Role of water storage reservoirs management and flood mitigation in climate change conditions

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ABSTRACT: The impacts of climate change are becoming increasingly pronounced in all aspects of human activity, but are especially evident in the field of water management. One of its most significant consequences is the increasingly pronounced temporal variability of river flows - frequent floods with increasing peak flows and long periods of low water flow. In such conditions, existing flood protection measures are often insufficient to secure the protected area. That is why flood protection systems must be constantly developed, considering their construction, as well as improvement of management measures. The paper presents the consequences of climate change on water resources on the territory of the Serbia. The main principles of water management in such conditions are defined, as well as the role of the estimation of flood hydrographs. The possibilities of applying mathematical models in order to improve the role of active flood protection measures of existing reservoirs are presented. The analyses are performed for water resources systems in the Trebišnjica and Vrbas river basins in the Republic of Srpska (Bosnia and Herzegovina). The main task was to analyse the reduction of peak flow in the urban areas downstream from the analysed reservoirs, taking into account the uncontrolled part of the watershed (between the urban area and the reservoir), from which the torrential tributaries originate. Performed analyses show that reservoirs (even of relatively small active storage) can significantly reduce the peak flow during flood events.

1 INTRODUCTION

Climate change is a process that is already occurring in all aspects of life. However, its greatest consequences are felt in the field of water resources. On one hand, there is an increase in high-intensity precipitation, resulting in shorter concentration times for flood waves and faster propagation of these waves. This is due to river training works that have raised river embankments and excluded or narrowed river flood zones, which were used to slow down and mitigate flood peaks. Consequently, the risk of flooding increases, and reservoirs play a more significant role in active flood protection. Their task is to mitigate the flood wave and to improve protection from high water levels downstream of the river, particularly in the urban areas and highly flood-sensitive industrial facilities.

On the other hand, the other hydrological extreme, low water periods, are significantly deteriorating in most rivers. Low water flows are decreasing, and their duration is longer. In general, flows are most drastically reduced during periods when water is most needed, such as vegetation periods, when the water demands of aquatic ecosystems and other water users are highest due to high temperatures.

The aforementioned consequences of climate change significantly change the conditions in the field of water resources. (a) There is a significant need for the construction of new reservoirs of all types of flow regulation, (b) Reservoirs are gaining additional objectives: creating conditions for reliable water supply for all users, active flood protection through the mitigation of flood waves, providing favorable conditions for the survival and development of aquatic ecosystems, etc. (c) The increasing number of objectives, especially in the field of flood protection, also affects the criteria for reservoir volume (larger reservoir volumes should be

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pursued in accordance with spatial limitations), as well as the selection and disposition of release facilities.

2 WATER RESOURCES IN SERBIA UNDER CLIMATE CHANGE CONDITIONS

Even before the recent trends in climate change, Serbia had unfavorable hydrological regimes, characterized by pronounced spatial and temporal variability. Considering domestic water resources, the average annual water flow in Serbia is approximately 508 m^3/s (Water Management Plan of Serbia 2001). However, during low-flow periods (which can last over 2 months) these quantities decrease below 50 m^3/s, causing a serious crisis for social, ecological and economic systems. Many rivers in Serbia are torrential, with over 50% of the annual water quantities passing through short torrential floods followed by long low-water periods. The relationship between low monthly flow $Q_{95\%}$ (the 95 percentage exceedances flow) and the flood flow of 1% probability for most rivers is between 800 and 1200, but on small streams, it can reach over 1:2000 (up to 5000).

The area of Serbia is also characterized by pronounced spatial variability of water resources. The average specific runoff for the entire country is around 5.7 $L/s{\cdot}km^2$. However, the northern part of Serbia, with the highest-quality soil resources suitable for agricultural production, faces the scarcest water resources, with a specific runoff of about 1-2 $L/s{\cdot}km^2$ or even less. In the mountainous parts of Serbia, this value rises to over 30 $L/s{\cdot}km^2$. There are large areas of the country where the average specific availability of water is less than 500 m^3 per capita annually.

Water regimes in Serbia, already highly unfavorable, are further worsening due to climate change conditions. An analysis of climate change on water regimes was conducted in 2019 as part of the III National Communication on Climate Change. Two scenarios of GSB emissions according to the IPCC were considered: RCP4.5 (moderate scenario) and RCP8.5 (intensive scenario), for three future time intervals. According to these models, the average temperature will increase from 0.6°C in the near future to 2°C by the end of the century, according to the moderate scenario. According intensive scenario the increase ranges from 1°C to even 4.3°C (Đurđević et al. 2018). An increase in precipitation is expected from an average of 0.7% in the near future to 2.3% by the end of the century, according to RCP4.5, or from 1% to 4.5% according to RCP8.5. The situation is significantly more unfavorable when considering the expected decrease in precipitation during the summer vegetation period.

The results of the analysis for scenario RCP4.5 indicate a tendency towards a certain increase in average flows in most river basins, ranging from around 2 to 12% in the near future. However, from the middle to the end of the century, these flows are expected to decrease to approximately the values of the reference period, with deviations ranging from -3% to +3% (Đurđević et al. 2019). According to the more intensive scenario of GSB emissions (RCP8.5), a decrease in average annual flows is expected on most rivers, ranging from 1 to 5% in the near future, and from 3 to 17% by the end of the century.

The real danger of these changes becomes evident when analyzing the impact of climate change on average monthly and daily flows. The results indicate that flows during the low-flow and warm period of the year (typically from June to October for most rivers) will further decrease. Compared to the reference period, a decrease in average monthly flows can be expected from April to October. On the other hand, an increase in average monthly flow values is expected during December, January, February, and for some rivers, March. This means that the period with higher monthly flows is shifting towards the beginning of the year, or towards the winter months. Consequently, maximum daily flows during winter periods will increase by an average of around 10% (up to 20% in some rivers), while minimum daily flows during low-flow periods will be significantly reduced. According to RCP4.5, the average flow reduction ranges from 5% in the near future to 35% by the end of the century.

It is evident that extreme events are becoming more frequent in Serbia and it is similar in the entire region. Nine of the ten warmest observed years occurred after 2000. Disastrous floods are also becoming more frequent. In early December 2010, a flood event with a return period of 20-year, or even 50-year occurred in the area of Montenegro and Herzegovina. It was the result of heavy precipitation, in some parts of Herzegovina up to 360 mm in 24 h, and in parts of Montenegro up to 260 mm in 2 days. In November 2019, heavy rainfall occurred again, with a maximum intensity of 312 mm in 24 h, and a total of 575 mm in 5 days (Vlahović 2020). The largest floods in the Sava River basin occurred in 2014, when parts of Serbia, Bosnia and Herzegovina and Croatia were affected. In some areas flood events of 100-year returned period have been recorded.

3 RESERVOIR MANAGEMENT DURING FLOOD EVENTS

It has already been emphasized that in the new hydrological conditions, the importance of reservoirs of all types of regulating storage is rapidly growing, especially those with the possibility of annual flow regulation. This paper deals with the problem of reservoir management in the conditions of the flood events, which is particularly significant when reservoir is located upstream of an urban area.

After the construction of the dam and reservoir, the downstream area is protected from floods, especially those with a shorter return period (2-year, 5-year, 10-year). Floods occur rarely and new urban facilities are very often situated closer to the river, sometimes even within the floodplain. Consequently, the urban area becomes more vulnerable to lower flood flows than before. In such conditions, reservoirs face the demanding task of mitigating flood waves more significantly than what was initially designed, and flood waves are more unfavorable, as a consequence of climate changes. To address this challenge, management decisions based on hydrology prognostic models and reservoir management models are necessary.

The article presents the results of the management model that provides optimal management of the releasing facilities on the dam (gates on spillways, valves on bottom outlets, operation of turbines in hydropower plant) in the case of flood event, according to the criterion of minimizing flow in the downstream urban area (Đorđević et al. 2012, Dašić et al. 2019). In addition to the flood wave in the main course of the river (which reaches the reservoir), there is also a flood wave that comes from the part of the catchment between the reservoir and the urban area, with no facilities to mitigate the flood wave (uncontrolled part of the catchment). The model was applied to two systems: the Trebišnjica Hydrosystem in East Herzegovina and the system on the Vrbas River in central Bosnia. The hydrological properties and reservoir storage capacities of presented examples are quite different. The Trebišnjica Hydrosystem, with annual regulating storage, is situated in one of most karstified regions of the world, with temporary rivers, underground flows, flooded karst poljes and extreme precipitations. The hydrosystem at Vrbas River, with weekly regulating storage, is characterised with well-developed surface river network and lower precipitation.

3.1 *Trebišnjica Hydrosystem case study*

The Trebišnjica Hydrosystem, located in Eastern Herzegovina (Bosnia and Herzegovina) is one of the most complex water resources systems in the region (Milanović 2002). Construction of the system began 60 years ago and is still ongoing. The backbone of the system is Trebišnjica River, the largest sinking river in Europe. Its catchment area is highly karstified with numerous sinkholes (ponors), springs, estaveles and underground connections with different capacity. It is the area with high precipitation and a high frequency of storm-induced events. The average annual precipitation in the region ranges between 1500 mm and 2000 mm, with extreme values reaching 3000 mm in the rainy years, and 700 mm in the droughty years. Most of the precipitation occurs in the cold part of the year, from October to March (75% of the total annual amount falling within that period), with especially heavy precipitation in the period between November and February. The summer period is often dry, with several months of little to no rainfall. The local population has been struggling with water-related challenges for centuries. During the cold (humid) period of the year (characterized by high precipitation when underground conduits are saturated and karst poljes are turned into lakes) they struggle with floods, while during the summer period (with low or without precipitation) they struggle with droughts.

With the construction of the complex Trebišnjica Hydrosystem, the recharge of the largest infiltration zones was reduced to specific, short-lasting, hydrological periods or completely blocked. Water is stored in reservoirs and transported through the tunnels and channels from higher elevated parts of catchment areas (~ 1,000 m a.s.l.) down to the sea. Along its route water is utilized for power production, irrigation, water supply and various of secondary benefits. The duration of flood events in karst poljes is limited and locally eliminated.

The Trebišnjica Hydrosystem consists of seven dams, six reservoirs, six tunnels (with a total length of 57 km), four channels with a total length of 74 km, and seven hydropower plants with a total installed capacity of 1069 MW.

Due to its complexity, the construction of the system has been divided into three phases. The I phase of the system (the most cost-effective part) includes the Grančarevo Dam, with HPP Trebinje I and the Gorica Dam with HPP Dubrovnik and HPP Trebinje II (Figure 1). This section serves as the „backbone" of the entire hydrosystem and was completed in 1975. The management model discussed in this article refers to this part of the system.

The main element of the system is Bileća Reservoir, created by 123 m high arch Grančarevo Dam. It has a total water storage volume of $1280 \cdot 10^6$ m^3, an active volume of $1100 \cdot 10^6$ m^3 and a normal operating level of 400 m a.s.l. There are two lateral spillways with radial gates for flood discharges, with maximum capacity of 874 m^3/s and two bottom outlets with maximum capacity of 266 m^3/s. HPP Trebinje I, with three Francis turbines of installed capacity 3×60 m^3/s, and installed power 171 MW, is located in the immediate proximity of the dam body.

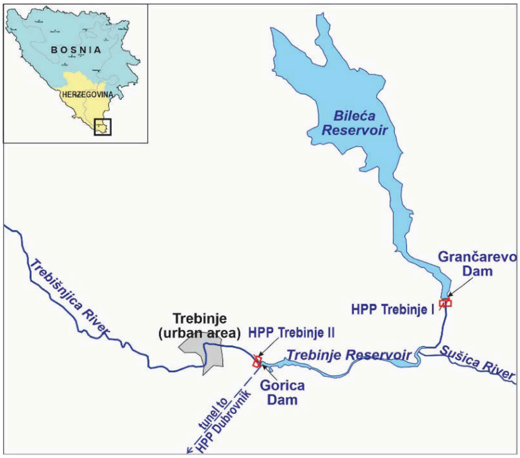

Figure 1. Trebišnjica Hydrosystem (I phase).

The concrete gravity Gorica Dam (33.5 m high) is situated 13.5 km downstream from the Grančarevo Dam. It forms Trebinje Reservoir, with total storage volume of $15.6 \cdot 10^6$ m^3 and normal operating level of 295 m a.s.l. There are two spillways in the center of the dam, with radial gates, providing a maximum capacity of 412 m^3/s and two bottom outlets with maximum capacity of 800 m^3/s. Two intakes for the HPP Dubrovnik are located at the left bank in the immediate proximity upstream of the dam body. HPP Dubrovnik is an underground hydropower plant, with 16.5 km long head race (tunnel and penstock) and two Francis turbines with an installed capacity 2×45 m^3/s and installed power of 2×108 MW. HPP Trebinje II with one Kaplan turbine (installed capacity 45 m^3/s) is situated in the left bank immediately downstream of the dam. The Gorica Dam must maintain an environmental flow of 8 m^3/s downstream.

The Trebinje Town is located 4 km downstream from the Gorica Dam. One of the important purposes of the system is flood protection of the Trebinje urban area. This purpose becomes increasingly important and complex in the climate changes conditions, when flood waves become more frequent and intense, as well as because of uncontrolled urbanization in the immediate vicinity of the river. Consequently, Trebinje is now endangered with flows exceeding 400 m^3/s, whereas the boundary flood flow was approximately 900 m^3/s before the development of this part of the Trebišnjica Hydrosystem.

Due to the high intensity of precipitation and the karst area characterized by high runoff coefficients and short concentration time, flood waves are very unfavorable. Analyzing the observed flood waves, the following characteristics can be defined: the time of concentration ranges from one to two days, the flow gradients can increase over 300m^3/s per day, the retardation time of waves is usually 6-8 days, it is possible for two or more flood waves to occur consecutively. The inflow from the watershed area between the Grančarevo and Gorica dams is torrential, with much shorter flood wave concentration time.

Although the Bileća reservoir has a large storage capacity, characteristics of flood waves and torrential inflows in Trebinje Reservoir make it difficult to manage the system and maintain the flows in Trebinje town below 400 m^3/s. To prevent damages, reservoir rule curves have been defined, specifying maximum water levels for each month, which provide empty space in the reservoir for flood wave mitigation during the flood event. To enhance the system's operating performance and optimize the utilization of the active volume, a management model for flood conditions (including a module for hydrological prediction) is currently under development. Its objective will be to predict flood flows (based on predicted precipitation) and to propose an optimal system management, with a criterion of minimizing the flow through the Trebinje town.

This paper presents the effects of the prediction of flood event on flood wave mitigation, considering how early the flood event was announced. All current rules for managing the release structures (gates, hydropower plant, outlets etc.) are incorporated in the model. Analyzes were conducted for a flood event occurring once in 100 years (FW100) and they included: several observed flood waves (with a maximum flow similar as the flows of the FW100 wave), a synthetic flood wave, and a wave resulting from three days of rainfall with a total precipitation of 282 mm and a maximum intensity of 95 mm in 3 hours in the central part of the rainfall episode. The results are presented for the 3-day rainfall wave, which is the most unfavorable among the analysed waves in terms of maximum flow and wave volume. The peak of the flood wave entering the Bileća Reservoir occurs approximately 40-44 hours after the most intense rainfall (with a maximum flow of 715 m^3/s), while the peak of the flood wave from the catchment area between Grančarevo and Gorica dams, flowing into the Trebinje Reservoir (with a maximum flow of 300 m^3/s) occurs after only 6-8 hours.

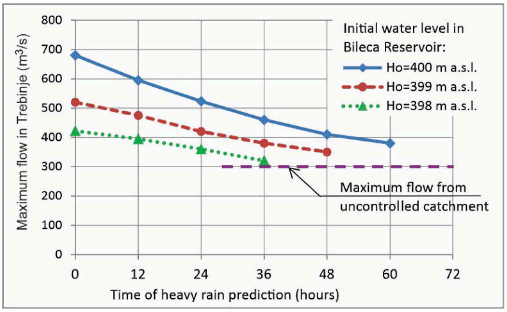

Figure 2. Maximum flow in Trebinje urban area for flood event of 100 year return period, for different initial water levels in Bileća Reservoir and for different times of heavy rain prediction.

The results of optimal management strategy for maximum flood wave mitigation through Trebinje town are presented at the Figure 2. Performed analyses indicate that if the Bileća Reservoir is full (water level 400 m a.s.l.), it is necessary to predict heavy rainfall at least 2 days in advance, to initiate timely reservoir emptying. The water level needs to be lowered to an elevation of 497.7 m to provide the volume of round $76 \cdot 10^6$ m^3, which is sufficient to completely accept flood wave. By employing the optimal management rules, it is possible to reduce the maximum flow through Trebinje town by over 50%, from 835 m^3/s to 400 m^3/s, assuming that all facilities of the system (gates, turbines in hydropower plants) are fully operational. If rain is predicted only one day in advance, the water level in the reservoir can be lowered approximately 1.1 m, resulting in a maximum flood flow of around 520 m^3/s through the urban area (assuming an initial reservoir level of 400 m a.s.l.). Even if optimal management begins during intense rainfall, it would still be possible to reduce the flood wave by nearly 150 m^3/s compared to the maximum flow that would occur without the reservoirs (825 m^3/s). Once completed with a prognostic hydrological module, this management model will enable the maximum utilization of the reservoir's active volume for hydropower production, while ensuring the safe transfer of flood waves without endangering Trebinje urban area.

3.2 *Vrbas River case study*

A similar control model was applied to analyze the optimal management of Bočac Reservoir, situated on the Vrbas River, with the aim of reducing flood waves in the city of Banja Luka. The Vrbas River is a right tributary of the Sava River, located in the central part of Bosnia and Herzegovina (Figure 3). The watershed covers an area of 6,273 km^2, with 63.5% falling within the Republic of Srpska and 36.5% in the FBiH. In the downstream part of the basin, the river flows through Banja Luka, the capital of Republika Srpska with approximately 180,000 inhabitants. The Vrbanja River, a torrential tributary, joins the Vrbas within the urban area. Banja Luka is protected from the flooding by passive protection measures - embankments along those two rivers. However, due to increasingly unfavorable flood events (such as the flood in 2014), which are a consequence of climate changes as well as changes in the watershed, additional protection measures are necessary in order to adequately protect the city.

There are four hydropower facilities in the Vrbas River basin. In the upstream part of the catchment, there is a diversion HPP Jajce I, with the reservoir on the Pliva River, with an active storage capacity of $4.2 \cdot 10^6$ m^3 (which enables daily flow regulation) and hydropower station on the Vrbas River. Downstream from that HPP is the diversion HPP Jajce II with very small active storage volume of only $2.1 \cdot 10^6$ m^3 (mostly backfilled) which operates as a run-of-river HPP. The only facility in the Vrbas River basin that has a significant possibility of flow regulation is the Bočac Reservoir with HPP Bočac. The active storage of that reservoir is $42.9 \cdot 10^6$ m^3 and it enables weekly flow regulation. HPP consists of two turbines, each with an installed capacity of 120 m^3/s. The normal water level in the reservoir is 282 m a.s.l., maximal 283 m a.s.l., and a working level is 281 m a.s.l. The Bočac Dam has three releasing facilities:

– a spillway with radial gates located on the right side of the dam. The spillway crest elevation is at 272 m a.s.l., and it has a capacity of 1345 m^3/s for water level of 283 m a.s.l.,
– a bottom outlet situated on the right side of the dam, with a maximum capacity of 127 m^3/s for a water level in the reservoir at 283 m a.s.l.,
– a free lateral spillway on the left side of the dam, constructed subsequently to increase the hydraulic reliability of the dam during extremely large flood waves. The crest elevation is at 283 m a.s.l. and it has an overflow capacity of 567 m^3/s for a reservoir water level of 286 m a.s.l.

HPP Bočac operates as a peak hydropower plant producing the variable energy. In order to protect the downstream area, particularly the town of Banja Luka, from sudden flow changes, a small reservoir with daily flow regulation was built downstream of the Bočac Dam. The gated structure is a low dam with two spillways, with a maximum capacity of 1450 m^3/s, and small run-of-river HPP Bočac 2 with an installed capacity of 110 m^3/s.

The average annual precipitation in the Vrbas basin varies from 800 mm in the Sava confluence zone to approximately 1500 mm in the southern mountainous part of the basin. The average flow of the Vrbas River is around Q_{av}=132 m^3/s, and the average specific runoff is about 20.7 $L/s{\cdot}km^2$. Flood flows of 1% occurrence for the Vrbas River is more than 10 times higher compared to average flows. A special problem for the city of Banja Luka is the torrential river Vrbanja with flood waves of very steep ascending and recession branches and a relatively small base of the hydrograph. Despite the Vrbanja catchment area being four times smaller than that of the Bočac Dam (804 km^2 compared to 3448 km^2), the maximum flood flows are higher for the Vrbanja River at the Vrbas confluence profile. Currently, there are no dams or reservoirs on the Vrbanja River to mitigate such unfavorable flood waves. The most unfavorable hydrological event for the city of Banja Luka is the coincidence of flood waves on Vrbas and Vrbanja rivers. In such circumstances, managing the Bočac Reservoir becomes crucial to reducing the maximum flows originating from the Vrbas River and delaying the peak flows until the flood wave from Vrbanja River has passed.

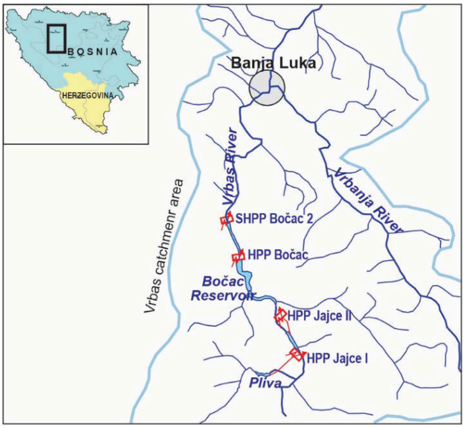

Figure 3. Part of the Vrbas River catchment.

Analyzes were performed for flood waves of different return periods: 20, 50 and 100 years (FW20, FW50 and FW100), which were determined by applying a hydrological model based on the simulation of rain episodes (Topalović et al. 2018). The rain duration in the upstream part of the catchment was 12 hours, with intensities from 87 mm to 103 mm (for the 100 years return period). In the downstream part of the catchment (Banja Luka region), the rain duration was 24 hours, with an intensity of 169 mm. All current rules for managing the release structures (gates, hydropower plant, outlets etc.) were incorporated in the model. The analyses were performed under the assumption that the initial water level in the reservoir was at 281 m a.s.l (working level), the maximum water level was 282 m a.s.l., and the minimum level was 271 m a.s.l. (during the intensive emptying of the reservoir).

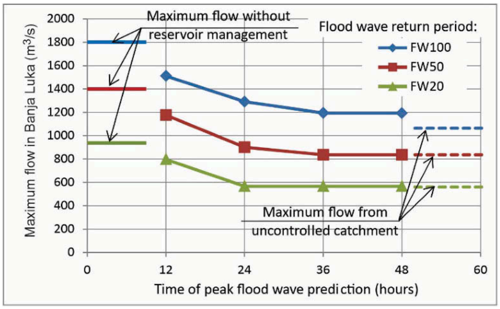

Figure 4. Maximum flows in Banja Luka for different flood waves return period and different times of peak flood wave prediction.

The results of performed analyses show that despite the relatively small reservoir volume it is possible to significantly reduce the maximum flows in the city of Banja Luka (Figure 4). By effectively managing the reservoir, it is possible to delay the peak of the flood wave from the Vrbas River, avoiding its coincidence with the wave from the Vrbanja River. This is particularly important for mitigating floods in Banja Luka due to the rapid occurrence and high peak flows of the Vrbanja flood waves When the optimal reservoir management strategy begins 36 hours before the peak flow, the maximum flows through Banja Luka do not exceed the maximum flows from the uncontrolled part of the catchment (Vrbanja River flood wave), for flood waves FW20 and FW50. Water is mostly discharged through the HPP Bočac. Gated spillways are open only a few hours (5 h for FW20 and 16 h for FW 50). For FW100 maximum flow is higher than the maximum flow from uncontrolled catchment (by 130 m^3/s), and about 600 m^3/s lower than the flow that would occur without the Bočac Reservoir. Even if the optimal reservoir management begins one day before the peak flow, significant mitigation of flood wave is possible. Maximum flow through Banja Luka in that case is slightly above maximum flow from the uncontrolled catchment for FW50, and flood wave FW100 can be significantly mitigated, with maximum flows 230 m^3/s higher than the maximum flows coming from the Vrbanja River.

4 CONCLUSIONS

In the climate change conditions and the increasing variability of water regimes, the importance of reservoirs of all types of regulation increases. Their role is significant in providing the required quantities of water (by balancing water within the year) as well as in active mitigation of flood waves. In order to use the active volume of the reservoir in the best possible way, it is necessary to improve the management of the reservoirs.

The analysis of a management model applied on two hydrosystems (with different reservoirs sizes) with a goal to minimize flow in downstream urban areas, shows that these models can be used successfully, particularly when coupled with hydrologic models that simulate hydrograph of flood event. With improved and more reliable meteorological forecasts, these models can effectively contribute to active flood mitigation, even when dealing with reservoirs of relatively small volumes.

In the analysed case studies, predicting the flood wave two days in advance and implementing optimal management measures for the simulated wave result in mitigation to the extent that peak flows through downstream urban areas do not exceed the peak flow from the uncontrolled catchment (between the dam and the urban area). This mitigation is achieved by reducing and delaying the peak flow of the mitigated flood wave. The analyses also indicate that it is necessary to have release facilities on the dam with capacities that can provide efficient release operation. The trend of increasing the installed capacity at storage hydropower plants (with the ratio Q_{inst}/Q_{av} reaching 6) is also auspicious for the active flood defense, because a significant part of the discharge can be carried out by forced operation of the HPP, and only if it is not sufficient, by other releasing facilities.

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