Possibilities of Design of Flood Protection Measures in the Catchment

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Abstract. The goal of the contribution is to present possibilities of comprehensive and complex procedures for proper design of flood protection measures in several parts of Slovakia. The complex approach consisted of mutual integration of results of partial mathematical models – rainfall-runoff model, sewage system model, 1-D hydrodynamic modelling of open channel flow together with partially covered flows, 2-D hydrodynamic modelling of flooding the town residential area. All modelling works were been done in DTM coming from aerial photography or in conditions of detailed morphological and geodetic survey of investigated rivers basins. According to the modelling process appropriate preventive flood protection measures have been designed and afterwards realised in the territory, i.e. detention reservoirs in the mountain region above the urban regions. Designed flood protection measures should store the flood wave volume and mitigate the effect of flush floods on residential areas of small and even larger cities. Several case studies are presented in the contribution all over the Slovak Republic to emphasize the variety of flood wave progress, its reduction in discharge and postponing in time in different hydrological, morphological and geological conditions of mountain regions. Most of the presented proposals of flood protection measures have been projected and some of them have been already realized.

1. Introduction
Flood is temporary flooding of the stream surroundings caused by the water level rising above the banks. Flood is considered as a phenomenon by which the water level rising caused socio-hazard. It is usually a natural disaster that occurs due to sudden or unexpected changes in the meteorological situation [1]. The flood is a relatively rare phenomenon with extraordinary performance in the runoff process. The genesis of the devastating floods, in addition to the high precipitation, cause many other factors. Besides to the existing orographic, hydrogeological, pedological and vegetation conditions, it is the saturation of the catchment area caused by previous precipitation, accumulated snow, human activity (for example, forest and agricultural management, development of the urban areas, rural settlements and landscape, construction of detention areas, stream training, etc.) but also, for example, the occurrence of plus air temperatures in winter [2].

Basic causes of the flood formation are [1]:
• sudden or intense rainfall, which sum exceeds 100 mm per m² per day. Such floods are called flash floods,
• long-time rainfall, often several (2 - 5) days, exceeding 50-125 mm per m², whereas it is possible that similar situation being repeated in a short time. They are mostly associated with the formation of long-term depression, in Slovakia, mainly occurred in summer and autumn,
• snow or ice melting,
• the occurrence of an obstacle in the stream river bed (e.g. the accumulation of iceberg or wood) and subsequent flooding of the neighbouring areas.

As defined in Directive 2007/60/ ES, three fundamental criteria are characteristic for the flood [2]:
• the flood has to flooded an area that is not usually covered by water,
• the flood usually causes water to be flooded from the water bodies - from rivers, branches, temporary streams or from the sea,
• flooding due to a failure of a technical facility may or may not be considered as a flood.

Slovak Law no. 7/2010 Collection of Laws on flood protection defines the flood as the temporary flooding of a normally unflooded area due to the effects of natural factors such as precipitation, snow melting, obstacles created by glaciers, ice blockade, various barriers constraining continuous water runoff regardless of whether the obstacles preventing water runoff created in the stream river bed or on the terrain. The only cause of the flood that may be caused by the failure of a technical facility is a failure on the water structure, while the flood of the area must cause the water flooded from the river bed. It means that as a flood cannot be considered area flooding caused by disruption of the water supply system, clogging of the sewer inlets or insufficient drainage capacity of the sewer collector [2].

2. Material and methods
The major part of population and goods are located in big urban areas so efforts for avoiding flood problems should be focused on these urban areas. River overflowing does not always cause urban floods; they can also be caused by high rain intensities over the city combined with inappropriate sewer systems. Special attention should be taken to the present drainage of rainwater, i.e. the capacity of the sewer systems of our cities. A strategy to manage floods in an ecological manner should be based on improving river basin land-use, prevent in rapid run-off both in rural and urban areas, and improving a transnational effort to restore rivers' natural flood zones. It tends to reactivate the ability of natural wetlands and floodplains to alleviate flood impacts. Development of manageable flood polders, which should be preferably used as extensive grassland or to restore alluvial forests at selected locations of former floodplains to reduce flood peaks, is also appropriate. In residential areas with limited space it is recommended to complement the flood protection by flood protection walls, mobile closures, superstructures or simple sandbags. The use of non-permanent forms of barrier for flood protection can provide much needed flexibility and increased opportunities for effective management of a wide range of flood events [3].

For the conditions in Slovakia it is possible to mention three basic ways through which the floods are flooding the territory [2]:
1. surface runoff caused by precipitation, intensive snow melting and combinations of each other:
   • by inflowing through the terrain from the hillslopes,
   • by preventing or restricting of the water runoff from the territory into the river beds,
2. by water coming up from the river beds to the banks:
   • when the discharge increasing above the flow capacity of the river bed,
   • after the obstruction occurrence in the stream river bed even at a relatively low discharge,
3. by groundwater coming up above the terrain:
   • due to the persistent high water levels in the surrounding streams,
   • after high or total saturation of the soil with water in the previous period, when other water from atmospheric precipitation cannot be absorbed because of the saturation of the entire soil profile.
2.1. Approach to the design of flood protection measures

The procedure of the flood protection measure design combines into one complex the technical knowledge, hydraulic calculations and simulations, requirements of the area of interest and spatial potentials. Each solved urban area is unique and therefore the design is limited by different boundary conditions, e.g. bridges, culverts directly in the stream, house-building very close to the streams, not sufficient place for the creating of the flooding areas, etc. In general should be kept following procedure, only own proposal will depend on the specific situation.

First of all, the basic data are required. Their validity (recency, accuracy) are the most important for the beginning of the preliminary design. From these data, the designer obtains relevant information and values for the design of the flood protection, but every design needs an individual approach. The water management data contains information about hydrological situation in the river catchment (daily and annual discharges, precipitations, flood wave, its peak and duration). The geomorphological data represent the terrain data, obtained by the survey and geodetic measurements of the area of interest, besides, it is appropriate to use an available map data for preliminary design. From these data should be detected protected area and problematic parts. Based on the analysis of geology it is possible to design a stable cross section of the stream, to choose appropriate profile of the detention reservoir, etc. The designer should make a detailed survey of the stream and its vicinity, it means topography of the original stream, to determine the cross sections by the geodetic measurements and to find out the discharge and water level in the stream in the same time for achieving the relevant values for the future mathematical model calibration. In this way should be obtain a review of the depths, longitudinal slopes of the river bed bottom, roughness coefficients and objects on the stream.

Following is the creation of a mathematical model of the present state in order to identify critical parts of the area to be protected by the flood protection measures, thus detecting the flow capacity of the stream that endangers the neighbouring area with floods. Therefore, 1- or 2-D mathematical model is building (1-D model is sufficient for the preliminary design), whose credibility is increased by calibration. In practice, it is not often that model is verified, because it is not possible to perform at the same time a water level and discharge measurements during flood situations. These are mainly small river basins where no gauging stations are available.

Then follows the proposal of flood protection measures according to the specific situation and conditions. This proposal is then inserted into the mathematical model of the present state where the effects of the proposed measures are find out. On the basis of the analysis of the stage without the designed measures and with them it can be stated their suitability and effectiveness.

The diversity of the nature makes impossible to apply everywhere a single method of the protection against floods. This fact, Law no. 7/2010 Collection of Laws on flood protection, is establishing in five basic groups of preventive technical and non-technical measures to protect against floods [2]:

1. Measures that increase the retention capacity of the catchment or in suitable localities support natural water accumulation, slow down the water runoff from the catchment into the stream river beds and which protect the area from flooding by surface runoff, e.g. management of the forests, farmlands and urbanized areas (Figure 1, Figure 2).
2. Measures that reduce the maximum flood discharges in the catchment, e.g. water structures (dams, weirs), reservoirs and detention reservoirs (Figure 3).
3. Measures that protect areas from flooding by water from stream river beds, e.g. water training, dykes or floodplains (Figure 4, Figure 5).
4. Measures that protect areas from flooding by internal waters, e.g. system of the drainage channels and pumping stations (Figure 6).
5. Measures which ensure the flow capacity of the stream river beds, e.g. removal of sediments from the river beds and vegetation from their banks (Figure 7).

![Figure 1. A wetland biofiltration basin adjacent to a natural creek line in Perth that treats stormwater before it enters the river and also receives high flows, moderate downstream flows during floods [4]](image)

![Figure 2. Flooding after deforestation of a hillside [4]](image)

![Figure 3. Detention reservoir on the torrent Ľubica, Slovak Republic [6]](image)
Figure 4. Mobile flood protection barriers on the Danube River in Bratislava, Slovakia

Figure 5. River training, dyke and floodplain on the Bodva River, Slovakia

Figure 6. System of the drainage channels and pumping stations in eastern part of the Slovakia

Figure 7. Removal of sediments from the river bed and vegetation from its banks on the Lukavica stream, Slovakia
3. Results and discussions

Based on the previous information and data should be stated that each area of interest endangered by flood events requires individual approach in the design of the flood protection measures. As examples of the possible solution of flood protection for river catchments with different conditions various studies are presented from last years.

3.1. Case study village Pila, stream Gidra and its tributary Kamenný stream

The village Pila which was affected by destructive flood in 2011. After this flood many buildings, roads and pavements had to be repaired but the flood protection was still non-existent. After the simulation of flood without proposed measures it was proceeded to design detention reservoirs because of spatial possibilities and existed objects (bridges and culverts) on the stream. The proposed detention reservoirs did not ensure complete flood protection of village. Instead of that, not too high reservoirs should be proposed in given locations. The reason was a fact that natural landscape of valleys in Small Carpathians above village should not be interrupt. Current state of this area today is very beautiful and natural. It would be destroyed by building big dams in these valleys. In this case, earth fill dams were proposed because of their more natural appearance. When proposing detention reservoir, the most important value is the capacity discharge of downstream channel and its structures. Usually, structures as bridges or culverts have less capacity than the channel itself, as it was in this case, as well. Firstly, there were 3 detention reservoirs chosen, after hydraulic evaluation two of them were designed for the flood protection purposes – one on the Kamenný stream and one (the upper) on the Gidra stream (table 1, figure 8). By synergy of the detention reservoirs the meridian flow has been reduced from original 24,6 m$^3$.s$^{-1}$ to value 11,10 m$^3$.s$^{-1}$ and has been delayed by 1,25 hour [7, 8].

| stream           | crest altitude (m a. s. l.) | dam height (m) | outlet structure diameter (m) | length of dam crest (m) | detention volume (m$^3$) |
|------------------|-----------------------------|----------------|-----------------------------|-------------------------|--------------------------|
| Kamenný          | 306,2                       | 5,6            | 1,10                        | 80                      | 50 000                   |
| Gidra - upper    | 300,5                       | 5,5            | 1,00                        | 140                     | 108 000                  |

Figure 8. Locations of the proposed detention reservoirs on the Kamenný and Gidra streams [7, 8]
3.2. Case study town Levice, Podlužianka River and its tributaries Čajkovský and Rybnicky streams

Slovak lowlands have been suffering from floods. The floods are formed in connection with rainfalls, arising water in rivers rising groundwater up above the terrain. The river, which flows through the district of Levice is the Podlužianka River with right-bank tributaries Čajkovský stream and Rybnicky stream. This area is often naturally flooded from all rivers during floods. Present conditions of the flood protection in the Levice district area are not sufficient. In case that the flood protection does not be realized in this flood location, surely flood flow rates will exceed and it will still cause massive damages on urban and private properties as previously. The river bed training of the Podlužianka River in the central part of Levice town was done in 2004. The town is protected with walls situated along the river bed and in the areas where the bridges are slide barriers were built. For the sufficient town protection, it is necessary to ensure increasing of the capacity of the river bed, to remove obstacles from the river bed, to adjust river banks and to store flood flow rates in detention reservoirs. Various alternatives were examined (up to 7 detention reservoirs were proposed and simulated in one mathematical unsteady model) and - on the basis of the economical and water management assessment – an alternative with 3 polders (table 2, figure 9) was chosen [9].

Table 2. Dimensions of the proposed detention reservoirs [9]

| stream            | crest altitude (m a. s. l.) | dam height (m) | outlet structure diameter (m) | length of dam crest (m) | detention volume (m³) |
|-------------------|------------------------------|----------------|-------------------------------|------------------------|-----------------------|
| Podlužianka (rkm 12,6) | 174,5                        | 5,5            | 2 x 1,6                       | 550                    | 670 506               |
| Podlužianka (rkm 19,9) | 248,5                        | 9,4            | 1,5                           | 80                     | 84 158                |
| Čajkovský          | 202,4                        | 6,9            | 1,3                           | 365                    | 181 907               |

Figure 9. Graphic presentation of the area of interest including situation of rivers and detention reservoirs (Hec-Ras) [9]

3.3. Case study town Bardejov, Topľa River

Analysis of the flood protection of the Bardejov town was performed because of insufficient flood protection of the centre of the city. Capacity of the river bed in the urban area of the town of Bardejov is insufficient, resulting in repeated floods. Because it is a downtown with a dense build-up, it was not possible to enlarge the dykes by earth, also river bed could not be trained or extended. Therefore, the flood protection of the middle part of the city was already realized by building of concrete walls. This realization was assessed by one dimensional open channel flow model of the Topľa River in Bardejov in non-uniform steady flow conditions. The results of mathematical modelling showed, that flood
protection walls designed and realized in the central part of the town (phase I.) must be supplemented in upstream and downstream sections (phases II. and III.) to ensure flood protection in whole solved section (figure 10). Recommended measures will increase flood protection of the town of Bardejov [10].

Figure 10. Bardejov – orthophoto map of planned phases and realized flood protection walls (phase I.)

3.4. Case study village Veľká Lúka, stream Lukavica
The stream Lukavica flows through the small village Veľká Lúka (located between towns Sliac and Zvolen). Through the common hydrological situations, this stream flows by the minimum water level (few centimetres). Houses in the central part of the village are built densely along the stream. Training of the Lukavica river bed was done only partially in different periods and for different capacities. In addition, there are two road bridges as well as a railway bridge (culvert) and a ford on the stream. The problem is the new building development under the central part of the village, which was already affected by floods (heavy storms and rapid snow melting - 2009, 2013, 2016). The river bed is loaded with sediments and overgrown with bush and willows. By the hydraulic analyses and simulations, based on the actual geodetic measurements of the area of interest, it has been proved that even by clean-up of the river bed (sediment dredging) there is insufficient flood protection of the municipality (figure 11). Expansion and training of the river bed nor the dyke’s construction is impossible, therefore a detention reservoir was proposed above the village (figure 12). However, the volume of the flood wave volume is so great that a relatively large detention reservoir has been proposed whereas the river bed in the village must be refined. In the part of expected planned house building damming of river banks by small walls was proposed, so that the outflowing discharge from the detention reservoir could not cause damages, anymore [11].

Figure 11. Cleaning of the Lukavica river bed in the central part of the village Veľká Lúka
4. Conclusions

Flash floods are becoming a phenomenon that troubles people more and more often in many Slovak under-mountain regions. Flash floods also called storm or sudden floods are a specific type of rain floods which typical sign is an intensive increase of water level in the river in a short time period (usually couple of hours). Mostly there are floods on small streams in upper parts of river basins and their starters are extreme storm rainfalls. Rainfall intensity and duration limits are not possible to determine exactly because they are dependent on many factors such as type and shape of landscape, soil water saturation and nonetheless they depend on anthropogenic activity (inadequate operation in the landscape). Due to the extremely short time of flood beginning, it is very difficult to alarm inhabitants and for carrying out operative flood protection measures like mobile flood-protection barriers it is mostly too late. That is the reason why it is necessary to prepare appropriate flood-protection measures, which do not need any operation and work automatically [7].

Flash floods that occur mainly in small water catchments are a specific case of devastating floods that cause rains characteristic of short duration, relatively large and significantly varying intensity; typically affecting small areas. The effects of flash floods - if they are not caused by a series of storms or a progressive flood - will disappear after a few tens of kilometres. Since 1995 up to now more than hundred floods occurred in Slovakia, and the frequency of their occurrence seems to be increasing [2]. Analyses of precipitation volume, runoff, their time course and situation on the affected river basins confirm that catastrophic flood events - as large surface range as well as in small river basins - are definitely caused by a large sum of high precipitation intensity that have fallen into basins almost completely saturated by previous precipitation. Last 15 years in Slovakia were extremely rich in precipitations [2].

The above-mentioned studies showed the possibilities of the flood protection measures designing in different conditions of small municipalities with relatively small river catchments but high flood discharges. Every suggestion has been sensitively tried to use the given site's capabilities with regard to maximum flood protection, functionality as well as an ecological site.

Rivers do not recognize national borders - experience has shown that local flood protection measures can have negative effects both downstream and upstream. Therefore, it is important to take the whole river basin into account. On transboundary rivers the international co-operation is needed [3].
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