APPLICATION OF DYNAMIC WATER QUANTITY AND/OR QUALITY MODELS (PILOT ACTION)

D.T2.4.1

Reports from testing the dynamic model to assess cumulative effect of N(S)WRM (Pilot Action)

Slaná river basin, Blh pilot catchment, Slovakia

Version 1
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REPORT FROM PILOT ACTION

SIMULATION OF THE FLOOD FORMATION, TIME AND SPATIAL DISTRIBUTION BY USING ADVANCED HYDRODYNAMIC MODELLING

SLOVAK WATER MANAGEMENT ENTERPRISE

state enterprise
Radničné námestie 8
969 55 Banská Štiavnica

Bratislava, June 2020

Simulation of the flood formation, time and spatial distribution by using advanced hydrodynamic modeling

The Slaná river basin is affected by floods, there have been identified 31 geographical areas with significant flood risk which are connected with 8 water bodies. At this step the creation calibration and validation took a place to determine the effects of floods in the catchment.

prof. Ing. Andrej Šoltész, PhD.

Prof. Ing. Milan Čistý, PhD.

Ing. Martin Orfánus, PhD.

Ing. Daniel Buček, PhD.

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Content

1. INTRODUCTION

The FramWat project aims to strengthen the joint regional framework for mitigation of consequences of floods, droughts and pollution by increasing absorption capacity of the landscape.

This will happen by systematic use of nature close (small) measures for water retention in the country. Project partners will develop methods which apply existing knowledge of nature close (small) retention measures water management practices in river basin management. The result will improve water balance, reduce sediment transport and restore nutrient cycles.

The project will be provided by the executive appropriate instruments to incorporate the nature of nearby measures to retention of water in the country to the next cycle of river basin management plans. It will also support and provide guidance on the horizontal integration of different strategic documents and plans in this area.

For pilot area in the catchment of Slaná River the ability of HEC-RAS was used as the primary tool to determine hydrodynamic run-off. In terms of simulation of the flash flood formation, time and spatial distribution, the 2D HEC-RAS 5.0.7 option was chosen.

HEC-RAS 2D flow modelling can be used in a variety of different situations:

- detailed 2D channel and floodplain modelling,
- combined 1D channel flow with 2D floodplain flow areas,
- combined 1D channel and overbank flow with 2D flow areas behind levees,
- simplified to detailed dam failure (i.e., dam breach) analyses,
- simplified to detailed levee failure (i.e., levee breach) analyses,
- 1D flow that suddenly expands laterally into the floodplain overbank area,
- flow outside of well-defined single channel,
- interconnected or braided creeks, meanders, loops,
- alluvial fans and estuaries,
- and many other situations.

To develop a 2D flow area model, an understanding of how the 2D flow model works is required. This study covers the basics of 2D flow modelling. HEC-RAS provides two methods for computing the flow field in a 2D mesh, both of which may be selected from the Unsteady Flow Computational Options dialog box available from the Analysis ribbon menu.

The 2D Diffusion Wave computational method is the default solver and allows the computations to run faster and with greater stability. Most 2D modelling situations, such as flood modelling, can be accurately modelled using this solver, where inertial forces tend to dominate frictional and other forces.

The Diffusion Wave computational method can be used in the following situations:

- flow is mainly driven by gravity and friction,
- fluid acceleration is monotonic and smooth (i.e., no waves),
- compute rough global estimates (i.e., flood extents),
- assess interior flooding (i.e., levee breach),
- quick estimate for using the Full Momentum computational method.

The 2D Full Momentum computational method, often referred to as the Saint Venant equations for shallow flow, can account for turbulence and Coriolis effects, making it applicable to a wider set of conditions. However, solving the 2D Saint Venant flow equations requires more computational power and thereby results in longer run times. In addition, the 2D Saint Venant flow equations can become numerically unstable in regions of the 2D mesh where the water surface profile or flow direction is changing rapidly. To avoid an unstable model, a finer mesh and a corresponding smaller time step will need to be used.

The Full Momentum computational method should be used in the following situations:

- dynamic flood waves (i.e., dam failure, rapid rise and fall),
- sudden expansion or contraction of flow with high velocity changes,
- detailed flow solutions around hydraulic structures and obstacles (i.e., bridge openings, piers or abutments),
- detailed mixed flow regime (i.e., hydraulic jumps, critical flow, etc.),
- wave propagation (i.e., waves reflecting off walls and structures),
- tidal boundary conditions (i.e., upstream wave propagation),
- super elevation around river bends.

Both the 2D Diffusion Wave and 2D Saint Venant solvers use an Implicit Finite Volume solution algorithm. The implicit solution method allows for larger computational time steps than explicit solution methods. In addition, the finite volume method provides a greater degree of stability and robustness over traditional finite difference and finite element methodologies. This computational algorithm is very robust and allows 2D cells to wet and dry. 2D flow areas can start completely dry and can handle a sudden rush of water into them. In addition, this algorithm can handle flow regimes that change with time:

- subcritical flow,
- supercritical flow or
- mixed flow (contains both subcritical and supercritical flow, including moving hydraulic jumps)

For the HEC-RAS 2D computational methodology, the following modelling guidance and assumptions are provided:

- vertical fluid motion is negligible,
- velocity is vertically averaged at the cell centre (depth averaged flow),

- energy head is computed at the cell centre,
- Manning’s roughness assigned on cell face using roughness value at cell face centre,
- Manning’s roughness assumed constant across each cell face, although each cell face can have its own value,
- rain on grid is applied uniformly to all cells of the 2D flow area,
- rainfall initial abstraction and other losses need to be accounted for prior to assigning precipitation data,
- at least one external boundary condition must exist on the 2D mesh,
- time step selection should consider cell size and wave speed.

In addition to hydraulic modelling using HEC-RAS 2D 5.0.7 also hydrologic simulations were accomplished to describe catchment from the hydrologic point of view. Furthermore, predictions of daily flows are possible by this type of modelling. Two hydrologic models were evaluated for this purpose – GIS-based distributed watershed model WetSpa (Liu et al., 2002), which uses digital terrain model and various spatial input data (raster layers). The second model used was the conceptual hydrologic TUW model. TUW model is a lumped conceptual rainfall-runoff model, following the structure of the HBV model. The model runs on a daily time step and consists of a snow routine, a soil moisture routine and a flow routing routine (Parajka et al., 2007). This model showed more precise results, and for this reason, only the TUW model version of hydrologic modelling is presented in this study.

2. CATCHMENT DESCRIPTION

The Slaná River basin is affected by floods, there have been identified 31 geographical areas with significant flood risk which are connected with 8 water bodies. At this step the creation, calibration and validation took place to determine the effects of flash floods in the catchment. The pilot area has 271 km^2 with 26 natural sub-catchments in the region of Teplý Vrch - Rimavská Seč of Slaná catchment.

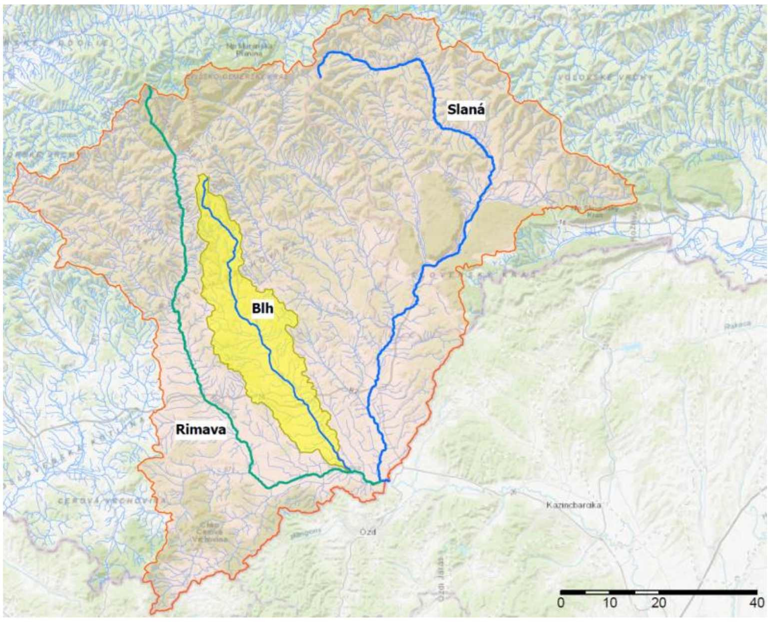


Fig. 1: Localization of Blh River pilot area within catchment of the Slaná River

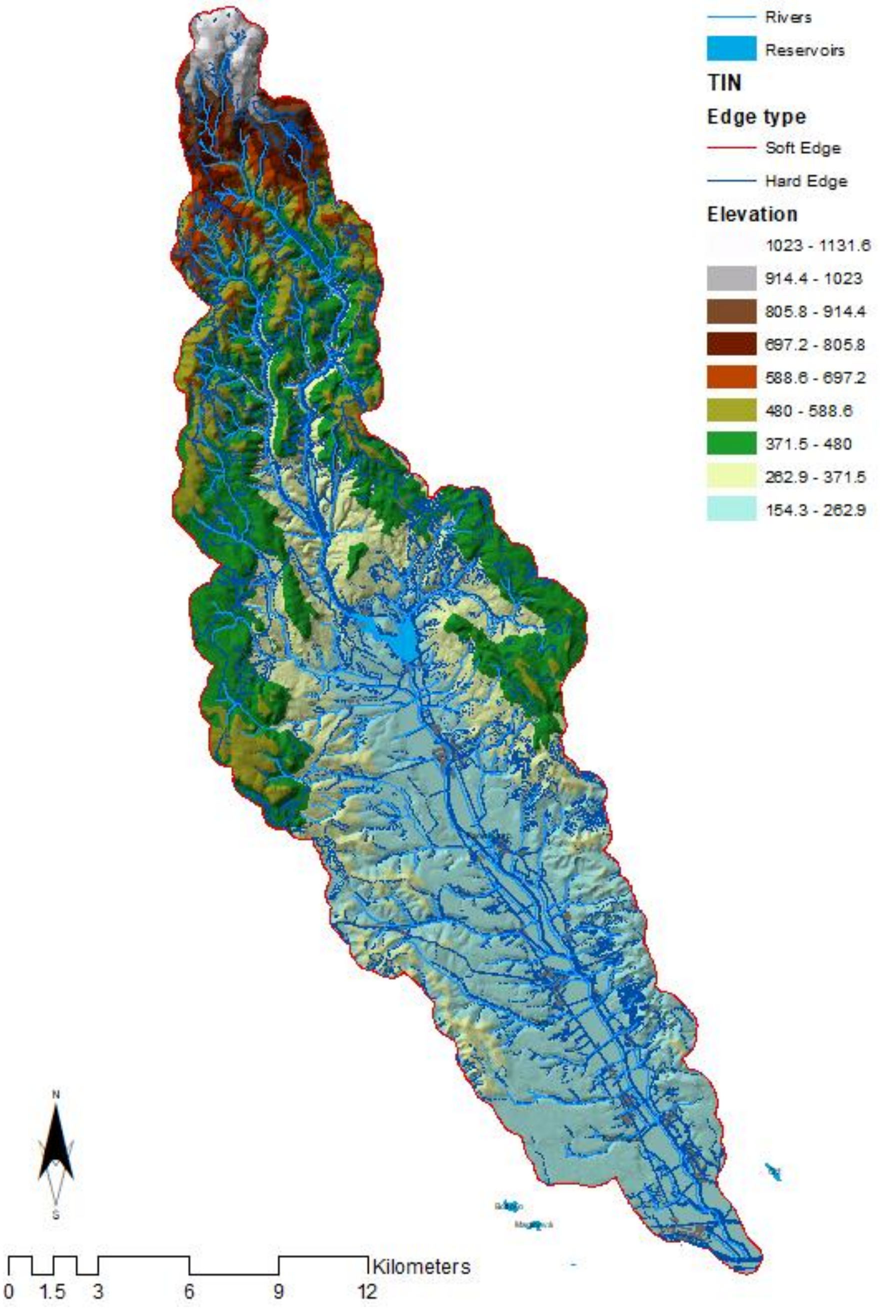


Fig. 2: Pilot area of Blh River (Catchment of the Slaná River)

2.1 Creeks and Rivers

Several significant rivers and creeks are located in the area with numerous tributaries and unnamed creeks. The most significant tributaries of major creek Blh (51.3 km) are Cerové (3.9 km), Radnovský creek (4.7 km), Hnojník (8.3 km), Tomášovský creek (7.7 km), Dražický creek (9.1 km), Panický creek (6.7 km), Veľký creek (7.7km), Papča (14.6 km), Budikovanský creek (6.1 km), Striežovský creek (13.1 km), Hlavinský creek (4.2 km).

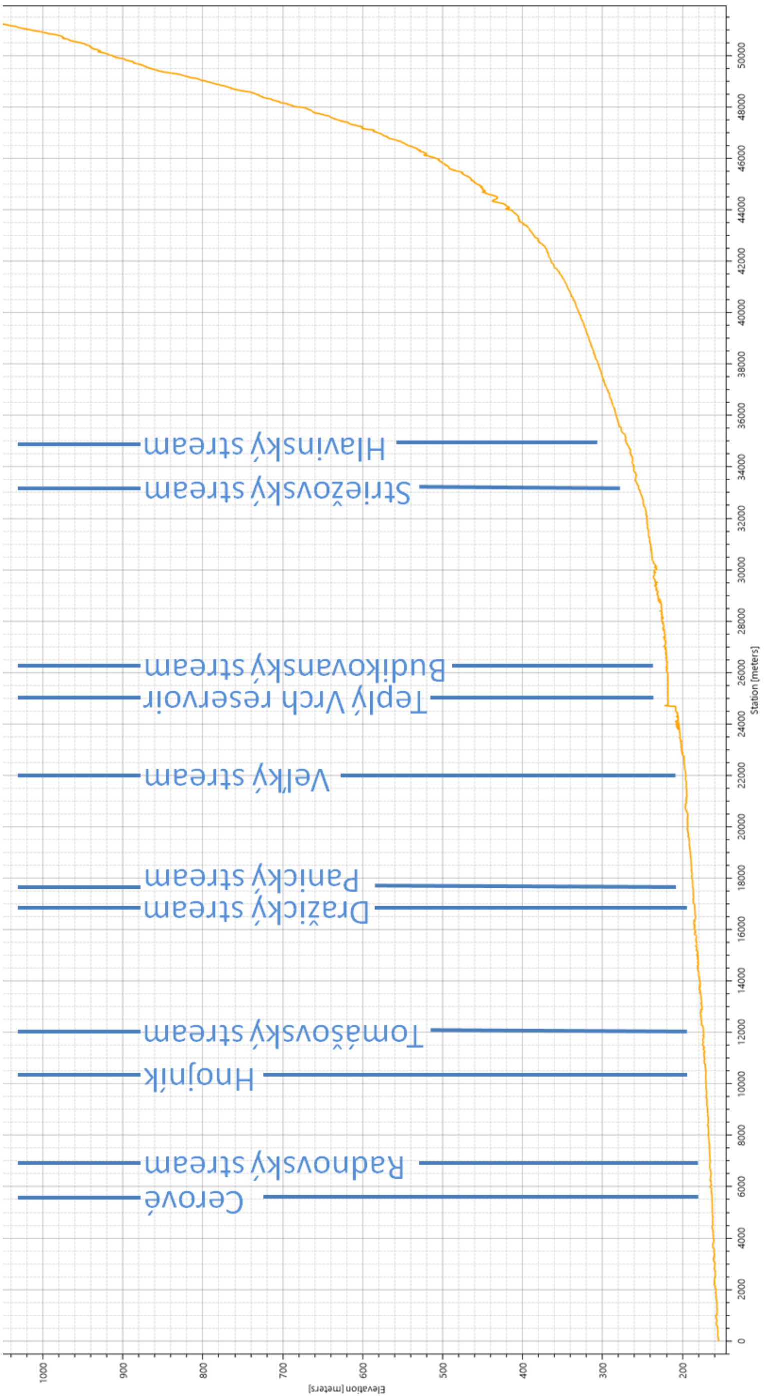


Fig. 3: Longitudinal profile of the Blh River with significant tributaries

2.1.1 Description of the flow regime in period 2003 - 2017

There are three discharge gauging stations in the area of interest, on the basis of which it is possible to describe the flow regime of the given area. These are the gauging stations Drienčany, Teplý Vrch and Rimavská Seč (Fig. 4).

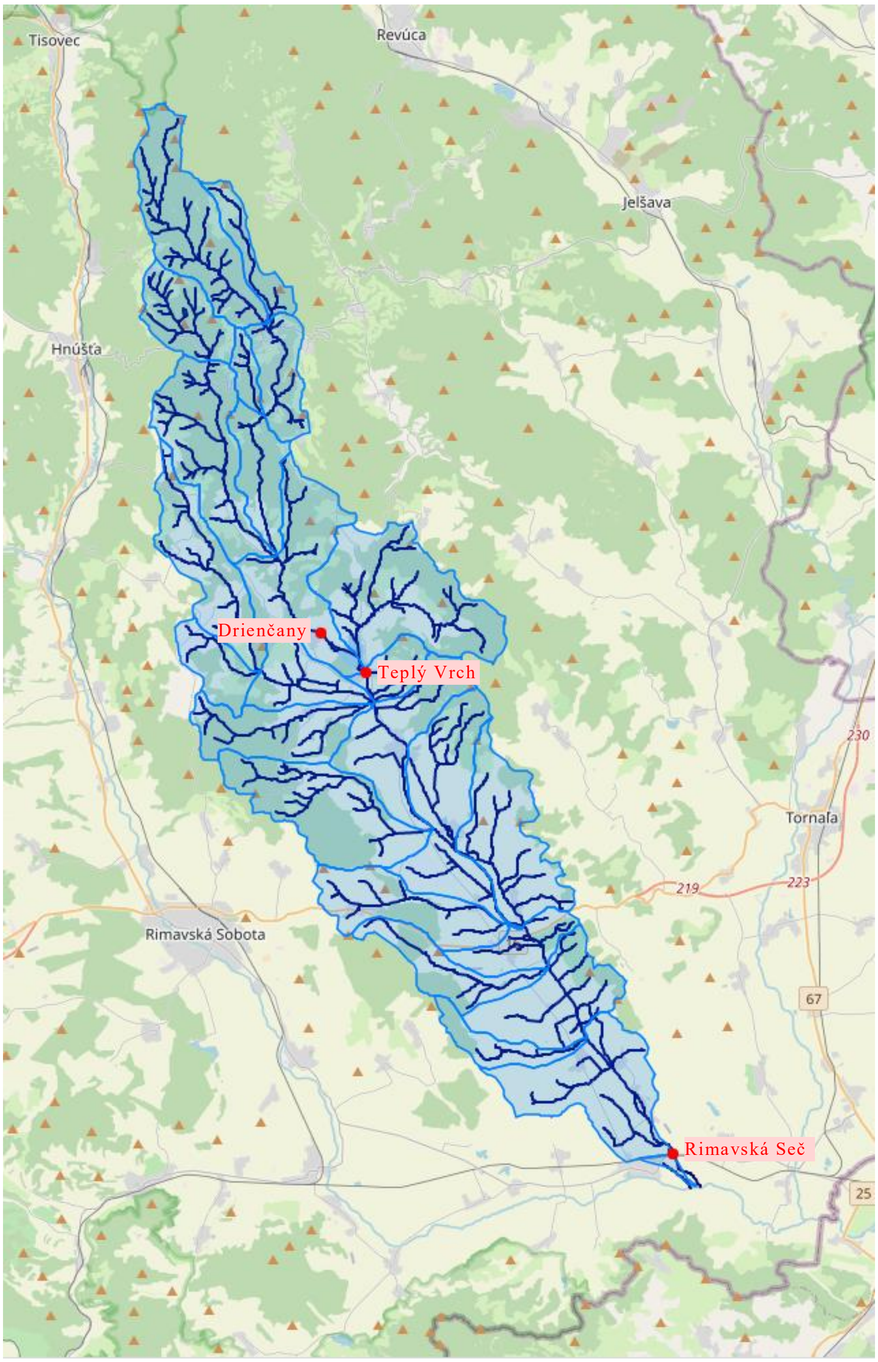


Fig. 4: Discharge gauging stations

In this chapter flow rates were analysed for the period 2003 – 2017 according to availability of hydrologic data. Due to shortness of the period we do not present results of the trend analysis. Data were checked by standard test of homogeneity with result to be accepted as homogeneous. Furthermore, the analysis of represented (uninfluenced) gauging station in Drienčany was performed. In Fig. 5 there are presented mean monthly flow rates, the course of them shows in the second part of the given period radicalization of reached maximum values. The similar reality shows Fig. 6, when evaluating annual flows in Drienčany gauging station.

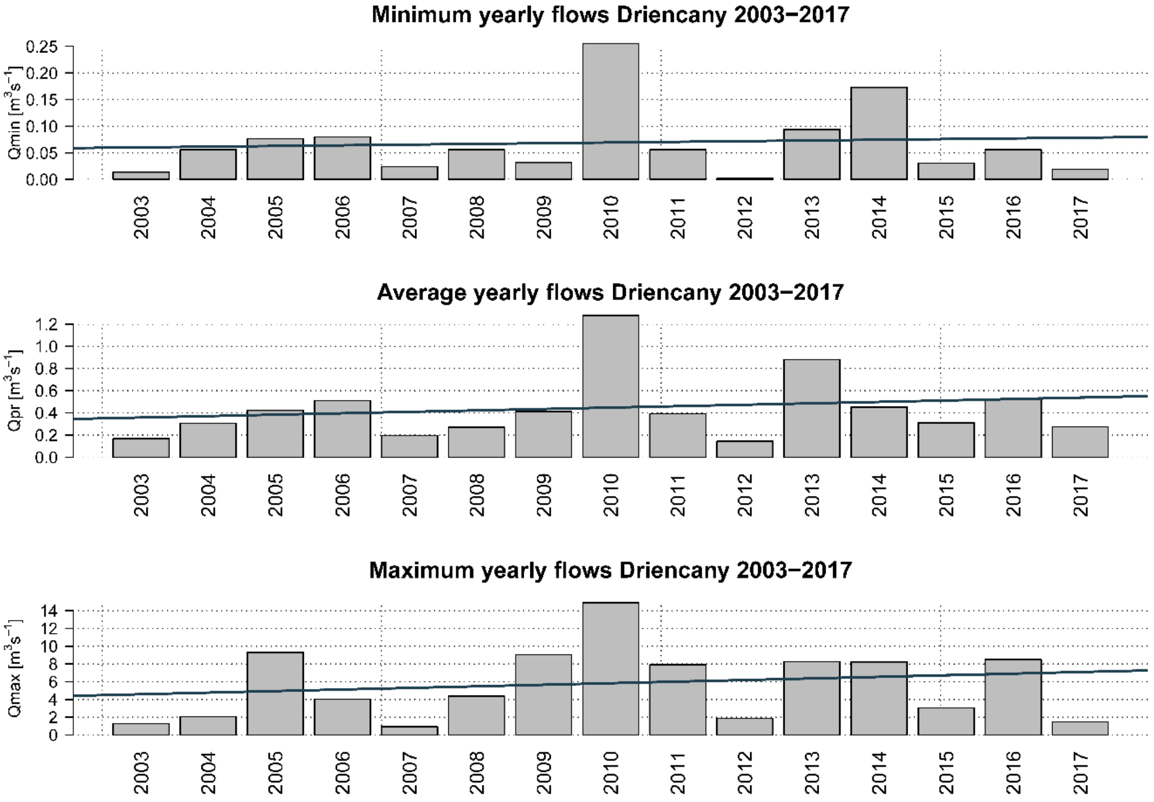


Fig. 5: Average monthly flowsFig. 6: Evaluation of annual flows in Drienčany

In Fig. 7 there is shown the variation of monthly flow rates as they were recorded in the period 2003 – 2017. Flow rates are evaluated by boxplots which represent for each month minimal, maximal measured flow rates and other characteristics of the data set. In Fig. 8 is illustrated time development of these flow rates in the observed period. Illustrated trends for individual months are statistically not significant, neither the trend in February data is practically caused by one exceptional flood in 2016 and therefore it cannot be generalized.

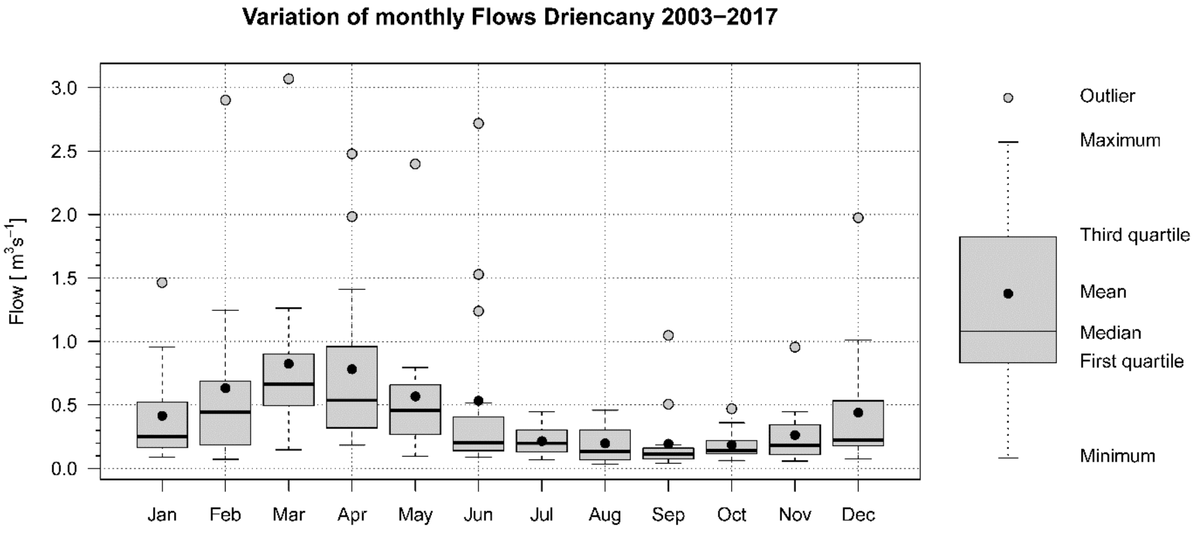


Fig. 7: Variance of monthly flows Drienčany 2003 – 2017

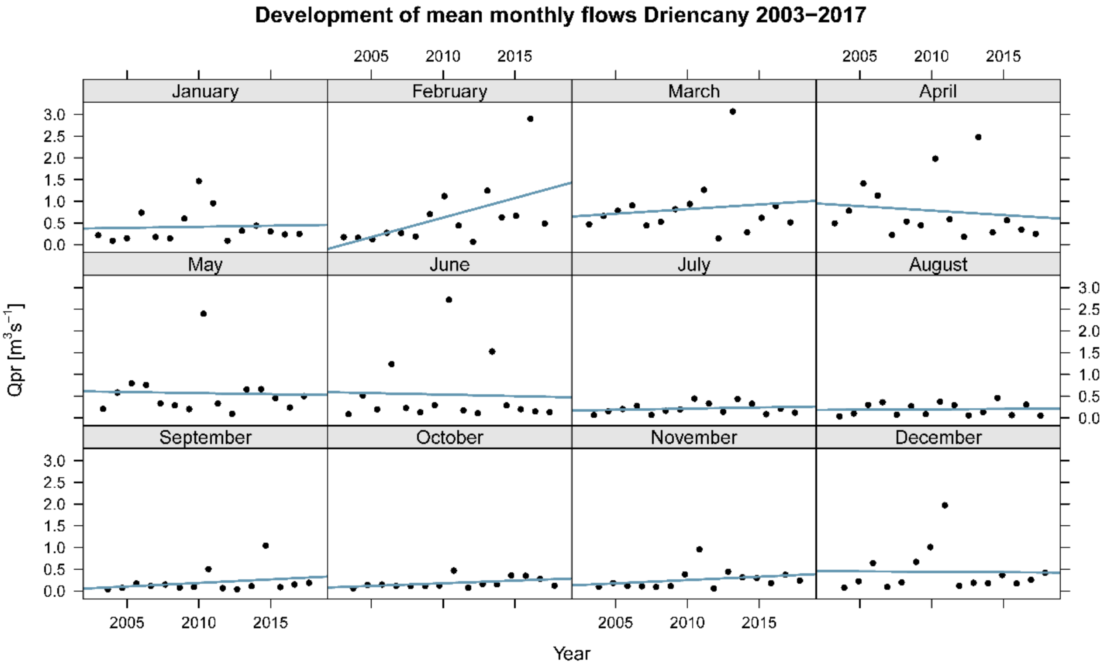


Fig. 8: Mean monthly flow rates in the period 2003 – 2017

On base of daily flow rates in the period 2003 – 2017 a flow duration curve was created (Fig. 9) which shows the data about 5, 30, 90, 180, 270, 330, 355 a 364- days flow rates.

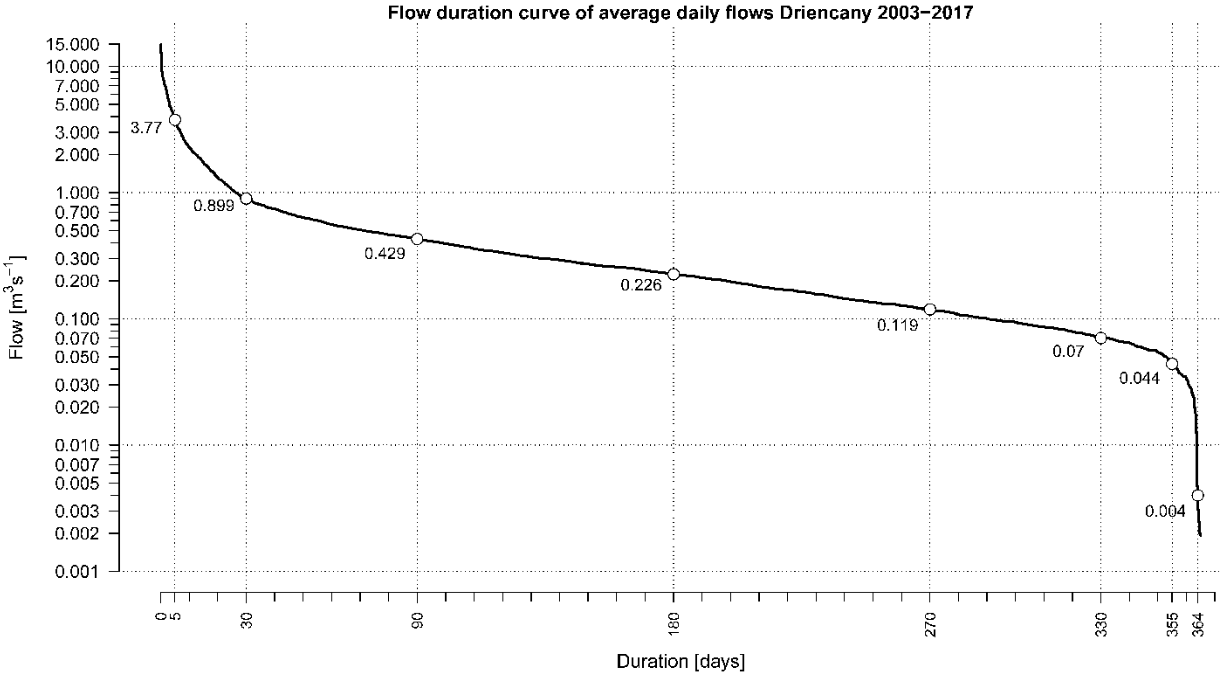


Fig. 9: Flow duration curve in Drienčany using flows from period 2003 – 2017

2.2 Reservoir Teplý Vrch

Water Structure Teplý Vrch is located on the river Blh 300 m below the inflow of the Hostišovský creek and should be considered as central hydraulic and hydrologic node of the pilot area with its functionality, position and operating capabilities.

Owner and administrator of the water structure:

SLOVAK WATER MANAGEMENT ENTERPRISE, state enterprise, branch Banská Bystrica

Partizánska cesta 69, 974 98 Banská Bystrica

Operator:

SLOVAK WATER MANAGEMENT ENTERPRISE, state enterprise, branch Banská Bystrica

Administration of the Slaná River Basin

Cukrovarská 54, 979 80 Rimavská Sobota

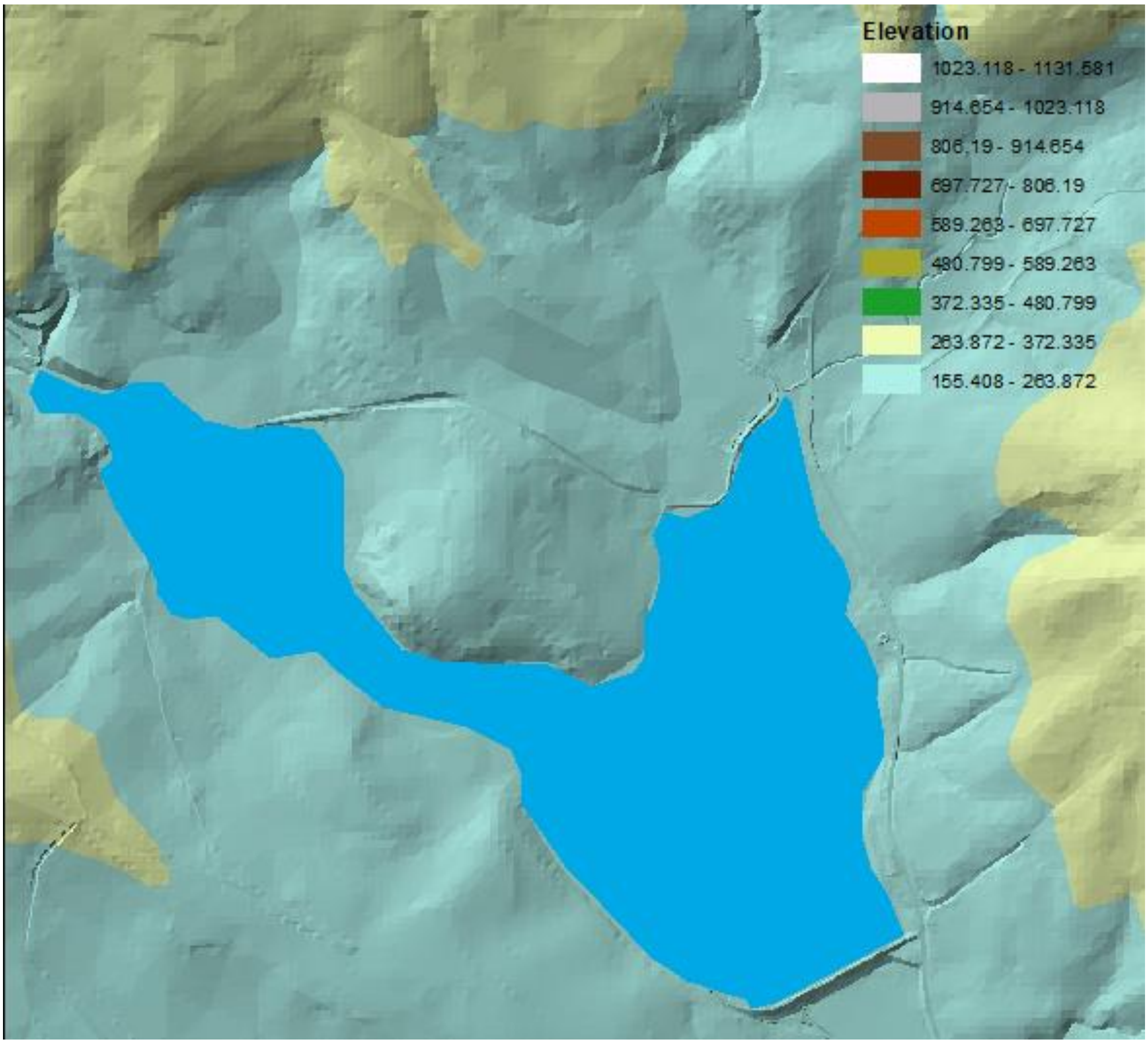


Fig. 10: Teplý Vrch reservoir

Main functions of the water structure:

- Flood wave mitigation and flattening (transformation)

At the maximum water level elevation of 221.20 m a.s.l., i.e. during the transition of flood wave the discharge from the reservoir will flow through the emergency spillway. The capacity of bottom culverts is 8.0 $m^3.s^{-1}$.

In the sense of the above mentioned, the individual levels of min. and max. operating levels on the water structure and the volumes are determined for this purpose for effective flood retention, as well as for re-evaluated procedures in relation to water level operation in the reservoir.

- Utilization of hydro-power potential

There is a small hydropower plant located beneath the water structure using minimum discharge from reservoir Q_{330} = 87 l/s.

- Ensure supply of irrigation water

Spring and summer flash floods are accumulated in the reservoir with subsequent use for irrigation purposes in the irrigation system Teplý Vrch - Rimavská Seč. In the past, 3 841 hectares of agricultural land were irrigated with a take-off security of 85%, what nowadays using the current technical state of the irrigation system is entirely not possible. This fact (non-operation of the irrigation system) is also conditioned by the current situation in agricultural production in Slovakia, as well as the fact that in recent years there have been implemented only sporadic irrigation water take-offs that did not affect the reservoir´s water regime.

- Recreation

Due to climatic conditions and the natural environment the reservoir provides very good conditions for recreation (the temperature of the water up to 30 ° C). Water reservoir is determined as so called Bathing Water profile.

- Fishing

The volume of the reservoir will be used for fish farming in the form of sport fishery.

The water structure was created on the Blh river in the river km 57.2. With its location and technical solution, it has merged in the surrounding natural environment.

Water Structure composition:

- levees,
- associated functional structure,
- emergency spillway,
- water level and discharge measurement devices,
- reservoir,
- control centre,
- small hydropower plant,
- dyke dam,
- Budíkovanský creek repositioning,
- drainage system.

From the point of view of the efficiency of retention of the 100-year flood wave and current capacities of structures as well as water management and operation with water, the following levels of water are set: 0.00 m a.s.l. the minimum operating level. From the bottom of the reservoir 210.00 m a.s.l. to a minimum operating level of 212.00 m a.s.l. the volume is 70 000 m^3. Flooded area at 212.00 m a.s.l. is 7 000 m^2, 0.50 m a.s.l. the maximum operating level is set in autumn, winter and spring months, that is, at the time of the expected higher flow rates. Considering that an unshielded safety strap is only capable of transferring Q_{10}, it is necessary to set the maximum operating level in this period to 218.50 m a.s.l. and thereby create a space for sufficient accumulation of higher floods in the reservoir. The volume at the surface of 218.50 m a.s.l. represents 2 727 mil. m^3 with flooded area of 770 000 m^2, 0.10 m a.s.l. is the maximum operating level set in the summer months (June, July, August) with regard to fulfilment of one of the functions of the water structure - securing suitable conditions for recreation. The water structure operator will maintain the level in the reservoir ranging from 219.00-219.10 m a.s.l. according to the current hydrological and meteorological situation. The volume of the storage space is 3 130 mil. m^3 at minimal level 219.00 m a.s.l. and 3 215 mil. m^3 at the level of the 219.10 m a.s.l. Flooded surface at the altitude 219.00 m a.s.l. is 840 000 m^2, at altitude of 219.10 m a.s.l. is 850 000 m^2, 221.20 m a.s.l. is the maximum allowed water level where the total volume is 5 282 mil. m^3 with flooded area 1 045 000 m^2 .

Volume of retention with respect to the max. permitted water level is:

- 2 485 mil. m^3 at max. operating level (spring, autumn, winter) at 218.50 m a.s.l. 7 mil. m^3 at max. operating level (summer) at the elevation of 218.10 m a.s.l.
- 2 082 mil. m^3 at max. operating level (summer) to the elevation of 218.30 m a.s.l.

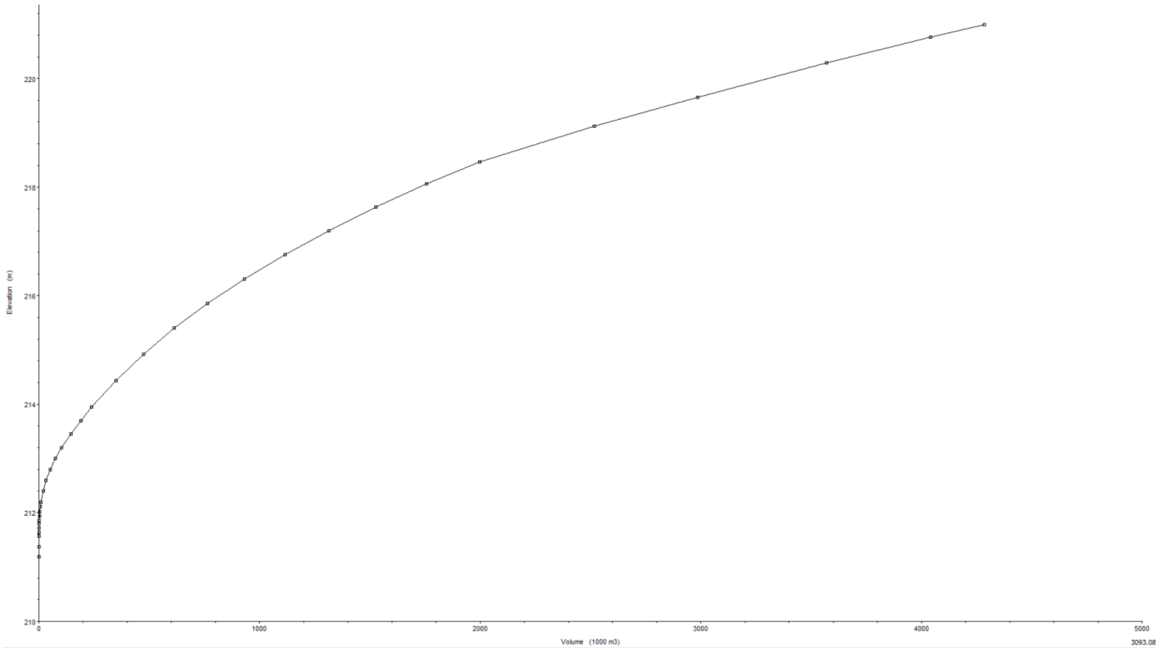


Fig. 11: Volume-Elevation curve of Teplý Vrch reservoir

2.3 Landcover

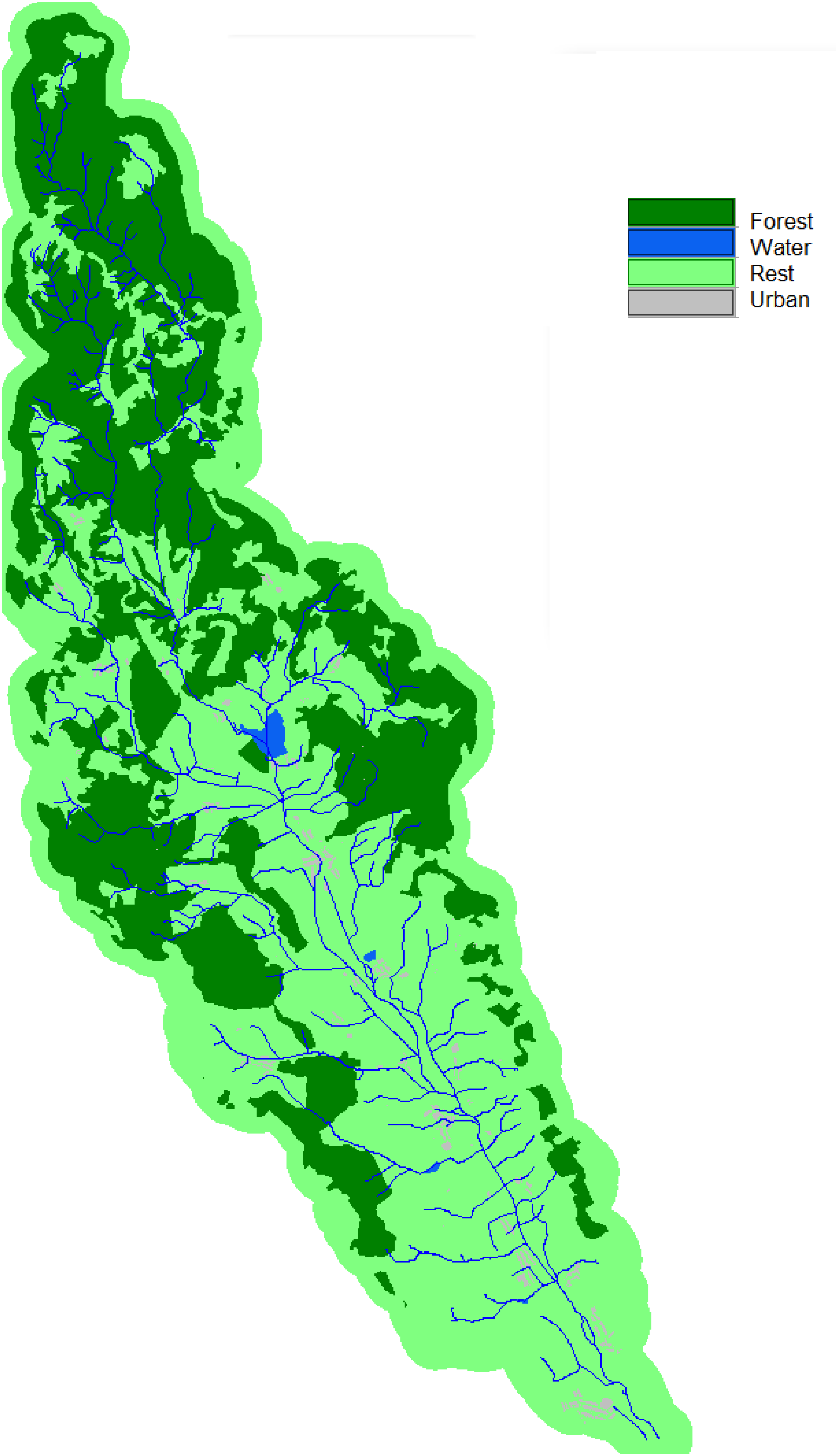


Fig. 12: Landcover map

2.4 Climatic conditions in period 2003 - 2018

The Blh River is a mountain-lowland type river in South-East part of Middle Slovakia. It springs in Stolické hills under peak Tŕstie (1120.9 m a.s.l.) at altitude about 980 m a.s.l. in cadastral area of Rimavská Seč village and it flows into Rimava River at altitude approx. 155 m a.s.l. It means that its river basin is spread in very differentiated region from altitude point of view what influences climatic conditions. Therefore, the evaluation of precipitation and temperatures for two stations are presented in the text below – one from more northern hilly region and the second one from the southern lowland part. For evaluation of precipitation meteorological stations Ratkovské Bystré and Bottovo were selected as well as for temperatures climatic stations Ratková and Rimavská Sobota (Fig. 13).

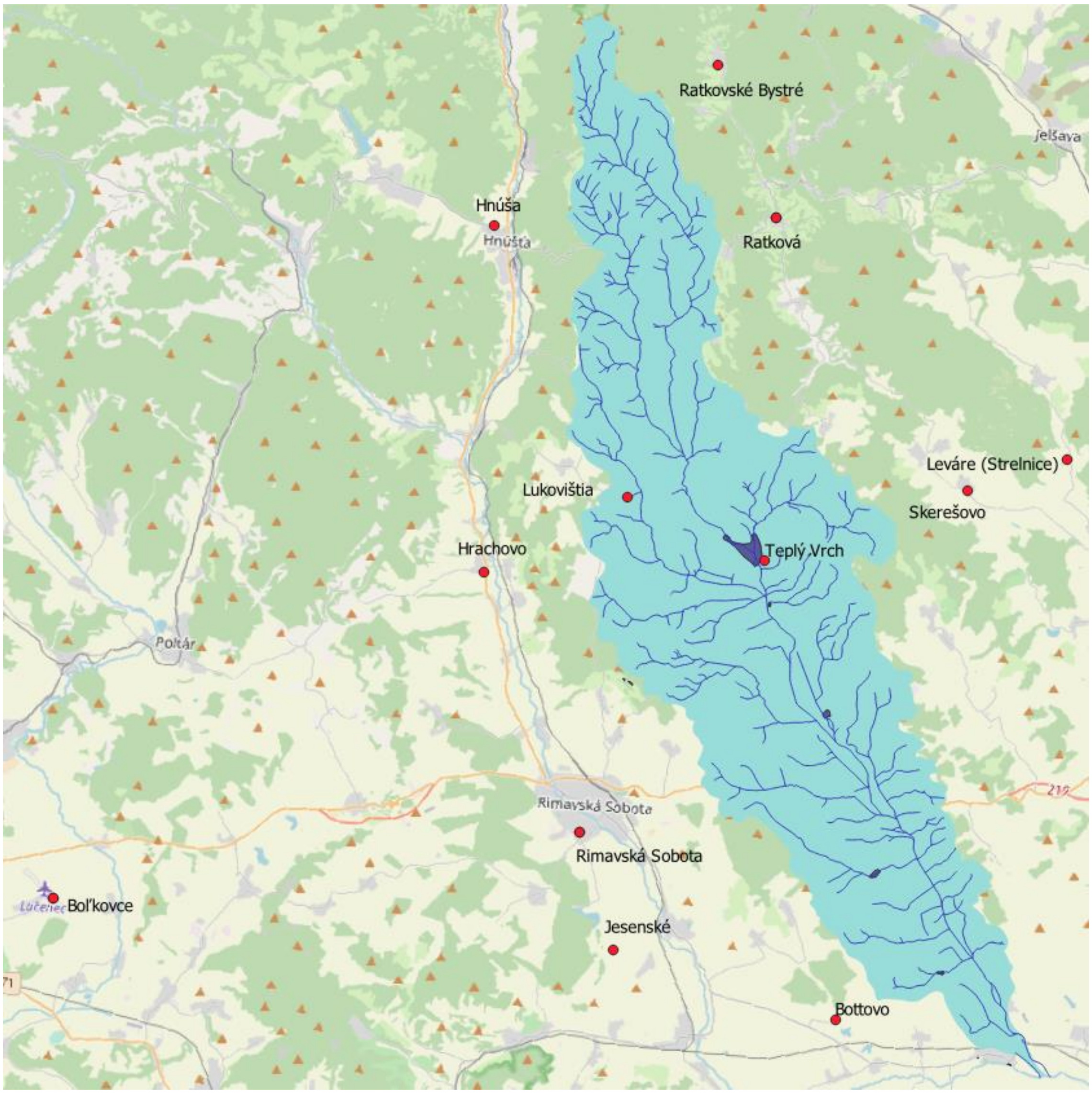


Fig. 13: Precipitation and climatic stations in area of interest

According to Climatic Atlas of Slovak Hydro-meteorological Institute (SHMI) belongs the river basin of the Blh River to region where:

- the mean annual precipitation sum is 580-800 mm,
- the mean seasonal number of days with snow cover is approx. 46 – 77 days,
- the mean annual temperature is 6 - 9 ℃,
- the mean annual wind speed is 2.5 – 4 m/s.

2.4.1 Precipitation

In the Blh River basin there are several precipitation gauging stations operated by SHMI. For characterization of precipitation conditions two stations were selected – Ratkovské Bystré and Bottovo (Fig. 13). In this figure are illustrated another stations, as well. The basic characteristics of these precipitation gauging stations are presented in Tab. 1. Different precipitation in these two stations is possible to compare in Fig. 14 a 15. The precipitation courses do not show any tendency.

Tab. 1: Basic information on precipitation gauging stations used for evaluation. Last column presents the mean annual precipitation total for period 2003 - 2018

ID SHMU	Name	LAT [˚]	LON [˚]	Z [m a.s.l.]	Mean. annual prec. total [mm]
53200	Ratkovské Bystré	48,6461	20,0597	402	843
54280	Bottovo	48,3139	20,1519	195	604

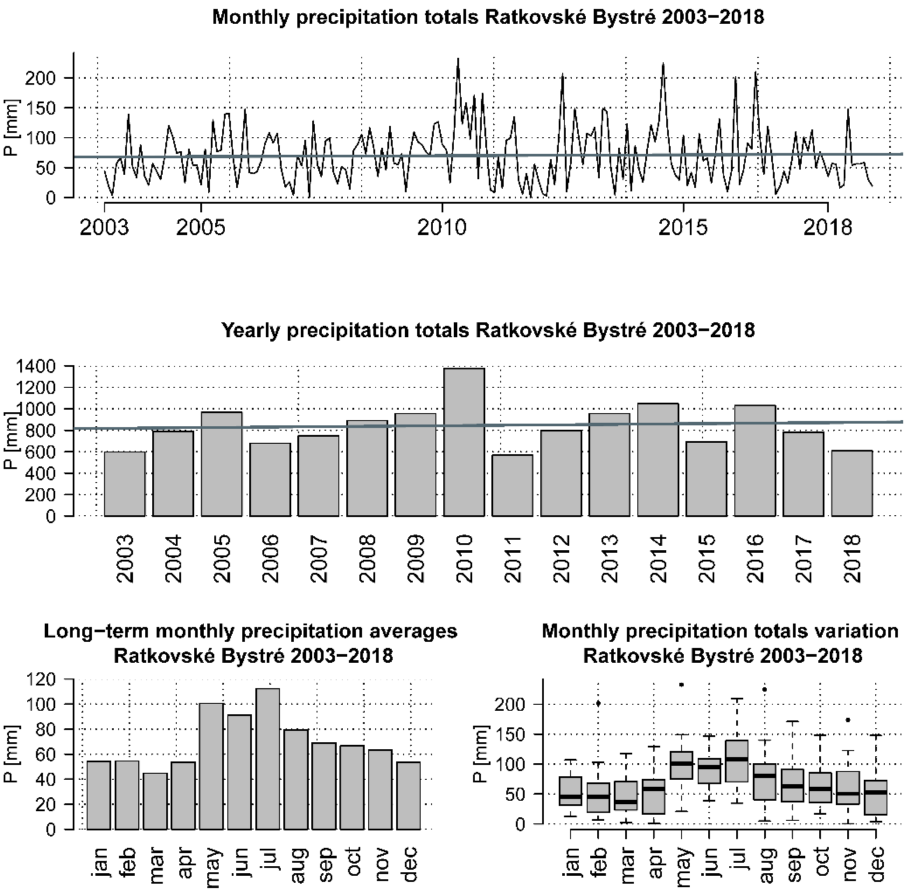
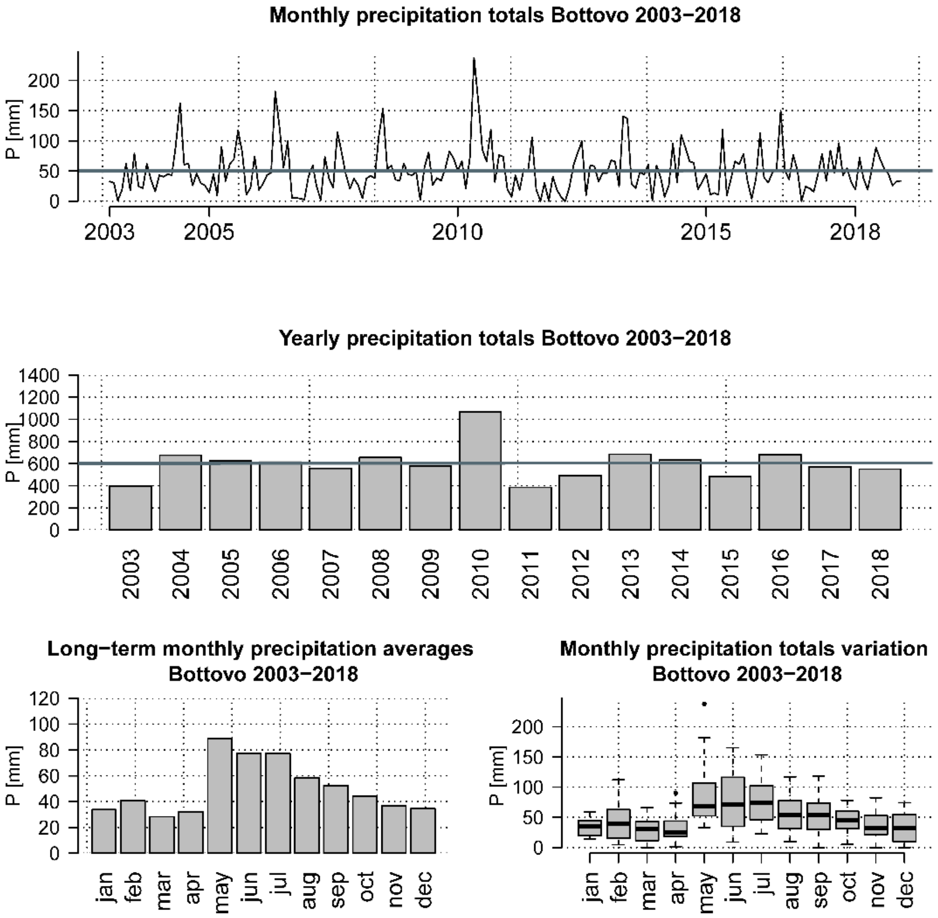


Fig. 14: Precipitation regime in the Ratkovské Bystré station in the period 2003 - 2018


Monthly precipitation totals Bottovo 2003−2018

Yearly precipitation totals Bottovo 2003−2018

Long−term monthly precipitation averages Bottovo 2003−2018

Monthly precipitation totals variation Bottovo 2003−2018

Fig. 15: Precipitation regime in the Bottovo station in the period 2003 - 2018

2.4.2 Temperatures

From close surrounding of the Blh River basin two climatic stations were selected for the assessment of temperature conditions – stations Ratková and Rimavská Sobota - both of them operated by SHMI. (Fig. 13). The first is located in the hilly part of the river basin and lower temperatures can be observed there comparing with data from Rimavská Sobota station which is located in the southern lowland part of the river basin. Temperature data show in the given period a gentle but statistically significant tendency, therefore the development of monthly temperatures are illustrated in following figures. Basic characteristics of these two climatic stations are given in Tab. 2. The different air temperature regime in these two climatic stations is possible to compare in Fig. 16 and Fig. 18. Fig. 17 and 19 demonstrate the trend characteristics in individual months.

Tab. 2: Basic information on climatic stations used for evaluation. Last column presents the mean annual temperature for the period from 2003 to 2018

ID SHMU	**Name**	**LAT [˚]**	**LON [˚]**	**Z [m a.s.l.]**	**Mean annual temperatures [˚C]**
11941	Ratková	48,5922	20,1000	311	9,2
11942	Rimavská Sobota	48,3739	20,0106	215	10,3

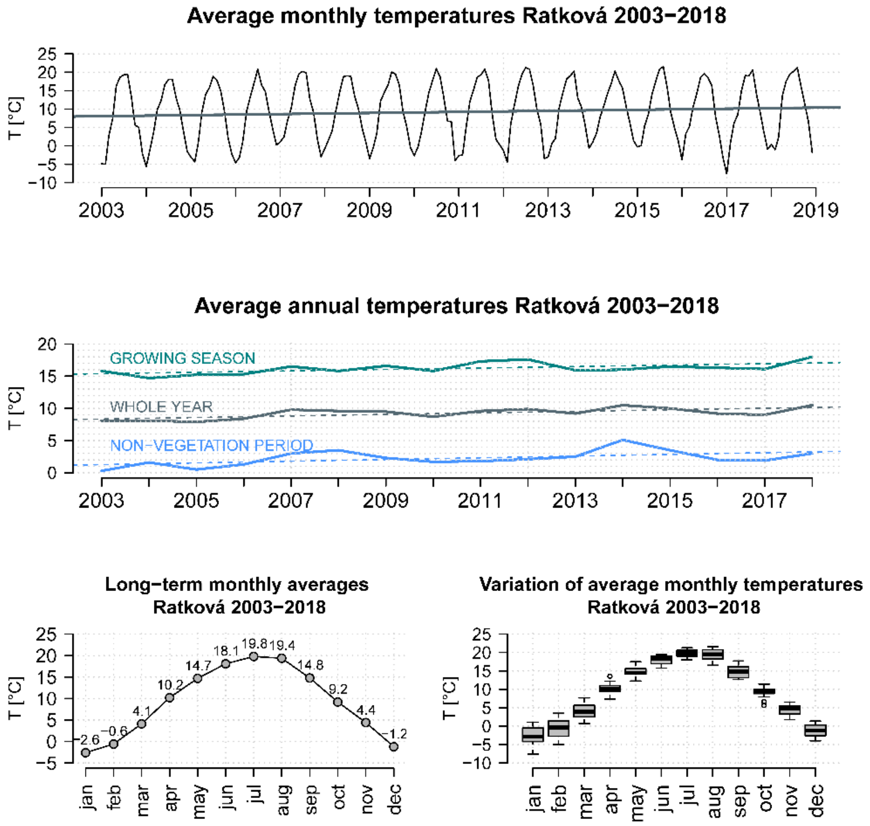


Fig. 16: Temperature regime in the Ratková station in the period 2003 – 2018

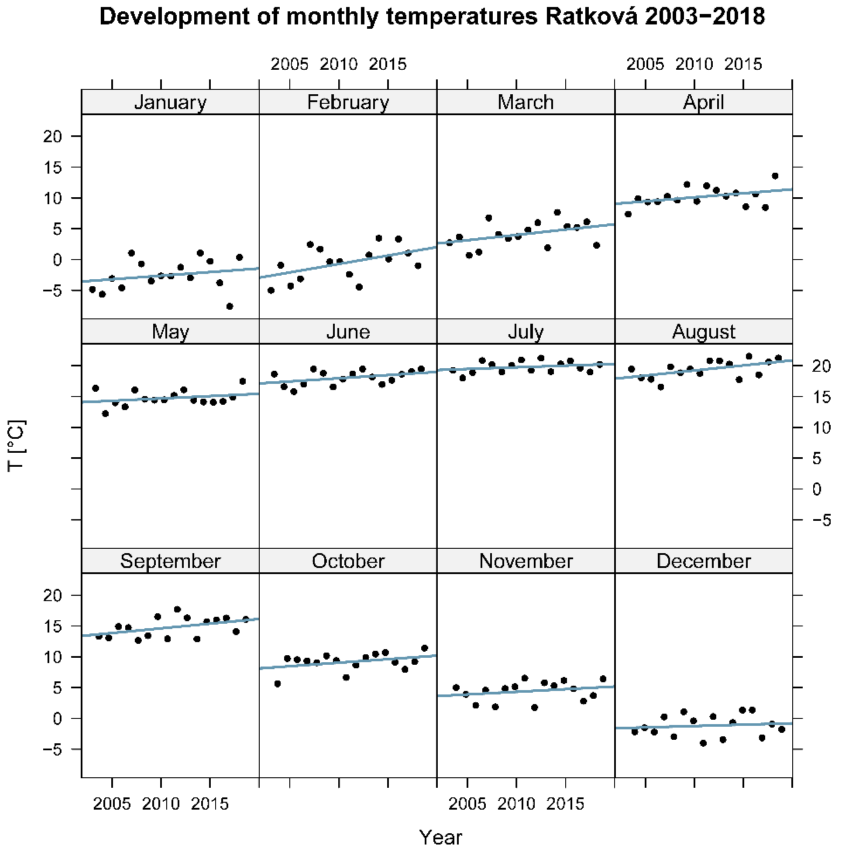


Fig. 17: Mean monthly temperatures at Ratková station for the period 2003 – 2018

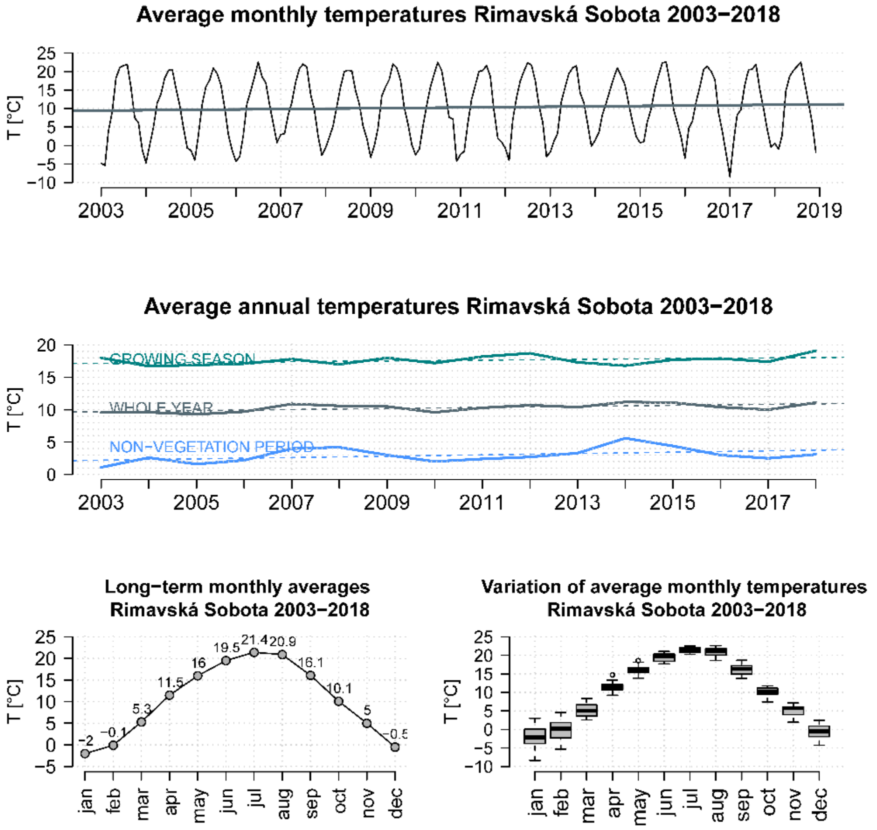


Fig. 18: Temperature regime in the Rimavská Sobota in the period 2003 - 2018

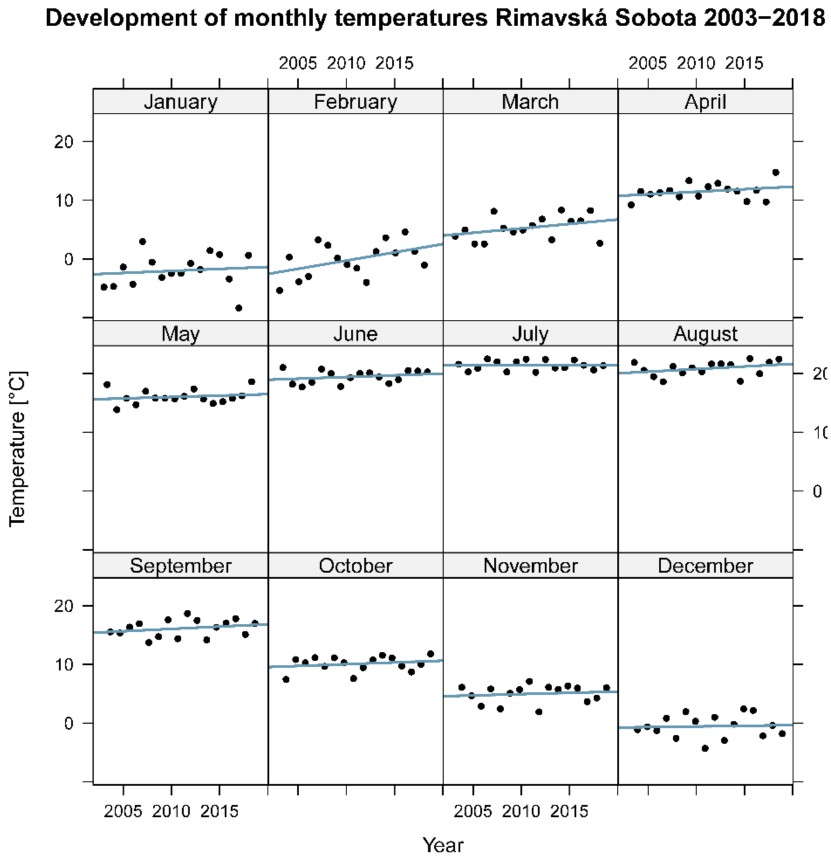


Fig. 19: Mean monthly temperatures in Rimavská Sobota for period 2003 – 2018

3. MODELLED CONDITIONS

2D flow areas are created by constructing polygon areas representing the regions to be modelled. Along the 2D flow area polygon mesh boundary, boundary condition polylines are defined to represent different flow conditions or constraints that are to be applied to the 2D flow area. Two main boundary conditions were applied for the purpose of hydrodynamic simulation of runoff in the pilot area of Slaná River catchment.

3.1 Precipitation

One type of boundary condition is precipitation. Precipitation is "area type" of boundary condition set for every computation node (mm per time unit) in the domain. The precipitation boundary condition should be set either as constant or time depended with defined time step.

3.2 Outflow

Outflow boundary condition represents **flux boundary** where flow leaves the 2D flow area. (Boundary conditions can also be defined within the interior of the 2D flow area, to represent additional discharge that enters the 2D flow area - such as flow from a wastewater treatment plant.)

Examples of flux boundaries are:

- Inflow hydrograph,
- stage hydrograph (time series),
- fixed water surface elevation,
- normal depth (given user-defined energy slope),
- tidal (time-series).

The normal depth boundary condition was set as the outflow.

3.3 Computational mesh

An important aspect of a 2D model is a computational mesh. The HEC-RAS program can handle a structured mesh or an unstructured mesh. A structured mesh is comprised of rectangular cells, and an unstructured mesh is comprised of cells that have an irregular shape.

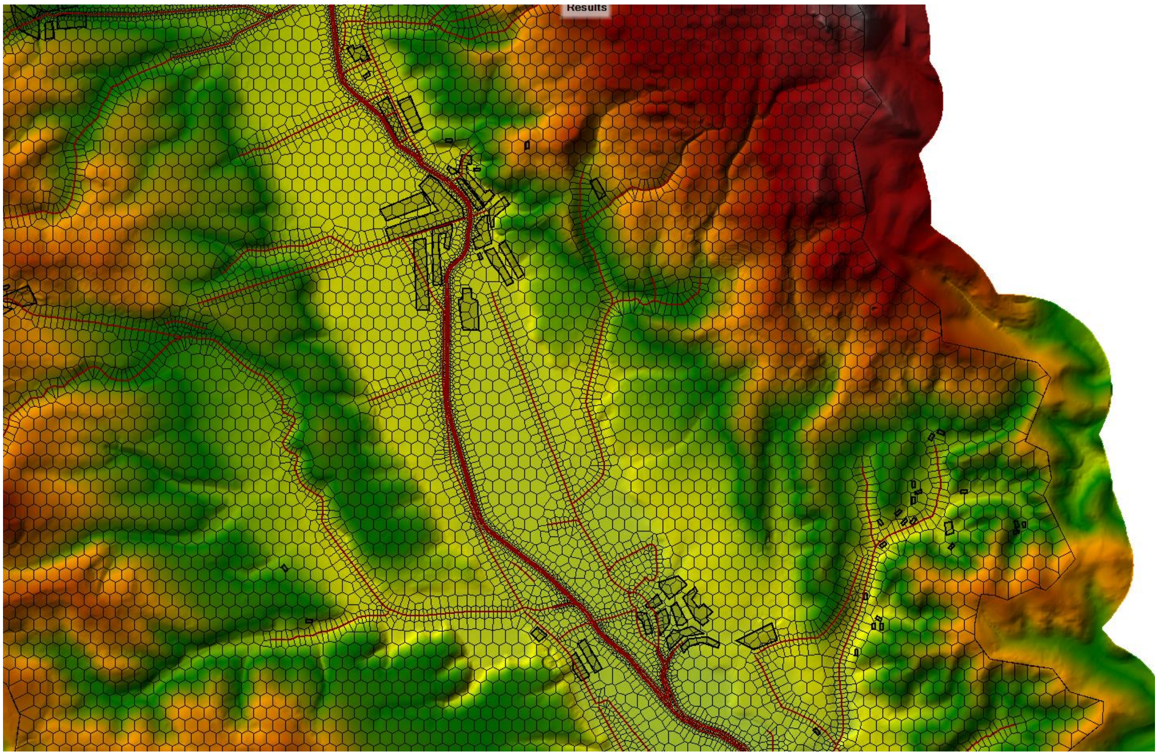


Fig. 20: Generated computational mesh

The resolution of the 2D model grid will impact the results in that it will determine the scale of physical features and flow behaviour. Cell size depends on a variety of factors including:

- The spatial resolution of the topographic data,
- the level of detail needed in the model outputs,
- run time and
- size of the study area.

Recommend starting out with a larger cell size. This will help user to identify issues quickly rather than running the model for eight hours before discovering a problem. It is important to note that when modelling areas where water surface and velocity changes, a small cell size should be used. A smaller cell size will minimize errors. It is important to note that it should be transition from larger cell sizes to smaller cell size *gradually* in order to improve computational accuracy.

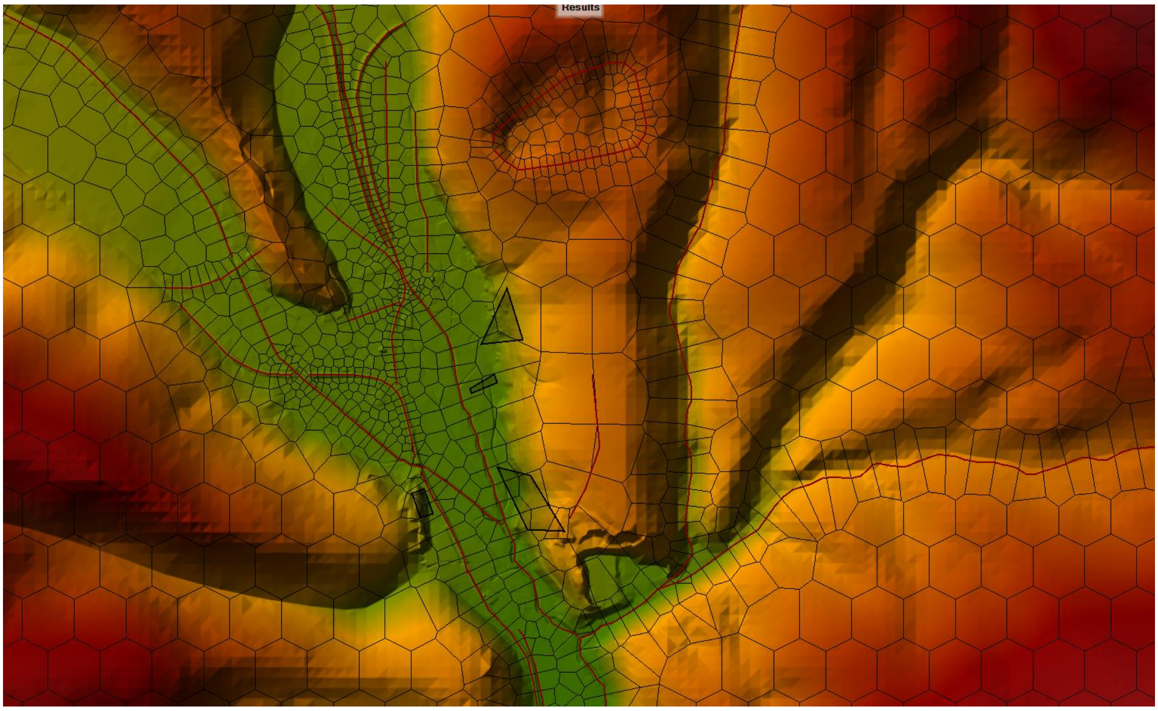


Fig. 21: Generated computational mesh - detail

The breaklines are used to refine the computational mesh and force the cell faces to align along a specified line. They are a critical part of realistic representing flow through an area.

4. CALIBRATION

The goal of the model calibration procedure was to quantify the mathematical model accuracy of an actual parameters setup, compare it to the real field measurements and decide if the modelling is accurate enough to be used as a relevant modelling tool. Basically it is a process of accuracy quantification and representativeness of mathematical model compared to real field data from possible utilization perspective.

Besides landcover/landuse parameters also simulation setup (numerical scheme, mesh resolution and existing structures parametrization, precipitation reduction factor) were calibrated to obtain most accurate results. At the stage of calibration also the correct time step increment method and limits were developed to ensure calculation stability and results reliability.

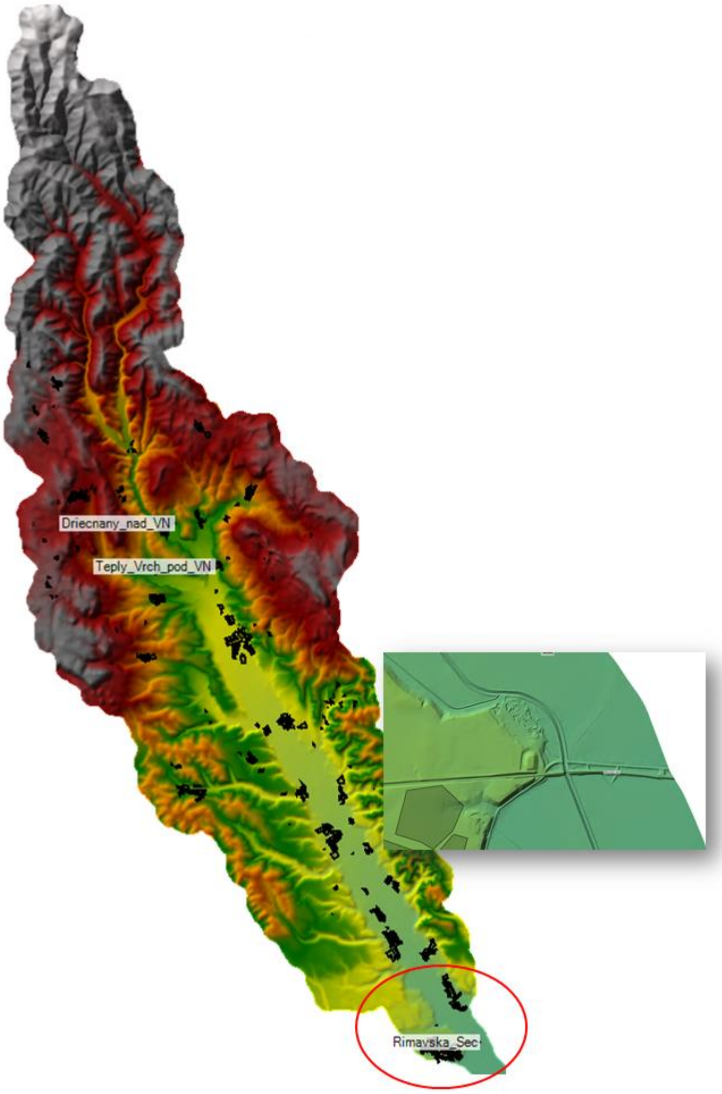


Fig. 22: Rimavská Seč – monitoring profile

The Blh pilot catchment was under heavy rain at the beginning of June 2010. The event was taken as calibration time window and lasts about 40 days. The data were collected and triangulated from 3 different hydrological stations. Peak discharge at the main monitoring profile was determined as Q_{20} flood discharge.

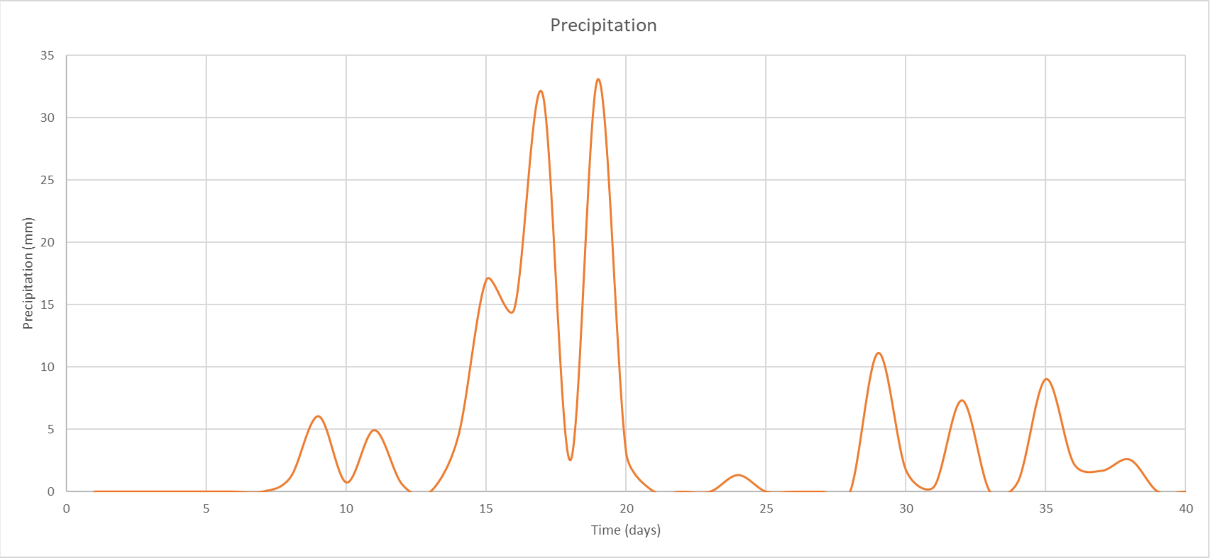


Fig. 23: Calibration - precipitation event

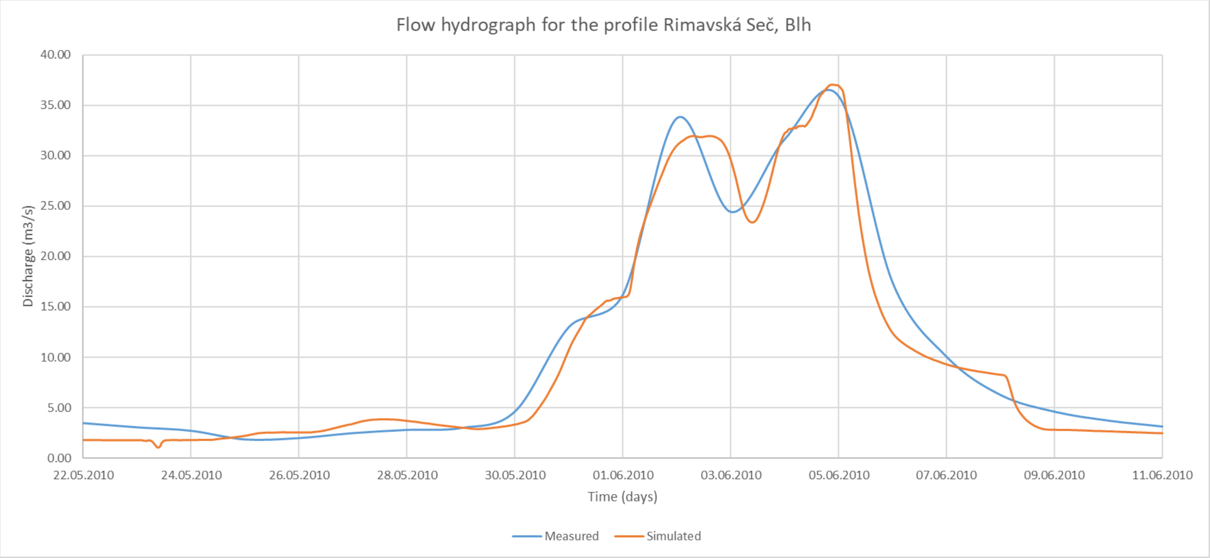


Fig. 24: Calibration – Comparison between measured and simulated results

5. VERIFICATION

Verification is the process of comparison of already calibrated model on the other set of precipitation data and the results with real field measurements.

The Blh pilot catchment was under heavy rain at the beginning of May 2010. The event was taken as verification time window and lasts about 30 days. The data were collected and triangulated from 3 different hydrological stations. Peak discharge at the main monitoring profile was determined as Q_5 flood discharge.

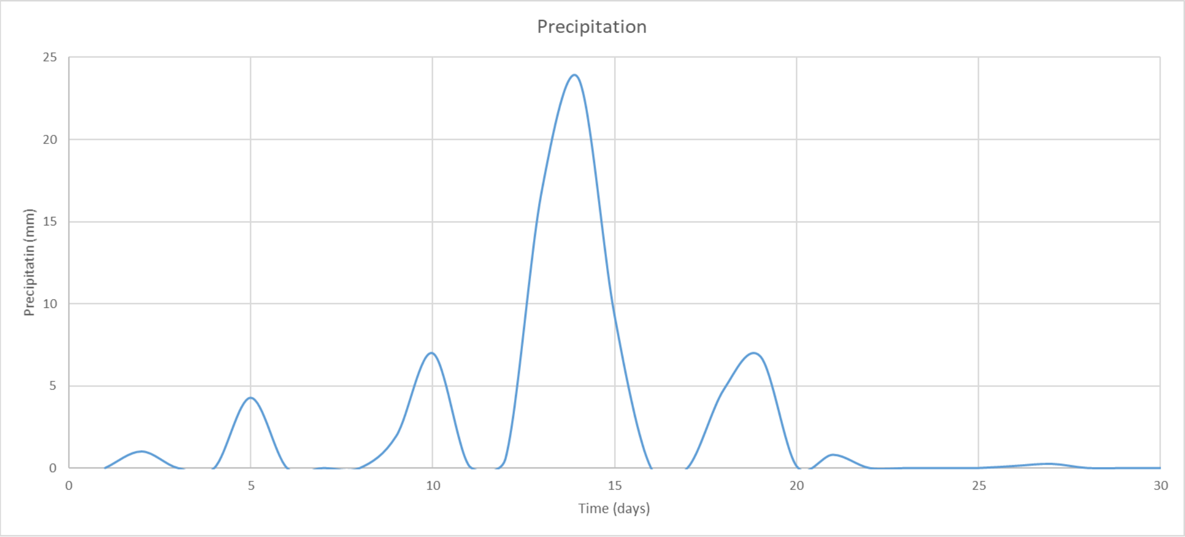


Fig. 25: Verification - precipitation event

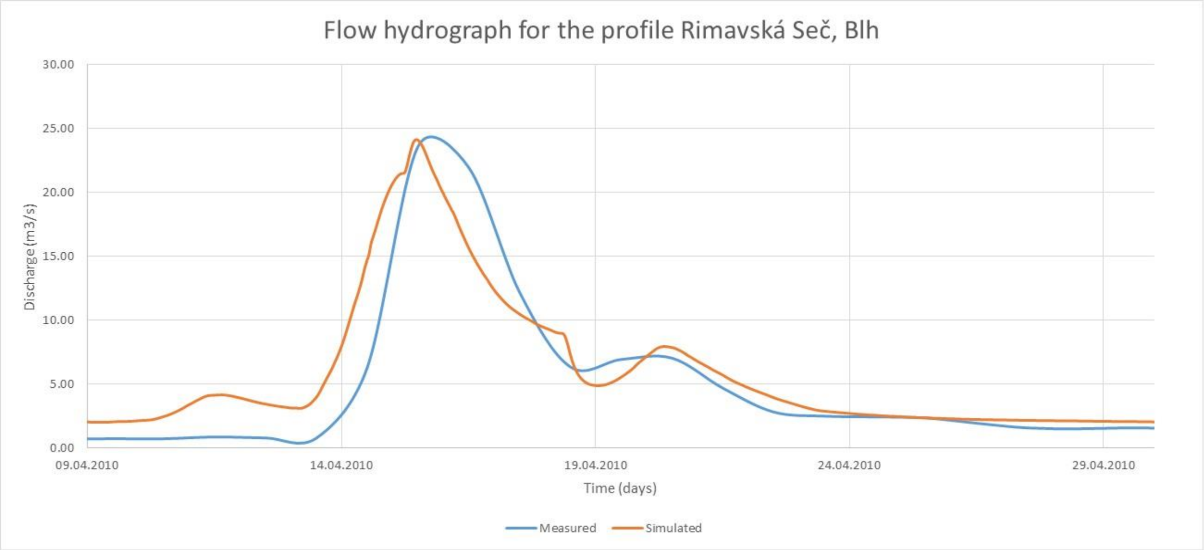


Fig. 26: Verification – Comparison between measured and simulated results

6. Long term precipitation event

For determining the worst possible flood event for the catchment of Blh River at current conditions the water level of Q_{100} had to be reached at the location of the main monitoring profile. As the highest risk the total volume of flood wave should be taken into account. The water level of Q_{100} at Rimavská Seč monitoring profile is 161.65 m a.s.l.

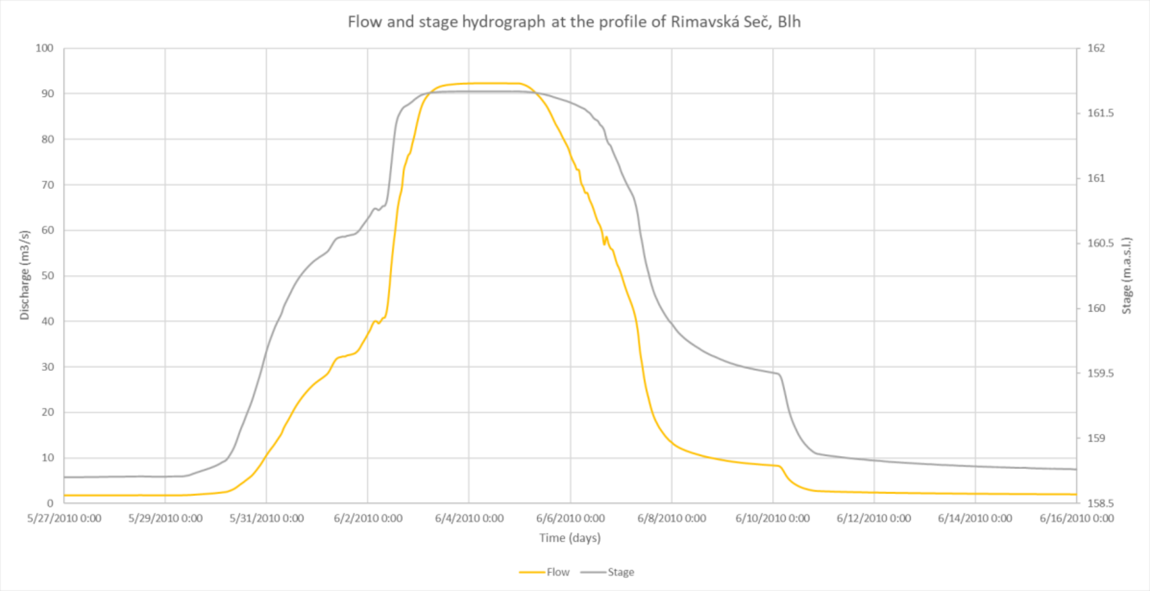


Fig. 27: Flow and stage hydrograph for proposed event – long term precipitation event

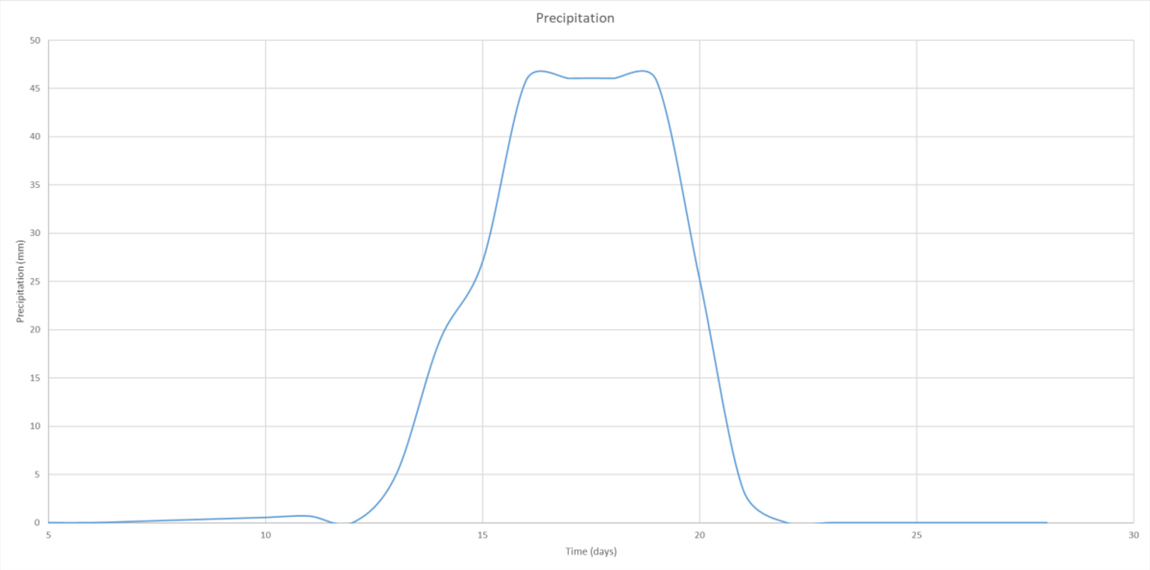


Fig. 28: Designed precipitation for proposed event – long term precipitation event

7. FLASH FLOOD PRECIPITATION EVENT

For determining the flash flood as possible flood event for the catchment of Blh River at current conditions with the water level of Q_{100} reached at the location of the main monitoring profile. As the biggest risk short time of flood wave formation should be taken into account. The water level of Q_{100} at Rimavská Seč monitoring profile is 161.65 m a.s.l.

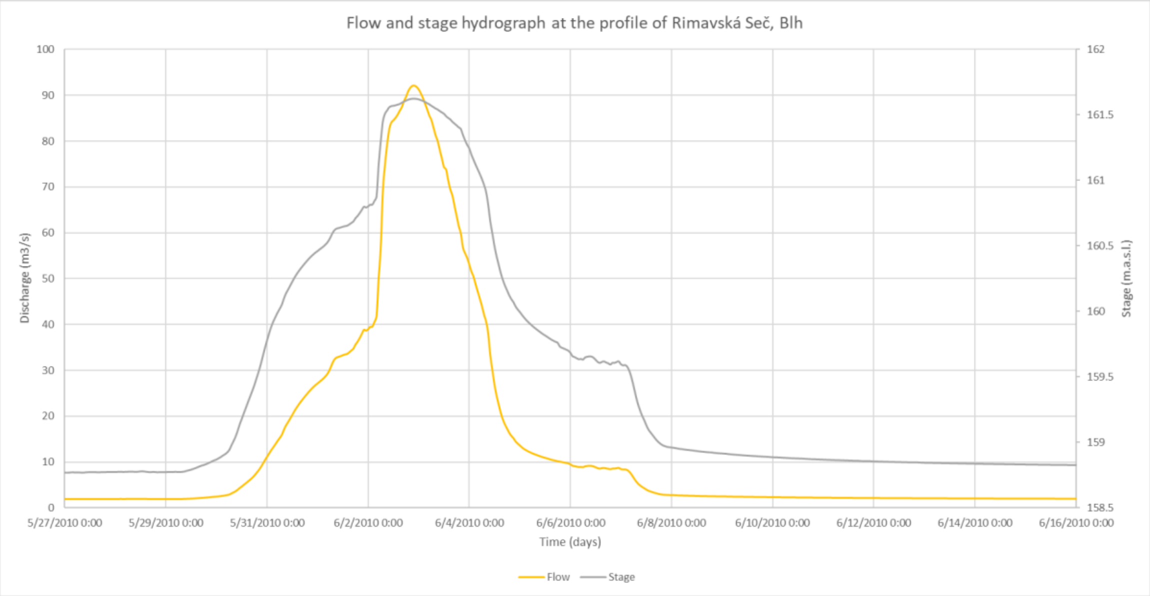


Fig. 29: Flow and stage hydrograph for proposed event – flash flood precipitation event

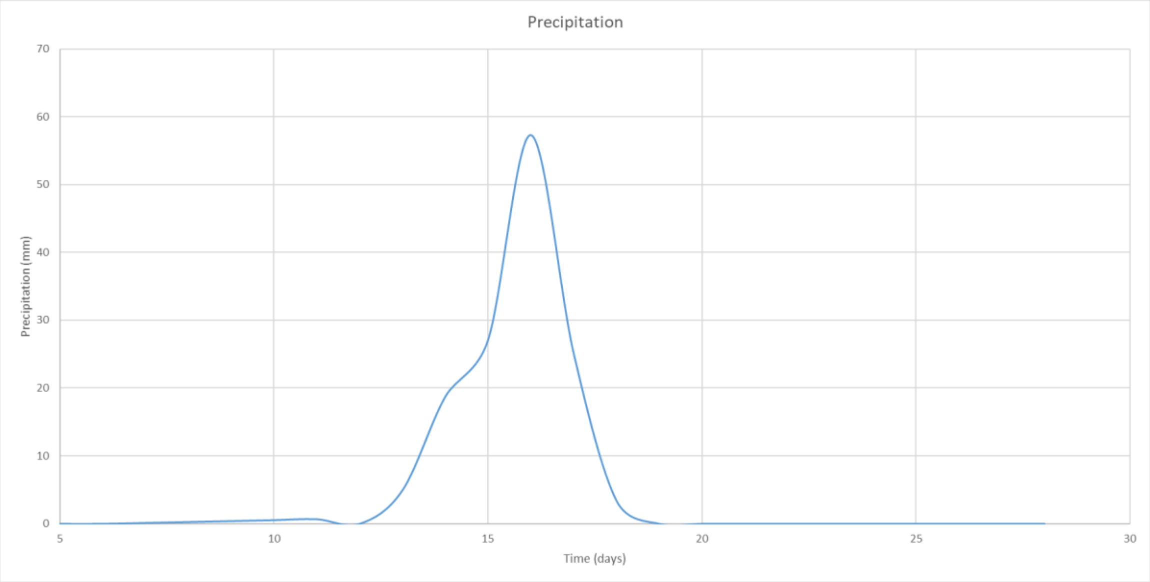


Fig. 30: Designed precipitation for proposed event – flash flood precipitation event

8. RESULTS

The primary objective at current project stage was to develop, calibrate and verify simulation model of the pilot area in Slovakia. The pilot area is located in Slaná catchment river basin. The area has 271 km^2 in the region of Teplý Vrch - Rimavská Seč.

2D hydrodynamic model HEC-RAS 5.0.7 was adopted to simulate precipitation runoff and the flood formation due the heavy rain event. Despite of the simplification of landcover/landuse parameterization only through the roughness evaluation it can be concluded that the calibration and verification process was successfully realized. The results are reliable for the flood formation simulations and prepared for next possible exploitation such as:

- floodplain mapping,
- velocity mapping,
- flood intensity mapping,
- potential of erosion and sedimentation in the catchment, stream power,
- assessment of flood protecting objects already constructed / planned to be realized,
- proposal and optimization of the flood protecting structures,
- other objectives in relation to the flood formation with spatial and time distribution.

The secondary objective was to propose measures and management procedures for flood wave transformation at the level equal to study/pilot report. It is needed to point out that this study has not proposed the flood protecting measures in detail. Optimization and other analyses are needed to propose flood protection effectively.

To effectively determine the highest possible risk in terms of spatial and time discharge distribution it is crucial to divide catchment into smaller logical units – Spatial Planning Units (SPU).

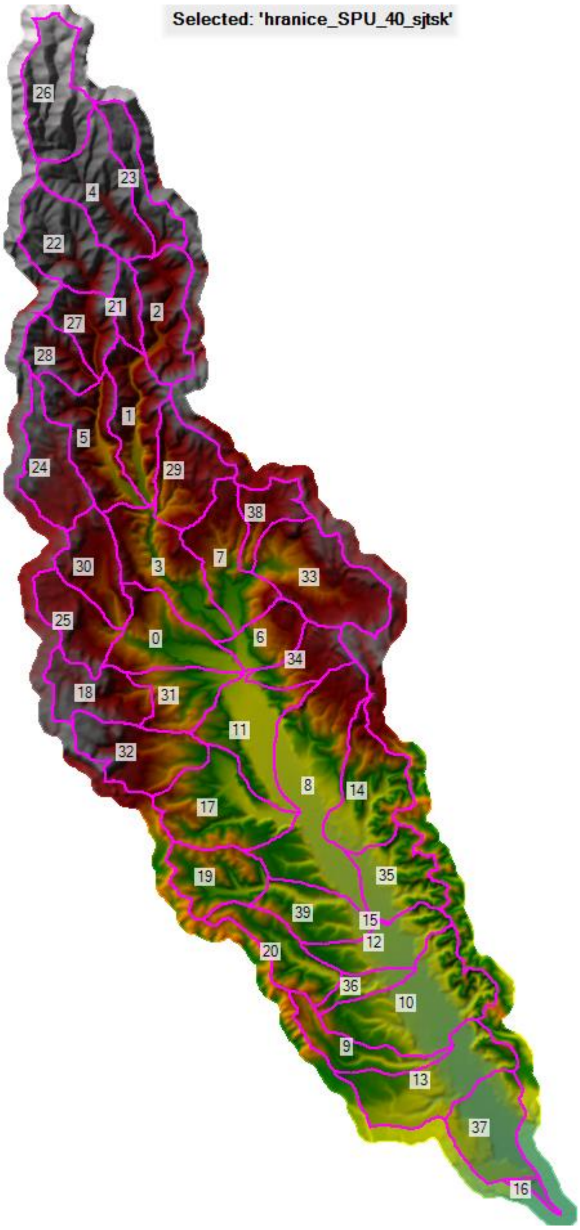


Fig. 31: Catchment of Blh River – SPU units

The catchment of Blh River was divided into the 40 SPU units with parameters as presented in Tab. 3.

Tab. 3: SPU Units parameters

id	Area	HCP	Boundary length
8	17197618	4-31-03-128	25244
10	13268821	4-31-03-134	17748
33	11565808	4-31-03-119	23480
17	10291550	4-31-03-127	21266
13	10095789	4-31-03-136	22240
3	9359132	4-31-03-118	24765

id	Area	HCP	Boundary length
4	9002057	4-31-03-111	22115
14	8801671	4-31-03-131	22914
11	8590527	4-31-03-126	20599
26	8461098	4-31-03-111	22115
5	8222841	4-31-03-117	21639
22	8163654	4-31-03-116	12154
7	7951895	4-31-03-119	23480
32	7871592	4-31-03-127	21266
0	7791755	4-31-03-123	14283
37	7731827	4-31-03-136	22240
1	7326634	4-31-03-115	14140
2	7270871	4-31-03-113	12619
29	7253801	4-31-03-118	24765
24	6816276	4-31-03-121	21922
35	6627416	4-31-03-131	22914
19	6164731	4-31-03-129	18615
30	6057845	4-31-03-121	21922
18	6039537	4-31-03-124	18267
12	5986664	4-31-03-132	12998
20	5837995	4-31-03-133	18099
39	5793520	4-31-03-129	18615
25	5612562	4-31-03-122	10884
31	5200388	4-31-03-124	18267
23	4595838	4-31-03-112	14587
9	4580624	4-31-03-135	14618
27	4536361	4-31-03-117	21639
6	4224668	4-31-03-120	8779
34	4076593	4-31-03-126	20599
28	3865218	4-31-03-117	21639
38	3672399	4-31-03-119	23480
21	2288860	4-31-03-114	7911
36	2142796	4-31-03-133	18099
16	623154	4-31-03-137	5174
15	41579	4-31-03-130	1223

8.1 Current state

Current state represents the catchment behaviour during designed heavy precipitation event. The goal is to identify and determine the representation of discharge runoff from every SPU unit.

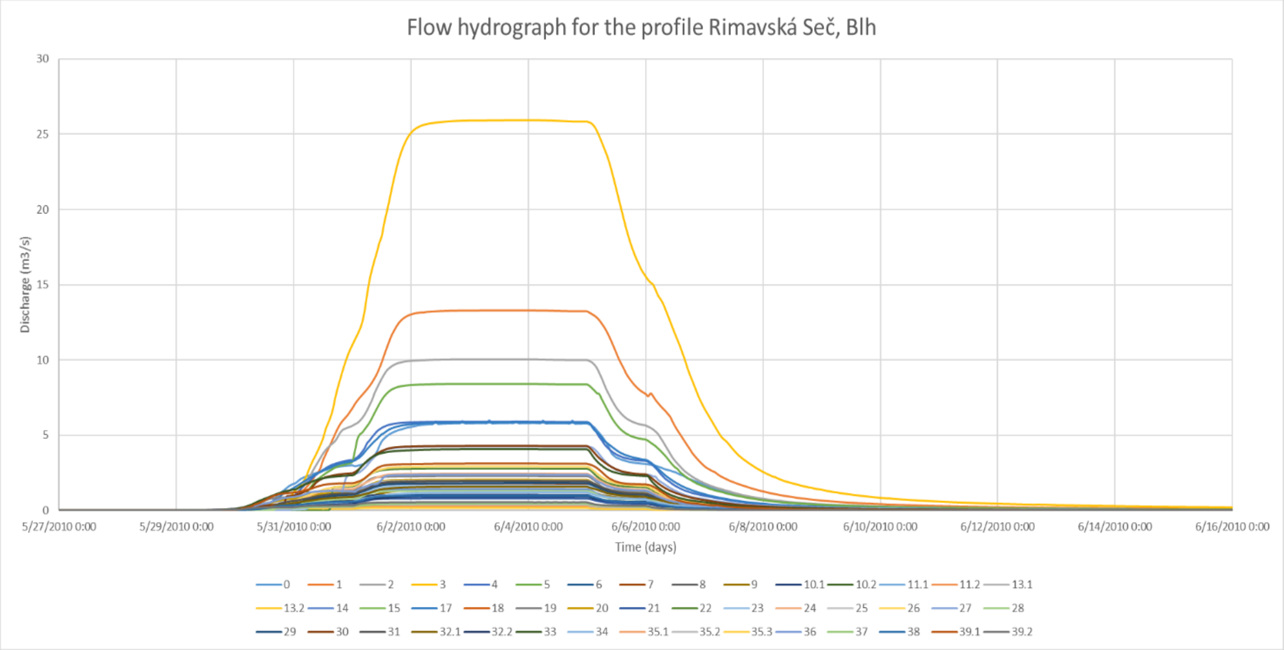


Fig. 32: Current state - Determination of flow hydrographs for each SPU unit

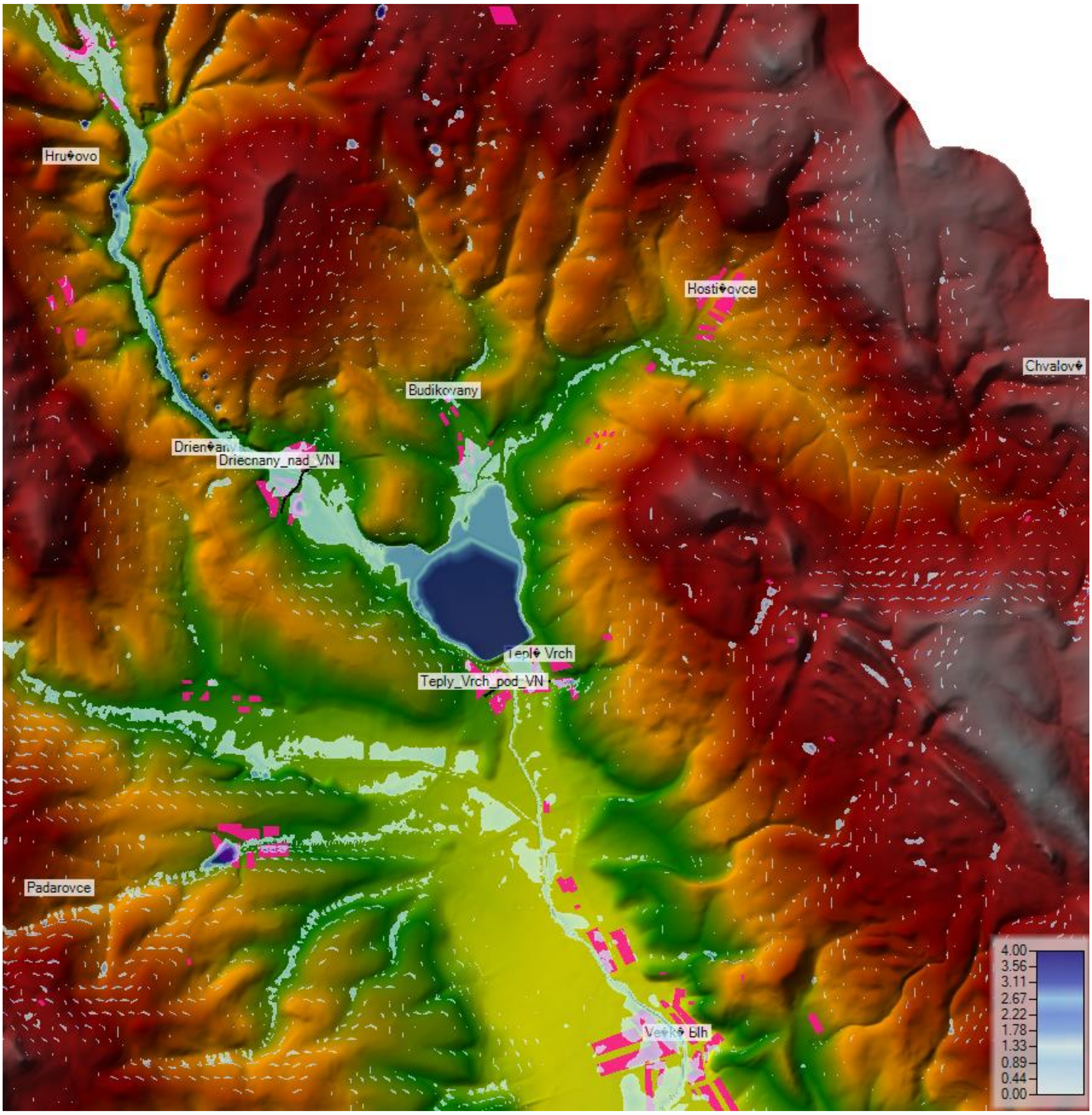


Fig. 33: Current state – map of depths (Teplý Vrch) – long term precipitation event

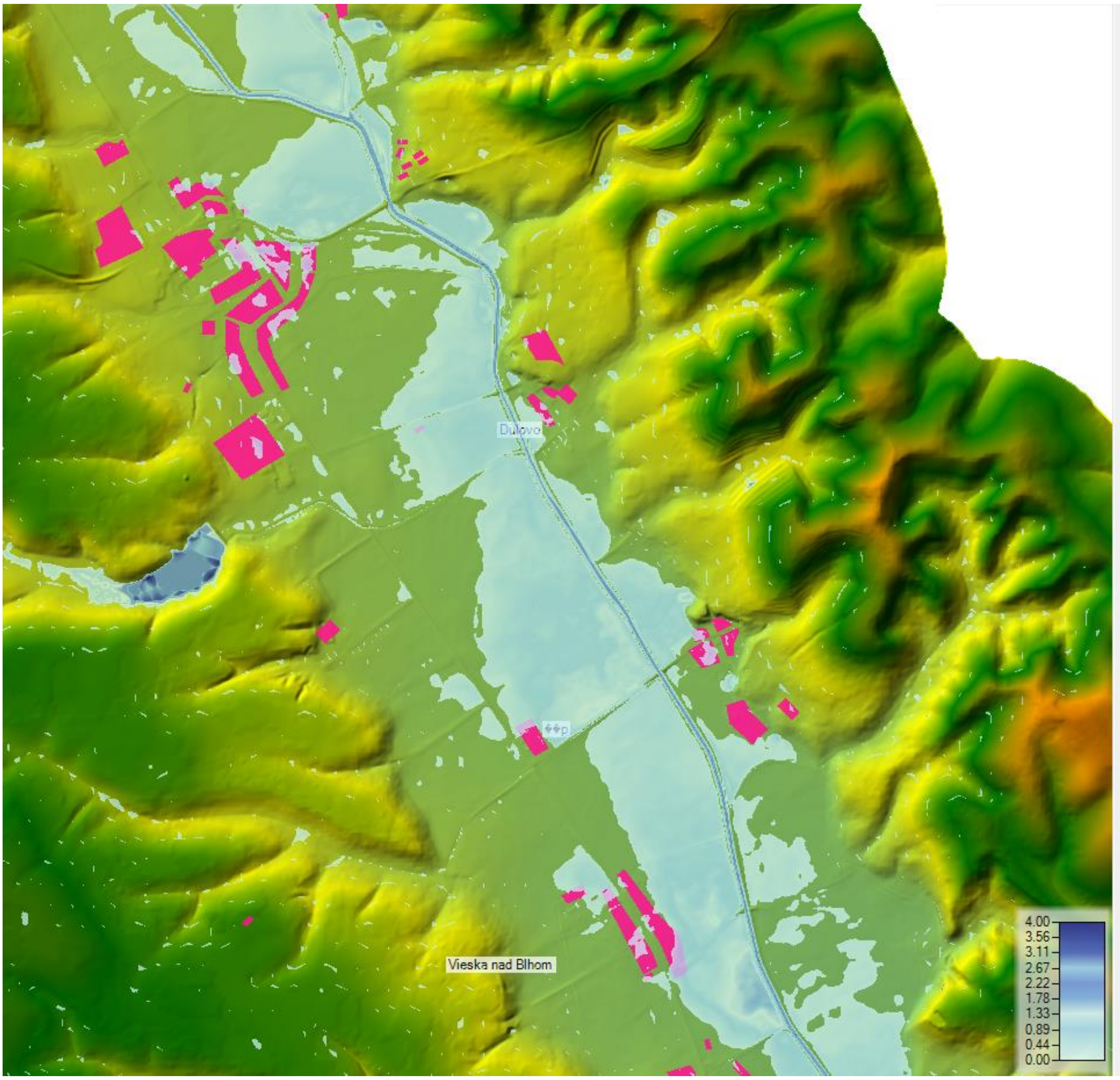


Fig. 34: Current state – map of depths (Vieska nad Blhom) – long term precipitation event

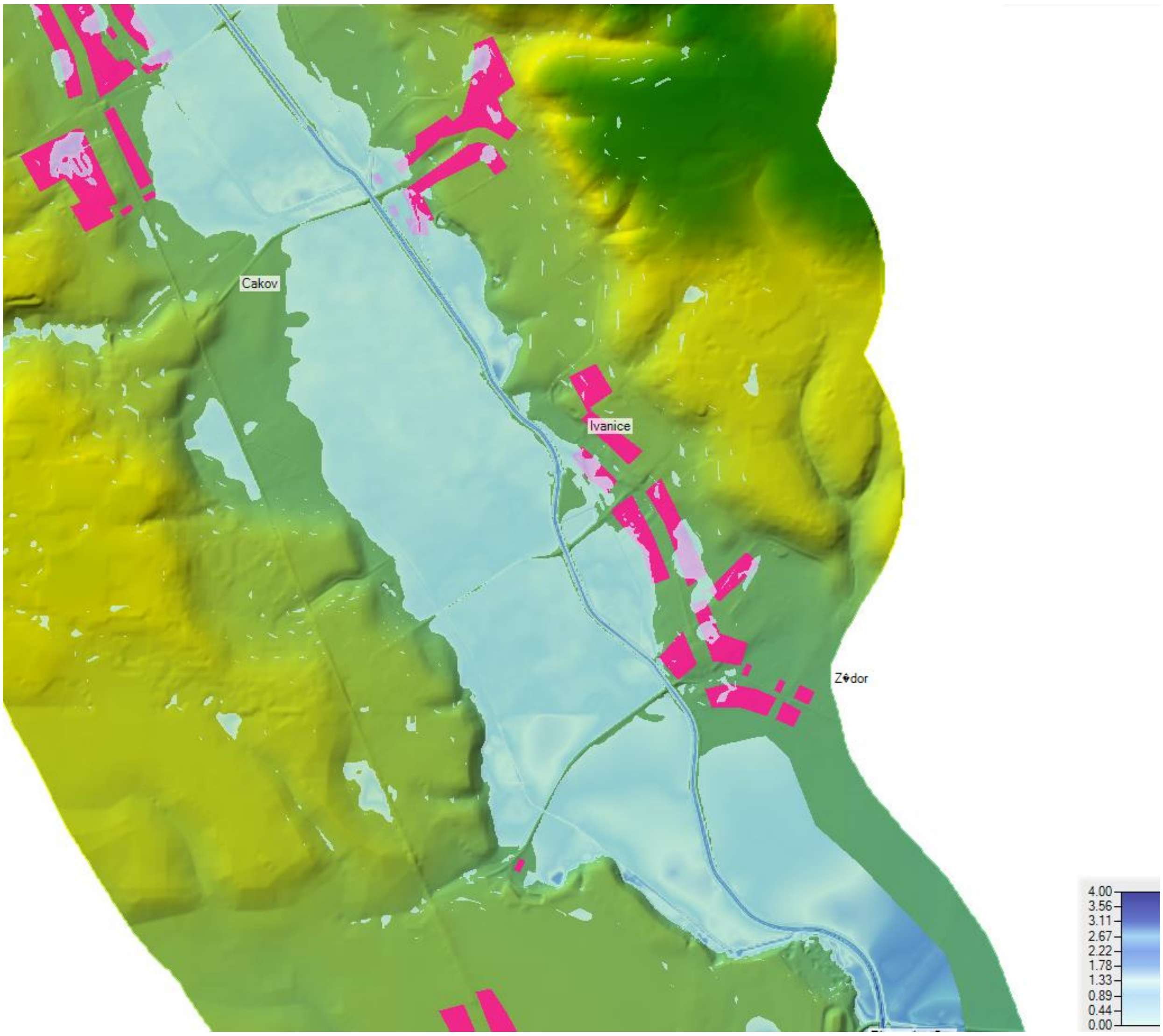


Fig. 35: Current state – map of depths (Rimavská Seč) – long term precipitation event

Based on the results of Q_{100} precipitation even the most exposed SPU units were defined (Tab. 4), it means the SPU units with highest amount of modelled discharges were identified.

Tab. 4: SPU units peak discharges

SPU	Discharge
0	5.98
1	13.29
2	10.04
3	25.94
4	5.90
5	8.41
6	0.35
7	1.78
8	2.00
9	1.37
10.1	1.04
10.2	0.48
11.1	0.30
11.2	0.30
13.1	1.65
13.2	0.16
14	1.40
15	2.02
17	5.85
18	1.96
19	2.29
20	2.03
21	0.79
22	2.78
23	1.66
24	2.46
25	1.98
26	2.92
27	4.25
28	1.30
29	1.83
30	4.29
31	1.96
32.1	1.57
32.2	0.93
33	4.07
34	1.20
35.1	0.39
35.2	0.40
35.3	0.49
36	2.38
37	0.45
38	0.97
39.1	3.11
39.2	0.55

With the aim to mitigate the flood risk for these SPU units, the alternatives of natural small water retention measures recommended by Slovak experts in the field of flood protection were proposed and their effects were modelled. There are best (standard) experiences with design of polders (T1) in Slovakia to gain multibenefits for targeted areas.

There were two options modelled:

- if the flood risk is eliminated in the SPUs with highest flood risk located in upper part of the pilot catchment and
- if the flood risk is eliminated in the SPUs with highest flood risk located in downstream part of the pilot catchment

For both approaches combination of measures located in different combinations of SPUs were proposed and their effects were modelled.

8.2 Management measures of areas suitable for the natural or artificial transformation of flood waves – alternative 1

Alternative 1 is analysing the possibilities and effect on flood wave transformation by using management measures of areas suitable for the natural or artificial transformation of flood waves at the upstream SPU units. The main philosophy was to develop the flood protection in SPU units which are generating the highest risk and are located in the upper part of the catchment. The two cases were examined – for long term precipitation event and for flash flood event.

Several polders (T1) in seven different SPU units determined as with the highest risk were proposed (unit: 17, 0, 7, 5, 1, 2, 4).

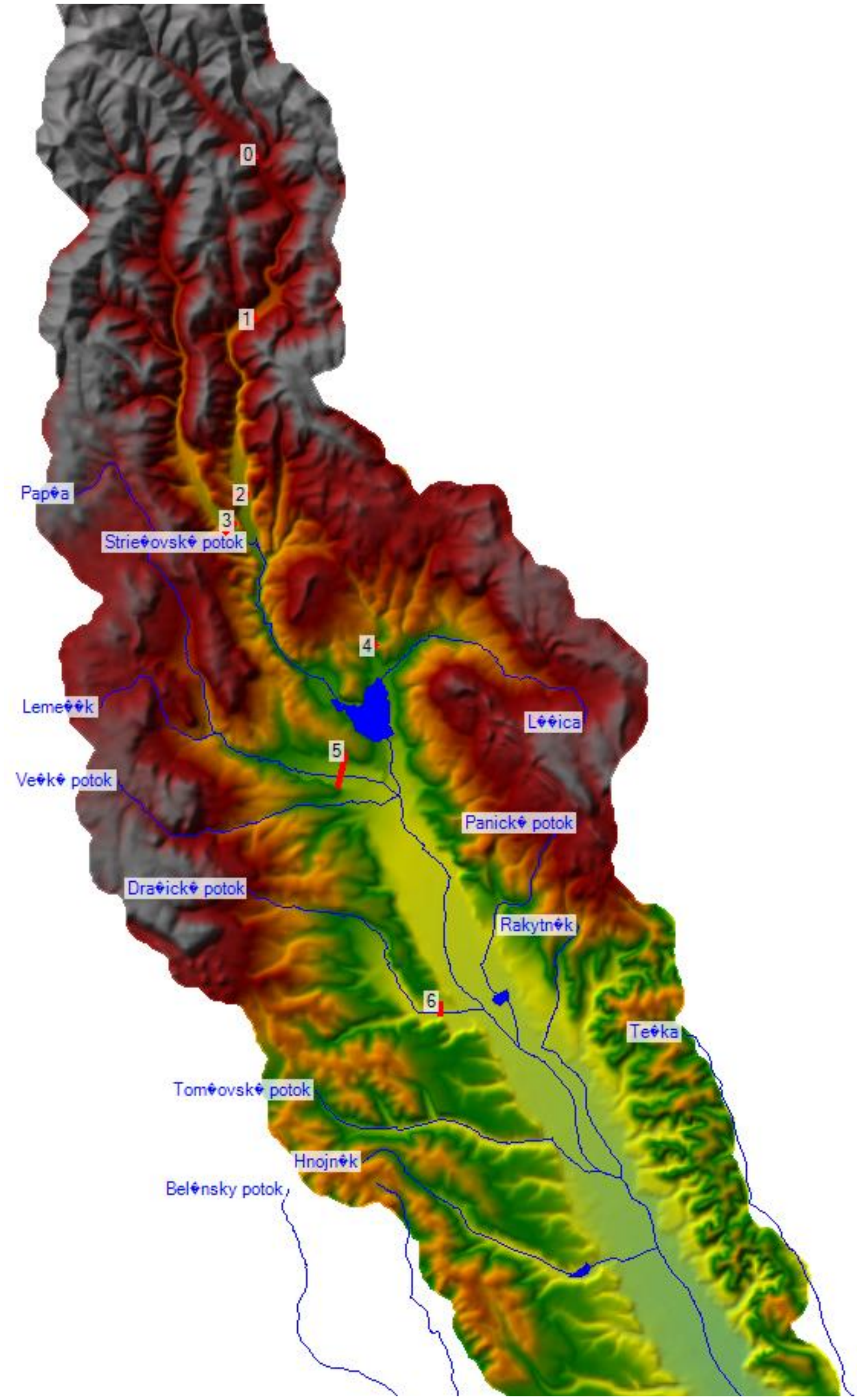


Fig. 36: Proposed polder profile locations – alternative 1

Tab. 5: Polders basic parameters

SPU unit	Polder crest elevation	Average terrain elevation	Culvert diameter
0	371.75	358.00	0.5
1	300.00	295.40	
2	255.50	247.50	
3	250.00	245.00	
4	246.50	234.70	
5	223.50	211.90	
6	202.7	193.90	

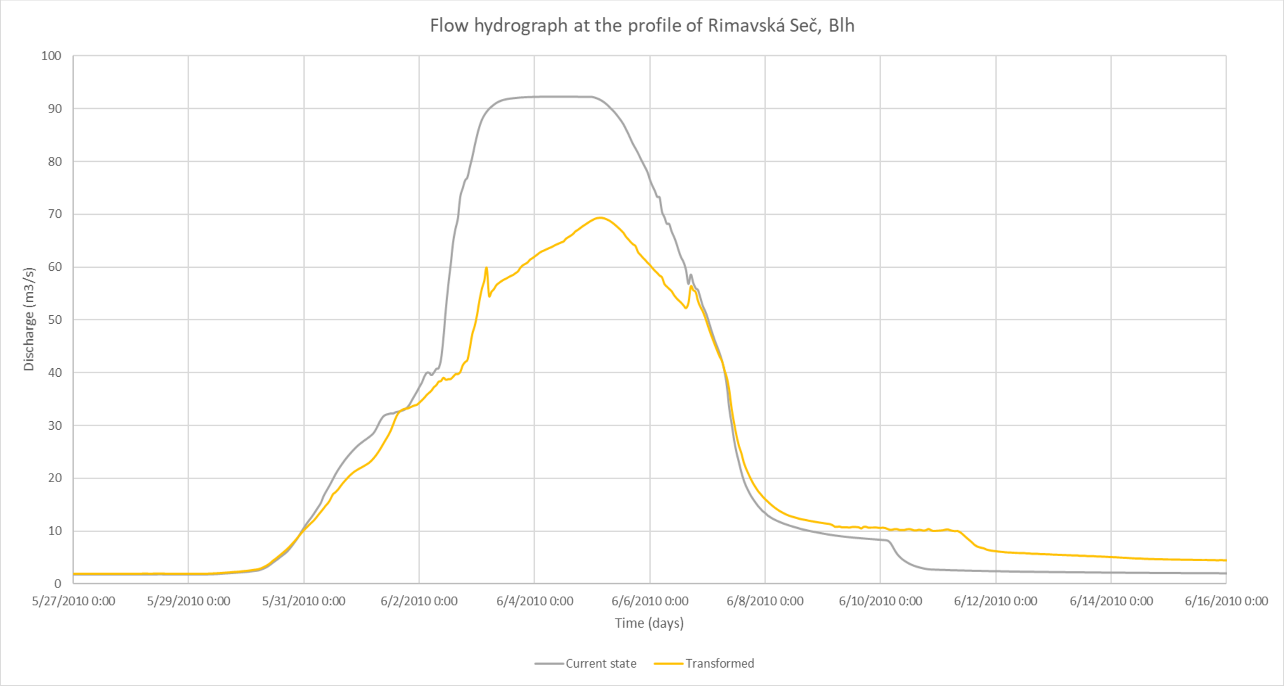


Fig. 37: Alternative 1 – Flow hydrograph for proposed event (Rimavská Seč) – long term precipitation event

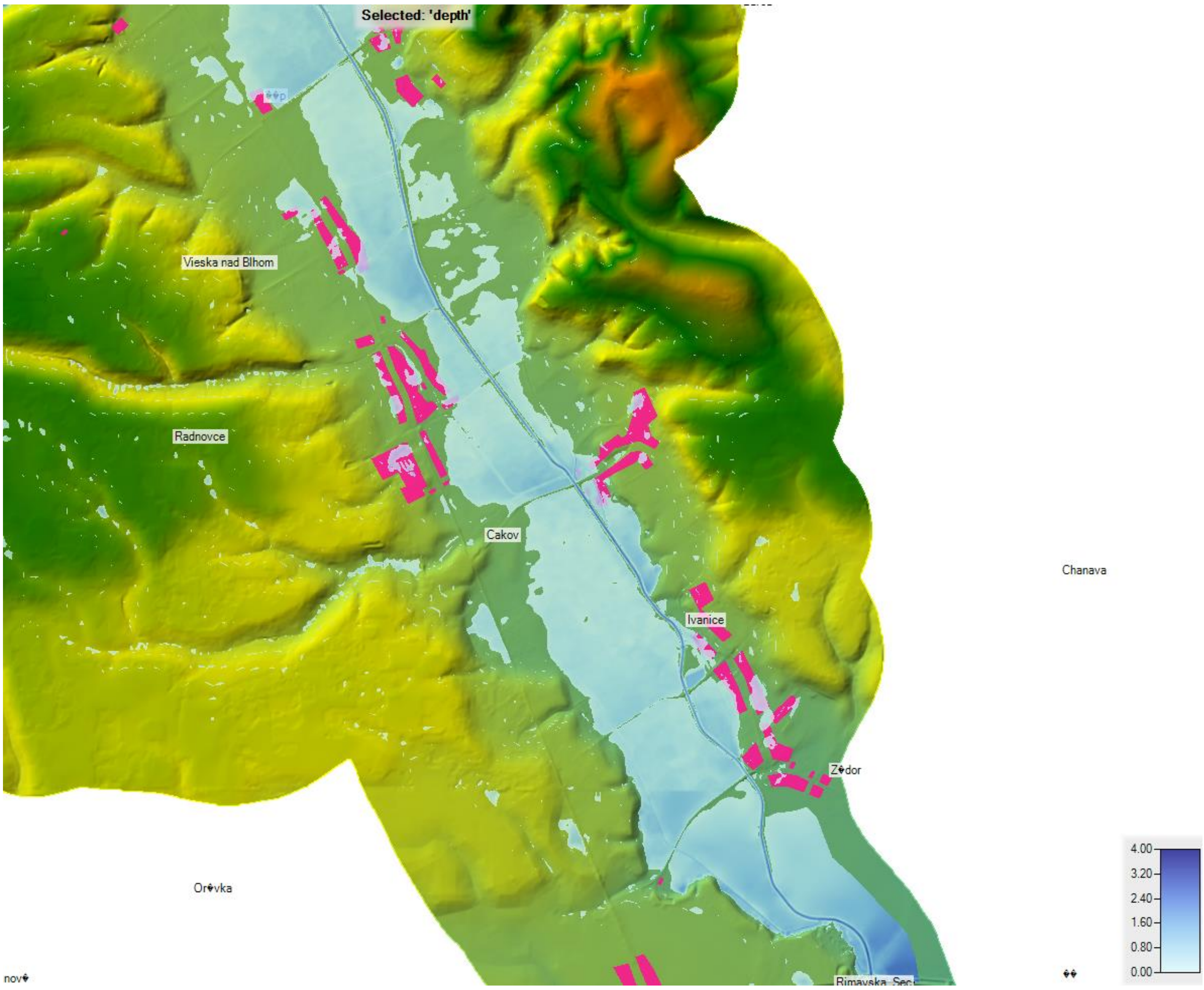


Fig. 38: Alternative 1 – map of depths (Rimavská Seč) – long term precipitation event

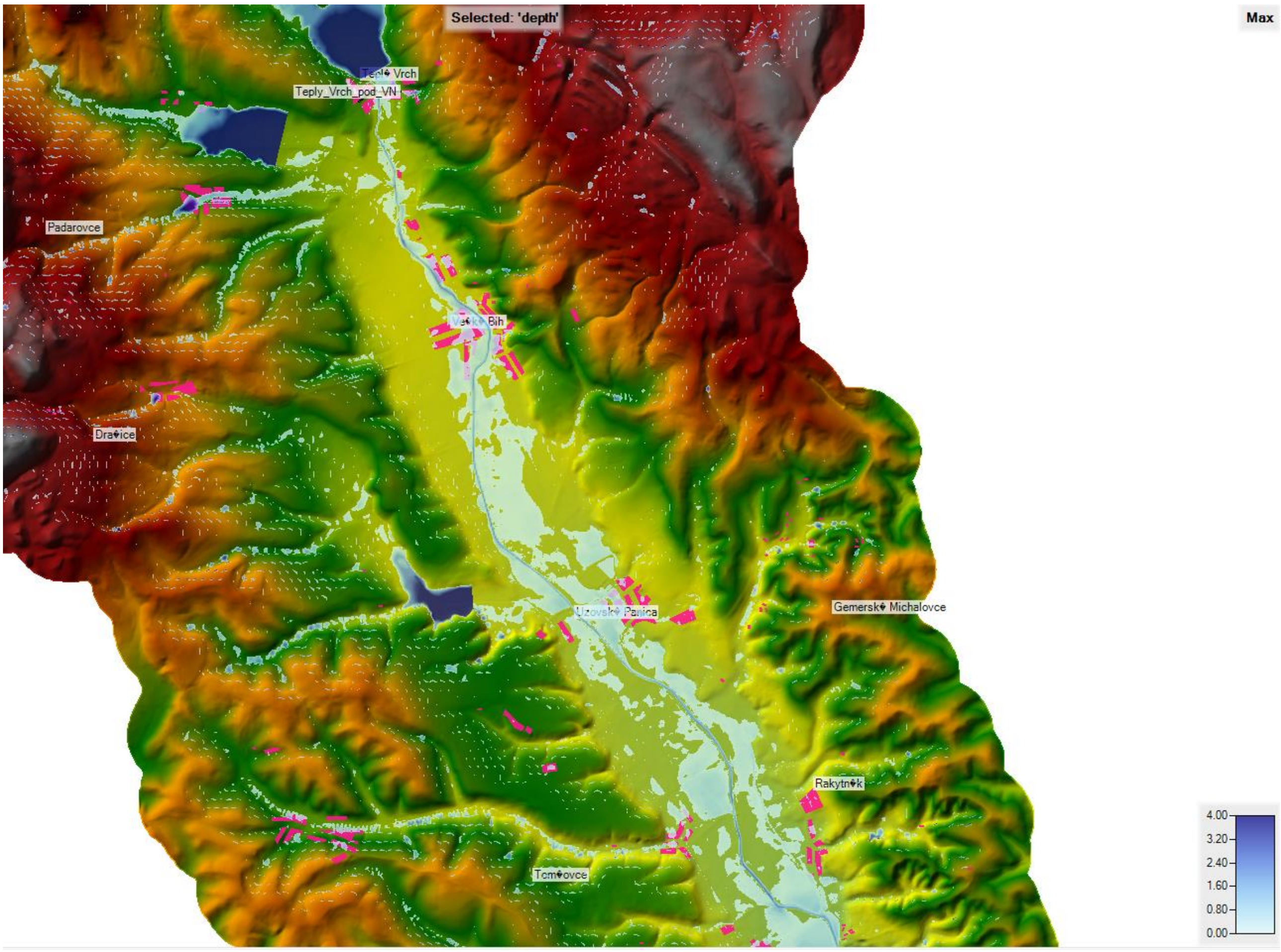


Fig. 39: Alternative 1 – map of depths (Teplý Vrch) – long term precipitation event

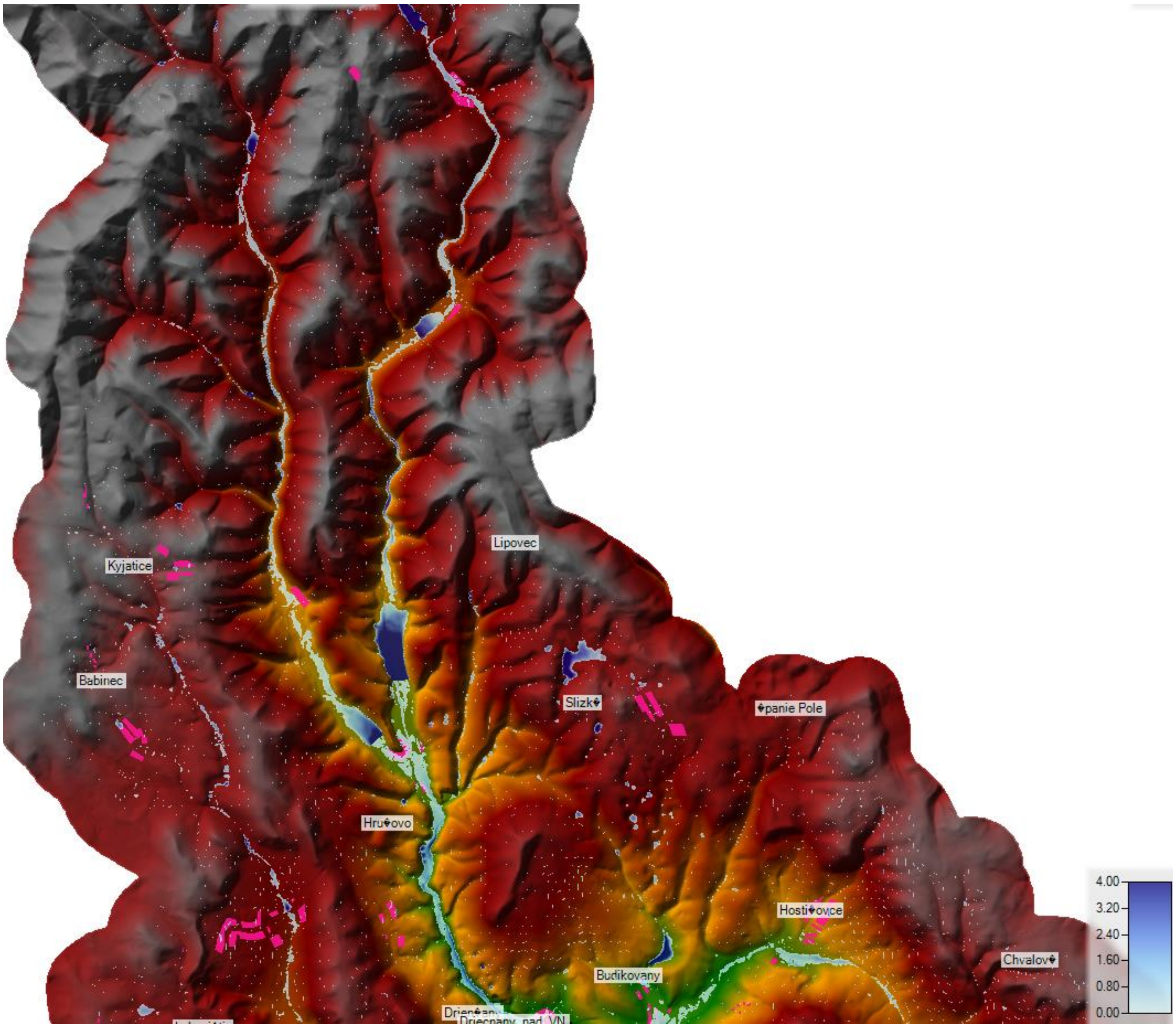


Fig. 40: Alternative 1 – map of depths (Lipovec) – long term precipitation event

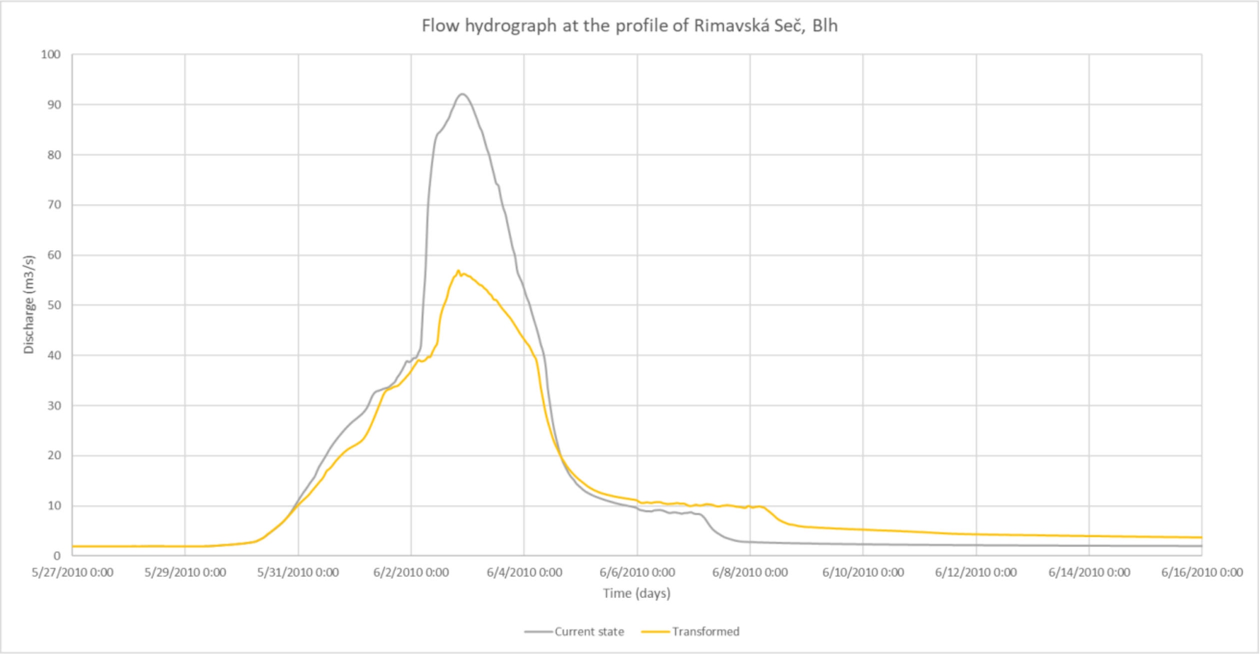


Fig. 41: Alternative 1 – Flow hydrograph for proposed event (Rimavská Seč) – flash flood precipitation event

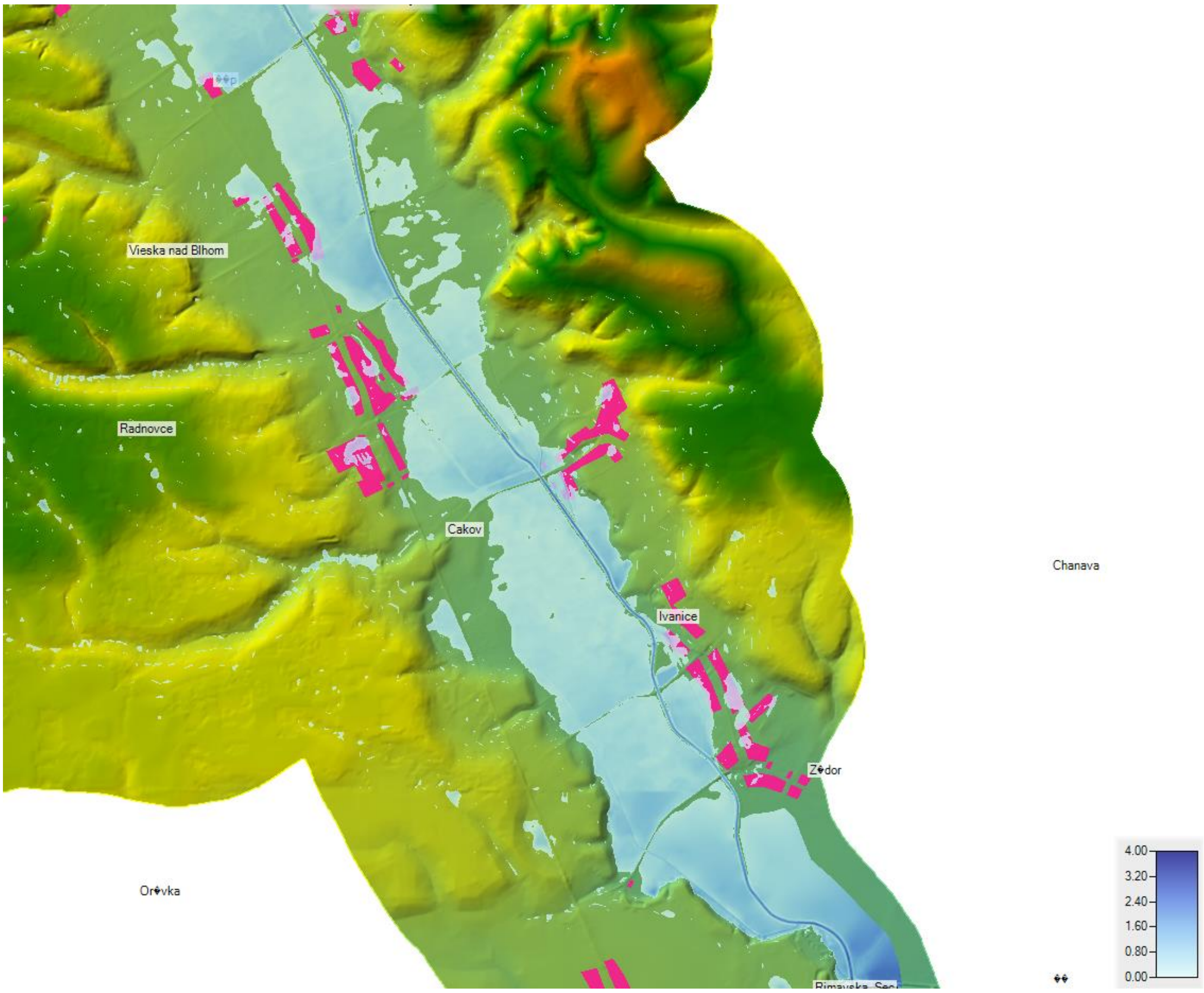


Fig. 42: Alternative 1 – map of depths (Rimavská Seč) – flash flood precipitation event

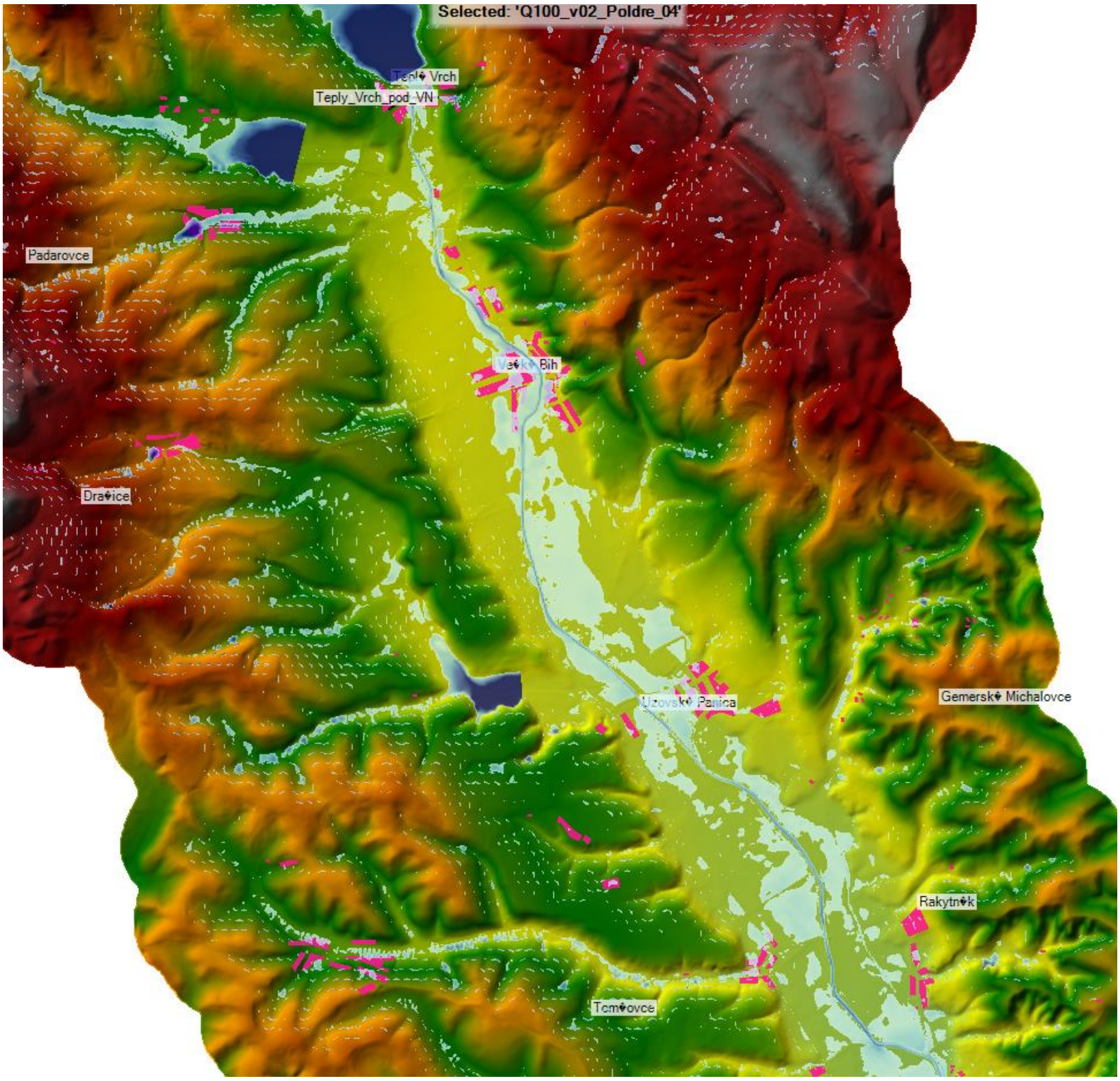


Fig. 43: Alternative 1 – map of depths (Teplý Vrch) – flash flood precipitation event

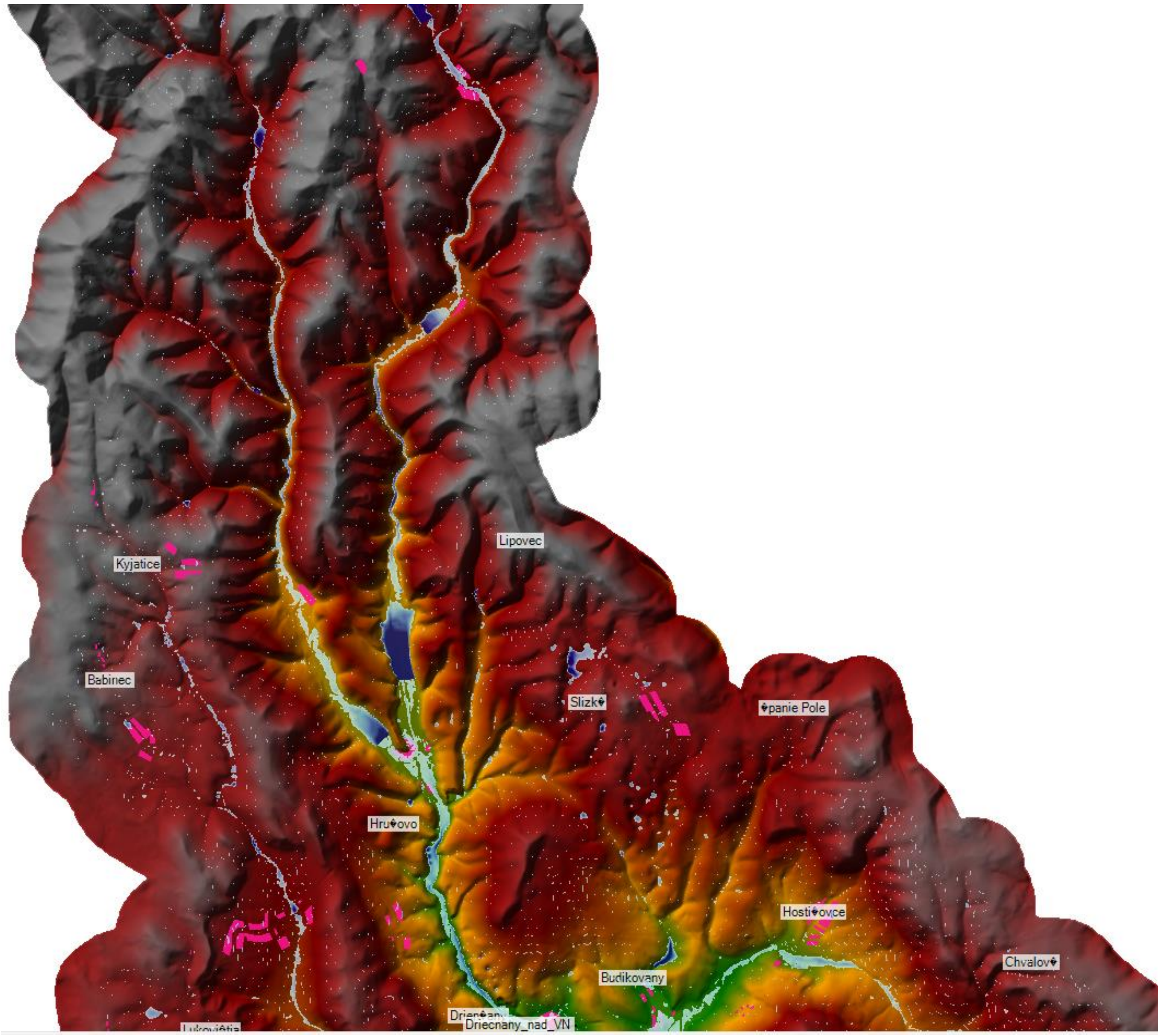


Fig. 44: Alternative 1 – map of depths (Lipovec) – flash flood precipitation event

Based on the amount of retained water it can be assumed that polders are more efficient for flash flood events.

8.3 Management measures of areas suitable for the natural or artificial transformation of flood waves – alternative 2

Alternative 2 is analysing the possibilities and effect on flood wave transformation by using management measures of areas suitable for the natural or artificial transformation of flood waves at the upstream SPU units. The main philosophy was to develop the massive flood protection in SPU units which are generating the highest risk and are located in the upper part of the catchment. The two cases were examined – for long term precipitation event and for flash flood event.

Several polders (T1) in ten different SPU units determined as with the highest risk were proposed (unit: 17, 0, 7, 5, 1, 2, 4, 9, 39, 3). It was considered to propose the polders with the highest possible retention volume to obtain an overview on the efficiency of such an object at given locations.

Tab. 6: Polders basic parameters

SPU unit	Polder crest elevation	Average terrain elevation	Culvert diameter
0	371.75	358.00	0.5
1	300.00	295.40	
2	255.50	247.50	
3	250.00	245.00	
4	246.50	234.70	
5	223.50	211.90	
6	202.70	193.90	
7	295.80	271.00	0.3
8	245.00	232.20	
9	194.30	189.90	
10	192.30	180.95	
11	240.00	228.90	
12	310.00	293.60	

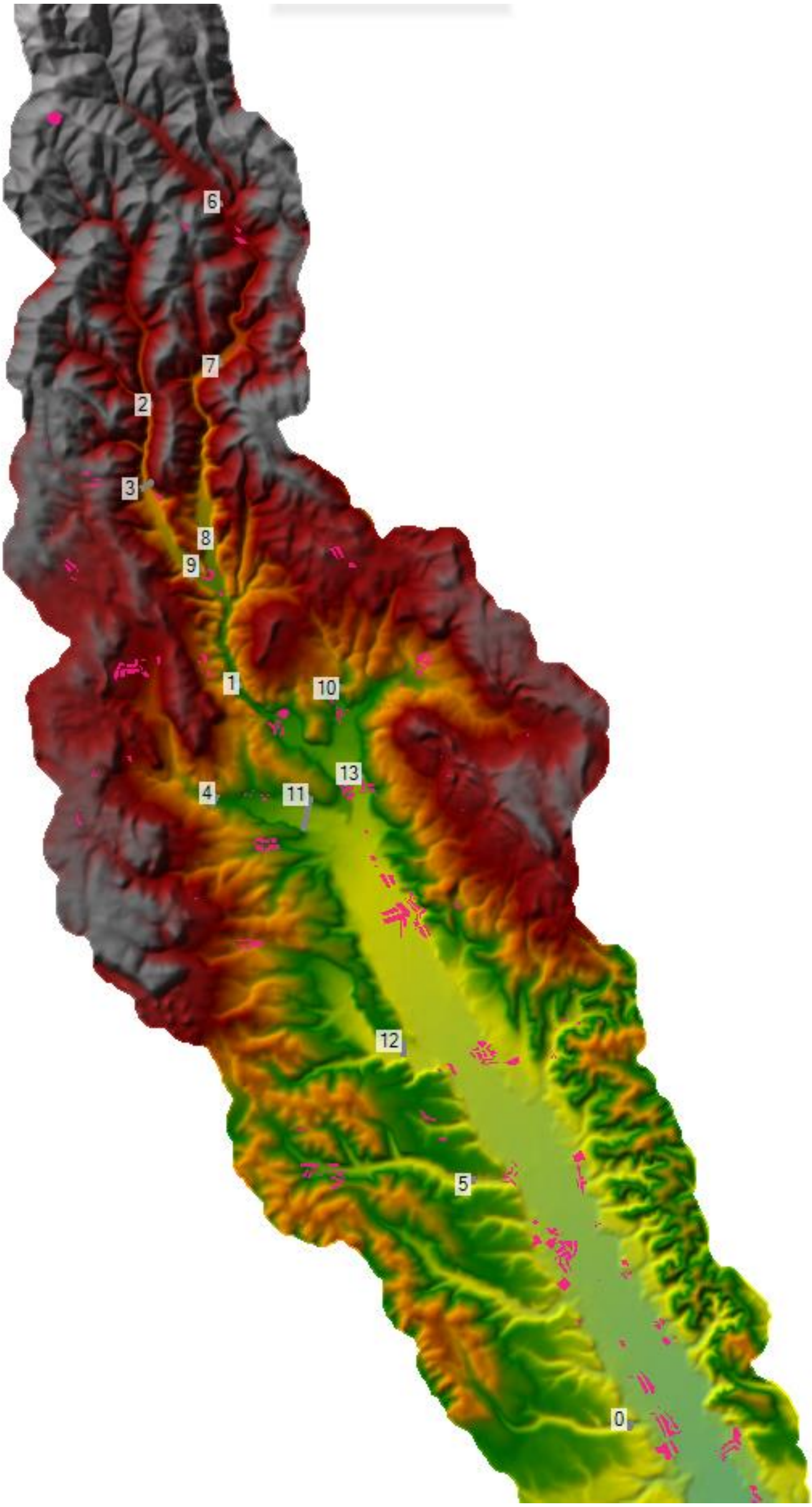


Fig. 45: Proposed polder profile locations – alternative 2

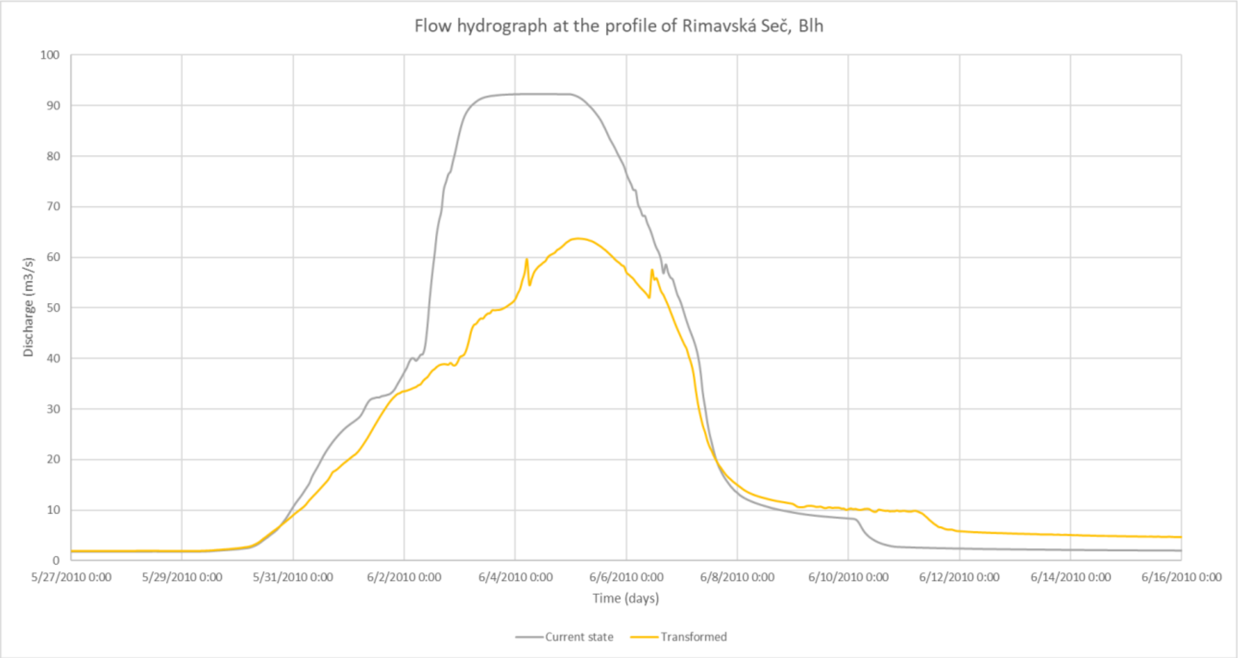
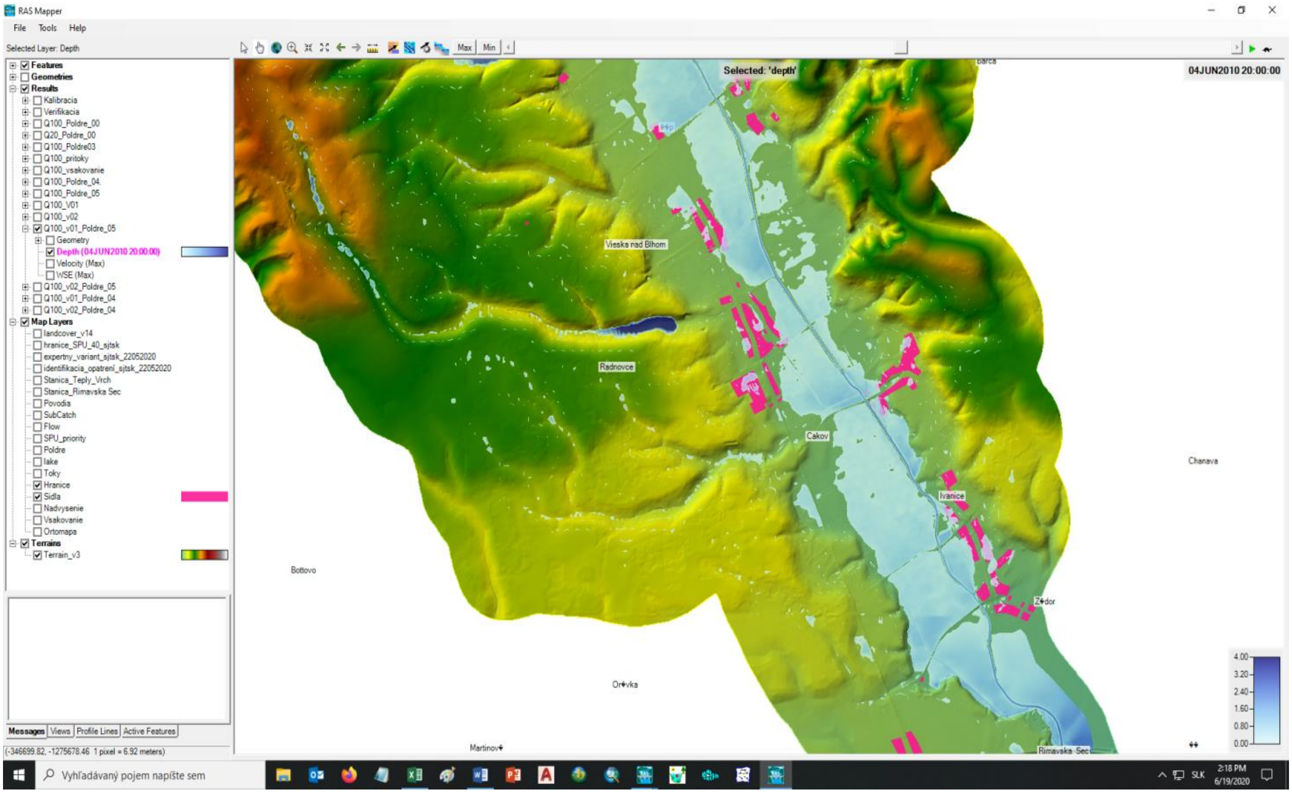


Fig. 46: Alternative 2 – Flow hydrograph for proposed event (Rimavská Seč) – long term precipitation event



Selected Layer: Depth

- ☑ **Features**
- ☐ **Geometries**
- ☑ **Results**
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  - ☐ Verifikacia
  - ☐ Q100_Poldre_00
  - ☐ Q20_Poldre_00
  - ☐ Q100_Poldre03
  - ☐ Q100_pritoky
  - ☐ Q100_vsakovanie
  - ☐ Q100_Poldre_04.
  - ☐ Q100_Poldre_05
  - ☐ Q100_V01
  - ☐ Q100_v02
  - ☑ Q100_v01_Poldre_05
    - ☐ Geometry
    - ☑ Depth (04JUN2010 20:00:00)
    - ☐ Velocity (Max)
    - ☐ WSE (Max)
  - ☐ Q100_v02_Poldre_05
  - ☐ Q100_v01_Poldre_04
  - ☐ Q100_v02_Poldre_04
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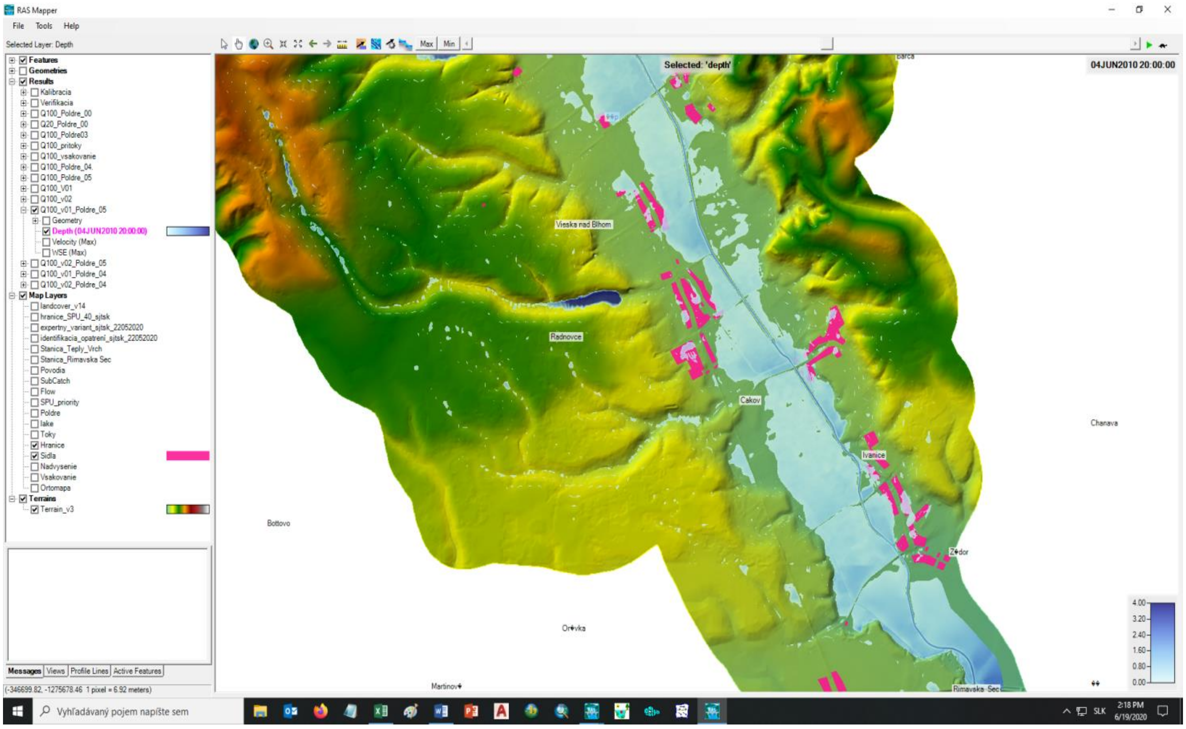
  - ☐ hranice_SPU_40_sjtsk
  - ☐ expertny_variant_sjtsk_22052020
  - ☐ identifikacia_opatreni_sjtsk_22052020
  - ☐ Stanica_Teply_Vrch
  - ☐ Stanica_Rimavska Sec
  - ☐ Povodia
  - ☐ SubCatch
  - ☐ Flow
  - ☐ SPU_priority
  - ☐ Poldre
  - ☐ lake
  - ☐ Toky
  - ☑ Hranice
  - ☑ Sidla
  - ☐ Nadvysenie
  - ☐ Vsakovanie
  - ☐ Ortomapa
- ☑ **Terrains**
  - ☑ Terrain_v3

(-346699.82, -1275678.46 1 pixel = 6.92 meters)

Fig. 47: Alternative 2 – map of depths (Rimavská Seč) – long term precipitation event



Selected Layer: Depth

- ☑ **Features**
- ☐ **Geometries**
- ☑ **Results**
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  - ☐ Verifikacia
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  - ☐ Q20_Poldre_00
  - ☐ Q100_Poldre03
  - ☐ Q100_pritoky
  - ☐ Q100_vsakovanie
  - ☐ Q100_Poldre_04.
  - ☐ Q100_Poldre_05
  - ☐ Q100_V01
  - ☐ Q100_v02
  - ☑ Q100_v01_Poldre_05
    - ☐ Geometry
    - ☑ Depth (04JUN2010 20:00:00)
    - ☐ Velocity (Max)
    - ☐ WSE (Max)
  - ☐ Q100_v02_Poldre_05
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  - ☐ identifikacia_opatreni_sjtsk_22052020
  - ☐ Stanica_Teply_Vrch
  - ☐ Stanica_Rimavska Sec
  - ☐ Povodia
  - ☐ SubCatch
  - ☐ Flow
  - ☐ SPU_priority
  - ☐ Poldre
  - ☐ lake
  - ☐ Toky
  - ☑ Hranice
  - ☑ Sidla
  - ☐ Nadvysenie
  - ☐ Vsakovanie
  - ☐ Ortomapa
- ☑ **Terrains**
  - ☑ Terrain_v3

(-346699.82, -1275678.46 1 pixel = 6.92 meters)

Fig. 48: Alternative 2 – map of depths (Rimavská Seč) – long term precipitation event

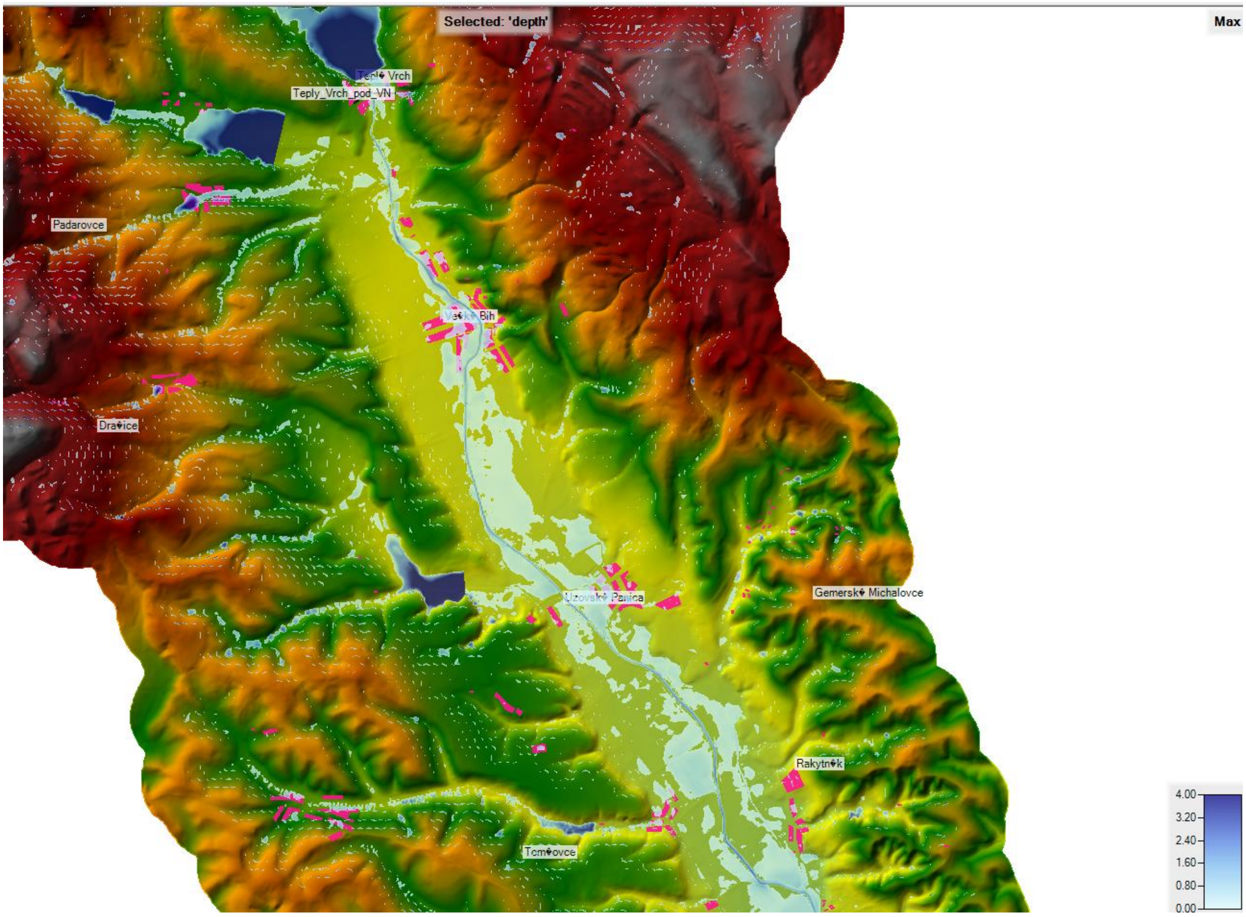

Fig. 49: Alternative 2 – map of depths(Teplý Vrch) – long term precipitation event

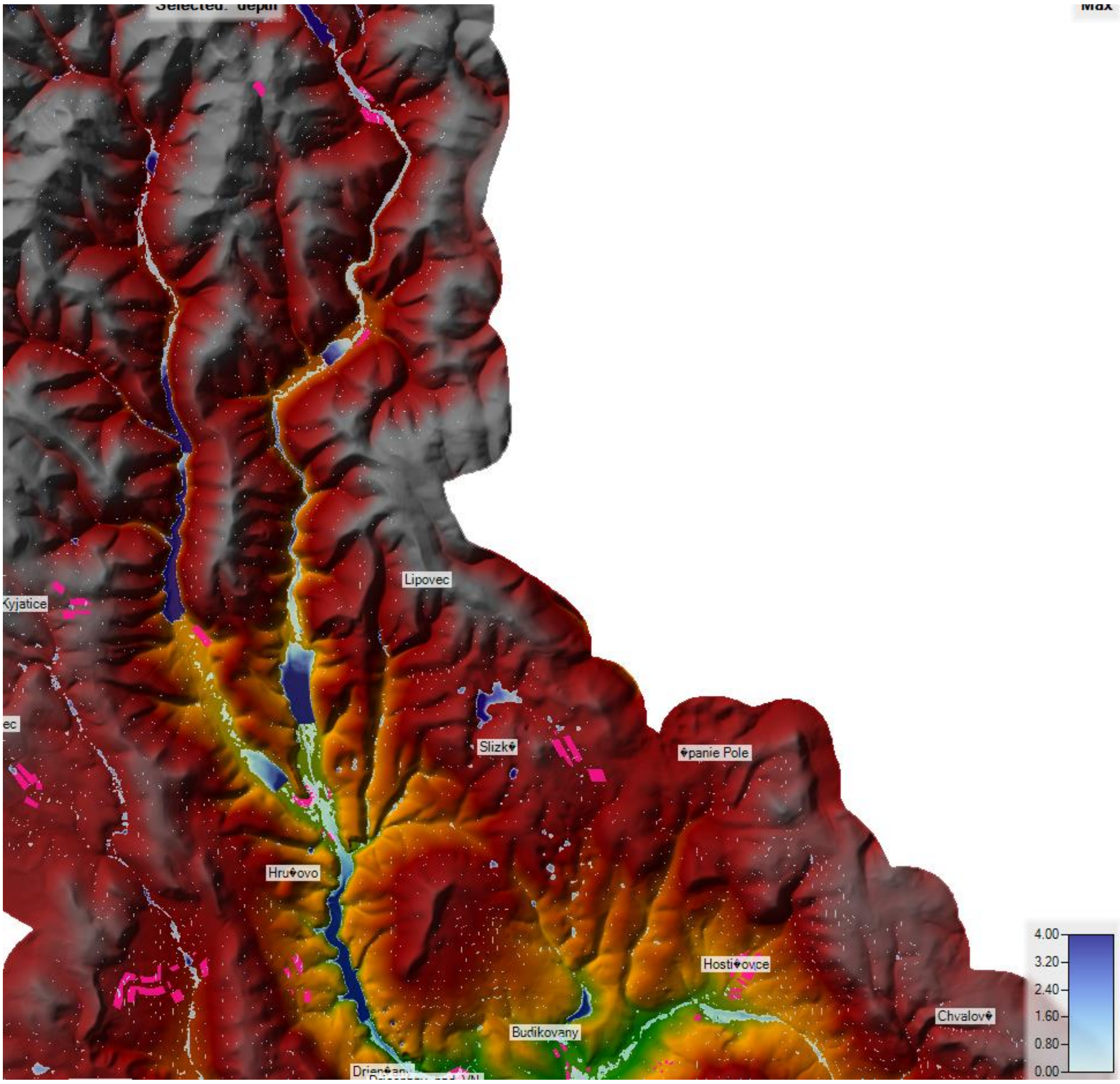

Fig. 50: Alternative 2 – map of depths (Lipovec) – long term precipitation event

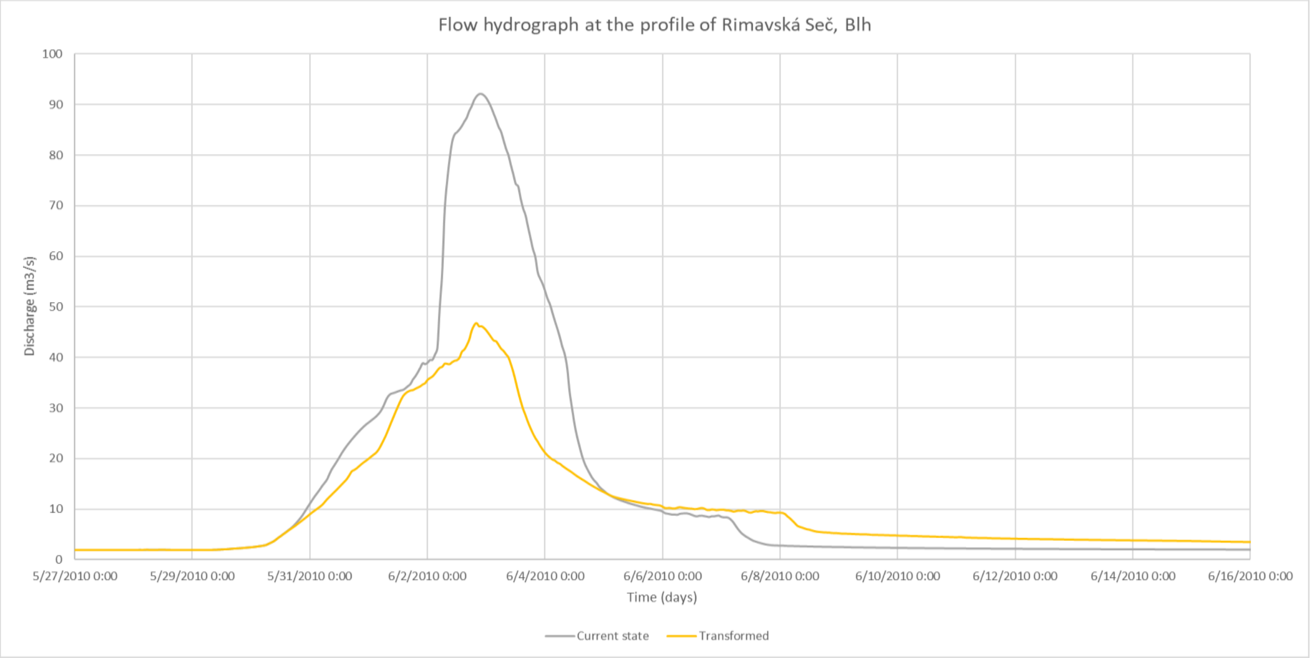

Fig. 51: Alternative 2 – Flow hydrograph for proposed event (Rimavská Seč) – flash flood precipitation event

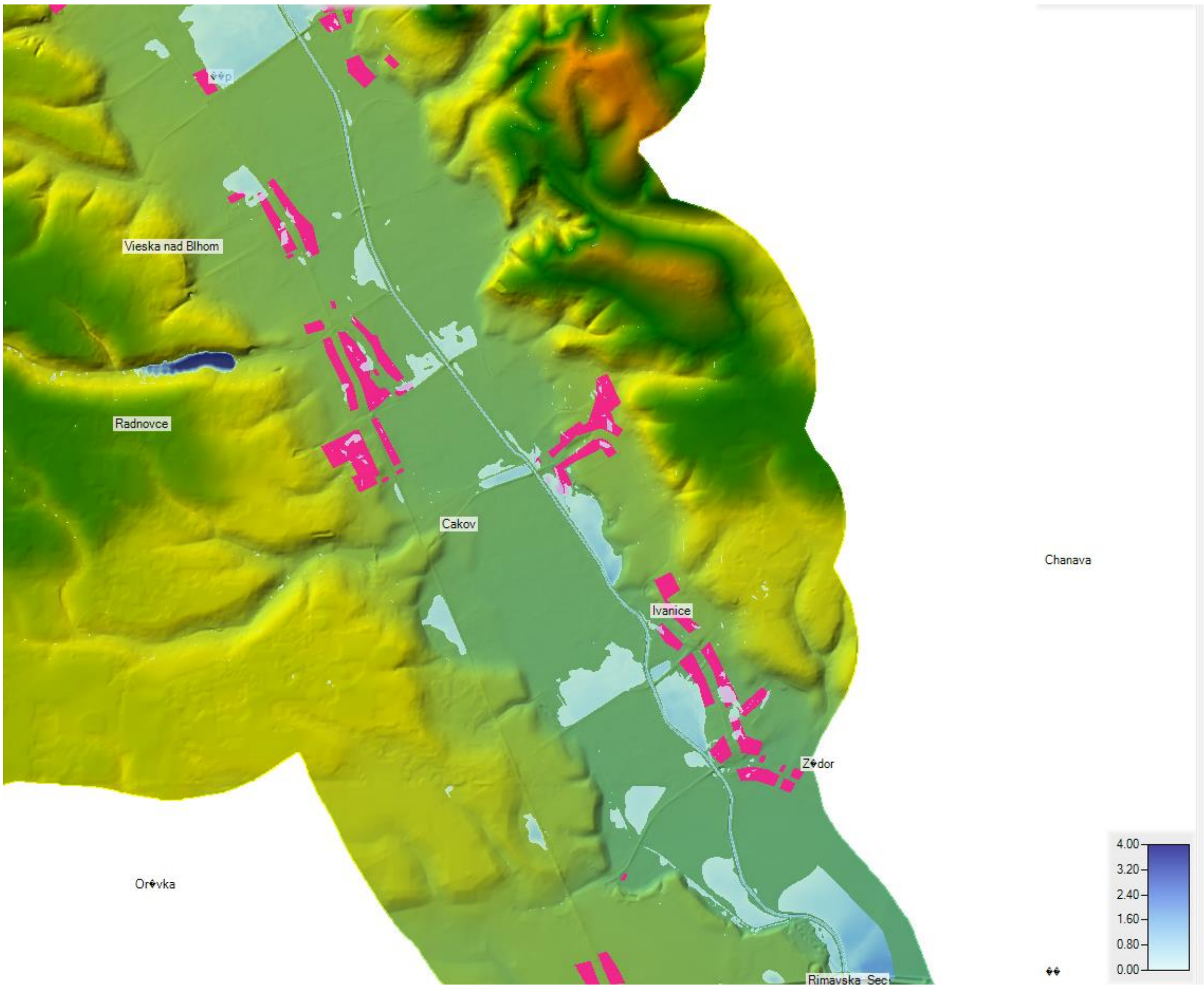

Fig. 52: Alternative 2 – map of depths (Rimavská Seč) – flash flood precipitation event

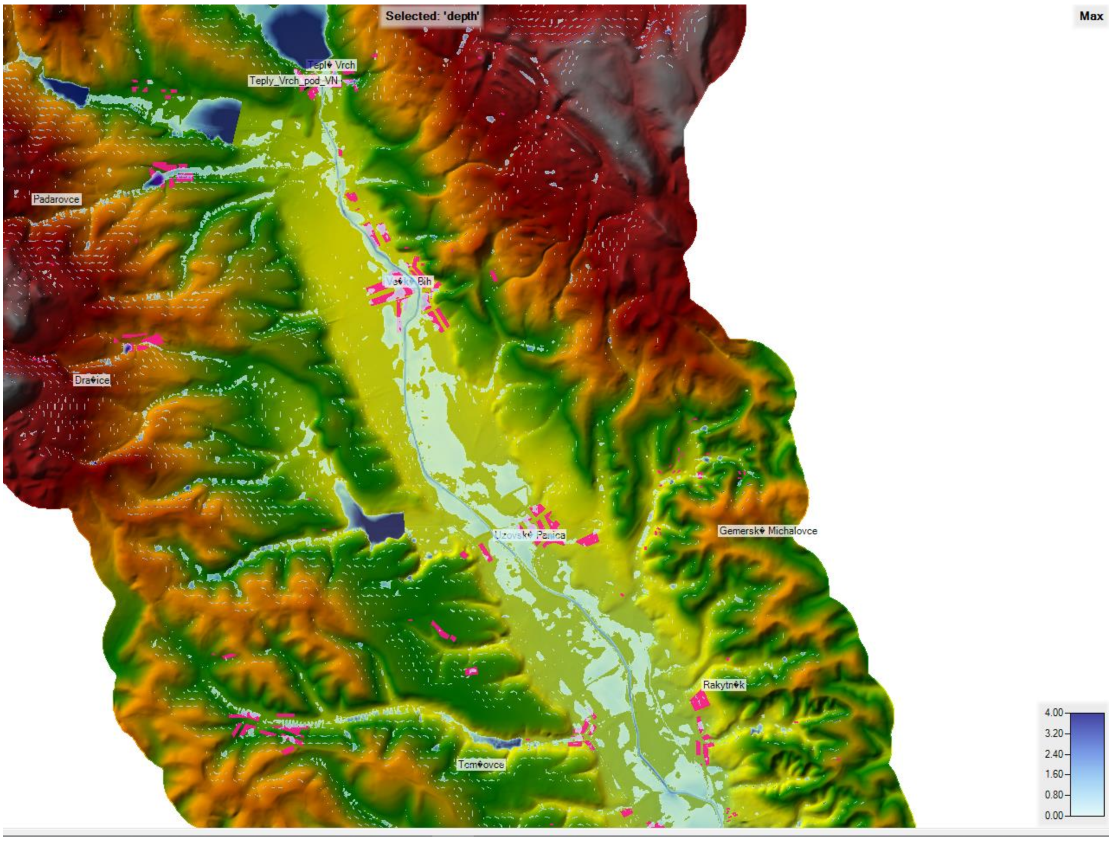

Fig. 53: Alternative 2 – map of depths (Teplý Vrch) – flash flood precipitation event

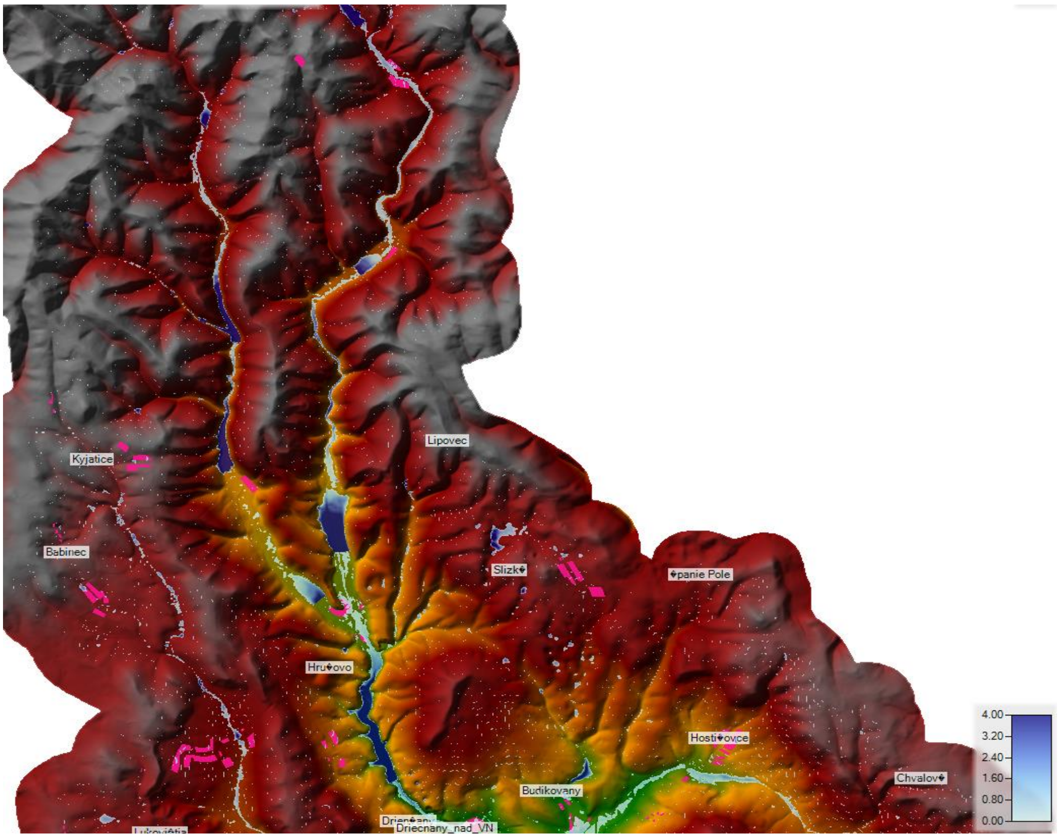

Fig. 54: Alternative 2 – map of depths (Lipovec) – flash flood precipitation event

Based on the amount of retained water it can be assumed that polders are more efficient for flash flood events.

8.4 Management measures of areas suitable for the natural or artificial transformation of flood waves – alternative 3

Alternative 3 is analysing the possibilities and effect on flood wave transformation by using management measures of areas suitable for the natural or artificial transformation of flood waves at the downstream SPU units. The main philosophy was to develop the flood protection in SPU units in the catchment with highest influence on the infrastructure and habitation. The two cases were examined – for long term precipitation event and for flash flood event.

Thirteen SPU units were identified as having the highest influence (unit: 5, 3, 0, 6, 11, 8, 35, 12, 36, 10, 9, 13, 37). It was considered to propose the polders with lateral spillways with the retention volume (T1) at the locations where the lowest possible damage during the flood event is expected (not habitated land, e.g. pasture land etc.).

Creating the polders with lateral spillways by using natural morphology and existing artificial objects provided retention volumes with transformation flood wave effect.

Tab. 7: Lateral polders basic parameters

Embankment id	Length	Height	Crest altitude	Culvert DN 1	Culvert DN2	Lateral spillway length	Lateral spillway crest
-	m	m	m a.s.l.	m	m	m	m a.s.l.
01	816	1.53	195.30	0.3	0.3	50	195.00
02	787	1.41	194.30	0.3	0.3	50	194.00
03	1098	1.79	193.45	0.3	1.0	na	na
04	1061	2.59	192.55	0.3	1.0	na	na
05	910	2.22	190.95	0.3	0.3	50	190.65
06	329	1.80	189.9	0.3	0.3	50	189.60

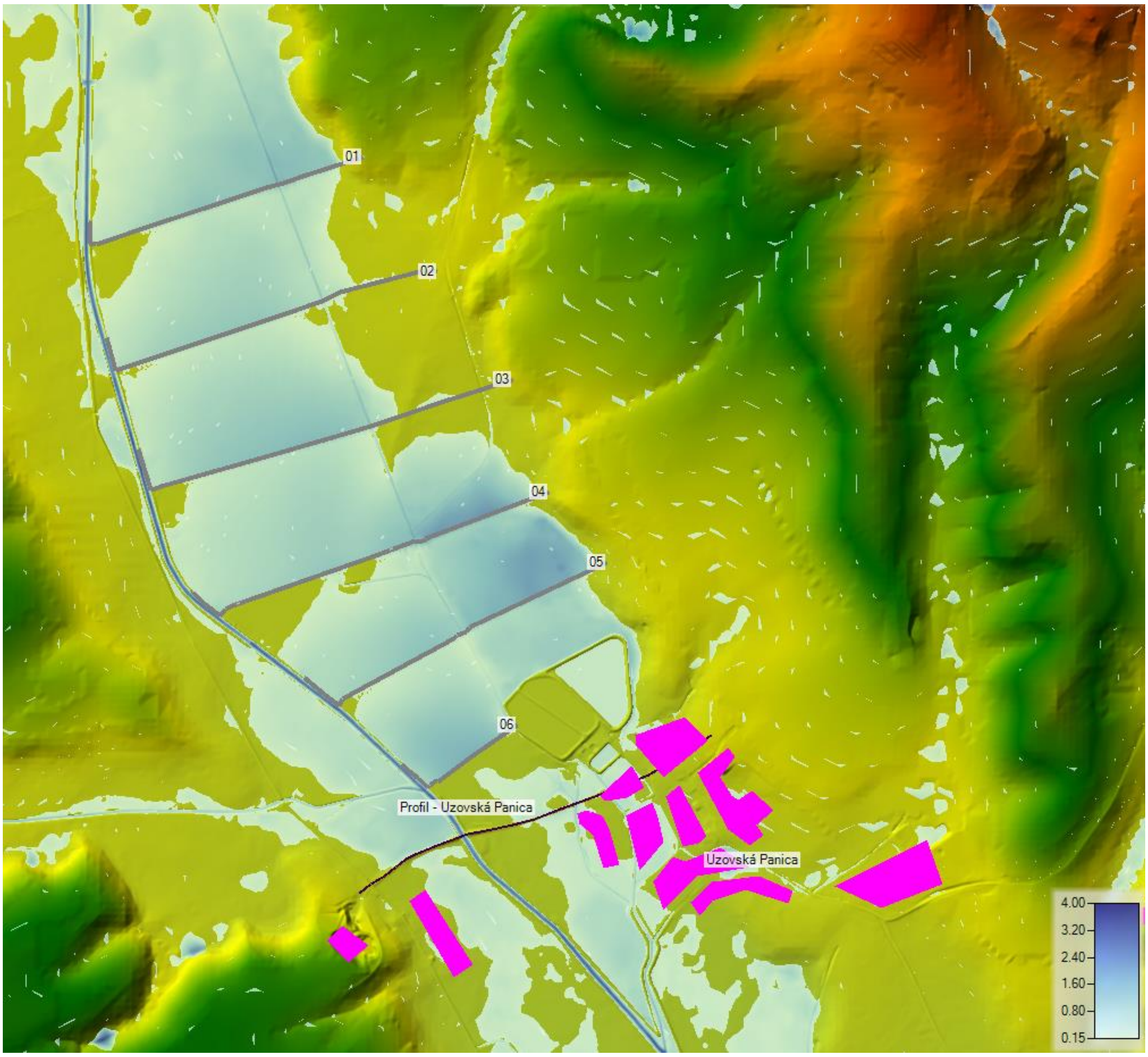

Fig. 55: Alternative 3 – map of depths (Uzovská Panica) – long term precipitation event

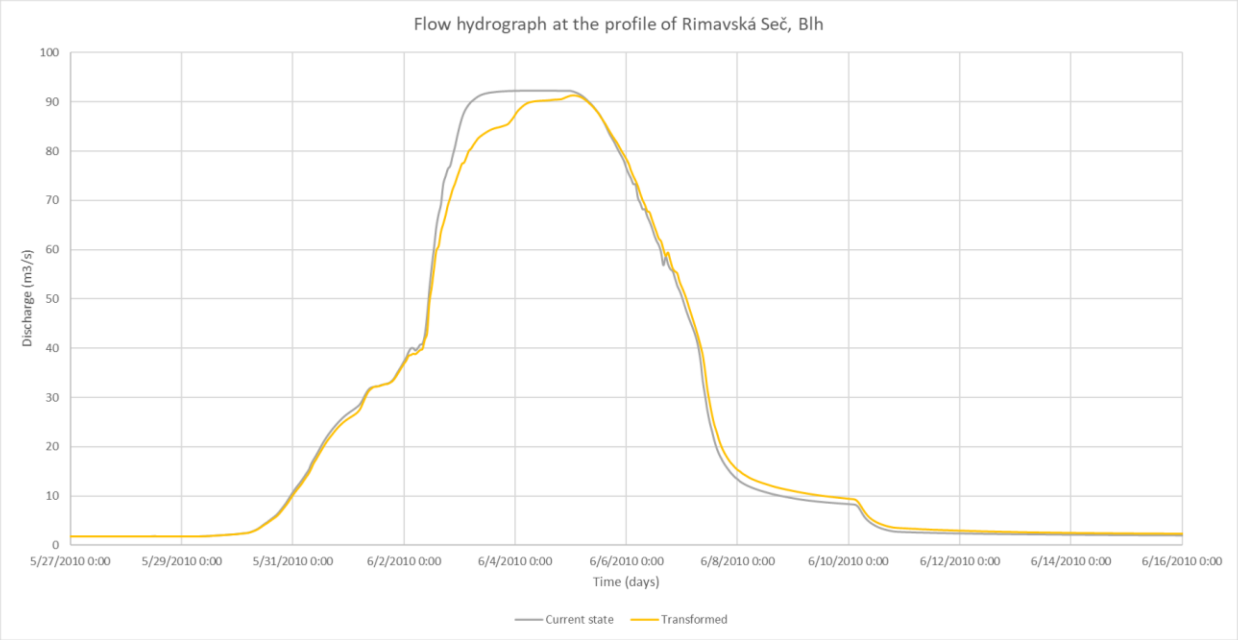

Fig. 56: Alternative 3 – Flow and stage hydrograph for proposed event – long term precipitation event

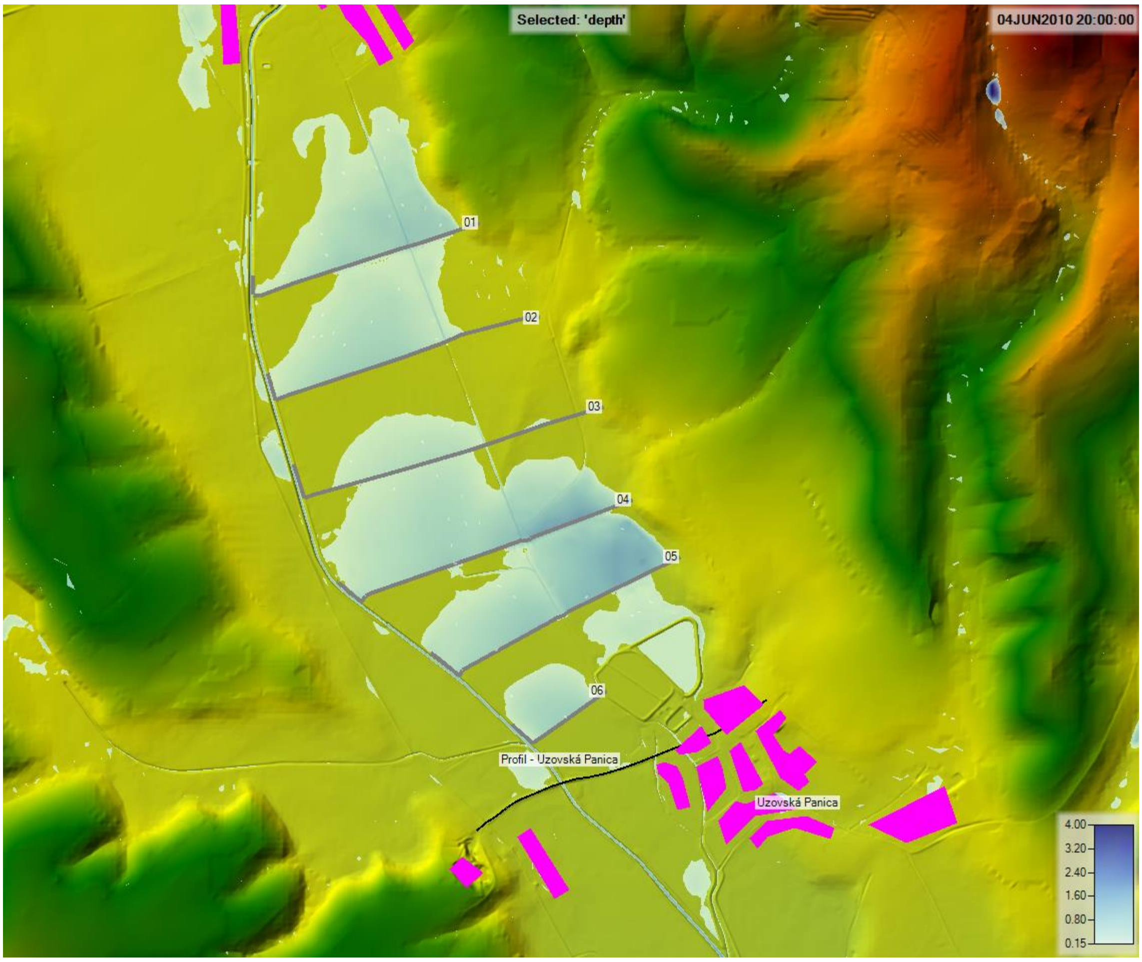

Fig. 57: Alternative 3 – map of depths (Uzovská Panica) – flash flood precipitation event

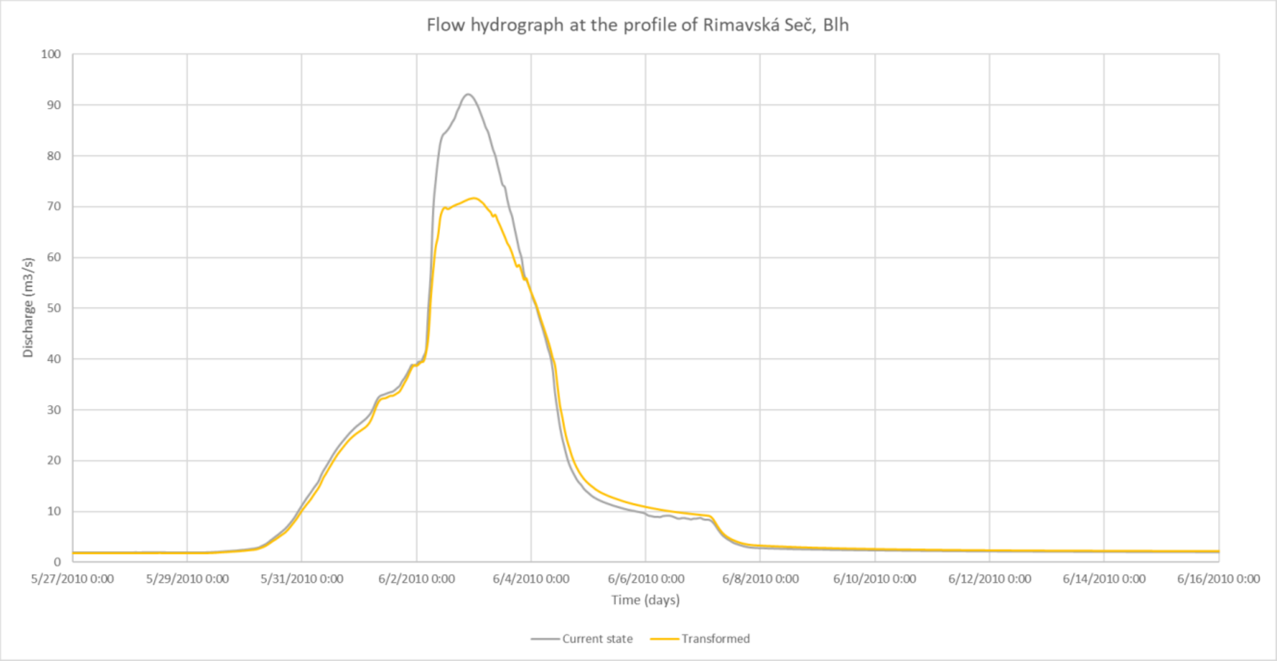

Fig. 58: Alternative 3 – Flow and stage hydrograph for proposed event – flash flood precipitation event

From the flow and stage hydrographs it can be assumed that this kind of measure is quite highly efficient for flash flood events (reduction of discharges in aprox. 20%). But due to limited volume of such polders in cascade the effect is rather low during long term precipitation events when amount of precipitation rises and saturation of land rises too.

8.5 Regulation of outflow from drainage systems in areas with hydro-melioration infrastructure

Floods occur essentially for numerous reasons. Inland waters are formed in certain areas by precipitation or snowmelt, cannot outflow freely from this area and create floods. Such areas can be, for example, vast lowlands, fenced areas or major terrain depressions. The third reason for floods may be an increase of groundwater level and the rise of groundwater above the ground.

Based on the results of Q_{100} simulation and characterization of flood formation a massive inland areas with isolated water areas were detected in lower part of the catchment. There was examined the case how to lower the risk of flooding the property in touched (flooded) municipalities during long term precipitation event.

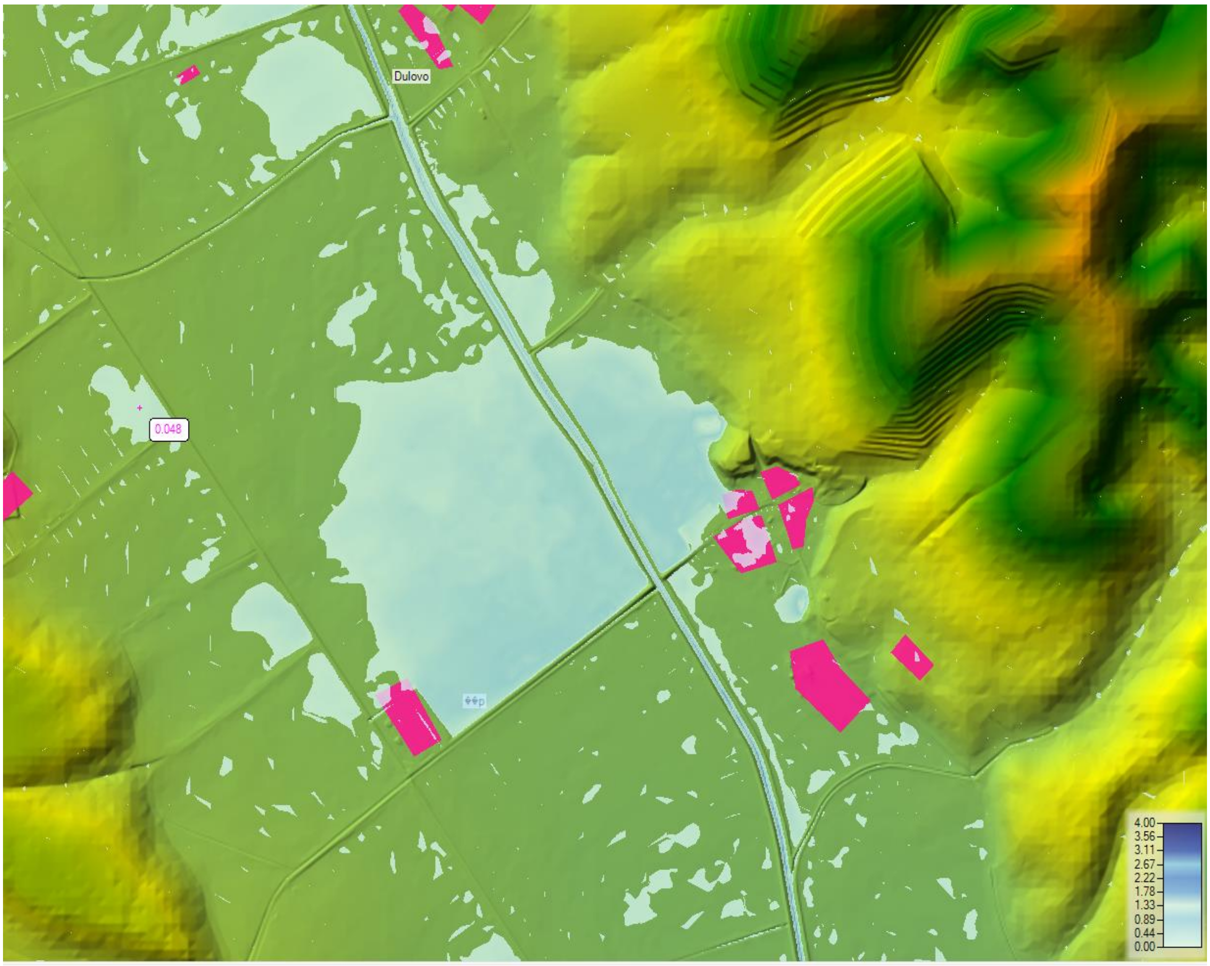

Fig. 59: Current state – map of depths (typical isolated water near Dulovo village) – long term precipitation event

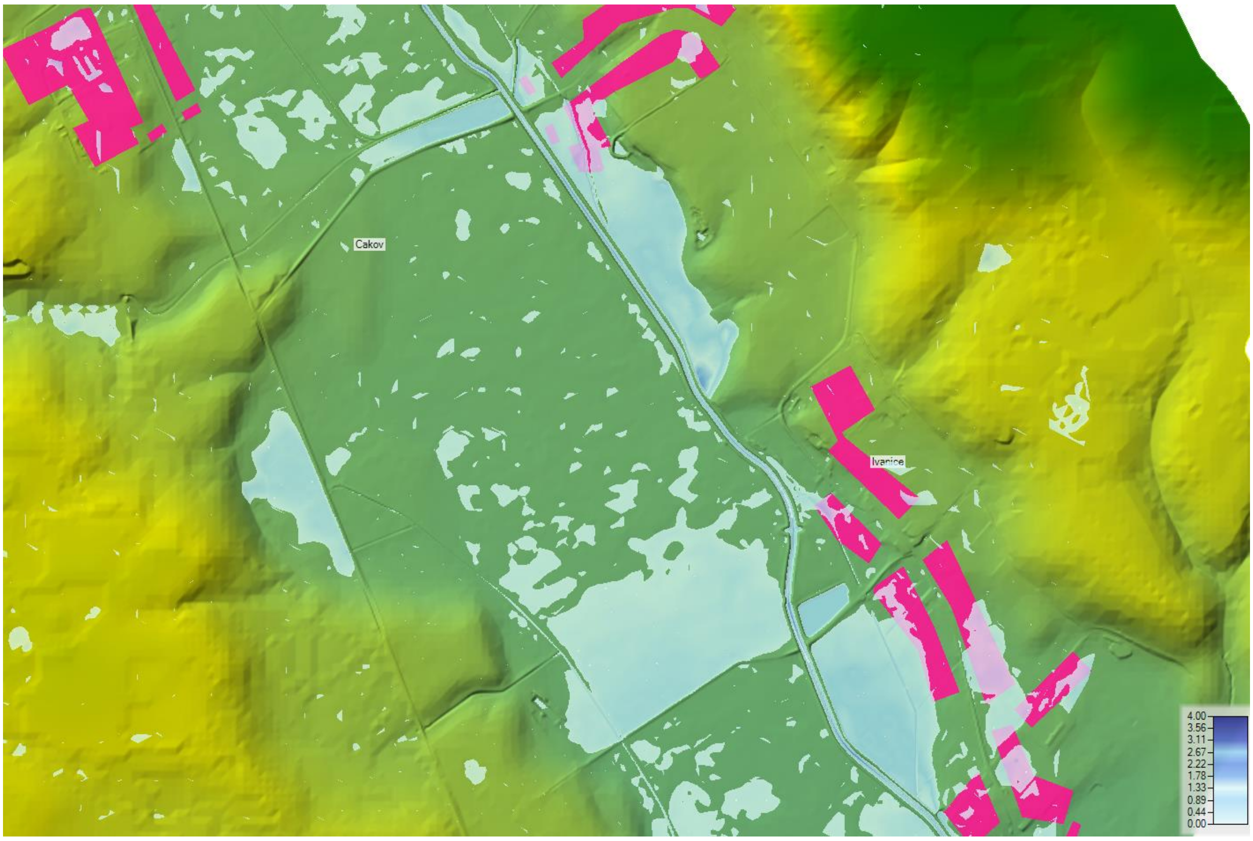

Fig. 60: Current state – map of depths (typical isolated water near Cakov village) – long term precipitation event

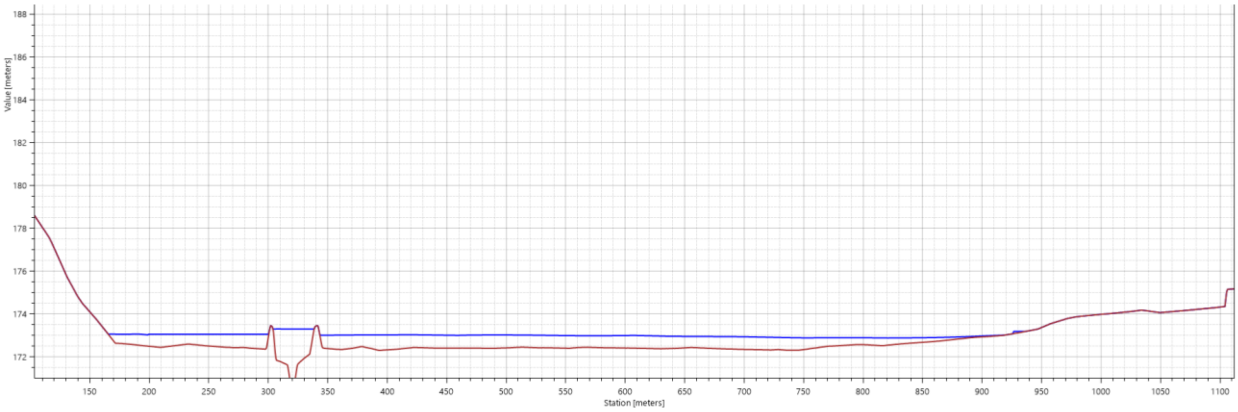

Fig. 61: Current state – cross section (typical isolated water near Dulovo village) – long term precipitation event

Tab. 8: Estimated lengths of drainage canals recommended for reconstruction

id	Length (m)
0	325.9
1	424.0
2	180.4
3	792.3
4	987.0
5	908.6
6	275.7
7	647.4
8	641.0
9	504.2
10	613.6
11	541.2
12	1100.7
13	433.1
14	915.9
15	1355.7
16	248.5
17	267.5
18	937.1
19	962.9
20	1903.6
21	416.3
22	1046.4
23	757.6
24	2275.3
25	486.4
26	656.1

During the long term precipitation events the ground is saturated and the infiltration of isolated water could be to slow. With the aim to minimize the damages (flood extent) on potential landuses (municipalities, agriculture) in particular areas, there are proposed reconstructions of existing drainage systems (D01) showed in Fig. 62.

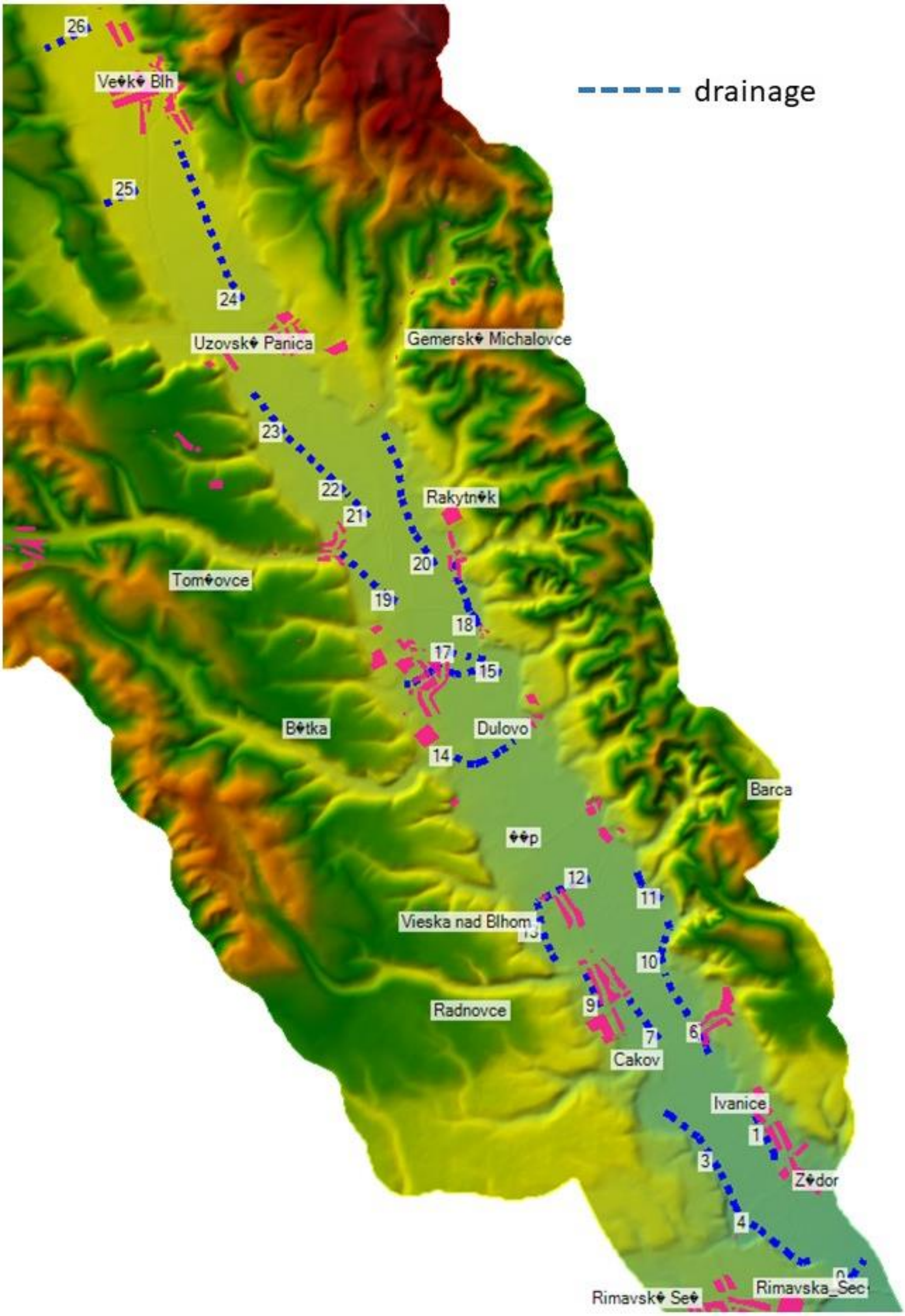

Fig. 62: Proposal of the drainage system reconstruction

8.6 Levees

In addition during modelling numerous places it the catchment of Blh River were identified where levees seems to be of insufficient height . Q_{100} flood event analyses showed critical locations in downstream part of the pilot catchment. It is recommended to increase the height of the existing levees up to 2 m.

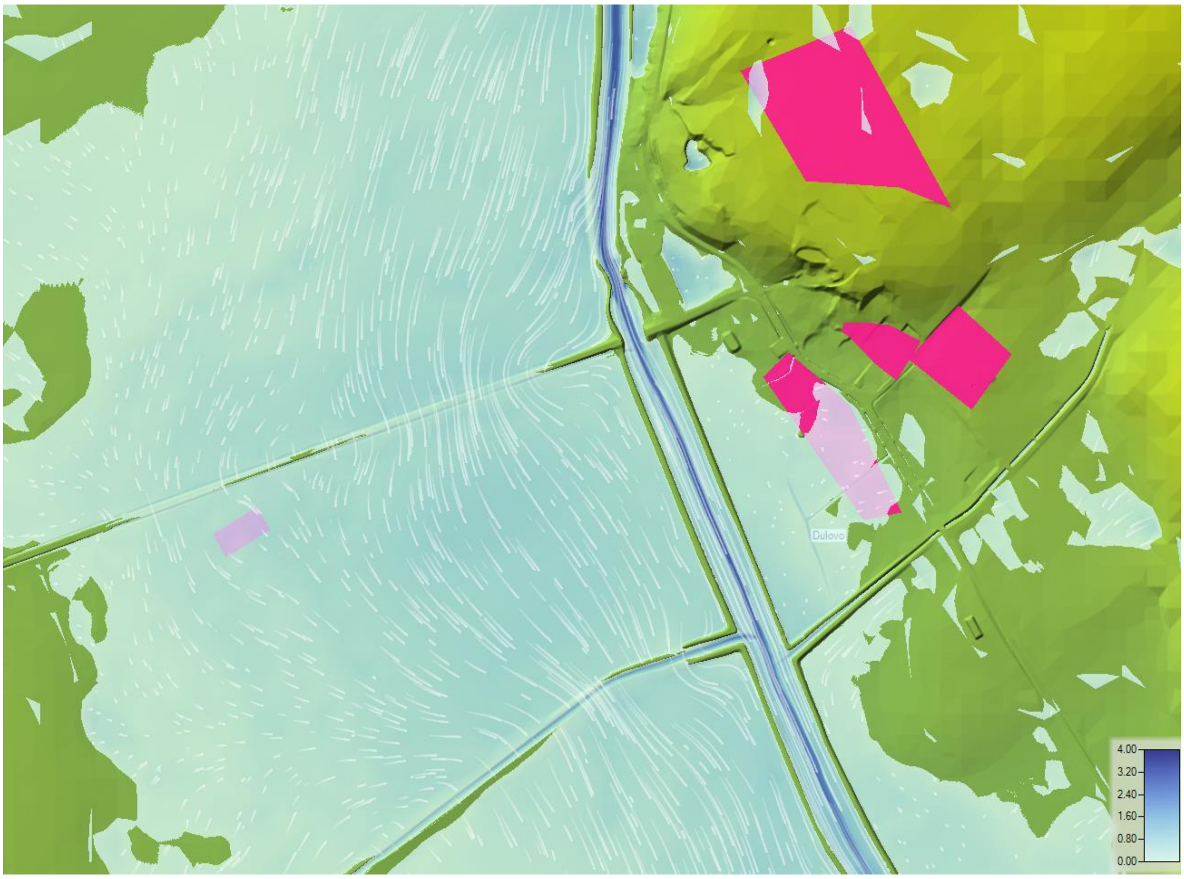

Fig. 63: Current state – map of depths, insufficient levees height (location of Dulovo)

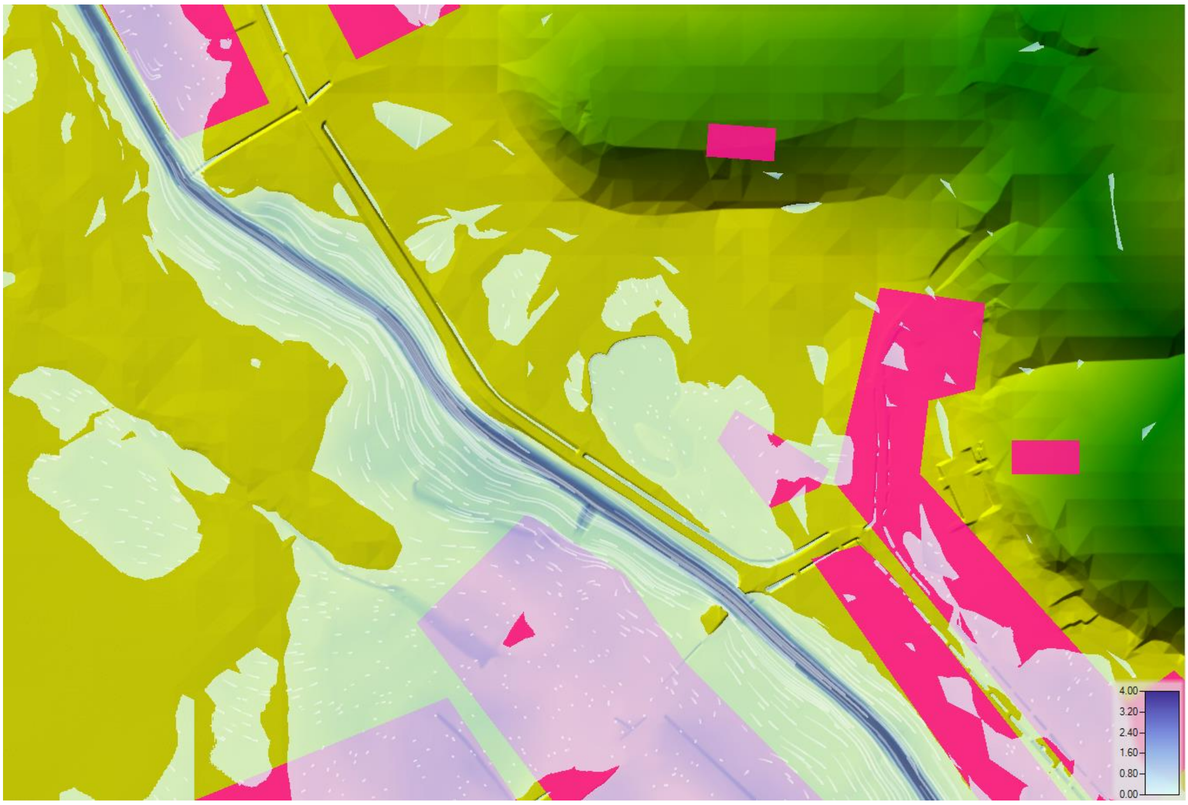

Fig. 64: Current state – map of depths, missing levees (location of Veľký Blh)

It is necessary to mention that in the pilot catchment the technical measures as Removal of sediments and/or bank vegetation (Tx) and Adjustment of watercourse (Ty) are planned by water management administration authority within Flood Risk Management Plans (i.e. standard river maintenance activities). In the case that sediment removal will be realised, it is necessary to remodel the situation as it can be assumed that in that case necessary enhancement of levees will be less.

9. HYDROLOGICAL SIMULATION

Creation of the hydrologic simulation model was the objective of the submission of the project which could be used for flow rate evaluation or for flood forecast. Nebolo cieľom zmodelovať opatrenia. There are several types of such models already mentioned in chapt. 1, we have used a conceptual model TUW (TU Wien). It was developed by Parajka and Viglione (2019). It consists of a snow routine, a soil moisture routine and a flow response and routing routine. The inputs are daily air temperature, precipitation and potential evapotranspiration. The snow routine is based on a degree-day concept and it is ruled by five parameters. The soil moisture routine represents soil moisture state changes and runoff generation. Finally, an upper and a lower soil reservoirs and a triangular transfer function compose the runoff response and routing routine. More details about the model structure can be found in Parajka et al. (2007). Tab. 9 briefly reports and describes the calibrated parameters, defining also their lower and upper bounds which were calibrated by genetic algorithms.

Tab. 9: TUW model parameters and their ranges

Parameter	Units	Range	Description
SCF	-	0.9 - 1.5	Snow correction factor
DDF	mm/(°C*day)	0 - 5	Degree day factor
LP	-	0 - 1	Parameter related to the limit of evaporation
FC	mm	0 - 600	Field capacity, i.e., max soil moisture storage
β	-	0 - 20	Non linear parameter for runoff production
k0	days	0 - 2	Storage coefficient for very fast response
k1	days	2.30	Storage coefficient for fast response
k2	days	30 - 250	Storage coefficient for slow response
LUZ	mm	0 - 100	Threshold storage state, very fast response starts if exceeded
Cperc	mm/day	0 - 8	Constant percolation rate
CROUTE	days/mm	0 - 50	Scaling parameter

The hydrological model is possible to create according to profiles where measurements are performed, in this case are these profiles gauging stations Drienčany, Teplý Vrch and Rimavská Seč (Fig. 65). Therefore, three consequential models described in the next chapters were carried out:

- Hydrologic model (*TUW1*) for river basin with final profile Drienčany,
- regression model *RM1*, which role was to simulate the transformation of flow rates by reservoir between Drienčany gauging station and reservoir Teplý Vrch,
- hydrologic model *TUW2* for part of the river basin between reservoir Teplý Vrch and gauging station Rimavská Seč which includes the inflow from the upper part of the river basin, i. e. the flow rates calculated by the foregoing model.

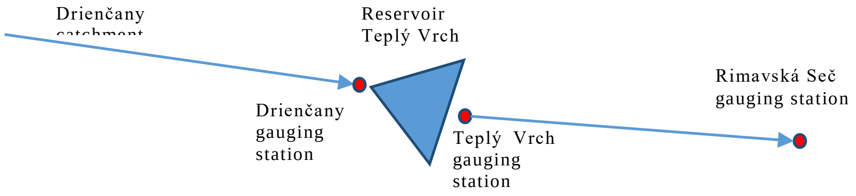

Fig. 65: Simplified scheme of the solved locality

9.1 Hydrological simulation of flow rates in Drienčany (model TUW1)

Hydrologic modelling proceed according to scheme – model being calibrated on one part of data and verified on another one data set which was not used at the creation of the model. It means the calibration procedure consists of finding optimum values of certain parameters of the model using genetic algorithm. Generally, the available data set will be divide into two periods – greater calibration period and a shorter (but still representative) testing part. The evaluation of the testing process gives a good view about the real behaviour and accuracy of the model. For such evaluation it is possible to use more statistical indicators and graphical illustration of results. The task of the described model is to simulate on base of precipitation data, temperatures and evapotranspiration the flow rates in gauging station Drienčany.

There are 15 years of complete measurements for precipitation, temperatures and flow rates. The precipitation data set was determined on base of weighted average value based on measurements from stations Teplý Vrch, Ratkovské Bystré, Hnúšť, Lukovištia a Ratková. The weighted average value was determined according to areas of Thiesen polygons, which can be assigned to particular stations (Fig. 66). The temperatures were obtained from the nearest climatic station which was the station Ratková. Potential evapotranspiration was calculated on base of temperature data. As calibration period was selected the period 2003 - 2011 (9 years) and as the testing period the period 2012 - 2017 (6 years) was selected.

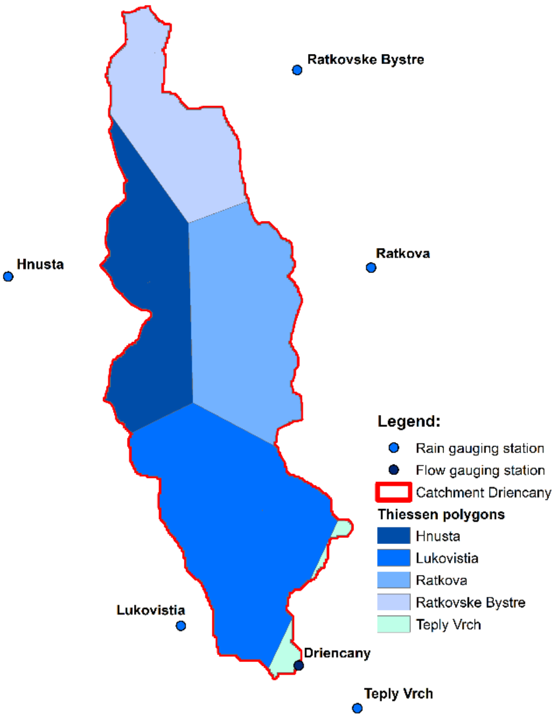

Fig. 66: Assignment of areas to precipitation stations using Thiessen polygons

After running of calibration process the model was verified on testing period. Evaluation of the accuracy of the applied model is illustrated in Fig. 67 and in Tab. 10. In Tab. 10 there are following indicators of the accuracy of the model:

- **NSE** - Nash–Sutcliffe model efficiency coefficient is the basic coefficient used in hydrology modelling. Nash–Sutcliffe efficiency can range from $-\infty$ to 1. An efficiency of 1 corresponds to a perfect match, an efficiency of 0 indicates that the model predictions are as accurate as the mean of the observed data, whereas an efficiency less than zero occurs when the observed mean is a better predictor than the model. Model performance can be evaluated as “satisfactory” if NSE > 0.50.
- **RMSE** – Root mean square error. RMSE gives the standard deviation of the model prediction error. A smaller value indicates better model performance.
- **R2** – Coefficient of Determination. Gives the proportion of the variance of one variable that is predictable from the other variable. Values (0 <= R2 <= 1), higher values is better.
- **PBIAS** - Percent bias (PBIAS) measures the average tendency of the simulated values to be larger or smaller than their observed ones. The optimal value of PBIAS is 0.0, acceptable values are up to ± 25%. Positive values indicate overestimation bias, whereas negative values indicate model underestimation bias.
- **VE** – Volumetric efficiency. It ranges from 0 to 1 and represents the fraction of water delivered at the proper time.

- **KGE** - Kling-Gupta efficiency. Kling-Gupta efficiencies range from - Inf to 1. Essentially, the closer to 1, the more accurate the model is.

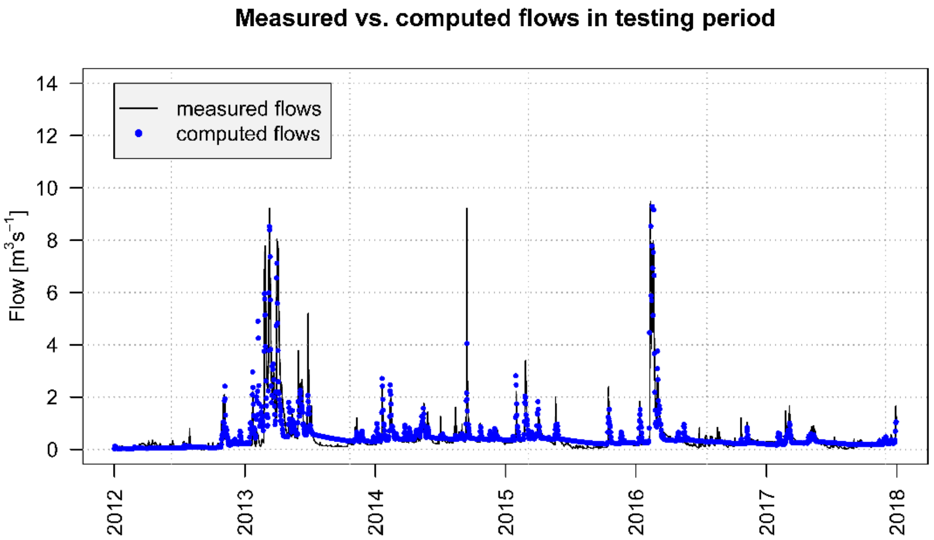

Fig. 67: Comparison of measured and simulated flow rates in Drienčany profile

Tab. 10: Statistical indicators of accuracy of the hydrologic model

Statistical indicator	NSE	RMSE	R2	PBIAS	KGE
value	0.77	0.44	0.77	7.5	0.83

9.2 Determination of flow rates in gauging station Teplý Vrch (model RM1)

Applied model takes over the flow rate results from the foregoing model in Drienčany station and transforms them through reservoir Teplý Vrch to achieve modelled flow rates in station Teplý Vrch bellow the reservoir. Those are in reality measured but the purpose of the modelling is their forecast or determination of theoretically possible situations. However, the reservoir has another tributary stream flowing from Drienčany, the hydrological solution was preferred using regression dependency. Independent variables are the flow rates above the reservoir in gauging station Drienčany and precipitation values in the river basin above the profile Teplý Vrch.

For the solution the linear regularized model LASSO was applied. The task of it is to eliminate the potential correlation among the input data what precludes the utilization of a standard linear regression. Modelling process was created on one part of input data set and tested on another data set to secure the correctness of modelling procedure. In Tab. 11 are presented statistical indicators as in previous chapter.

Tab. 11: Statistical indicators of accuracy of the hydrologic model

Statistical indicator	NSE	RMSE	R2	PBIAS	KGE
value	0.87	0.36	0.87	-2.4	0.91

9.3 Hydrological simulation of flow rates in Rimavská Seč (model TUW2)

In third model the simulation procedure was performed by hydrologic model TUW on interface river basin between Teplý Vrch and Rimanská Seč gauging stations. Resulting flow rates were increased by flow rate coming in upper part Teplý Vrch reservoir which was calculated by foregoing model. The calibration period was again the selected period 2003 – 2011 (9 years) as it was in foregoing model TUW1 and for the testing period the period 2012 - 2017 (6 years) was selected. Results of the modelling are illustrated in Fig. 68 and in Tab. 12. According to the value of Nash-Sutcliff coefficient it is possible to point out the sufficient accuracy of the model.

Tab. 12: Statistical indicators of accuracy of the hydrologic model

Statistical indicator	NSE	RMSE	R2	PBIAS	KGE
value	0.76	0.45	0.76	6.4	0.83

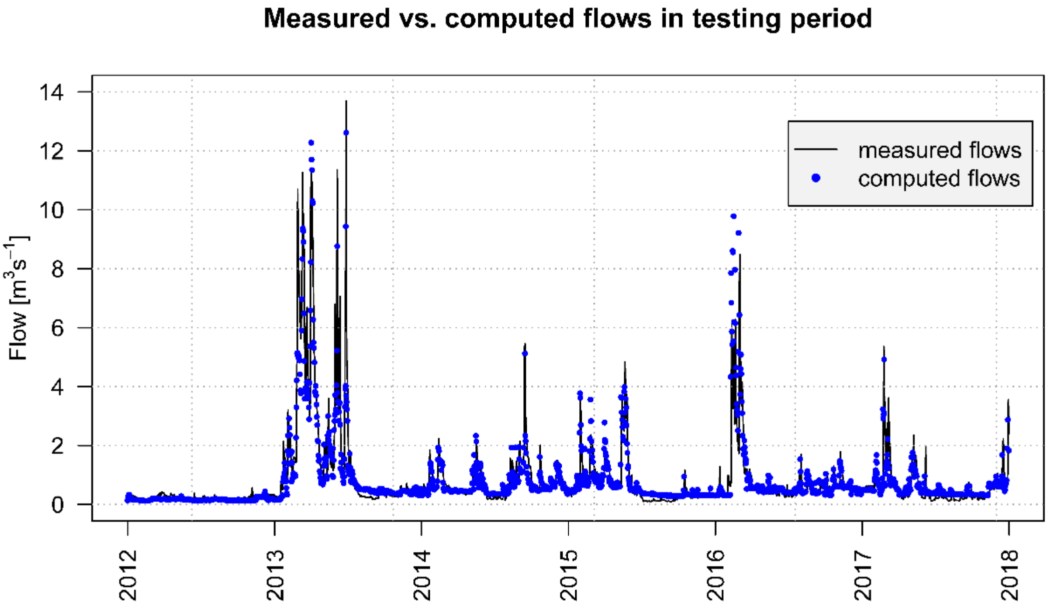

Fig. 68: Comparison of measured and simulated flow rates in profile Rimavská Seč

Based on the above mentioned results of all of three parts of hydrological model and assuming accuracy of statistical indicators shown in tables above it can be assumed that hydrological model TUW developed by Parajka and Viglione (2019) shows good results for flow rates evaluation and for flood forecast in the pilot catchment.

10. CONCLUSION

The main objective of hydrodynamic modelling was to determine the flood risk potential for given catchment and propose possible solutions to transform the flood designed waves by using regulation of outflow from drainage systems in areas with hydro-melioration infrastructure or management measures of areas suitable for the natural or artificial transformation of flood waves. Optimal flood protecting realization at the Blh catchment will be a combination of studied solutions.

The primary objective was to develop, calibrate and verify simulation model. HEC-RAS 2D 5.0.7 hydrodynamic model was adopted to simulate precipitation runoff and the flood formation due to heavy rain event. The calibration, verification and proposal simulation showed that HEC-RAS as a tool for hydrodynamic flood modelling is suitable and highly effective.

This study was not tasked to design and model the flood protecting measures in detail. Optimization and other analyses are needed to effectively propose the flood protection for given catchment.

It needs to be pointed out that the length or total volume of the flood wave has the major effect on the flood protecting proposals, especially measures with limited retention volumes. Numerous simulations showed that high effective measures during flash flood event had very limited effect on the transformation of long term precipitation event. From the analyses done it seems like alternative 2 which tries to keep water in the upper part of catchment is the most efficient for pilot catchment, as the amount of water retained is the highest in time (assuming for long term precipitation event and for flash flood precipitation event too). In addition levees at the whole area need to be considered and proposed.

Based on the results of hydrological modelling it can be assumed that hydrological model TUW developed by Parajka and Viglione (2019) is suitable for flow rates evaluation and for flood forecast in the Blh pilot catchment.

11. LIST OF FIGURES

12. LIST OF TABLES

13. BIBLIOGRAPHY

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