ELEMENTS OF DECISION SUPPORT SYSTEM FOR FLOOD CONTROL IN THE NYSA KŁODZKA CATCHMENT

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Abstract

The paper reflects the results of the project supported by Polish Committee for Scientific Research (PO4D 032 19) and coordinated by Institute of Geophysics PAS [1]. The objective of the project that covers a broad range of flood related research problems was to develop modules of Decision Support System for flood control. Particular modules were tested and verified for watersheds mostly jeopardized to severe flood events, mainly for the Nysa Kłodzka River and a selected reach of the Odra River. In the paper the current trends and needs in the modeling of flood related problems and flood control, numerical weather prediction, rainfall-runoff simulations and fluid motion in rivers are discussed. Further the precipitation forecast module is presented that based on a number of rainfall stations and with the help of General Circulation Model calculates hourly precipitation rates for appropriate time horizon. Then rainfall-runoff transformation model, namely semi-distributed HEC-HMS model is discussed. The next problem addressed is the proper selection of flood routing models in channels. Solution of the flood operating problem requires repeated solving of unsteady flow equations for successively generated operation scenarios. Thus the solution algorithms applied in such a case should be maximally efficient in respect to time of computations required to obtain the solution. Finally computer-based analysis and control mechanisms for flood control in multireservoir systems are presented. The main task is to point out the role of computer simulation in the development of control mechanisms for large scale environmental systems.

Keywords
Flood control, flow transformation models, rainfall-runoff simulation, DSS.

1. Nysa Kłodzka Catchment – Case Study System

The water resources in Poland are quite modest. The average annual rainfall over its territory is about 600 mm. However, the flood risk is very high, especially in mountain areas. The annual precipitation in these regions is much higher than the average in Poland. Therefore, the case study area, namely the Nysa Kłodzka catchment in the southern part of the country is considered of high importance. This river is a tributary of the Odra, one of two biggest rivers in the country. The length of the catchment is 181.7 km and its area is 4565.7 km^2. It is one third of the Odra river basin in the junction of both rivers, which means it is the biggest tributary of the Odra in this region. The population and industry density in the catchment is very large. The safety of big cities like Wrocław, Brzeg, Oława depends on the flow conditions in these two rivers.

The annual rainfall in the case study region varies between 700-1200 mm. The wettest season is July, when precipitation is 100-140 mm. The rainfalls are often very quick and intensive. The resulting fast runoff causes a sudden increase of flow in rivers and channels. Floods are very frequent phenomena in the area. Since they are very sudden and wide-spread, such kinds of flood protection as building dikes or standard water management in reservoirs are very difficult to implement. During the control action taken to prevent floods the complexity of the system should be taken into account. Simple water management based on engineering rules applied in existing reservoirs may secure the area located below the reservoirs. However, it may cause flood wave interaction in the junction of both rivers.

The system is shown in Figure 1. It consists of two big channels: the Odra and its tributary, the Nysa Kłodzka. Two reservoirs (Otmuchow and the Głębinów) are located on the tributary. Their storages are about 100 million m^3. The river reach between the source and the reservoirs is a typical mountain river reach with a bottom slope of about 10‰ and a number of highland tributaries.

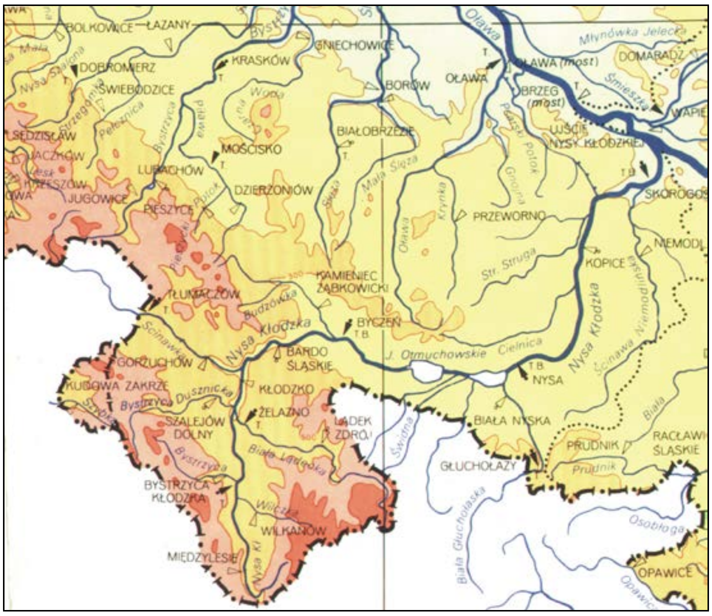

Figure 1. The Nysa Kłodzka Catchment

The set of inflows to the system consists of the main (integrated) inflow to the upper reservoir, aggregated lateral inflow to the lower one, lateral inflow along the Nysa Kłodzka channel below the reservoirs and flow in the Odra river. The outflows from the reservoirs are controlled. The outflow from the lower reservoir is routed in the Nysa Kłodzka.

2. The Decision Support System for Flood Control

The Decision Support System for flood control in the Nysa Kłodzka catchment includes (see Figure 2) parts responsible for precipitation forecast, rainfall-runoff transformation, reservoirs performance, unsteady flow routing and the optimisation structure controlling the performance of the system.

The main goal of the control is the protection against flooding by minimizing the maximum peak of the superposition of waves on the Nysa Kłodzka and the Odra rivers. This can be achieved by desynchronization of the flow peaks via accelerating or retarding of a flood wave on the Nysa River. The second objective is the storing water for future needs after flood.

On the basis of measurements in meteorological stations located in the catchment the rainfall forecast is formed. The forecast allows to determine the transformed inflows to the reservoirs and the channel. The controlled outflow from reservoirs with the lateral inflow along the channel form the outflow from the system.

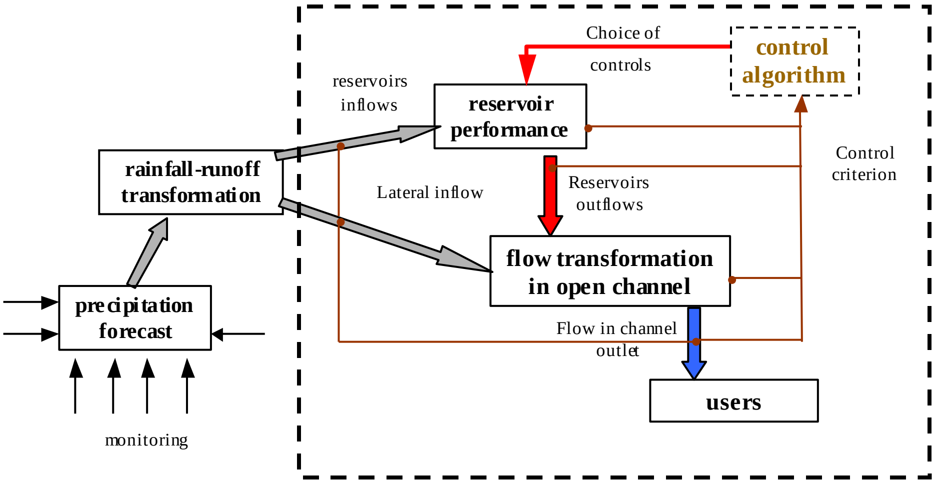

Figure 2. Cooperation of DSS Modules

The control structure consists of the model of reservoirs performance, transformation of flow in open channels and evaluation of control effects. Its effectiveness depends on the quality of the forecast module results. The precipitation forecast and rainfall-runoff transformation model form the second module.

The result of next computations are the hydrographs of inflows to the reservoirs system and channels. The forecast or assumed inflows scenario is the data for the control module.

After some period of time new forecast is estimated and the inflows to the system are updated. It is the basis for determination of the new reservoirs outflows, but this time the initial conditions are the state of the system in the time of updating. Also the control horizon is shifted.

3. Precipitation Forecast Module

To simulate precipitation events over a hydrological catchment, a mesoscale atmospheric model used at Interdisciplinary Centre for Mathematical and Computational Modelling of Warsaw University (ICM) was applied. The model is called UMPL (Unified Model for Poland area) and is based on the United Kingdom Met. Office Unified Model version 4.5. The UMPL model is capable of simulating and predicting a large variety of atmospheric phenomena, and producing high-resolution, 4-dimensional, dynamically consistent data sets. In the experiments described here the UMPL system with horizontal grid spacing of 17 km was used. A full domain of the model covers most of the area of Central Europe. In our application we concentrated on a mountainous subdomain over the Nysa Kłodzka catchment area of dimension 2 degrees of latitude by 3 degrees of longitude which consists of 13*15 grid-points.

The model uses a rotated equatorial longitude-latitude grid with constant spatial increments of 0.15 degree between grid-points. After conversion of rotated co-ordinates to geographical co-ordinates, distances between grid-points are no longer constant, and therefore each point has to have coordinates specified separately. We used a sample of simulated precipitation patterns for warm periods (May-September) in 1997-2000.The study was based on observed daily precipitation totals from 70 rain gauges within the catchment obtained from the Institute of Meteorology and Water Management. The quality of forecast is shown in Fig.3.

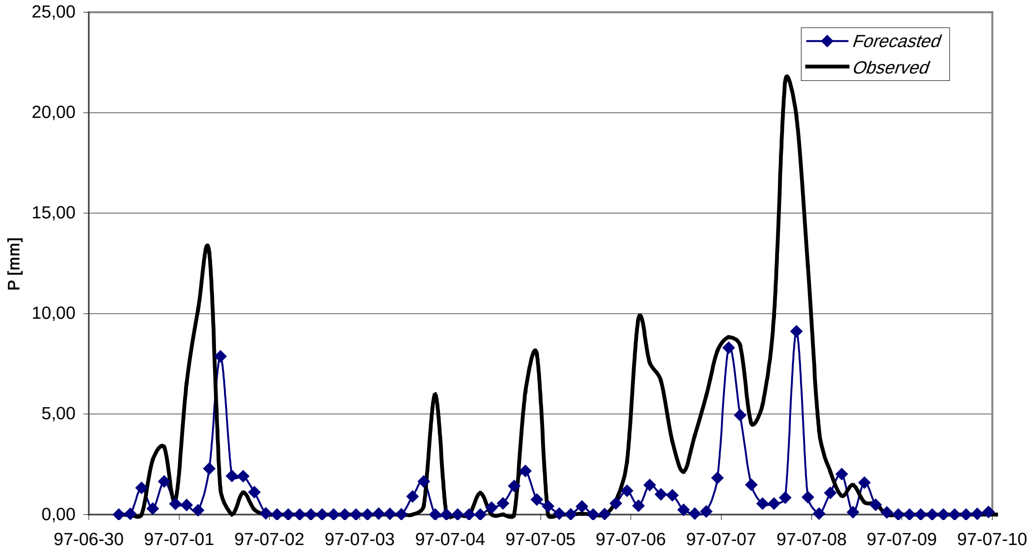

Figure 3.Comparison of observed 3-hour precipitation amounts with forecasted by UMPL model (over the Nysa Kłodzka catchment up to Bardo cross-section).

4. Rainfall-Runoff Module

Outflow formation from the river catchment is a complex process. Water movement is affected by morphologic, geologic and climatic conditions like slope and relief of the area, land cover, structure and present soil moisture and the intensity and duration of rainfall. Practically, using mathematical models to simulate and predict the outflow in a real time only some elements of the complex hydrological cycle are considered. Sometimes more useful are conceptual models of non-distributed parameters built when particular processes and relationships are not fully determined or when we do not have sufficient measurements.

4.1 HEC-HMS Model Using GIS

The HEC-HMS model simulates rainfall-runoff and routing processes of watershed systems. It consists of three modules: basin model, meteorological model and control specification.

The basin model contains inputs for simulating subbasin runoff, losses due to soil abstraction and storage, transformation of excess precipitation into runoff, routing of runoff into and through channels, and diversion in the natural flow path. There are a number of different methods which can be apply to any of these calculations (see HEC-HMS user manual).

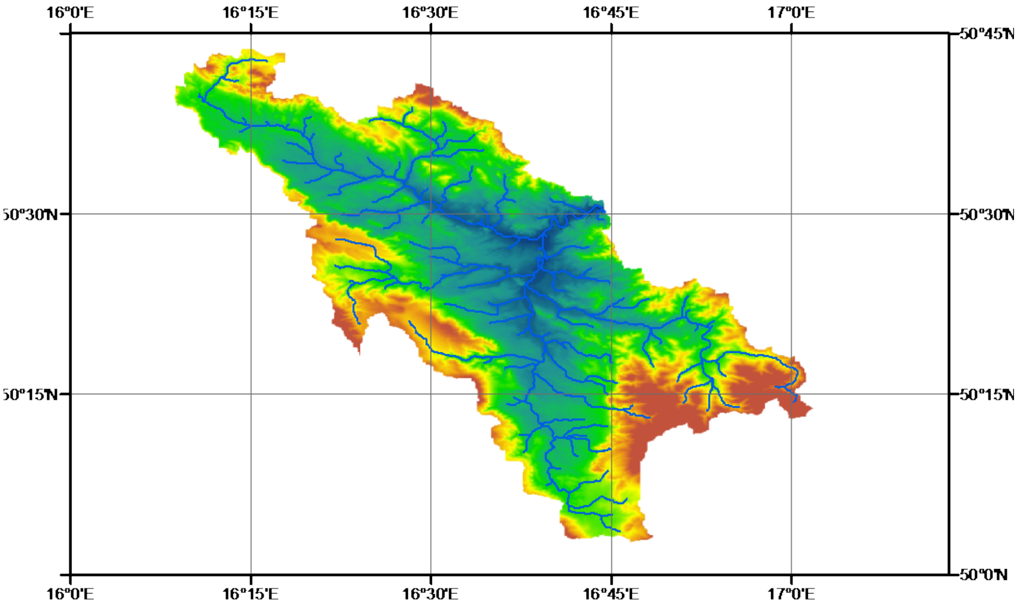

Figure 4. The Nysa Kłodzka catchment up to Bardo cross-section: the major river system and topography

The first step in applying the HEC-HMS model is to derive information on the topography of the basin. For the Nysa Kłodzka catchment Digital Terrain Elevation DATA-DTED Level 2 was used as the basic data source from which the basin, subbasin, slopes are defined. The 0,003 deg resolution DEM was first prepared in the ArcGIS geographic information systems (Fig.4). PrePro 2002 was used to derive basin topography from the DEM. This very helpful program assists to find stream and outlets, delineate watershed and translate all relevant data into basin file, appropriate and recognizable for HEC-HMS. PrePro localizes sinks, which are cells whose elevation are lower than all of their nearest neighbors. In the next step determined flow direction by calculation of the elevation between each cell and its eight nearest neighbors and flow accumulation. As a result HEC-HMS basin file was prepared. Modeled basin consists of 7 subbasin, 10 reaches, 10 junctions and 1 sink.

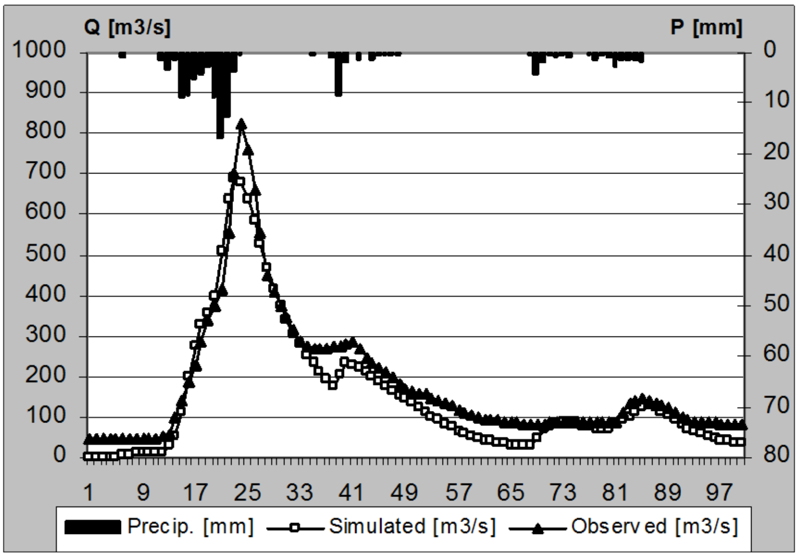

Figure 5. Verification results for 1965 flood event

Precipitation values and distribution over the region are specified in the precipitation model. There is a variety of methods and formats including spatially averaged values of measured data from rain gages with user or model derived gauge weights. In our study Thiessen polygon method was applied to estimate catchment precipitation. This method is a widely recognized scheme proven to be reasonably accurate at modeling of actual precipitation distributions and so was the method of choice for this study. Precipitation model (user gage weights) was easily calculated with help ArcGIS.

The above model was calibrated for Bardo gauging station for 1997 flood event and then verified for 1965 flood event (see Fig.5).

4.2 Artificial Neural Network Model

Multi-Layer Perceptron Artificial Neural Networks have become widespread in recent years and the researchers often claim that they provide a useful tool for the predictions of river flow. Three layer networks with sufficient number of hidden nodes are usually applied due to the continuity of the relevant function. Every network contains an appropriate number of input and output nodes which is equal to the number of input and output variables, and the assumed number of hidden nodes. There is no effective rule for the estimate of the number of hidden nodes. In this study it usually turns out to be close to the number of input nodes, but in each case it is experimentally verified.

The ANN was trained at the Bardo cross-section for 1997 flood wave and then used for 12-hour forecast of flow (see Fig.6).

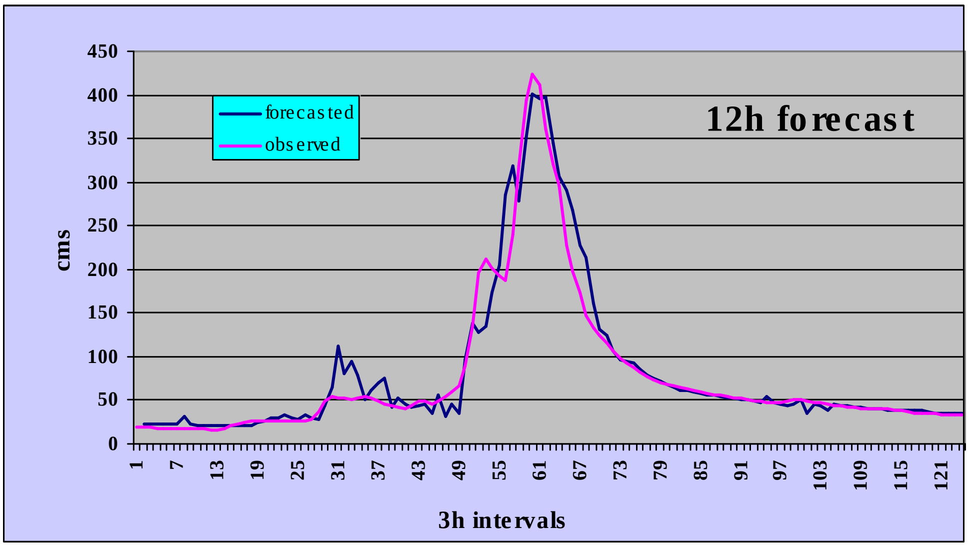

Figure 6. Observed flow and 12-hour forecast of flow for 1977 data

5. Flood Routing Models

In the discussed optimisation problem flood routing model for the river reach of the Nysa Kłodzka between the lower reservoirs and the Odra River is required. For quasi regular cross-sections and the bottom slope of about 3‰ one can expect subcritical flow conditions for this particular river reach. However some local depressions cause the transition from supercritical to subcritical flow, backwater, etc. Moreover irregular shape of the cross-section and the problems involved in the determination of roughness coefficient, further complicate the calculations of flow transformation in the Nysa Kłodzka river.

To describe the flow transformation between reservoir and two types of flood routing models are used. The first model is based on the de Saint – Venant equations with simplified trapezoidal geometry of channel cross–sections.

$$\frac{\partial H}{\partial t}+\frac{1}{B}\frac{\partial Q}{\partial x}=\frac{q}{B} \tag{1}$$

$$\frac{\partial Q}{\partial t}+\frac{\partial}{\partial x}\left(\frac{Q^2}{A}\right)+gA\frac{\partial H}{\partial t}-gA\left(S_0-S_f\right)=0 \tag{2}$$

where x – distance, t – time, $Q(x,t)$ - discharge, $H(x,t)$ – water depth, A - cross-section area, B – width of the water surface, q – lateral inflow, g – acceleration of gravity, S_0 – bottom slope, S_f – hydraulic slope according to Manning equation.
This model guarantees accurate description of the transformation process but requires long computational time. Therefore to speed up numerical computations kinematic wave model was tested (obtained by neglecting the first three terms in eq. (2)).

6. Optimization Module

The considered system, schematically shown in Fig.7, consists of two reservoirs in series and open channel reach with lateral inflow q.

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 is described by the dynamics of a simple tank, with one forecasted inflow $I_j(t)$ and one controlled output $u_j(t)$, j=[1,2].

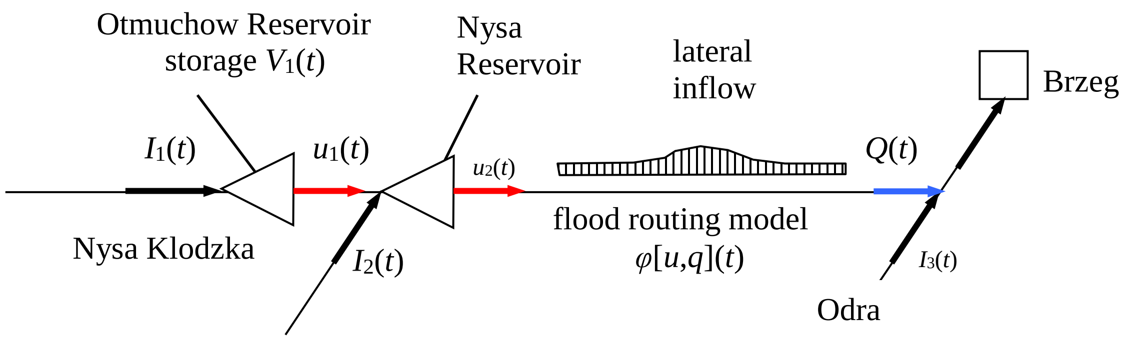

Figure 7. Schematic representation of the system

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 the Nysa and the Odra rivers, respectively. This can be achieved by desynchronization of the flow peaks via accelerating or retarding flood wave on the 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:

$$\min_{u_j,\,j=\overline{1,N}}\left\{\max_{t\in[0,T_H]}\left[Q(t)+I_3(t)\right]+\beta\sum_{k=1}^{N}\left[V_k(T_H)-V_{\max k}\right]^2\right\} \tag{3}$$

where the symbol β denotes appropriate weighting coefficient and T_H is the optimisation time horizon.

To solve this problem the sequential optimisation algorithm has been developed and applied. This technique enables the control of a system of reservoirs in series. It is based on the decomposition of the system in space. Hence the general problem is divided into two local problems related to two reservoirs in the system.

It may be noticed that if the outflow from upper reservoir is known the problem is simply reduced to the control problem of lower reservoir. The possible modification of the lower reservoir behaviour does not require any modification of the upper reservoir performance.

However, if the outflow and the storage of lower reservoir are known, the problem is also reduced to the control of one reservoir but the upper reservoir influences the behaviour of the lower one. So, every modification of the upper parameters involves the corresponding modification of the outflow from the lower reservoir.

Control Random Search method

The functions $u_j(t)$, j=1,2 are 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 $u(t)$.

The optimisation problems for the lower reservoir and the upper reservoir were solved by means of the global random search procedure, namely the special version of Controlled Random Search (CRS2). 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 and the worst x_H points are determined and a simplex in n-space is formed with the best point x_L and n points ($x_2,\ldots,x_{n+1}$) randomly chosen from S. Afterwards, the centroid x_G of points $x_L,x_2,\ldots,x_n$ 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

7. Results of Tests for Historical Data

The described sequential optimisation was tested and verified against a number of historical and synthetic flood events and for two types of flood routing models described above. The results for one of them, namely for the historical floods in the Nysa catchment in 1997 and for the kinematic wave model, are presented below.

The floods in 1997 were caused by the most disastrous recent abundance of water in the region. During the first stage of the 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 and the historic stage record was exceeded by 70 cm. Several all-time maximum stages recorded were largely exceeded by that flood.

Fig.8 shows the flow at the cross-section below the junction of the Nysa and the Odra rivers. As one can see, by an appropriate choice of the control functions the peaks of the waves on the Nysa Kłodzka and the Odra rivers were desynchronised and the culminations did not overlap.

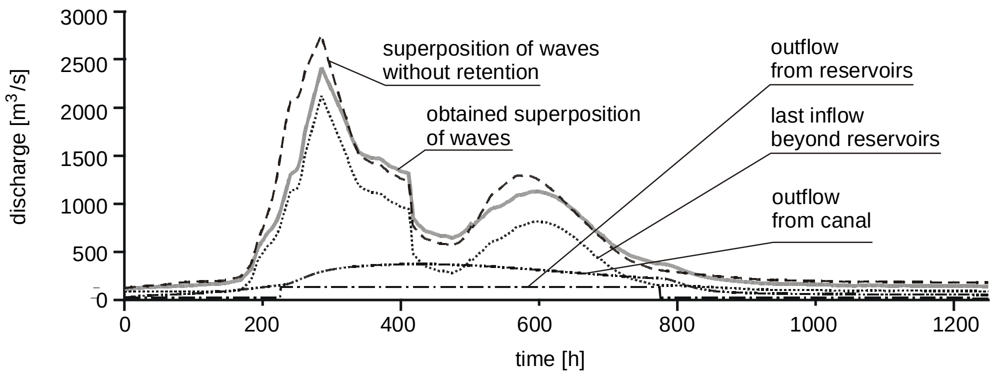

Figure 8. Flow below the junction of the Nysa and the Odra rivers –1997 data

8. Conclusions

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 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.

Because of nondifferentiability of global and two local performance indices, the global optimisation technique CRS is used.

The results of applications of the sequential optimisation to determine the reservoir decision rules during flooding are encouraging. Accuracy of the proposed method is satisfactory. The described control structure of the Nysa Kłodzka reservoirs system includes 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.

References

[1]. Modelling and Control of Floods, Publications of the Institute of Geophysics, Polish Academy of Sciences, Monographic Volume, E-3 (365), Editor: Jarosław J. Napiórkowski