MODELLING THE EFFECT OF SMALL RESERVOIRS ON FLOOD REGIME IN THE CHOMUTOVKA RIVER BASIN

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Abstract

The aim of this article is to present partial results of more extensive research which is focused on the impact of integrated flood protection on extreme hydrological events. One of several aims is to design a system of flood protection measures in a small mountain catchment. This system could cause the decrease of flood flows. With help of deterministic lumped model HEC-HMS (Hydrologic Engineering Center - Hydrologic Modeling System) several simulations of the impact of potential uncontrolled small reservoirs system on flood flows reduction were carried out. As an experimental catchment a headwater part of the Chomutovka River basin in the Ore Mountains was chosen (northwest of the Czech Republic, area 14.5 km²). In this catchment 3 locations which could be potentially used for establishment of small water reservoirs were proposed. The main influence on the effect of uncontrolled small reservoirs system during flood (besides retained volume) is the type and parameters of the dam body it means a system of culverts and spillways. First a hydrological model of the real basin (without reservoirs) was build up and with the help of measured data calibrated and verified. Then the reservoirs system was implemented. In the model, each of reservoirs is defined by the functional relation between altitude and competent volume. The behaviour of the system is possible to describe with the concept of the linear or non-linear cascade. For assessment the impact on hydrological regime of the basin four scenarios were carried out – 10, 20, 50 and 100-year recurrence interval of 1-day precipitation.

Keywords: Rainfall-runoff models, HEC-HMS, Floods, Flood protection, uncontrolled small reservoirs, Chomutovka River, Czech Republic

1 INTRODUCTION

The question of water retention by landscape is nowadays a great point of issue and together with global climate change also very popular. The aim of this article is to present partial results of more extensive research which is focused on the impact of the integrated flood protection on extreme hydrological events. As the study area the Chomutovka River basin in the Ore Mountains was chosen (see figure 1). Its total area is 14.5 km² to outlet profile Tišina (gauge station).

Currently many authors deal with the question how the integrated flood protection could be effective for flood wave reduction. In the last decades there was a “centralize” approach to the flood protection, it means, that only a system of big reservoirs can be effective. This approach was connected to other functions of reservoirs – energetic, provider of fresh water, recreation, etc. Over the time another approach has come – make the flood protection “decentralized”, it means to make a system of smaller measures which are closer to nature – to make the flood protection
in the area integrated. In the Czech Republic this approach mainly after extreme floods in August 2002 became actual (Kašpárek et al., 2006; Hladný et. al, 2004; Šercl et al, 2004).

This concept movement is for example from studies by Böltscher and Schulte (2007), or Jeniček (2007) obvious. In these articles an effort to implement the flood protective measures which are “close to nature” exists. Interesting is also renaturation of human affected mountain areas like peat bogs and improvement their role in flood regime of the catchment (Kocum and Janský, 2007).

It is clear that by water management not only a flood protection exists. So, the main task always remains to find a “trade-off” solution for every need of water management.

2 METHODOLOGY

The runoff response to several rainfall events for two different basin stages was assessed. First a current stage of the basin was set up, calibrated and verified (based on two different extreme events). Then a system of hypothetical uncontrolled small reservoirs was added to the basin and the change of runoff response to different rainfall extremities was simulated (see below). A deterministic lumped model HEC-HMS (Hydrologic Engineering Center - Hydrologic Modelling System) was applied. The location of hypothetical reservoirs is displayed in the figure 2.

For runoff-volume computation (Runoff-Volume Model) a SCS CN method was used (Soil Conservation Service Curve Number). This method uses a CN method (Curve Number) for precipitation lost determination (USACE, 1994; Feldman, 2000). The main reason of its application was, above all, a simplicity and availability of input data. The SCS CN method determines an effective precipitation (total precipitation less precipitation loss) as a function of total precipitation, soil characteristics, vegetation cover and antecedent moisture. For direct runoff computation (Direct-Runoff Model) a Clark Unit Hydrograph method was used. For computation two parameters are necessary to derive, namely $T_c$ (Time of concentration) and $R_c$ (Storage coefficient). Time of concentration was computed based on SCS methodology with help of $T_{lag}$ – Lag time. Storage coefficient was derived according to USGS methodology – U. S. Geological Survey (Straub et al., 2000). For base flow...
computation (Baseflow Model) a method of exponential recession was applied. All parameters were estimated based on the literature and the hydrograph analysis. For channel flow computation (Channel Model) a Muskingum method was applied.

Three hypothetical small uncontrolled reservoirs in two variants were implemented in the catchment. Variant “A” supposes 3 reservoirs with maximal dam height of 4 meters (security spillway 3,5 m). Their total volume reach 54,74 thousand m$^3$. Variant “B” supposes 3 reservoirs with maximal dam height of 5 meters (security spillway 4,5 m). Their total volume reach 110,7 thousand m$^3$. The volume was derived in ArcGIS according to digital elevation model (DEM). Some parameters of all reservoirs are shown in the table 1.

<table>
<thead>
<tr>
<th>Variant A</th>
<th>Reservoir 1</th>
<th>29,70</th>
<th>1,73</th>
<th>824</th>
<th>828</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Reservoir 2</td>
<td>24,64</td>
<td>1,77</td>
<td>804</td>
<td>808</td>
</tr>
<tr>
<td></td>
<td>Reservoir 3</td>
<td>23,75</td>
<td>1,64</td>
<td>764</td>
<td>768</td>
</tr>
<tr>
<td>Variant B</td>
<td>Reservoir 1</td>
<td>55,54</td>
<td>3,00</td>
<td>824</td>
<td>829</td>
</tr>
<tr>
<td></td>
<td>Reservoir 2</td>
<td>46,55</td>
<td>2,58</td>
<td>804</td>
<td>809</td>
</tr>
<tr>
<td></td>
<td>Reservoir 3</td>
<td>45,98</td>
<td>2,49</td>
<td>764</td>
<td>769</td>
</tr>
</tbody>
</table>

Modelling of the runoff change between current stage and hypothetical stages with reservoirs system ran for four precipitation events of different extremity. First it was a 1-day precipitation with the probability of occurrence 0,1 (10-year recurrence interval.
of the precipitation), next there were 20-year, 50-year and 100-year recurrence interval of the precipitation. Combination of manual and automatic calibration (Univariate Gradient method) in the period from 27.9.2007 to 1.10.2007 was used (Nash-Sutcliffe criterion reached the value 0.89). As the verification period the period from 11.8.2002 to 19.8.2002 (extreme flood in August 2002) was chosen. A time step of the computation was in all cases 15 minutes. Evapotranspiration was not considered.

3 RESULTS

A general characteristic of the most of rainfall-runoff models is the basin decomposition to several zones, mainly vertically ordered. Each zone has its volume, inflow and outflow, which is computed based on a concept of linear cascade. By simulations a main factor was taken into account that by extreme event a hydrograph is made mainly by direct runoff and considerable part of base flow becomes important as much as on the falling limb of the flood hydrograph. Evapotranspiration that stands at the beginning of the runoff process was not taken into account. Its importance to peak or volume of the flood wave is too small and this approximation is therefore acceptable. Influence of the reservoirs system by different scenarios is displayed in the figure 3.

Figure 3. Impact of the small reservoirs system on runoff process by different rainfall extremity – 10-year recurrence interval of precipitation (top left), 20-year (top right), 50-year (bottom left) and 100-year (bottom right). Legend: Precipitation – causal precipitation of the N-year extremity, Current stage – a present (real) stage of the basin, Variant A – a hypothetic stage of the basin with 3 reservoirs of maximal dam height 4 meters, Variant B – a hypothetic stage of the basin with 3 reservoirs of maximal dam height 5 meters.
In all graphs in the figure 3 a significant decrease of peak discharge is apparent. First variant (smaller “A” variant) generates rather lower decreasing compare to the variant “B”. The reason is a smaller capacity of “A” variant reservoirs and also a different location of culverts and security spillways. In the top left picture (10-year recurrence interval of precipitation) is the only stage where no differences between both variants were simulated. In this case no water flew over the security spillway. Results for all scenarios are concluded in the table 2.

<table>
<thead>
<tr>
<th></th>
<th>N10</th>
<th>N20</th>
<th>N50</th>
<th>N100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current Stage</td>
<td>4.24</td>
<td>6.01</td>
<td>8.61</td>
<td>10.72</td>
</tr>
<tr>
<td>Variant A</td>
<td>2.47</td>
<td>3.72</td>
<td>6.45</td>
<td>8.45</td>
</tr>
<tr>
<td>Variant B</td>
<td>2.47</td>
<td>3.40</td>
<td>4.78</td>
<td>5.96</td>
</tr>
<tr>
<td>Change A [%]</td>
<td>41.75</td>
<td>38.10</td>
<td>38.10</td>
<td>21.18</td>
</tr>
<tr>
<td>Change B [%]</td>
<td>41.75</td>
<td>44.48</td>
<td>44.48</td>
<td>44.40</td>
</tr>
</tbody>
</table>

The verification of the storage capacity and location and capacity of the security spillways ran for the biggest measured flood (according to rainfall amount, peak discharge and flood volume) – flood in August 2002. In this time 237 mm in three days has fallen in the catchment. By simulation of this flood with implemented reservoirs system a decrease of peak discharge (compared to present stage) was only by first flood wave (decrease from 25.4 m³.s⁻¹ to 22.4 m³.s⁻¹, it means 11.8 % with delay 60 minutes). There was no influence of the reservoirs system on the second flood wave that came 12 hours after (peak discharge 24.7 m³.s⁻¹). The safety of whole system was verified (no water flew over the dam crest).

4 DISCUSSION

Generally it is possible to distinguish several categories of problems and uncertainties generated by certain hydrological task. These problems and uncertainties are related to particular phases of the model composition. The main question by model composition and verification is an application of the suitable runoff-volume method. In this study applied SCS CN method is available as a modelling technique in the system HEC-HMS. It is suitable mainly due to its simplicity and availability of the input data. But it uses numerous simplifications and its application is therefore limited (assumes homogenous rainfall distribution both in time and space, don’t take into account a classic theories of flows in unsaturated soils, it concerns a model of saturation-excess type and exceeding of the potential infiltration rate – infiltration excess model – is not taken into account, etc.). After all, this method is often applied, both in the Czech Republic and in the world.
Time series assessment (mainly precipitation) ran with help of standard statistic methods. The biggest uncertainty appears by interpolation of point values to area. By data processing also a choice of suitable time and space scale is necessary. Modelling of processes between earth surface and atmosphere requires the knowledge of model reaction to space and time step changes. Many studies, for example Payraudeau et al. (2003), Finnerty et al. (1997) or Koren et al. (1999) demonstrate the fact, that by time or space step change a new calibration is necessary (due to changes in parameters). In this study used time step 15 minutes appears suitably. It is possible to come out from other studies from the Chomutovka River catchment (Jeníček, 2007).

Generally there are many parameters in the rainfall-runoff model, which are burden with certain degree of uncertainty. Some of them are let in the model as they were measured, some of them can by calibrated. In the Chomutovka River catchment both manual and automatic calibration were made. The list of calibrated parameters is in the table 3.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Model</th>
<th>Name of the parameter</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ia</td>
<td>Runoff-Volume Model</td>
<td>Initial Abstraction</td>
<td>0,9</td>
</tr>
<tr>
<td>CN</td>
<td>Runoff-Volume Model</td>
<td>Curve Number</td>
<td>1</td>
</tr>
<tr>
<td>Tc</td>
<td>Direct-Runoff Model</td>
<td>Time of Concentration</td>
<td>1,02 - 1,52</td>
</tr>
<tr>
<td>ReC</td>
<td>Baseflow Model</td>
<td>Recession Constant</td>
<td>0,82</td>
</tr>
<tr>
<td>Ratio to Peak</td>
<td>Baseflow Model</td>
<td>Threshold Value</td>
<td>1</td>
</tr>
</tbody>
</table>

Other uncertainties are connected to reservoirs system and derivation of their parameters. First of all it is the estimation of the reservoir volume. In this study only a GIS-based estimation was made (with digital elevation model). In the running research a more accurately measurement with geodetic station is necessary. The question is also the total capacity of the reservoir system. Realized simulations have shown satisfactory results by rainfall extremities up to 100-year recurrence interval of 1-day precipitation. However, for floods with greater extremity such as the one in August 2002, the total capacity is not sufficient. From this point of view the storage of the reservoir 1 seems to be crucial, because it has the largest basin and thus the greatest amount of concentrated water.

Very important is also a calibration of the dam parameters, such as location of culverts and security spillways of each reservoir. The system of culverts in several levels (elevations) generates the best results. The final effect is a non-linear course of the outflow curve from the reservoir together with the best “timing” of the flood wave (peak delay, possibly non-colliding of the flood peaks from the subbasins).

5 CONCLUSION

Modelling the impact of integrated flood protection on extreme hydrological events in the Chomutovka River basin came through four scenarios – 10, 20, 50 and 100-year recurrence interval of 1-day precipitation in two variants of the reservoirs capacity. In the first scenario the decrease of flood peak about 42 % in the outfall Tišina was simulated (present stage compared with hypothetical stage). In the fourth scenario
100-year precipitation) it was 21,18 % by “A” variant and 44,4 % in case of grater “B” variant. The sufficient function of small uncontrolled water reservoirs was approved. Model HEC-HMS and its water control facilities model appears for this kind of hydrological problem suitable. However, it requires a precision by parameters derivation, mainly parameters of the dam body (number and location of culverts).

A concept of the location of culverts in different levels (elevation) seems to be applicable. Through this concept a non-linearity of the outflow from the reservoir is ensured.

In the following research it is necessary to better specify some parameters, such as the volume of reservoirs and also to propose sufficient total capacity which prevent extreme floods like in August 2002.

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References


