Flash flood simulation in the urbanised catchment: a case study of Bratislava-Karlova Ves

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Abstract: *Flash floods are a dangerous phenomenon that generally affects small drainage basins. They are primarily initiated in the upper parts of the slopes, but their damaging effects are manifested mostly in residential areas, where naturally flowing streams were removed from the surface to the underground artificial channels. Therefore, there are no precise data about stream water levels available and only using surface runoff modelling is possible to simulate what happened during flash floods. Karlova Ves (Bratislava City District), formerly a small viniculture village, was threatened by floods (most probably including pluvial type) in history. In this paper, we used GRASS GIS tool r.sim.water to simulate the surface runoff of a flash flood that occurred in summer 2014 in the catchment of Čierny potok. The flood on 23 August 2014 was reported to have the highest rainfall per hour ~40 mm during the time of local meteorological measurements. The current orthophotomap was used to classify the land cover classes, which were assigned the value of the Manning's roughness coefficient and infiltration rate. The topography was expressed by DTM from high-resolution LiDAR data. Our preliminary results indicate that land cover and land use are the essential factors that influence the initiation of flash floods, although the main driver of lower infiltration and change in flow direction is caused by urbanisation and a high proportion of impervious areas. Simulation showed that during 60 minutes of extreme rainfall (40 mm/hr) a surface runoff can reach a depth of water up to two meters in terrain depressions by a maximum discharge of 25 cubic meters. The revitalisation of natural urban areas by increasing vegetation cover in areas prone to flash floods and accumulation of water during higher rainfalls helps to prevent the damage caused by floods.*

Keywords *Čierny potok stream, flash flood, GRASS GIS, LiDAR, CORINE Land Cover, Bratislava*

Introduction

Flash floods are worldwide one of the most dangerous natural global hazards because they often cause human casualties and significant material damage (Boardman et al. 2003, Karagiorgos et al. 2016, Miller and Hutchins 2017). These types of floods occur in several European countries (Gaume et al. 2009) including Slovakia (Solín and Cebecauer 1998, Stankoviansky 2002, 2009, Urbánek 2005, Stankoviansky and Frandofer 2012). The terminology used is not uniform, with several synonyms or different definitions describing flood-type as pluvial floods or muddy floods (Gaume et al. 2009, Johnson and Priest 2008). While the classification is specific for smaller streams or dry valleys without permanent water levels where episodic water flow-induces gully formations in extreme rainfall (Urbánek 2005), it differs for sediments contained in the flood-waters.

https://doi.org/10.33542/GC2022-2-01

The occurrence of flash floods is conditioned by several factors. The watershed area and the relative percentage of deforested soil prone to erosion and further sediment transport are as important as the rainfall intensity. In addition, land cover and land use are key drivers of water infiltration in flash flood formation and its mitigation (Stankoviansky 2002, Stankoviansky and Barka 2007).

Although the origin of flash floods is connected to the surrounding agricultural land, they cause major damage in the urban areas with a lack of infiltration surfaces. Artificial surfaces (paved roads, etc.) cannot sufficiently withhold and/or infiltrate water but support its runoff. Ephemeral forest pavements and field roads in dry valleys and road inclination in slope direction in the urbanised areas cause faster water runoff during extreme rainfall events, and these corridors can also become episodic channels (Stankoviansky and Frandofer 2012, Danáčová et al. 2015).

In the current Bratislava City area, major urbanisation processes manifested as a transformation from previous rural communes to the current residential areas in the city (Pazúr et al. 2017). Many changes in land cover and land use occurred during this transformation in the mid-20th century when the dominant functional land use changed from agricultural to urbanised-residential construction. This activated faster surface water runoff and further degradation of natural landscape elements. Smaller alluvial areas and riparian forests were replaced with impermeable landscapes of residential buildings and surrounding infrastructure with roads and pavements, etc. (concrete). Destruction of natural alluvial habitats and green areas with orchards or shrubs and trees affected the functional land use and ecosystem services. In addition, it increased the hazard of flash floods in the diverse hilly areas of higher slopes. Higher frequency of extreme drought and rainfall (Lapin et al. 2019) in a studied region contributes to the multiplier effect of several factors mentioned above. A change of land use in hilly areas from intensive agriculture to build-up area with multilevel buildings and transporation infrastructure is among the factors singificantly influcencing occurence and effects of the flash floods (Prokešová et al. 2022).

Flash floods simulations in areas without continual water discharge data are based on surface runoff models counted from the elementary continuity equation (Kirkby 1971). Surface runoff exists only if the amount of water falling to the surface unit is higher than the infiltration rate (influenced by soil and vegetation cover) and such runoff is strongly determined by slope and surface roughness (Hofierka et al. 2017). Differential equations derived from the Saint-Venant continuity equation usually used for such simulations have a few approximations (kinematic wave approximation I, II) (Mitasova et al. 2004, Hofierka and Knutová 2015). The GRASS GIS module r.sim.water is part of the SIMWE model (Mitas and Mitasova 1998) that was established on diffusion wave approximation (or dynamic wave approximation) and Monte Carlo simulations (Mitasova et al. 2004, Hofierka and Knutová 2015). The input parameters include elevation, channel slope, rainfall intensity, and Manning's roughness coefficient (Engman 1986) and the output is presented as a depth of water (in meters) and discharge (in units m^3/s).

The aim of this article is a simulation of the extreme rainfall event and the following flash flood that occurred in Bratislava (borough Karlova Ves) in the small stream of Čierny potok watershed in 2014. Similar rainfalls are expected to appear in this region as a consequence of climate change, and the local government is interested in possible mitigation measures in the future urban planning and sustainable development study.

Study area

Flash flood problems were recorded in the Karlova Ves borough in Bratislava, which is located in the Little Carpathians Mountain foothills (Fig. 1).

There is especially higher flood frequency in Líščie údolie street, with constant threat of extreme flood events. This street becomes flooded in intensive rains because some houses reside in the depressions of the prior Čierny potok stream alluvial area.

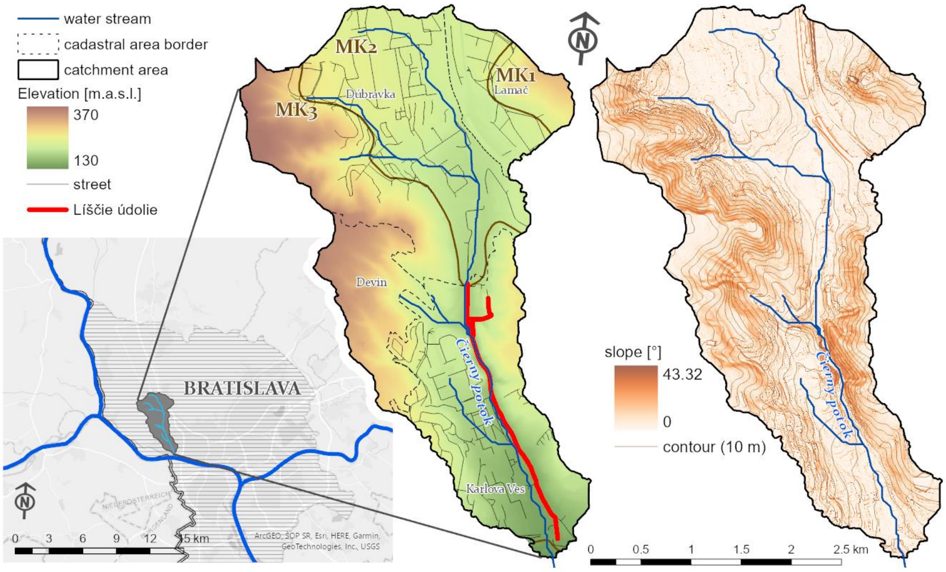

Fig. 1. *Location of the Čierny potok stream and basic geomorphological characteristics and division MK1 – MK3 of the Little Carpathians Mts.*

Karlova Ves was a small vineyard village at the beginning of the 20th century, it had a simple linear type of settlement structure. Its character was transformed only in the second half of the 20th century when it was changed to the characteristic panel building blocks as it was attached to growing Bratislava. During this transformation, the Čierny potok stream was redirected to the sewerage and the natural alluvial area was mainly destroyed (Šrámek 2014). Some parts of the naturally flowing stream area in Karlova Ves go through forests above the Líščie údolie park area (SNP park).

The number of inhabitants of the Karlova Ves increased from 1447 in 1961 to 14 468 in 1970 and over 35 000 in 2021. However, in 1850 it was only a small settlement with 170 inhabitants (Bartovič et al. 1993). Built-up areas constituted only 8 ha during first Military survey (1764-1787) but they enlarged to 182.6 ha in 1981 (Bartovič et al. 1993) and 331.31 ha as of today (ÚGKK SR 2021).

Krumpolec et al. (2017) reported flooding in the Líščie údolie region at the beginning of the 19th century, and the frequency of intensive rainfalls and flash flooding in the budding residential area has increased in recent decades. The combined factors responsible for this include the key driver of land cover change (Prokešová et al. 2022).

The Čierny potok stream watershed includes parts of the Bratislava-Karlova Ves, Dúbravka, Lamač and Devín residential areas, but flash flood damage is concentrated in Karlova Ves in the lower part of the watershed area near its confluence with the Danube (Fig. 1). The Čierny potok stream is a Danube left tributary, and it was recorded with the Morava River as the historic “dry Vydrica”. The Vydrica stream is also a left Danube tributary, recorded as “*Siccum Weydrich*” in 1226 (Krumpolec et al. 2017, Bel 1735). The Vydrica is now a natural stream which only partly flows through the Karlova Ves forested area, because it is hidden in the sewerage system without other traces of its existence. Finally, the previous mill at the end of the Líščie údolie valley existed until the shopping centre was built and the alluvial area was transformed into services areas.

The Čierny potok stream has a relatively small 10.02 km^2 watershed, with significant relief amplitude from fluvially-induced erosion of the uplifted Little Carpathians Mts. (MK in Fig. 1). The main valley was modelled by the stream and partly by the Danube. The surroundings area as follows; it is surrounded from the west by the Devínske Carpathians subdivision, the Bratislavské predhorie foothills and the Lamačská brána Gate (MK2 – MK3 in Fig. 1, Kočický and Ivanič 2011), and from the east by the Pezinské Carpathians (MK1 in Fig. 1, and Kočický and Ivanič 2011).

The area’s geology is Palaeozoic granitoid and metamorphic layers of the Tatricum Little Carpathian Mts. with denuded remains of Miocene tertiary clay and sandstone sediments. The Quaternary cover is fluvial sediments of the river terraces and loess with combined diluvial sediments (Polák et al. 2011).

Data from the closest meteorological station at Mlynská dolina provided mean yearly rainfall approaching 640 mm in 1981-2015, with the highest 60-70 mm rainfalls mostly in the May to September summer months. The highest 64 mm daily rainfall over the last 6 years was recorded at the end of August 2014, and 56 mm was also reported in August/September 2018 (Lapin et al. 2019).

Methodology and data

Input data for rainfall event simulation

Information on rainfall events was collected free-of-charge from the *Microstep Company* database at the Mlynská dolina meteorological station. We required input of the extreme mm/hr rainfall intensity for the investigated area for our simulations. Lapin et al. (2019) evaluated the daily high-intensity here at 40 mm, and this occurs approximately once every 50 years. The highest value obtained from our hourly data from *Microstep Inc.* was 40 mm/hour on 23 August 2014, so this value was the basis for further calculations of the extreme rainfall event and subsequent flash floods.

DTM processing

The basic input required for the simulation is DTM which we downloaded from the DMR 5.0 product available at © ÚGKK SR. This originates from LiDAR aerial laser scanning. There are 42 localities available for the Slovakia area, and the Karlova Ves, Dubravka, Devín and Lamač cadastral areas form part of three of these 42 localities. They have an elevation proclamation with 5 cm precision.

The model therefore captures important terrain features in sufficient detail to provide the path and direction of natural and human-influenced surface water runoff during extreme rainfall events. We merged the DMR 5.0 cadastral sub-areas with the Mosaic to New Raster tool and then cut the resulting elevation raster (DTM) for the Čierny potok stream watershed in 1 m x 1 m cell resolution (Fig. 1). Finally, we created an auxiliary derivative layer with the *r.slope.aspect* tool in the form of a slope raster in degrees (Fig. 1). This method computed the individual elevation derivatives in the x and y directions, in addition to the slope (Fig. 2).

Land cover classification

The latest orthophotomap available in ArcGIS v. 10.3 is the "*base map*" from 2017. We employed this to map the land cover by manual classification, based on detailed modification of the CORINE Land Cover method. (Feranec and Oťaheľ 1999, Druga et al. 2015, Oťaheľ et al. 2017, Falťan et al. 2018). This is at the 5th hierarchical level of the CLC at 1:10 000 scale, with the smallest mapping area set at 0.1 ha, 1000 m^2. It was then important to delineate areas with different possibility of rainfall water-infiltration. We separated buildings (11210) from roadways and adjacent paved surfaces such as pathways, concrete impervious surfaces- parking lots (12212) and different sites in the residential area with urban green space (11212, 11211). Tram-line reconstruction is separately allocated under 12231. This provides additional grassland in these places, and it aids water retention function. Finally, it was important to establish barriers to stormwater runoff, including highways and railway infrastructure.

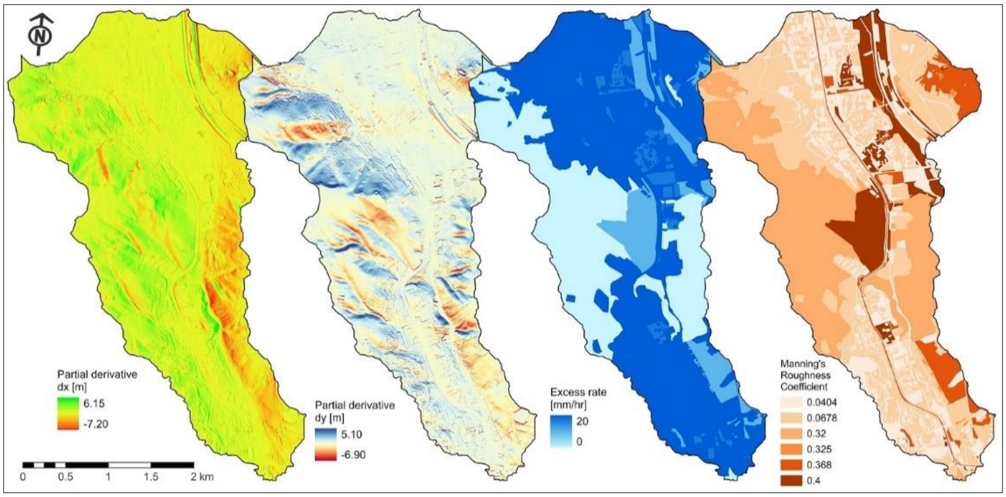

Fig. 2. *Input data preparation into the r.sim.water module: partial derivative of elevation in the x and y directions, excess rate (subtraction of the rainfall value and infiltration rate), Manning's roughness coefficient*

The infiltration rate and Manning's roughness coefficient values were subsequently assigned to the land cover classes (Tab. 1). Here, literature study identified that authors' work on Manning's roughness and infiltration differed remarkably (Hofierka and Knutová 2015, Pappaioannou et al. 2018, Harmon 2022, Alizadehtazi et al. 2016).

The authors investigated different-sized model territories and used different element resolution levels for each infiltration and Manning's roughness coefficient value. More complex methods then assigned different values to approximately the same classes. For example, 'forest' was assigned 0.4 Manning's coefficient value by Hofierka and Knutová (2015) and 0.1 by Pappaioannou et al (2018). The 'built-up area' was designated 20 mm/hr value by Hofierka and Knutová (2015) and 36-400 mm/hr by Alizadehtazi et al (2016). Our research was therefore conducted on iterative test simulations to establish these coefficient values (Tab. 1).

Surface runoff modelling and simulation

We employed the *r.sim.water* module in GRASS GIS software v. 7.8.6 to model runoff routes in residential areas lacking the possibility of otherwise obtaining water level and flow data, (Fig. 3, and Mitasova et al. 2004, Hofierka et al. 2002). The *r.sim.water* module is a raster-based tool that simulates the rainfall-runoff relationships in a given area using elevation data (DTM) and the differing surface properties of the area. These are most often expressed by different infiltration rates and Manning's roughness coefficient. Therefore, we converted all input layers into raster form using the Polygon to Raster, Reclassify and Raster calculator.

This had a cell resolution of 1x1m, so that the raster cells fit the original DTM. The following input layers were prepared and modified for the simulation to run-off (Fig. 3):

- our DTM was derived from LiDAR data (Fig. 1),
- partial elevation derivatives in the x and y directions were by *r.slope.aspect* (Fig. 2),
- *rainfall intensity* in mm/hr minus the *infiltration rate* in mm/hr equals the *rainfall excess rate*: equals the run-off rate in mm/hr (Fig. 2),
- Manning's roughness coefficient (*Manning's n*) (Fig. 2).

Other values were left as default, and further optional input data was excluded from our simulation.

Prior to simulation, we set the time series output option and the time interval of the entire simulation to one hour. We then set the time interval of the partial output to 10 minutes, and designated the depth-depth water column drained in metres and the discharge-flow-runoff in m^3/s from the optional outputs. This provided 12 layers from each simulation, with 6 layers for each depth and discharge variable in 10, 20, 30, 40, 50- and 60-minutes time-frames.

Tab. 1. *Area of land cover classes (by CLC5) in the Čierny potok stream watershed with associated Manning's roughness coefficient values and infiltration rates per hour used as input data in the surface runoff model*

code CLC5	name of CLC class	area [m²]	area %	Manning's coefficient	infiltration rate [mm/hr]
11210	Discontinuous built-up areas with prevailing multi-flat houses	831 250	8.29	0.0404	15
11211	Discontinuous urban fabric prevailingly with multi-flat houses and a marked proportion of grass plots	351 483	3.51	0.0678	20
11212	Discontinuous built-up area of residential buildings in tree (settlement) greenery	863 691	8.62	0.0678	20
11213	Discontinuous built-up area prevailingly with multi-flat buildings with gardens	1 813 270	18.09	0.0678	20
11222	Gardens next to single-family houses	11 040	0.11	0.3680	25
11230	Prevailingly cultivated greenery in areas of services	18 314	0.18	0.0678	20
12111	Areas of shops and shopping centres	84 722	0.85	0.0404	15
12114	Areas of schools and research centres	208 614	2.08	0.0404	15
12117	Discontinuous built-up area of residential buildings in tree (settlement) greenery	148 611	1.48	0.0678	20
12121	Infrastructure of buildings and artificial surfaces	26 441	0.26	0.0404	15
12123	Accompanying (grass and woody) vegetation in areas of production	7 738	0.08	0.3680	25
12211	Motorways and two-lane expressways	52 584	0.52	0.0404	15
12212	Roads with a paved surface	914 286	9.12	0.0404	15
12221	Railway tracks and railyards	40 198	0.40	0.0404	15
12231	Accompanying prevailing grass vegetation	104 704	1.04	0.3680	25
12232	Accompanying prevailing shrub vegetation	44 054	0.44	0.4	35
12233	Accompanying prevailing tree vegetation	45 197	0.45	0.4	35
13311	Construction of the residential areas	43 481	0.43	0.0404	15
14111	Parks with prevalence of woody vegetation	140 332	1.40	0.4	35
14112	Parks with prevalence of grass vegetation	66 669	0.67	0.3680	25
14120	Cemeteries in inner settlement territories	11 368	0.11	0.0678	20
14130	Uncultivated settlement greenery	38 584	0.38	0.4	35
14211	Areas of sports with prevailing natural surfaces	96 457	0.96	0.0678	20
14212	Buildings and areas of sports with artificial surfaces, e.g. halls and sports plots	26 717	0.27	0.0404	15
22121	Small-block vineyards with indistinctive proportion of woody vegetation	20 528	0.20	0.3250	25
22212	Overgrown orchards	672 786	6.71	0.4	35
23120	Grass stands with dispersed trees and shrubs	499 406	4.98	0.3680	25
31110	Broad-leaved forests with a continuous canopy	2 841 057	28.34	0.3200	50
TOTAL	-	10 023 579	100	-	-

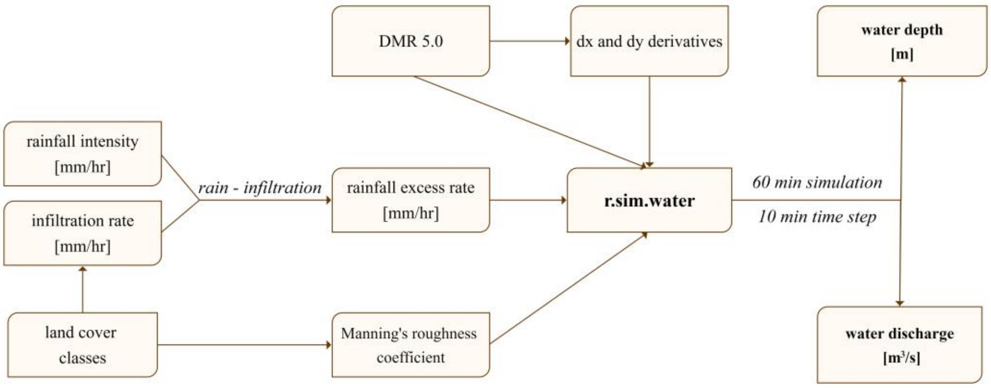

Fig. 3. *Flow diagram of the r.sim.water module in GRASS GIS*

Results

Present Land cover status

The current land cover structure (Fig. 4, Tab. 1) is distinctly fragmented. It includes several classes reflecting intensive urbanisation, with almost 20% of the area covered by buildings, road networks, and concrete surfaces. However, the large 28% part of the catchment area is also currently occupied by woodland (31110). This is mostly Carpathian oak-hornbeam forests, and some thermophilic oak and oak-cedar forests on the warmer western slopes. Other urban green areas, parks and accompanying vegetation to roads were recorded at approximately 23.9% of the residential area, and these areas have different infiltration possibilities during rainfall events, depending on the predominance of trees, shrubs and grasses. The smaller 7% portion of the area comprises former agricultural areas, and it currently has overgrown gardens, orchards and vineyards. The larger 18% of the area has houses with gardens (11213). These polygons were assigned to special land cover classes, dependent on whether the garden area is at least twice the area of the family house area or if the construction is specially marked as a building (11210). Finally, intensive urban development and grassland urban green space (11211) are prevalent in the lower part of the Čierny potok stream catchment area.

Occurrence of extreme rainfall events in the catchment area

The highest daily precipitation totals at the Mlynská dolina station in the last 10 years were recorded at the end of August 2014 when there were several consecutive days of increased precipitation. The highest 64 mm was on the 23 August 2014, and there was also high rainfall at the end of August and beginning of September in 2018, with 56 mm maximum on the 1st of September (SHMÚ). The highest hourly rainfall was recorded by *Microstep* rainfall automated gauging station data on the 23 of August 2014 when 40.8mm fell between 13:40 and 14:40 hours. Herein, we used 40 mm followed by flash-flooding as an example of extreme rainfall in the monitored watershed.

Surface runoff model

Our simulation showed that an extreme rainfall event can reach water depths of up to 2 m through surface runoff (Fig. 5). The maximum flow generated locally during the hour-long simulation is 25 m^3/s. The partial outputs of 10-60 minutes indicate that artificial surfaces, especially those linear in nature such as roads and pathways, immediately create runoff paths for the rainfall event. This water can subsequently enter terrain depressions or areas with water accumulation barriers created, for example, by train and tramway embankments. These depressions then gradually fill with water throughout the rainfall event and water can flood surrounding areas, dependent on the nature of the terrain.

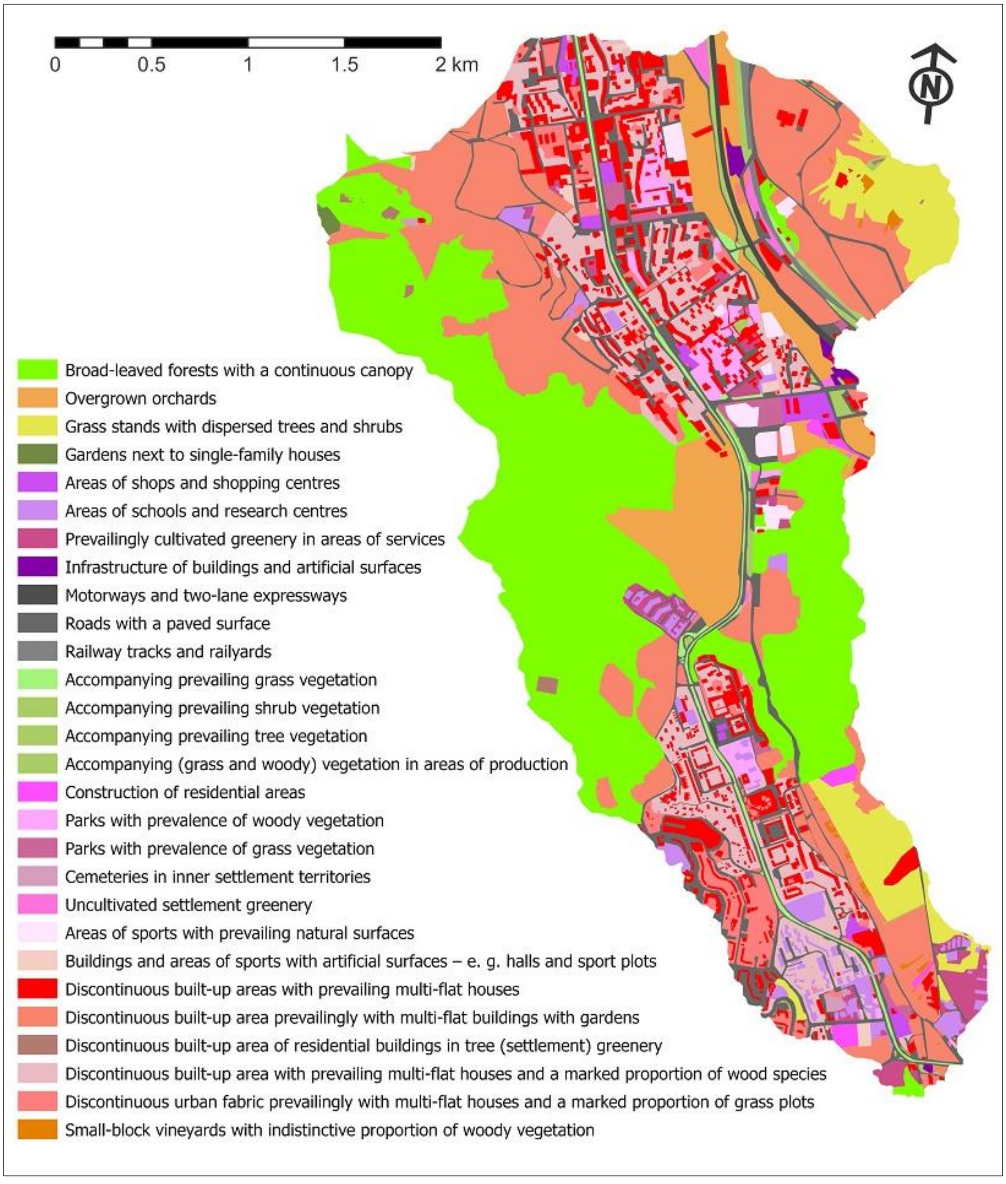

Fig. 4. *Current land cover of the Čierny potok stream watershed according to the CORINE Land Cover methodology at the 5th hierarchical level*

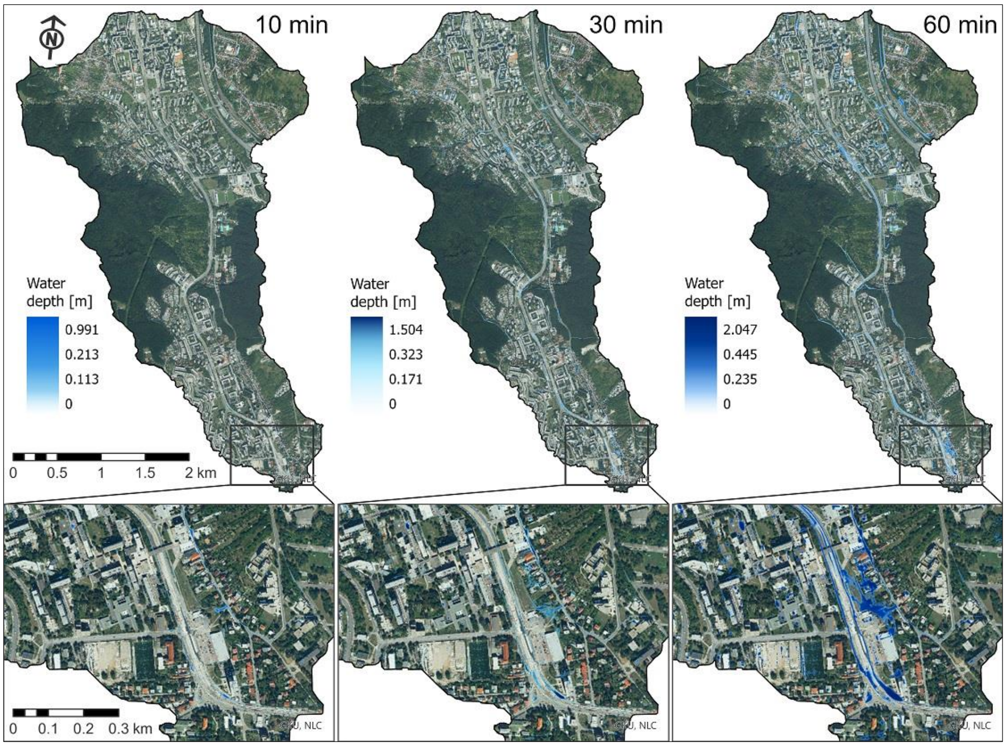

Fig. 5. *Surface water flow simulation in the watershed with water depth output after 10, 30 and 60 minutes after 40 mm/hr rainfall intensity*

The terrain depression resolution level is directly related to the digital terrain model employed. Therefore, we used DMR 5.0 from LiDAR airborne laser scanning to create the DTM in our locations. This accuracy ensured capture of even very small depressions and drainage paths.

It is alarming that the largest accumulated urban water-pools are often concentrated in houses and gardens. This leads to property damage and threats to human health and life, and it is especially conspicuous in Líščie údolie street in Karlova Ves and in the Bratislava-Dúbravka catchment area. Concurrently, artificially created depressions, including foundation pits of buildings under construction and inappropriate land modifications, create potential reservoirs for runoff water which have a "broken-dam" effect in extreme rainfalls. This creates no problems if this rainwater is captured, but the water can pool if the depression fills up and rainwater continues to flow from adjacent slopes. Run offs in this accumulated form most often occur along natural gullies and artificial valley roads.

Water originating from forest gullies may also collect in artificially created depressions transporting rock fragments, sediment soil and vegetation. This material then clogs the drainage system, increasing surface runoff and creating episodic road channels (Fig. 6).

Fig. 6. *Flash flood on Líščie údolie street (27.7.2019, 23.9 mm/day)*

Discussion

Authors use different methods to model surface runoff (Unucka and Adamec 2008, Ruman et al. 2021, Aragaw et al. 2021). Most consider that vegetation cover has a significant impact in their models. Herein, we concur with Prokešová et al. (2022) on the different soil property settings used in the SCS-CN method for the Čierny potok stream catchment. Results from 40 mm/hour rainfall are quite similar, because the main soil properties in the urban area have lower or no infiltration. The soil properties are strongly reflected in the land cover because the key flash -flood initiator appears increased in areas with artificial concrete surfaces (Jahan et al. 2021). Soil compaction is one cause of soil-infiltration reduction in urban areas (Yang and Zhang 2011), and there is also greater impact of increased urbanised surface runoff in the more permeable soils. Therefore, urbanisation on sandy substrates is much more prone to higher surface runoff than soils with higher clay content (Sjöman and Gill 2014). Moreover, building on higher slopes in our area increases runoff to an even greater extent (Kumar et al. 2013).

Land cover and the interpretation of its contours and infiltration capacity are most important modelling factors. We concluded that these factors partly cover soil properties, and detailed land cover classes were therefore divided for urban vegetation and surrounding forest in the catchment area. The strong correlation of concrete surfaces increased with urban area growth, and mapping these in the land cover changes is imperative in intensive surface runoff after heavy rainfalls (Coutu and Vega 2007, Sun et al. 2013).

Several series of simulations for different input-layer parameter settings in different surface types proved quite significant in the modelling. The forests (31110) have the best overall infiltration rate compared to other urban landscape surfaces. They can therefore capture and infiltrate most regular rainfall, with no surface runoff generated in the built-up area. However, the up to 50 mm/hr forest infiltration rate proved a significant difference parameter in our simulations (Fig. 7). Accordingly, our extreme 40 mm/hr rainfall value remains less than the forest infiltration rate.

Therefore, the model can infiltrate the precipitation that falls on the forest surface in the simulation, and surface runoff did not occur in the simulation. To illustrate this, we created a further series of simulations where we deliberately reduced the forest infiltration rate, thus "deforesting" the area of interest. This simulation showed that the runoff pathways and their areal extent increased significantly, and it demonstrates the significant forest water retention and infiltration rate in the urban landscape. Green space and parks are a very important part of residential areas. These increase their attraction for both healthy living and water retention functions, and this is supported by other authors (as in Kuehler et al. 2017).

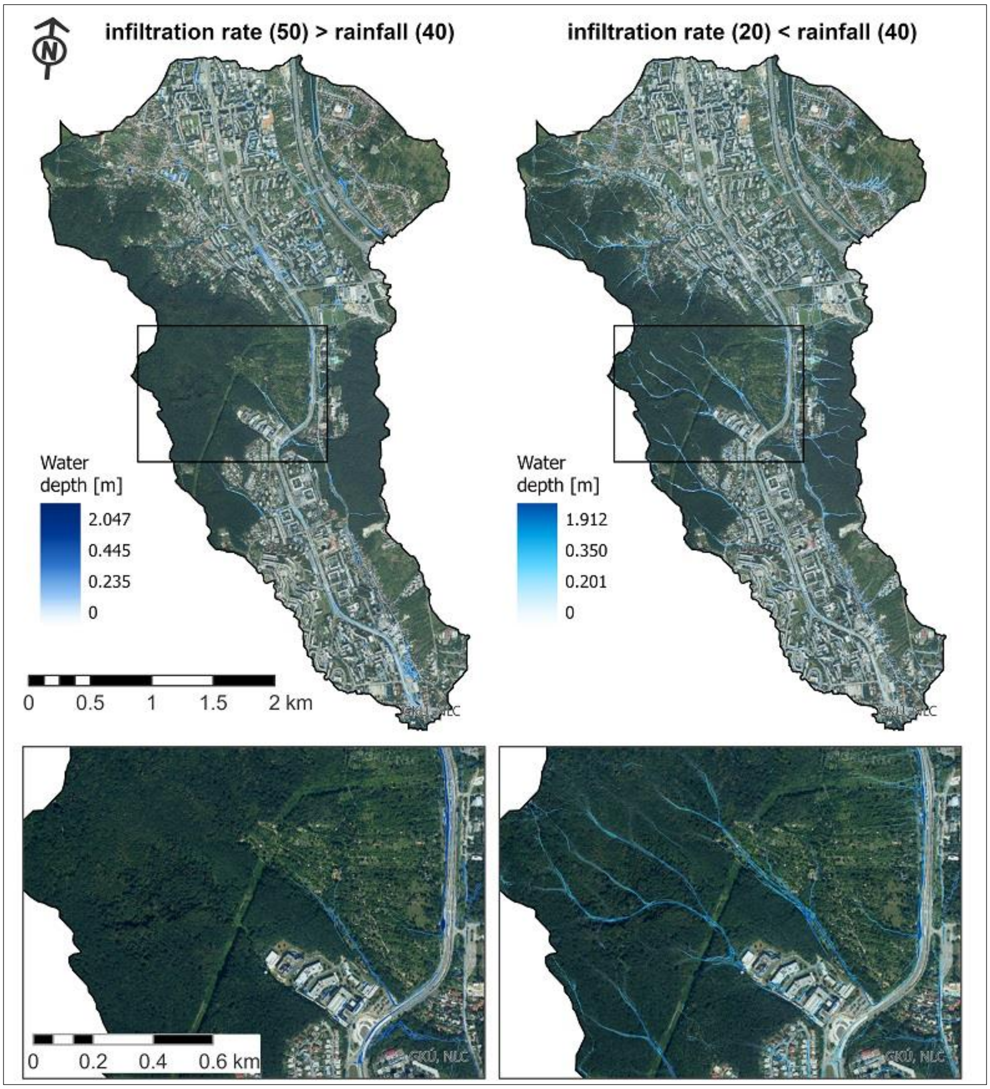

Fig. 7. *Surface water flow simulation in the watershed with surface flow direction and depth of water according to higher and lower forested area infiltration rate ability (for example, in case of deforestation)*

The problem of water-logging is unattended in modelling, because the actual infiltration rate can be different after a rain-soaked week to that observed after several days of drought. It is most likely that more detailed observation of the flash flood occurrence at certain sites and rainfall intensity data will provide improved results. Additional information should be applied in the future to further monitor the origin of the flash floods and the exact border value of its occurrence in damage-affected urban areas. Moreover, obtaining our data on flash floods was quite difficult, and therefore more rewarding research requires long-term monitoring. This work is further exacerbated by the continuous construction of new building areas and ongoing land cover changes. Most growth areas with new buildings and infrastructure are replacing areas with higher infiltration rates. These include the abandoned gardens or previous garden-areas with orchards where dominant tree vegetation with good infiltration will be rapidly reduced (Fig. 8).

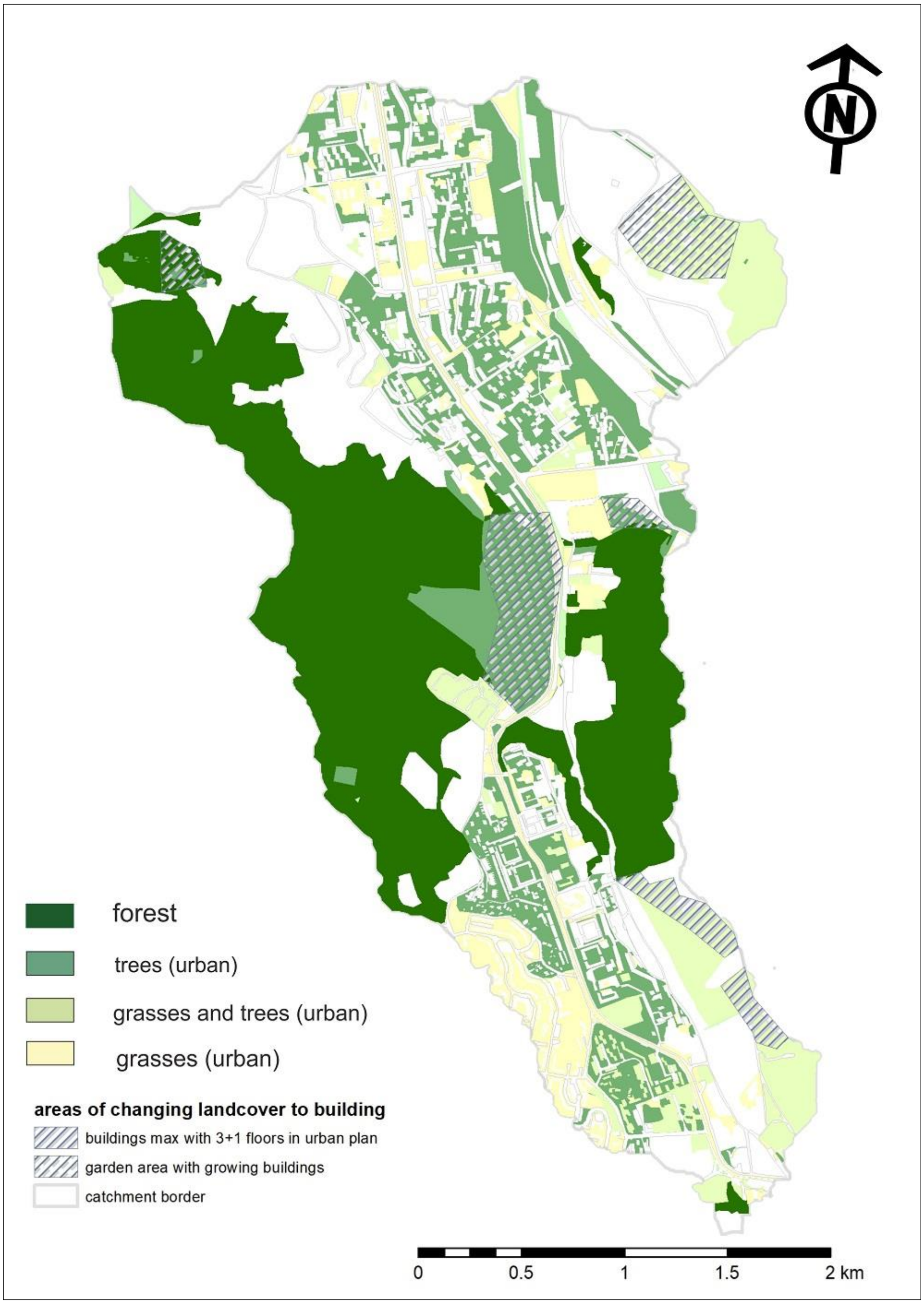

Fig. 8. *Generalised areas of land cover with urban tree and grassland vegetation and forests able to infiltrate higher rainfall and planned/continuing building, or replacement with artificial surfaces in the catchment*

The most likely key drivers that influence surface runoff leading to flash floods are as follows; intensive building on the steeper slopes of the Little Carpathians Mts. and the orientation of roads in the valleys and gullies directed downslope. These drivers greatly increase the water flow. It is unfortunate that this area's development prior to 1989 political change did not consider sustainable development and planning or the necessity for water retention. This is now further exacerbated by climate change. The loss of water to sewage was not incorporated in the model. This is despite Karlova Ves municipality management claiming that its sewerage equipment requires increased cleaning because it is often blocked by sediment after flash flooding from heavy rainfalls. Therefore, simple sewerage blockage can influence the initiation of flash floods. Similar model weaknesses are supported by other authors working in the urban area (Tyrna and Hochshild 2010).

The disconnection of the natural alluvial area from the stream and its redirection is a clear urban management error, but this can be rectified. Restoration of smaller streams is a basic part of climate change mitigation measures applied in cities, and it has been confirmed effective in city areas (Kim et al. 2019, Lim et al. 2013). City areas with higher moisture, such as water-retention ponds and restored side-channels and streams, improve the perception of urban heat islands during summers.

Conclusions and recommendations

The occurrence of flash floods can arise even without an extreme rainfall event, especially in this era of climate change and the higher frequency of intensive storms in a shorter interval (Prokešová et al. 2022). Moreover, flash flood occurrence is strongly influenced by land cover, and the effect of forested areas in our model is quite significant. When forested areas are transformed to buildings and concrete spaces, the stream catchment loses important water retention and infiltration storage that cannot be replaced by urban greenery. However, urban green areas with a majority of tree vegetation should be an additional concern for urban development management to protect areas with higher flash flood potential. GIS presents important possibilities for runoff modelling, and the open source *r.sim.water* module in GRASS GIS provides a great advantage in catchments which lack sufficient discharge data or create episodic stream and river channels.

Previous forest logging and heavy rainfalls that can decrease infiltration rate influence the extent, initiation or existence of flash floods in urban areas. The key driver of flash flooding in the catchment area is intensive building construction on slopes of the Little Carpathians mountains, with prior agricultural land unsuitable for urbanisation. Moreover, increased city concrete areas and decreased green areas do not satisfy residents' expectations and needs. This remains a problem because development pressure keeps increasing to build new residential areas close to central Bratislava.

In conclusion, extensive future evaluation is required for sustainable urban planning, and this is imperative for the planned Number IX Koliba-Slavín-Sitina bio-corridor (Balašová 2018). New development projects must carefully plan water retention measures as part of green infrastructure. This is essential when buildings on higher slopes block runoff during intensive rainfalls (Mišík et al. 2019). Finally, these remediation measures should be part of nature-based restorations where rivers and even smaller streams can be reconnected to urban and residential areas, with further socio-economic benefit and climate change mitigation.

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Acknowledgement: This research was funded from the support of the Grant research Agency VEGA of the Ministry of Education, Science, Research and Sport of the Slovak Republic in the project no.2/0052/21. We would like to thank local citizens for photographs, especially to Mr. I. Gašparík and for providing rainfall data from the Mlynská dolina station to the company MicroStep.

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