Complex Proposal of Flood Protection Measures for Small Municipalities in the Area of Small Carpathians

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Abstract. The article describes problems associated with the design of the flood protection measures for small settlements situated at the foot of a mountain. In recent years, these settlements have had problems with flood discharges due to the new development (concreted areas), land/soil management change (private owners farming on their own grounds and do not cooperate together), neglecting of maintenance of surface drains (or their full filling) and river bed channels of the small streams (often dried up during the year, overgrown with woody plants, covered with waste), and of course, also due to climate changes, where the flood discharges are revalued – they are increased. In addition, sub-mountain regions are also characterized by flash floods when a large amount of rainfall falls on a relatively small area with a steeper longitudinal slope. Since the creeks are small there, it could be said to be insignificant, no gauging stations are being built there, so the hydrological data necessary for the design of the flood protection measures are missing. In the article, the procedure of the flood protection measure design for a small sub-mountain area is described which resulted in the design of additional detention reservoirs, complementing the existing detention reservoirs. The HEC-HMS software was used for the hydraulic calculation and the GEOSTUDIO program was used to assess the bank slope stability of the proposed detention reservoirs.

1. Introduction
Flash floods, also referred to as sudden or storm floods are recorded in our country in recent years in small river basins, mostly mountain and foothill areas. They were initiated by rainstorms belonging to extreme meteorological phenomena during which a large amount of precipitation falls in a short time on a relatively very small and sharply bounded area of several km². The occurrence of a flash flood is secondarily affected locally or due to regional physical-geographical and hydrological conditions which can accelerate or moderate the process initiated by rainstorms. Each flash flood has its own specifics, which reflect local conditions of the given river basin [1, 2].

The occurrence of a flood is a result of several factors. Except for precipitation, it is not possible to forget about other factors such as soil-water saturation, current water level stage, eventually existing snow cover and, last but not least, the state of the river bed, drainage cuts (influence of anthropogenic
activity – various obstacles). It is necessary to know the overall orographic, geological and geographical conditions of the area of interest. Slovakia, especially foothill areas have been affected several times in recent years by floods which are difficult to predict in advance due to the formation at the beginning of the river basin where no water-gauging station is established and the inhabitants cannot be warned of impending danger in time. Therefore, several projects were created to solve the problems of the foothill areas of Slovakia. One of them was also the project of under mountain villages in the Small Carpathians which dealt with the flood protection of the town of Modra.

2. Material and methods

The territory of the town of Modra is characterized by its location and the existing river network. It is a typical foothill region. During extreme runoff situations, water flows over paved surfaces as well as over the surface of land and field roads. One of the possible reason is that streams, drainage channels or cuts do not have sufficient capacity to drain the inflowing water smoothly. Also, the conditions of the riverbed, drainage channels and trash racks in the parts where the streams pass into the covered profile contribute to this water overflowing. The capacity of the pipelines themselves, whose long sections leading under a large part of the city of Modra, may not be sufficient. The impact of extreme runoff in the winter season consists mainly in their duration, and therefore the increase in the volume of the flood wave is caused by runoff from snow melting, but less in the extremity of the peak flow achieved. However, the town of Modra is also threatened by short-term high-intensity rainfalls where a significant factor is the current state of saturation of the river basins of the stream lying above the city of Modra.

The area of interest of Modra town is characterized by a large number of small streams which are not monitored or measured and many parts of these streams are routed in the pipeline. The town of Modra is situated between the foothills of the Carpathians at an altitude of 175 m a. s. l. and is characterized by its greatest super-elevation (height difference between the city centre and part called Piesok). Significant for this area is also the highest located natural swimming pool in the Small Carpathians, and at the same time, it is the southernmost town in Slovakia with a ski resort in its town district [3, 4]. The area belongs hydrologically into the Danube and Váh river basins. Water from the area of interest of the town of Modra is drained by several water bodies, while this river network is relatively dense. List of streams (Figure 1): Vištucký stream, Žliabok, Stoličný stream, Holombek 1, Holombek 2, Trniansky stream, Procházkov stream, Hruškov stream.

![Figure 1. Area of interest – the town of Modra with all identified streams, water-gauging station (red point), precipitation stations (green points), climatic station (brown point) WR – water reservoir, DR – detention reservoir](image_url)
The streams are fan-shaped and are inclined in the vicinity of Modra. This fact has caused considerable problems with floods in the past, not only in Modra but also in adjacent areas. Therefore, water reservoirs (Vinosady, Zadný Šúr, Harmónia, Vištuk, Budmerice) and two detention reservoirs lying on the streams Holombek 1 and Holombek 2 with the same name were built in the urban area of Modra (Figure 1). Based on the experience of flood events in recent years, it has been confirmed that the existed water reservoirs built in the past and two detention reservoirs lying on the Holombek 1 and Holombek 2 streams in the urban area of cadastre are not sufficient to protect the city of Modra and adjacent municipalities from floods caused by storm waters from foothill areas [3, 4].

Based on the analysis of the data, reconnaissance of the terrain and surveys with local residents, but especially on the processing of the hydrology of the solved area, new detention reservoirs were designed - on Vištucký stream above a natural swimming pool (locality Piesok = Sand), which will supplement existing flood protection measures - existing detention reservoirs Holombek 1 and Holombek 2, a detention reservoir on the Žliabok stream and a system of smaller detention reservoirs on the Paták stream. This article will describe in detail the design of the detention reservoir on the Vištucký stream.

2.1. Hydrological data
Vištucký stream (also referred to as Kamenný or Stoličný) is a stream of the 5th order, a left tributary of Stoličný stream. Its length is 21 km, catchment area 240 km². It springs on the northern hillside of Veľká Homola (709 m a. s. l.), flows through the edge of Čermáková meadow, through the Panský dvor locality and the natural swimming pool at Zochova cottage (Piesok locality), then flows in the Harmónia reservoir, from which it flows through the Kráľová locality into the water reservoir Vištuk. On Vištucký stream there is also the only water-gauging station in the area of interest of the town of Modra (in the monitoring network of surface waters of Slovak Hydrometeorological Institute (SHMI)) built in 1962. The average annual discharge is 0.104 m³·s⁻¹ (period 1963 – 2009). Maximum annual discharges were achieved in 1997 and 2002 [3, 4].

In the cadastral area of the town of Modra, there are also precipitation stations Modra (18060) and Modra-Piesok (18050), where observations have been carried out since 1981 and 1988. Station Modra is located in the lowland part of the cadastral area and the mean annual precipitation total is 650 – 700 mm. As the altitude increases, the amount of precipitation increases, in the mountain part of Modra-Piesok there is an annual total of approximately 850 – 900 mm. From the assessment of the change in the annual precipitation totals for the period 1989 – 2009, a slight increase can be observed. The highest amount of precipitation falls in the summer (V – IX) and autumn (XI – XII) season, the least rainfall falls in October and winter-spring season (I – IV). During the average vegetation period (April to September), about 50 – 55% of the annual total fall [3].

For determination of the design discharges for flood protection measures proposal hydrology analysis of the catchment area was carried out using indirect estimation of N-year maximum discharges but also direct estimation of the 100-year maximum discharge on the Vištucký stream where the water-gauging station was established. To be safe at designing flood protection measures as the design Q₁₀₀ discharge, it is necessary to choose from several estimates of the highest value of Q₁₀₀ from the estimated ones, as it can be assumed that the extremes will increase in the future. The SHMI's expert estimates achieved the highest values of Q₁₀₀ discharges and therefore were recommended to use them at the design of flood protection measures.

From the point of view of the flood protection of the urban area of Modra town and the adjacent villages of Harmónia and Kráľová, the retention function of the detention reservoir on the Vištucký stream will ensure the flood wave transformation and will significantly contribute to the prevention against flash floods. As follows from the course of the flood wave (SHMI) on the Vištucký stream in rkm 25 its expected development indicates a sharp ascending branch lasting 3.1 hours and a descending...
branch with a duration of 11.5 hours with a peak discharge of 4.7 m$^3$.s$^{-1}$ and flood volume of up to 59,000 m$^3$. (Figure 2) [3].

Figure 2. Design flood wave Q$_{100}$ on the Višťucký stream, rkm 25 (SHMI)

3. Results and discussions

3.1. Water management solution of the detention reservoir

The location of the detention reservoir was proposed above the existing so-called natural swimming pool at Zochova cottage. From the morphological point of view, it is an asymmetrical valley, on the right side wide open with a slight bank slope, on the left side with a steeper bank slope (Figure 3).

Figure 3. The area of Višťucký stream above the so-called natural swimming pool at Zochova cottage (view upstream the water), location of the designed profile of the dyke of the detention reservoir
In addition to the design flood wave \( Q_{100} \) (Figure 2), the basic data of the water management solution of the storage volume of the detentions reservoir includes basic characteristics of the reservoir – area-elevation curve and storage-elevation curve. In the absence of a topographical and elevation survey of the area of interest of the Vištucký stream in the area above the proposed dam profile, it was necessary to result from commonly available map materials. The partial survey, which was provided to us by co-researchers from the Department of Geodesy, had only a limited use, in the range of possible backwater of the considered detention reservoir to a height of 4.5 m. Such data did not cover the required volume limit of the detention reservoir, which was determined by the total flood wave volume of 59,000 m\(^3\). In order to obtain an area-elevation curve and storage-elevation curve, it was necessary to harmonize the commonly available map data with the provided partial survey. As the accuracy of commonly available map data is insufficient for such task we recommend the area-elevation curve and storage-elevation curve exceeding the height level of 4.5 m to be perceived with a certain margin. Such an approach can be acceptable for an ideal design. The basic parameters of the area-elevation curve and the storage-elevation curve are presented in Table 1 [3].

| Variant according to | Elevation (m a. s. l.) | Elevation of the dam (m) | Area (m\(^2\)) | Volume (m\(^3\)) |
|-----------------------|-------------------------|--------------------------|----------------|-----------------|
| Geodetic survey       | 437.0                   | 0.0                      | 0.0            | 0.0             |
|                       | 437.5                   | 0.5                      | 150.0          | 29.75           | 25.00           |
|                       | 438.0                   | 1.0                      | 485.8          | 198.3           | 175.96          |
|                       | 438.5                   | 1.5                      | 825.4          | 524.2           | 500.03          |
|                       | 439.0                   | 2.0                      | 1211.6         | 1040.6          | 1006.20         |
|                       | 439.5                   | 2.5                      | 1667.2         | 1755.4          | 1722.88         |
|                       | 440.0                   | 3.0                      | 2166.4         | 2708.1          | 2678.56         |
|                       | 440.5                   | 3.5                      | 2794.1         | 3933.3          | 3915.36         |
|                       | 441.0                   | 4.0                      | 3488.5         | 5507.6          | 5482.80         |
|                       | 441.5                   | 4.5                      | 4189.3         | 7429.7          | 7399.58         |
| Map                   | 445.0                   | 8.0                      | 11227.0        | missing data    | 33386.36        |
|                       | 450.0                   | 13.0                     | 32421.0        | missing data    | 137930.60       |
|                       | 455.0                   | 15.0                     | 69283.0        | missing data    | 386427.80       |

In Figure 4 is the detail of the storage-elevation curve for flood wave resulting from the hydrological data, i.e. 59,000 m\(^3\). It is clear from the above results of the solution that assuming the storage of the entire volume of the flood wave (the degree of reliability of its determination is not given), the minimum height of the dam of the detention reservoir at the freeboard of 1 m would be about 10 m [3].
3.2. Hydraulic calculation of detention reservoir parameters

Detention reservoir, sometimes called a dry reservoir, functions during a flood on a similar principle as the retention space of a reservoir. The specificity of the detention reservoir in comparison with the water reservoir is the absence of a permanent and storage volume. The task of the detention reservoir is to store during flood flow rates a substantial part of the inflowing volume of the flood wave in the space created by the dam of the detention reservoir which is normally empty. After the largest discharges are over, the accumulated water is then safely released in the stream under the dam profile. The correct function of the detention reservoir is ensured by the correct design of its functional structures - the bottom outlet and the emergency spillway. Because of rare operation of detention reservoirs during floods, their operation is usually unattended - the bottom outlet has no gates, the emergency spillway is proposed as uncontrolled. With the most common type of detention reservoirs - overflowed detention reservoirs, the bottom outlet is used during normal discharges to carry water through the profile of the dam. During a flood, with increasing water level the bottom outlet is gradually clogged, what results in filling of the reservoir. The filling of the reservoir space depends on the dimensions of the bottom outlet. The optimal design of the dimensions of the bottom outlet is such that during the design flood wave it ensures the filling of the detention reservoir to the dimension of the edge of the safety spillway and at the same time the discharge, which is flowing through the bottom outlet does not exceed the value of harmless outflow. The emergency spillway only comes into operation when the design flood wave is exceeded.

When designing the functional structures of the detention reservoir on the Višťucky stream the bottom outlet circular cross-section was considered. The size of the harmless runoff was not determined during the hydrological assessment of the area of interest, the design value of the harmless runoff in three alternatives based on the mapping of the area under the proposed dam profile as follows: \( Q_{1\text{harmless}} = 0.5 \text{ m}^3.\text{s}^{-1} \), \( Q_{2\text{harmless}} = 0.75 \text{ m}^3.\text{s}^{-1} \), \( Q_{3\text{harmless}} = 1.0 \text{ m}^3.\text{s}^{-1} \) was taken into account [3].

For the hydraulic calculation, the HEC-HMS program was used which is determined to model rainfall-runoff conditions in river basins. The task was solved parametrically. With the constant course of the flood wave and the storage-elevation curve, we were looking for such a combination of the
parameters of the bottom outlet and the emergency spillway which will ensure a harmless outflow. The predominant criterion was the height of the dam, which will ensure the required transformation of the flood wave at chosen parameters of the bottom outlet. The results of the solution are for the previously mentioned three alternatives summarized in Table 2 [3].

Table 2. Results of the hydraulic solution of the parameters of the detention reservoir for \( Q_{100} = 4.7 \text{ m}^3\text{s}^{-1} \)

| Alternative | Q_{harmless} (m^3.s^{-1}) | Overflow crest height (m) | Reservoir volume (m^3) | Transformed flood wave (m^3.s^{-1}) | Culminating water level (m / m a. s. l.) |
|-------------|---------------------------|--------------------------|------------------------|-------------------------------------|----------------------------------------|
| 0.5         |                           |                          |                        |                                     |                                        |
|             | 4                         | 8 900                    | 3.7                    | 4.7 / 441.7                         |                                        |
|             | 5                         | 15 100                   | 2.7                    | 5.5 / 442.5                         |                                        |
|             | 6                         | 21 600                   | 1.9                    | 6.4 / 443.4                         |                                        |
|             | 7                         | 28 100                   | 1.4                    | 7.3 / 444.3                         |                                        |
| 0.75        |                           |                          |                        |                                     |                                        |
|             | 4                         | 8 600                    | 3.7                    | 4.7 / 441.7                         |                                        |
|             | 5                         | 14 600                   | 2.5                    | 5.5 / 442.5                         |                                        |
|             | 6                         | 21 000                   | 1.8                    | 6.3 / 443.3                         |                                        |
|             | 7                         | 27 300                   | 1.2                    | 7.2 / 444.2                         |                                        |
| 1.0         |                           |                          |                        |                                     |                                        |
|             | 4                         | 8 200                    | 3.6                    | 4.6 / 441.6                         |                                        |
|             | 5                         | 14 100                   | 2.4                    | 5.4 / 442.4                         |                                        |
|             | 6                         | 20 300                   | 1.6                    | 6.2 / 443.2                         |                                        |
|             | 7                         | 24 400                   | 1.0                    | 6.8 / 443.8                         |                                        |

The presented analysis shows that with the required transformation of the flood wave to harmless outflow \( Q_{harmless} = 0.5 \text{ m}^3\text{s}^{-1} \), or \( Q_{harmless} = 0.75 \text{ m}^3\text{s}^{-1} \) the calculated height of the dam exceeds the economically tolerable rate. Therefore, it would be suitable to re-evaluate the capacity of the existing bypass of the natural swimming pool at Zochova cottage and, if necessary, to ensure its parameters for the capacity up \( Q_{harmless} = 1.0 \text{ m}^3\text{s}^{-1} \).

Under such conditions it means in the case of the design flood wave and the approximately determined basic parameters of the reservoir (the area-elevation curve and the storage-elevation curve), it will ensure the reduction of the flood discharge \( Q_{100} \) to the required harmless outflow discharge - \( Q_{harmless} \) detention reservoir with the following parameters [3]:
- bottom outlet of circular cross-section with a diameter of 0.45 m, a length of 40 m and a longitudinal slope of 0.5 %,
- height of the overflow crest 7.0 m above the terrain,
- height of the dam 8 m,
- when considering max. overflow height 0.5 m,
- the overflow width 6.0 m,
- reservoir volume 24 400 m^3.

With these parameters of the detention reservoir, the flood wave can be reduced to the required \( Q_{harmless} = 1.0 \text{ m}^3\text{s}^{-1} \). The flattening of the flood wave, as well as the water level course in the reservoir and the development of the volume of retained water during the transformation of the design flood wave, is shown in Figure 5. The emergency spillway was designed for a capacity of 5 m^3.s^{-1}, which is the magnitude of the peak discharge of the flood wave [3].
3.3. Geotechnical aspects of the design of the detention reservoir

As one of the possibilities of technical measures of flood protection, detention reservoirs have a specific position in hydraulic engineering. This position is determined by their short-term hydrodynamic stress which is interrupted by various lengths of time without loading. If we add to this the variability of the input data - whether hydrological, engineering-geological, geotechnical and others, it is clear that these dams must be assessed as particularly special structures that require special attention. In contrast to dams of retention reservoirs, whose quality of construction and reliability of anti-seepage measures is verified immediately after its construction, starting with the first filling and subsequently in the verification operation, this is not the case of dams of detention reservoirs. This important factor in verifying the quality of the structure and the reliability of their function is usually tested only during its first filling in the event of flood discharges.

The register of detention reservoirs built and designed so far in Slovakia shows that the bulk of detention reservoirs dams are built as homogeneous earth-filled dams made of local materials. The advantage of this type of dam is a relatively simple construction technology, the use of material from the neighbourhood of the dam profile and low demands on the bearing capacity of the foundation soil. A sample of material taken from the dam profile, which was classified as GC - gravel clay meets the requirements for material embedded into the body of homogeneous dams, it is a material sufficiently impermeable with adequate shear strength to allow relatively economical slopes of the dam banks. In accordance with the requirements of the Slovak Technical Standard No. 73 6824, it is possible to design the upstream slope of the dam 1: 2.5 and the downstream slope 1: 2.3 at a given stage of knowledge [3].

The assessment of the stability of the dam slopes on the Višťucký stream was processed in the GEOSTUDIO program. The stability of the slopes of dam banks and dams should be investigated under both normal and extreme loading conditions that may occur during the life of the structure. The basic
loading condition assessed was the state of the empty reservoir, in which the dam of the retention reservoir is located in the majority of the year. Another investigated loading condition was the transition of the design flood wave through the detention reservoir. Stability was assessed even with a fictitious drop in the water level, from the state of the maximum operating level with a stable depression curve, until the reservoir was completely released. However, this scenario is unlikely. It can be assumed only if the detention reservoir was filled during a flood, its bottom outlet would become inoperable and in a reasonably long time, the dam body would become saturated. Then a continuous depression curve would form in its body and after the bottom outlet starts to operate, a subsequent sudden drop in the water level will occur [3].

The minimum values of the degree of stability at all investigated loading cases are clearly shown in Table 3. The required degree of slope stability has a value of 1.5 at normal loading conditions and 1.1 at extreme loading conditions, which means that the developed design meets the requirements for slope stability in all investigated loading conditions. Figure 6 shows the output from the GEOSTUDIO program - the calculation of the stability of the upstream slope for an empty reservoir [3].

Table 3. Minimum values of the degree of stability for the upstream and downstream dam bank

| Loading case          | Minimum degree of stability for the upstream bank | Minimum degree of stability for the downstream bank |
|-----------------------|--------------------------------------------------|--------------------------------------------------|
| Empty reservoir       | 1.837                                            | 1.863                                            |
| Fulfilled reservoir   | 2.314                                            | 1.639                                            |
| Flood wave transition| 1.873                                            | 1.878                                            |
| Sudden drop of the water level | 1.313                                   | 1.637                                            |

Figure 6. Output from the GEOSTUDIO program when calculating the stability of the upstream slope

4. Conclusions
The conceptual design of the solved detention reservoir on the Vištucký stream was processed in the form of a parametric study, where, taking into account 3 alternatives of a harmless outflow, the optimal parameters of the detention reservoir were sought, in which its maximum effect is achieved. Based on the water management solution using the HEC-HMS program, we achieved the following parameters of the detention reservoir: height of the dam - 8.0 m above the terrain, height of the overflow crest 7.0 m above the terrain, storage volume of the reservoir 24,400 m³. In the given morphological, preliminary determined engineering-geological conditions, a homogeneous dam made of local materials appears to be the ideal type of the dam construction. The results of the laboratory tests on a soil sample taken from the given locality confirmed that the local material - clay gravel (GC) is suitable for the construction of homogeneous dams of water structures. At a height of 8 m and proposed bank slopes of 1: 2.3 and 1: 2.5, the stability calculations using the GEOSTUDIO program confirmed the fulfilment of the recommendations of the valid standards.
The above described detention reservoir design procedure is only a partial task of solving the whole area of interest. The most serious problem was the obtaining of the input data, in situ measurements, evaluation of possible risks in the design, as well as communication with inhabitants and local government. In the area of Modra, a detention reservoir on the Žliabok stream and a system of smaller polders on the Paták stream are also proposed, which resulted from the hydrology of the streams around Modra, as well as the morphology of the area.

The need of a solution of the flood protection of foothill settlements is becoming more and more relevant in the context of climate change, which has an impact on the change of maximum precipitation, runoff, $Q_{100}$ and thus also on the size of the flood wave. Human being also contributes to this negative state of climate with his activities and buildings, which are becoming increasingly dense even in sloping terrain. Due to the concreting of larger areas, the runoff from precipitation then accelerates and by its accumulation, a flood with a larger volume than expected in the past occurs [5, 6]. The design of effective technical flood protection measures, such as detention reservoirs, in conjunction with forestry and agrotechnical measures, sufficient maintenance of river beds, cuts and sewers, will ensure the protection of lives and property of inhabitants not only in the foothill regions.

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