower reservoir takes form:

$$\min_{u_2}\left\{\beta_1 \max_{t\in[0,T_H]}\left(Q^{(k)}+I_3\right)+\beta_2\left[V_2^{(k)}(T_H)-V_{\max 2}\right]^2\right\} \tag{3.1}$$

under constraints

$$\frac{dV_2^{(k)}}{dt} = \hat{u}_1^{(k-1)} + I_2 - u_2^{(k)} \tag{3.2}$$

$$Q^{(k)}(t) = u_2^{(k)}(t - T_0) \tag{3.3}$$

$$V_{\min 2} \le V_2^{(k)}(t) \le V_{\max 2} \qquad U_{\min 2} \le u_2^{(k)}(t) \le U_{\max 2} \tag{3.4}$$

After solving optimisation problem (3.1), i.e. after solving for $\hat{u}_2^{(k)}$ and $\hat{V}_2^{(k)}$, the control and retention of the upper reservoir are modified so that to improve the primary objective function (2.5), while maintaining $\hat{V}_2^{(k)}$; all modifications of the control function $u_1$ are directly transferred to the control function $u_2$ that describes the outflow from the reservoir system. The optimisation problem for the upper reservoir takes form:

$$\min_{u_1^{(k)}}\left\{\beta_1 \max_{t\in[0,T_H]}\left(Q^{(k_1)}+I_3\right)+\beta_2\left[V_1^{(k)}(T_H)-V_{\max 1}\right]^2\right\} \tag{3.5}$$

under direct constraints

$$\frac{dV_1^{(k)}}{dt}=I_1-u_1^{(k)} \tag{3.6}$$

$$V_{\min 1}\le V_1^{(k)}(t)\le V_{\max 1} \qquad U_{\min 1}\le u_1^{(k)}(t)\le U_{\max 1} \tag{3.7}$$

and indirect constraints resulting from eq.(2.2)

$$u_2^{(k_1)}=\hat{u}_2^{(k)}+u_1^{(k)}-\hat{u}_1^{(k-1)} \tag{3.8}$$

$$Q^{(k_1)}(t)=u_2^{(k_1)}(t-T_0) \tag{3.9}$$

$$U_{\min 2}\le u_2^{(k_1)}(t)\le U_{\max 2} \tag{3.10}$$

where $u_2^{(k_1)}$ is improved outflow from the lower reservoir.

The solutions of the optimisation problem (3.5) – (3.10) are the optimal trajectories of $u_1=\hat{u}_1^{(k)}$, $V_1=\hat{V}_1^{(k)}$ and $u_2=\hat{u}_2^{(k_1)}$. Therefore the solutions of the primary optimisation problem at $k$-th iteration step are these three functions and the $V_2=\hat{V}_2^{(k)}$ trajectory determined at the previous stage.

After solving the problems for lower and upper reservoirs, i.e. completing k-th step of sequential optimisation, one can go to the next step, $k+1$, once more solving the optimisation problem (3.1) – (3.4) using the values obtained at the step $k$. Calculations terminate when the stopping rule is met. In our case the chosen criterion is the difference $\varepsilon$ between outflows from the system at first and second stage for the current iteration step k.

$$\int_0^{T_H}\left[\hat{u}_2^{(k_1)}-\hat{u}_2^{(k)}\right]^2 dt\le\varepsilon \tag{3.11}$$

The essential problem related to the described algorithm is the selection of initial values approximation of $\hat{u}_1^{(k=0)}$ and $\hat{V}_1^{(k=0)}$. Among different options two cases can be intuitively justified. In the first case one can assume a constant retention of the upper reservoir:

$$\frac{d\hat{V}_1^{(k=0)}}{dt}=0 \qquad \Rightarrow \qquad \hat{u}_1^{(k=0)}=I_1 \tag{3.12}$$

It means that at the first stage of the next step, all inflows to the system must pass through the lower reservoir. This requirements can negatively affect the performance of the algorithm due to constraints (3.4). In some cases the better initial approximation is given by:

$$\hat{u}_1^{(k=0)}=0 \qquad \Rightarrow \qquad \frac{d\hat{V}_1^{(k=0)}}{dt}=I_1 \tag{3.13}$$

In the majority of cases, the above formula does not guarantee that initial approximation meets the constraints(2.3) imposed on retention of upper reservoir. However, violation of the constraints resulting from (3.13) will be corrected at the second stage.

## 4 Control random search method

The functions $u_j(t)$, $j=\overline{1,2}$ 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 optimisation problems for the lower reservoir (3.1) and the upper reservoir (3.5) 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., $Q(x_Q) \leq Q(x_H)$), 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).

## 5 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, 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.

## 6 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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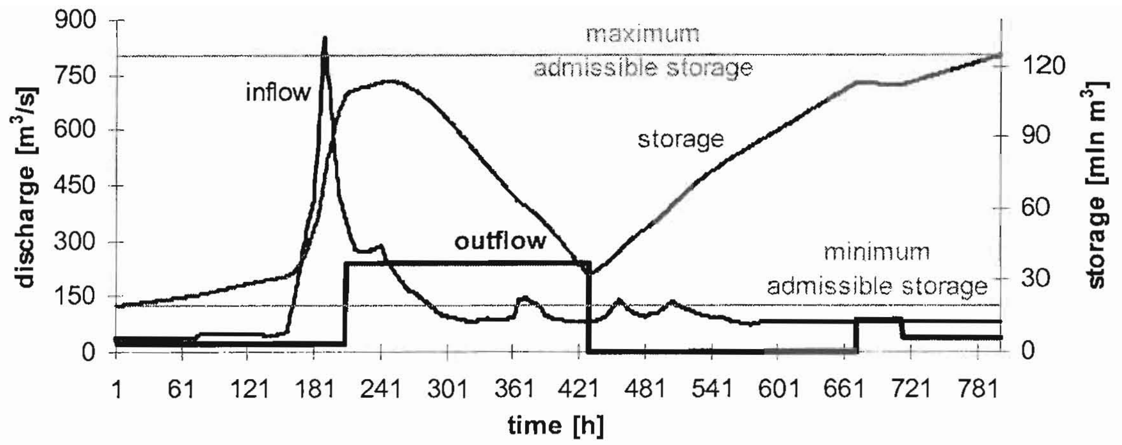


***Figure 4a*** *Performance of Otmuchów reservoir – data from*

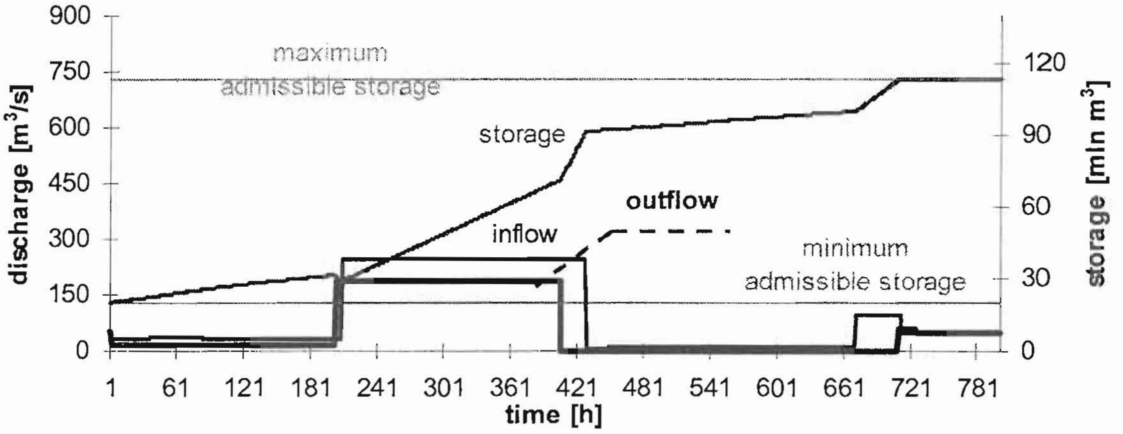


***Figure 4b*** *Performance of Nysa reservoir – data from 1965*

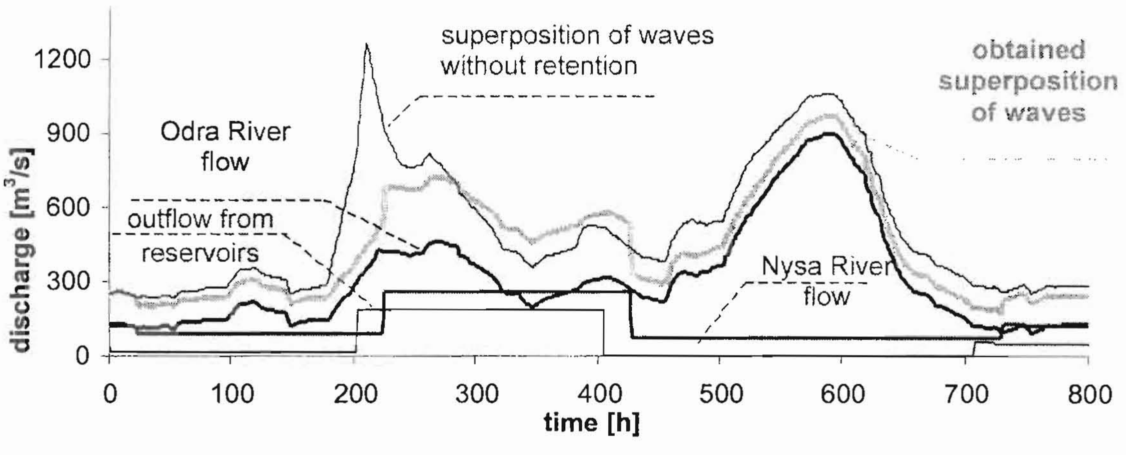


***Figure 4c*** *Flow below the junction of Nysa and Odra Rivers –1965 data*

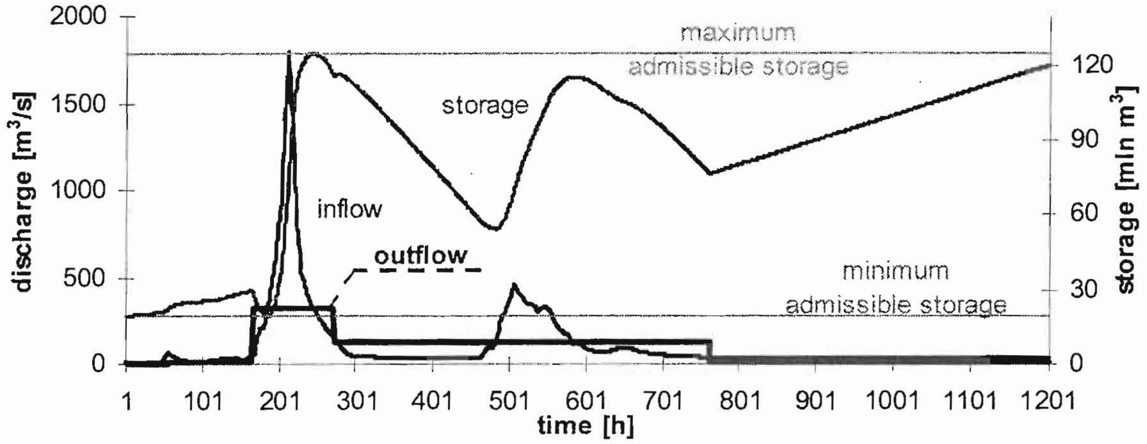


***Figure 5a** Performance of Otmuchów reservoir – data from 1997*

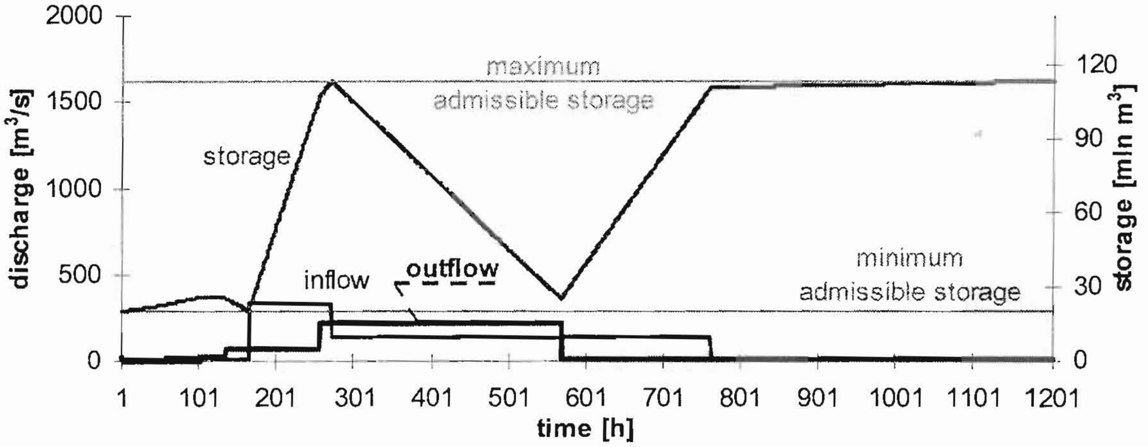


***Figure 5b** Performance of Nysa reservoir – data from 1997*

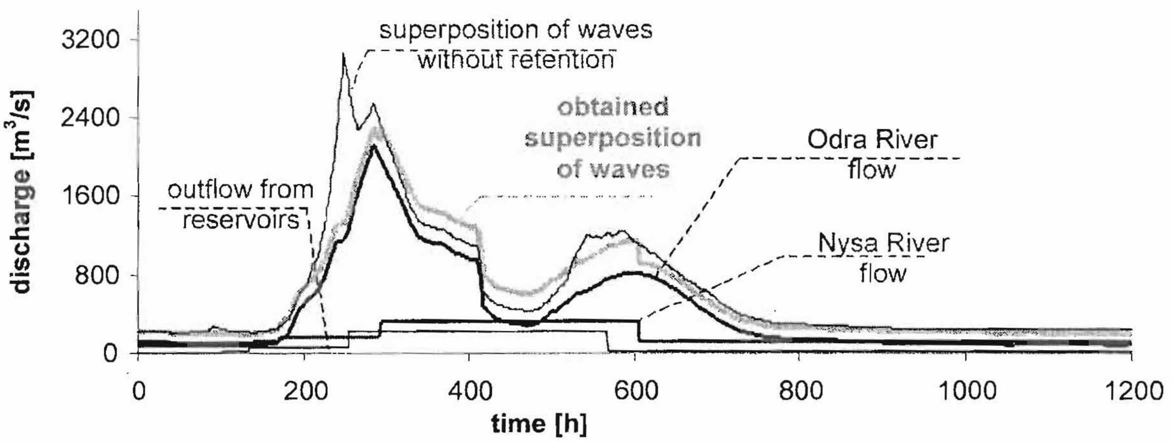


***Figure 5c** Flow below the junction of Nysa and Odra Rivers –1997 data*