Impact of land use changes on surface runoff in urban areas - Case study of Myslavsky Creek Basin in Slovakia

Martina Zeleňáková[1], *Adam Repel*[1], *Zuzana Vranayová*[2], *Daniela Kaposztasová*[2] and *Hany F. Abd-Elhamid*[3]

The task of this work was to analyze the drainage conditions of the river basin Myslavsky Creek with the aim of proving the increasing flood risk in the area of Hornad River Basin as a result of newly constructed built areas. Drainage conditions of the reference area were compared on the basis of two time periods, for years 1980 and 2010. Two maps of land use were processed for two years. Total runoff coefficients were calculated based on the processed maps, which differed because in 1980 the territory was not so built up compared to now. The calculated results were also proved by using PCSWMM – Storm Water Management Model. The results prove that the maximum 2010 runoff at the area has increased by almost double from 1980. The increased discharge, therefore, requires flood protection measures in the area.

Keywords: *land use; runoff coefficient; urban areas, Myslavsky Creek*

Introduction

An accurate estimate of runoff from rain and snowmelt is one of the most important elements of the flood forecast process (Weng, 2001). It is important for flood control channel construction and possible flood zone hazard delineation (Bronstert, Niehoff, Bürger, 2002). A high runoff coefficient (*C*) value may indicate flash flooding areas during storms as water moves fast overland on its way to a river or a valley floor (Zeleňáková, 2018). Runoff coefficient is measured by determining the soil type, gradient, permeability and land use (Okkan, 2018). Hydrometeorological hazards, flood and drought especially, stand nowadays as some of the most frequent and disturbing danger phenomena (Mititelu-Ionuș, Licurici, 2018). Urbanization lowers maximum potential storage and increases runoff coefficient values (Wilby, 2007). As a consequence of increasing urbanization as well as rainfall totals and intensities over the second half of the 20th century, signs of increased flooding probability in many areas of the basins have been documented (Nirupama, Simonovic, 2007), (Kiss et al. 2014). These changes affecting rainfall characteristics are most evidently due to an increase in westerly atmospheric circulation types (Pfister et al., 2004). Land use changes, particularly urbanization, have significant effects in small basins (headwaters) with respect to flooding, especially during heavy local rainstorms (Vranayová et al., 2011) (Stec et al., 2017). The rainfall-runoff process depends not only on the space-time distribution of the rainfall but also on the kind and the state of the basin (Sivakumar et al., 2000), which in turn, depend on the climatic condition and vegetation states (Šlezingr, Fialová, 2012). Therefore, what is really important is a unified description of the complex behaviour of the dynamic system arising from the combination of all of its components (Zeleňáková et al., 2011) (Zeleňáková, Rejdovjanová, 2011), (Blišťanová and Blišťan, 2014), (Blišťanová, et al. 2016).

To model runoff from urbanized areas, the SWMM (Storm Water Management Model) is successfully used in different areas of the world. SWMM, a free-ride rainwater management model is a dynamic rainfall-drain simulation model used to simulate the quantity and quality of runoff from primary urbanized areas (Lewis, Rossman, 2015). Drainage modelling based on the principle of sub-basins that are exposed to precipitation create drains loaded with pollutants (Diaconu et al., 2017a). The SWMM model can be used in the following situations: drainage from the site, design and modelling of surface drainage, retention reservoir design, application of Low Impact Development (LID) to the area and their impact on runoff, drainage quality, design and modelling underground sewerage and drainage network, design and modelling of a single sewerage network, etc. (Gironás, Roesner, Davis, 2009; Diaconu et al., 2017b).

There were compared the results of the LID editor with those obtained by a detailed demand-driven tank model scheme used as a benchmark and developed using basic functions of SWMM. The comparison showed the LID Editor-based model generally overestimates the benchmark model in the evaluation of both volumetric and peak retention efficiency. The high variability of the results of the comparison suggested the use of the LID

[1] *Martina Zeleňáková, Adam Repel,* Department of Environmental Engineering, Faculty of Civil Engineering, Technical University of Košice, Košice 042 00, Slovakia, martina.zelenakova@tuke.sk
[2] *Zuzana Vranayová,* Department of Architectural Engineering, Faculty of Civil Engineering, Technical University of Košice, Košice 042 00, Slovakia
[3] *Hany F. Abd-Elhamid*, Department of Water and Water Structures Engineering, Faculty of Engineering, Zagazig University, Zagazig, 44519, Egypt, Civil Engineering Department, College of Engineering, Shaqra University, 11911, Duwadimi, Saudi Arabia.

editor rain barrel option for long-term simulation but not for single event analysis. A sensitivity analysis revealed that overestimation provided by the rain barrel option was significant for tanks smaller than 2 m^3 tank sizes for major collection of domestic rainwater (Campisano, Catania, Modica, 2017).

Long-term modelling of the green roof using SWMM presented the results of the monitoring of the extensive green roof in Bologna (Italy). The model simulated the hydrological behaviour of the green roof over one year and compared it with an adjacent impermeable roof of the same size. There was also a comparison of rainfall retention in the green and also in the classical impermeable roof. The total retention of the green roof was 48%, while the impermeable roof was only able to retain 11% of the precipitation (Cipolla et al., 2016).

In the study (Ouyang et al., 2012), runoff samples were collected and analyzed during rainy events in Beijing. Indicators such as chemical oxygen demand, total suspended solids, or total phosphorus were analyzed. In addition, the drainage water outflow from different substrates was analysed. The contribution expressed the relationship between the impermeability of the substrate and the total amount of effluent. It was clear from the results that in the sub-basin, which was made up of impermeable surfaces, the amount of runoff was almost equal to the amount of rainfall (Ouyang et al., 2012).

Palla and Gnecco (Palla, Gnecco, 2015) analyzed the implementation of LID systems as a solution to slow drainage during rainfall events. Their modelling explored the same territory with different scenarios of land use and hard surfaces, including the use of green roofs and permeable walkways. Modelling itself was done using SWMM. The authors stated that the suitability of the use of LID systems (green roofs, permeable walkways) in the management of precipitation-runoff processes in urbanized areas had been confirmed, as their use not only reduced the maximum runoff but also slowed down the overall runoff (Palla, Gnecco, 2015).

Rainwater system modelling is often used to manage rainfall-drainage processes in urbanized areas, in particular, to estimate rainfall drainage and the quality of drained and retained rainfall. These models are usually not adequately calibrated and verified due to limited availability of rainfall quantity and quality data (Sterren et al., 2014). They described the calibration and validation of the rainwater tank model using SWMM, which used data obtained from two systems of rainwater tanks in Sydney, Australia. The modelling takes into account the maximum inflow and volume of the rainwater reservoir, as well as water quality parameters (total phosphorus (P), total nitrogen (N) and insoluble matter). The authors suggested that the amount of P and N can be modelled more accurately than the amount of insoluble matter in the effluent. It has also been found that a drainage retention reservoir can significantly reduce the drainage of rainwater from the area (Sterren et al., 2014).

Tavakol-Davani et al. assessed the impact of climate change on single sewerage networks and the possibility of reducing these impacts in Toledo, Ohio. The aim of this study was to evaluate the effectiveness of rainwater retention in mitigating the potential impacts of climate change on sewer networks. For this purpose, Coupled Model Intercomparison Project Phase 5 (CMIP5) predicted future deductions based on historical records. Subsequently, SWMM runoff modelling was used to determine how the existing single sink system will respond to its expected impact in the future. The results of the study showed that 12% to 18% increase in the volume of water alone in the sewer system during intense rainfall might occur in future climate change developments. In order to mitigate these impacts, the study proposed a water retention plan in the country by using a tank of 0.76 m^3 (200 gallons) for half of the buildings from the whole area and modelling proved that such a measure is able to ensure the proper functioning of the single sewer system also in the future (Tavakol-Davani et al., 2016).

Application of permeable walkways and reinforced surfaces as systems to mitigate the negative impacts of urbanization on the outflow of water from the territory was a case study in Southern Spain (Rodriguer-Rojas et al., 2018). This was a project, where the hydrological performance of three types of permeable walkways had been analysed. Passable walkways were investigated directly in the field, but drains were also modelled using SWMM software. The pattern of such permeable walkways proved to be highly efficient, with up to 70% reduction in runoff compared to conventional reinforced surfaces. Permeable walkways appear to be a more appropriate alternative to green roofs from the results of this study since they are more effective, but also have a wider application (Rodriguer-Rojas et al., 2018).

From the above mentioned, it is obvious that SWMM has a very wide application and was also used in the current study. The aim of this paper is to evaluate the effects of surface condition and calculated runoff coefficient on the degree of flood protection in low lying areas and design potential measures to stabilize conditions in the drainage basin of Myslavsky Creek. The paper presents the current state of drainage situation in the study area – part of Kosice City in Slovakia – taking into account the existing outlets of rainwater drainage of the newly built constructions buildings, hypermarkets, etc.

Materials and methods

The methodology of the current research consists of the following steps:

1. Characteristics of the river basin of Myslavsky Creek.

2. Collecting the input data from the Chief Architect Department, Kosice (DCAK) and Slovak Water Management Enterprise, s.c. branch office Kosice (SWME), specifically:
   - Maps of land-use in the scale of 1:5 000 and 1:2 000; (*source: DCAK*),
   - Maps of land-use in digital form in .dwg (AutoCAD); (*source: DCAK*),
   - The situation of the basin in the scale of 1:50 000; (*source: SWME*).
3. Processing of input data:
   - Calculation of runoff coefficients,
   - Calculation of the total runoff.
4. Propose measures to stabilize the drainage conditions into the stream basin of Myslavsky Creek.

Study area

The study area is situated in the eastern part of Slovakia (Figure 1) near Kosice City.

Figure 1. Location map of the study area

Myslavsky Creek is the right-hand tributary of the Hornad River, which opens into the southern part of Kosice (Figure 2) (Hornad River basin).

Myslavsky creek is the right tributary of Hornad River (Figure 2). It opens into the Hornad in 135.70 river kilometre. Its catchment area is 59.67 km^2. From the west, it is defined by a sub-catchment of the Bodva River Basin. The highest point of the basin is at an altitude of 940 m above sea level; the lowest point is at an elevation of 188.90 m above sea level (Zeleňáková, 2014). Basic characteristics of the catchment are presented in Table 1.

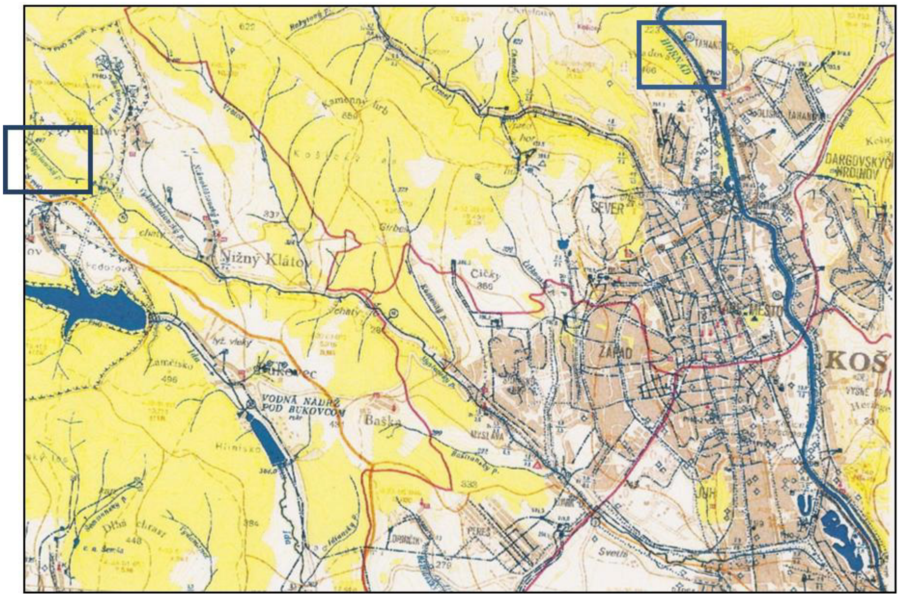

Figure 2. Myslavsky Creek, the right tributary of the Hornad River

Table 1. The basic characteristic of the catchment (Zeleňáková, 2014)

Basin area	The highest point	The lowest point	Runoff from the basin	Maximum flow stream
59.67 km^2	940 m asl.	188.90 m asl.	9.5 $l.s^{-1}.km^{-2}$	52 $m^3.s^{-1}$

Myslavsky Creek was regulated mainly within the boundaries of the city of Kosice and Myslava. A number of unilateral purpose-built bank reinforcements and many different types of bridges were constructed by landowners in the agricultural area. A large part of the basin is located in an urbanized area, which may significantly alter hydrological conditions.

The most frequent occurrence of floods is during the summer months, due to storms. The last major flood in the Myslavsky Creek occurred in May and June 2010 after long-term rains. The flood damages for Kosice city were enumerated at 11.935 € for Kosice and 69.566 € for a rural area.

Runoff calculations

The Rational method of runoff coefficient (*C*) calculation is a function of the soil type and drainage of the basin. The larger values correspond to higher runoff and lower filtration. The Rational equation is the simplest method to determine peak discharge from drainage basin runoff. A rational equation is as follows:

$$Q_{\max} = C \cdot i \cdot A \quad (l.s^{-1}) \tag{1}$$

Where: Qmax = peak discharge ($l.s^{-1}$),
C = rational method runoff coefficient (-),
i = rainfall intensity ($l.s^{-1}.ha^{-1}$) in time t (min),
A = drainage area (ha).

Runoff coefficient for the whole area was calculated as weighted average as follows:

$$C = \frac{\Sigma(C_i . A_i)}{\Sigma A_i} \quad (-) \tag{2}$$

The rainfall intensity (*i*) is typically found from Intensity Duration Frequency (IDF) curves for rainfall events in the geographical region of interest. The duration is usually equivalent to the time of concentration of the drainage area. The storm frequency is typically stated by local authorities depending on the impact of the development. A 10-yr, 25-yr, 50-yr, or even 100-yr storm frequency may be specified.

Runoff modelling

The PCSWMM modelling software, which is based on SWMM 5 model, was used for comparison of two different scenarios from the view of runoff from the area. SWMM (Storm Water Management Model), a free-ride rainwater management model is a dynamic rainfall-drain simulation model used to simulate the quantity and quality of runoff from primary urbanized areas. The SWMM monitors the amount and quality of runoff in each sub-basin, as well as the flow rate, water depth in pipelines and channels throughout the simulation time. The program itself is therefore used to plan, analyze, and design a drainage water system. It is also used to design uniform sewer systems and various rainwater management systems in the country (Cipolla et al., 2016).

In PCSWMM software, one sub-basin with the size of 431.961 ha was created. The runoff was modelled according to the values in Table 2. A difference between scenarios was presented by the percentage of impervious area.

Table 2. Basic characteristics of the catchment (Zeleňáková, 2014)

Ground cover	Area in 1980 A_i (m^2)	Partial runoff coefficient C_i (-)	Area in 2010 A_i (m^2)	Partial runoff coefficient C_i (-)
Roofs	139 978.60	0.8	473 427.26	0.8
Roads and streets	391 895.15	0.9	962 407.09	0.9
Cemeteries	140 911.91	0.15	174 441.46	0.15
Greenery	3 587 398.15	0.15	2 649 908.00	0.15
Un-built areas	59 425.98	0.3	59 425.98	0.3

Results and Discussion

Two maps were prepared for years, 1980 and 2010 for the whole catchment of the Myslavsky Creek. The maps of the selected area of the catchment, exactly the area of Košice city, where land use changed and human activities are manifested as presented in Figures 3 and 4.

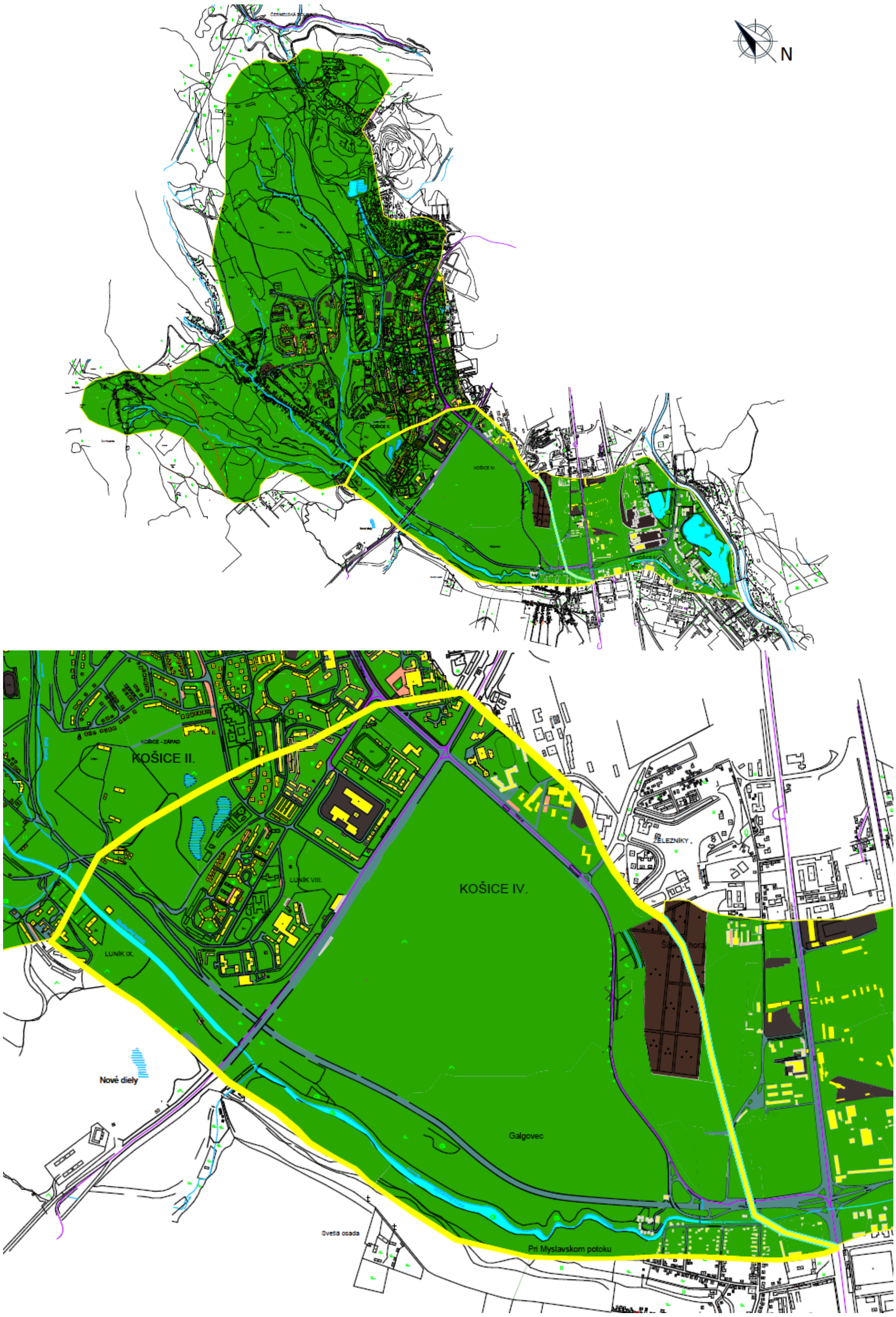

Figure 3. The selected area of Myslavsky Creek basin – land use in 1980

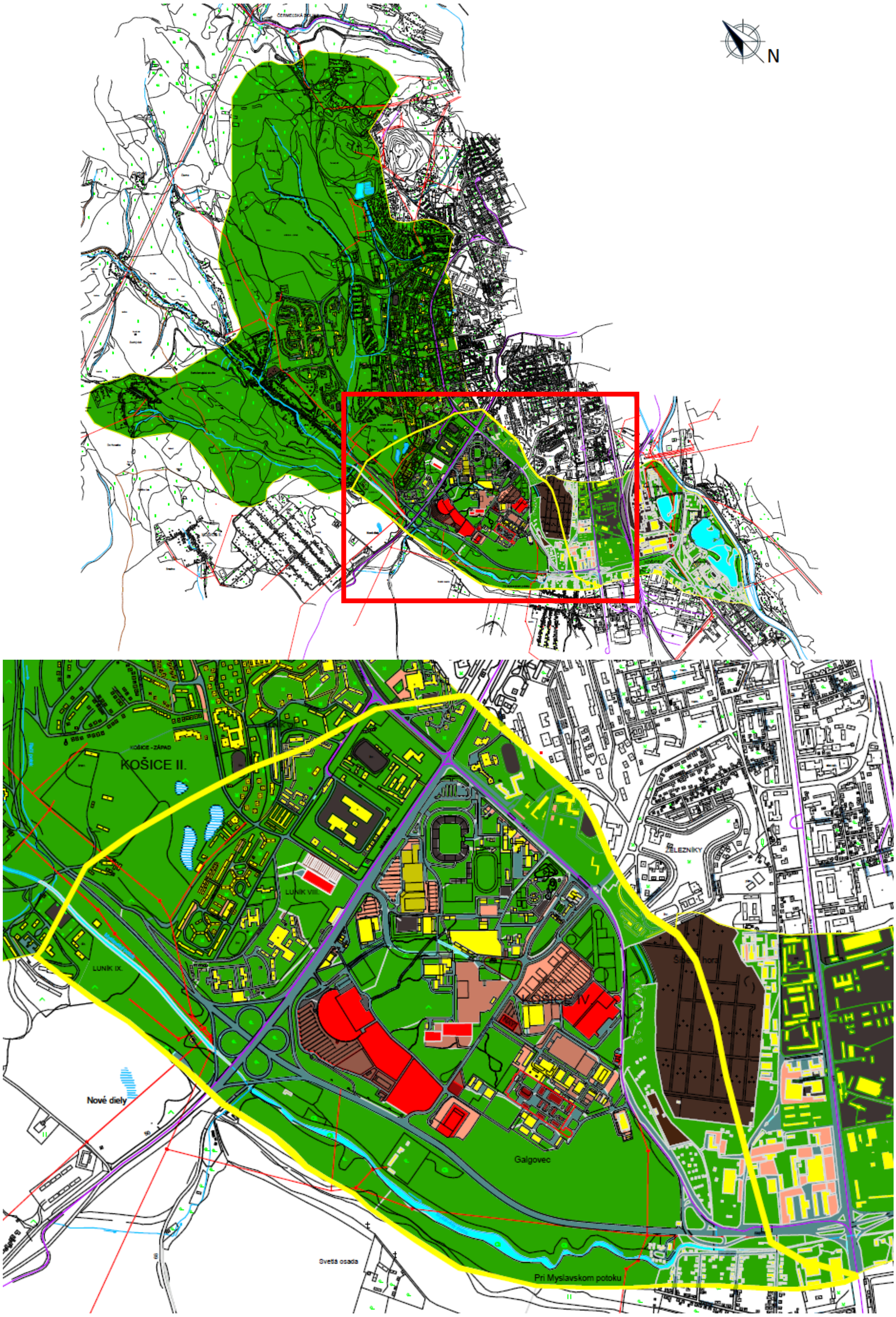

Figure 4. The selected area of Myslavsky Creek Basin – Land use in 2010

Legend:

- greenery
- roofs
- roads, and paved areas
- selected object
- un-built areas
- cemeteries
- parking
- border of the catchment

There were huge constructions in a given area during the period 1995-2005. The land use of the area is the same nowadays as is presented in Fig. 4.

According to equation (2) runoff coefficients were manually calculated for the two time periods for significantly influenced locality by human activities, with a different area of different land use of Myslavsky Creek Basin. The value of runoff coefficient is changed by 0.10 over the 30-years. Based on the calculated total runoff coefficients *C*, the drainage area of Myslavsky Creek and for a specific amount of rainfall was calculated maximum runoff for both time periods year 1980 and 2010 according to equation (1). The results are presented in Table 3.

Table 3. The maximum discharge Q for the year 1980 and 2010

Year	*C* (-)	*i* ($l.s^{-1}.ha^{-1}$)	*A* (ha)	*t* (min)	*Q* ($l.s^{-1}$)
1980	0.2412	139.8	431.9609	15	14 565.62
2010	0.3404	139.8	431.9609	15	20 556.12

For the selected part of Myslavsky Creek river basin in 2010, the above table of values indicates the maximum runoff *Q*, for 15 minute periods of rain was 20 556.12 $l.s^{-1}$. Compared to 1980, when the *Q* value was 14 565.62 $l.s^{-1}$, it represents an increase of 42% for the same drainage area.

The results from modelling by PCSWMM software are as follows.

It was determined that there was 12.31% of the impervious area on the modelled sub-basin in 1980, whereas in 2010, there was 33.24% of the impervious area. It is clear from this that the size of the impervious surfaces on the sub-basin has more than doubled. The period of 15 minutes' rainfall with a constant intensity of 50.328 mm/min was used to obtain the results of total runoff from the area with the same conditions as rainfall in the calculation method. Comparison of the total run-off from the model in 1980 (at 12.31% of impermeable areas) and in 2010 (at 33.24% of impermeable areas) during a 15-minute rain of constant intensity is presented in Figure 5 and Table 4.

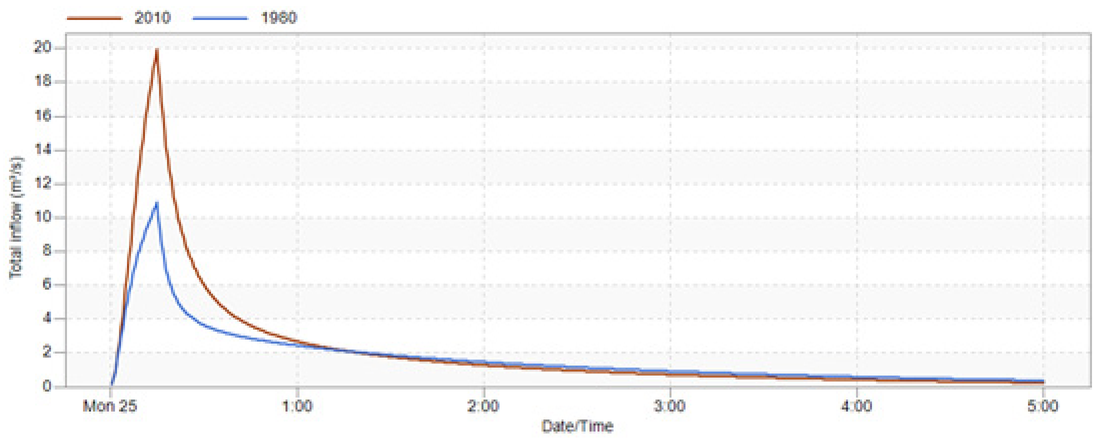

Figure 5. Run-off from the modelled area using PCSWMM

Table 4. Run-off in 1980 and 2010 using PCSWMM

	Outfall 1980	**Outfall 2000**
Maximum total inflow (m^3/sec)	10.9	19.93
Minimum total inflow (m^3/sec)	0.1859	0.1897
Mean total inflow (m^3/sec)	1.736	2.152
Duration of exceedances (h)	4.992	4.992
Duration of deficits (h)	0	0
Number of exceedances	1	1
Number of deficits	0	0
Volume of exceedances (m^3)	31190	38670
Volume of deficits (m^3)	0	0
Total inflow (m^3)	31200	38670

It is obvious that the maximum runoff at 2010 in the area has increased by almost double - as was the case with the rational method.

There are 10 objects which drained rainwater from the catchment of Myslavsky Creek to the water stream which are mainly business and shopping centres. From Figure 6, it is possible to see their location in the study area.

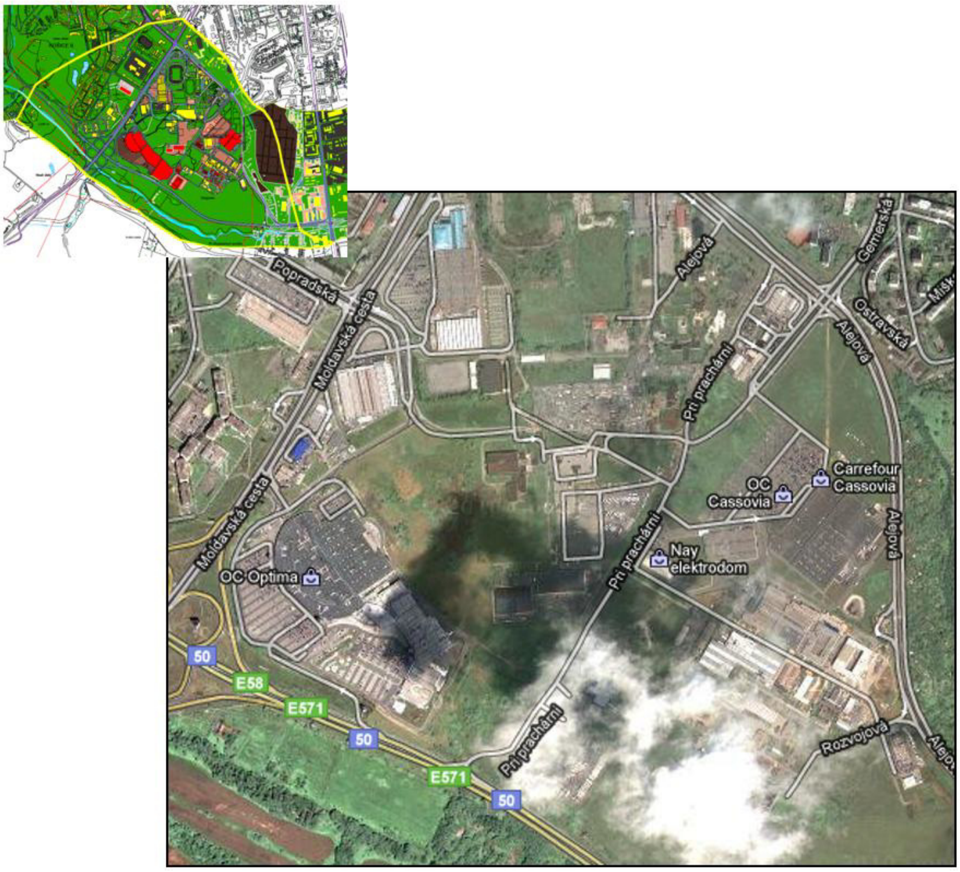

Figure 6. Business and shopping centres in the study area

Individual objects are equipped with different types of oil separators or grease traps, through which water from the surface runoff is purified before discharging into Myslavsky Creek. Some of the selected objects also have retention tanks. The drained water of the objects significantly increases the discharge in Myslavsky Creek, which resulted in the occurrence of the increased flow in the stream. Four drains were identified on the Myslavsky Creek by a survey of the area, which diverts the water from the surface runoff from selected objects, thus increasing the flow of the Myslavsky Creek Figure (Figure 7). Its level increases enormously and causes flooding of the surrounding area. This is due to the fact that in the past there were no so many built-up areas as today, and rainwater filtered into the soil, reducing the threat of a large flood.

Based on the changed outflows of the Myslavsky Creek, it is necessary to propose potential measures to stabilize the runoff in the catchment area, thus increasing the flood protection in the lowland areas. Protection measures may be environmental (removal of obstacles) as well as organizational (compliance with water management decisions, design of retention areas).

Proposal of protection measures for runoff condition stabilisation with the aim of flood protection of lower laying areas are the following:

a) non-structural flood mitigation measures- water management decision,

b) structural flood mitigation measures:
- directing the stream flow by removing sharp meanders
- removal of islands and random obstacles
- creation of longitudinal stream slopes, which creates a more steady-state of a river bed
- creation of a stream cross-section trough of a size and shape to harmlessly divert flow prior to such fortification, preventing the erosion and flush out of the banks.

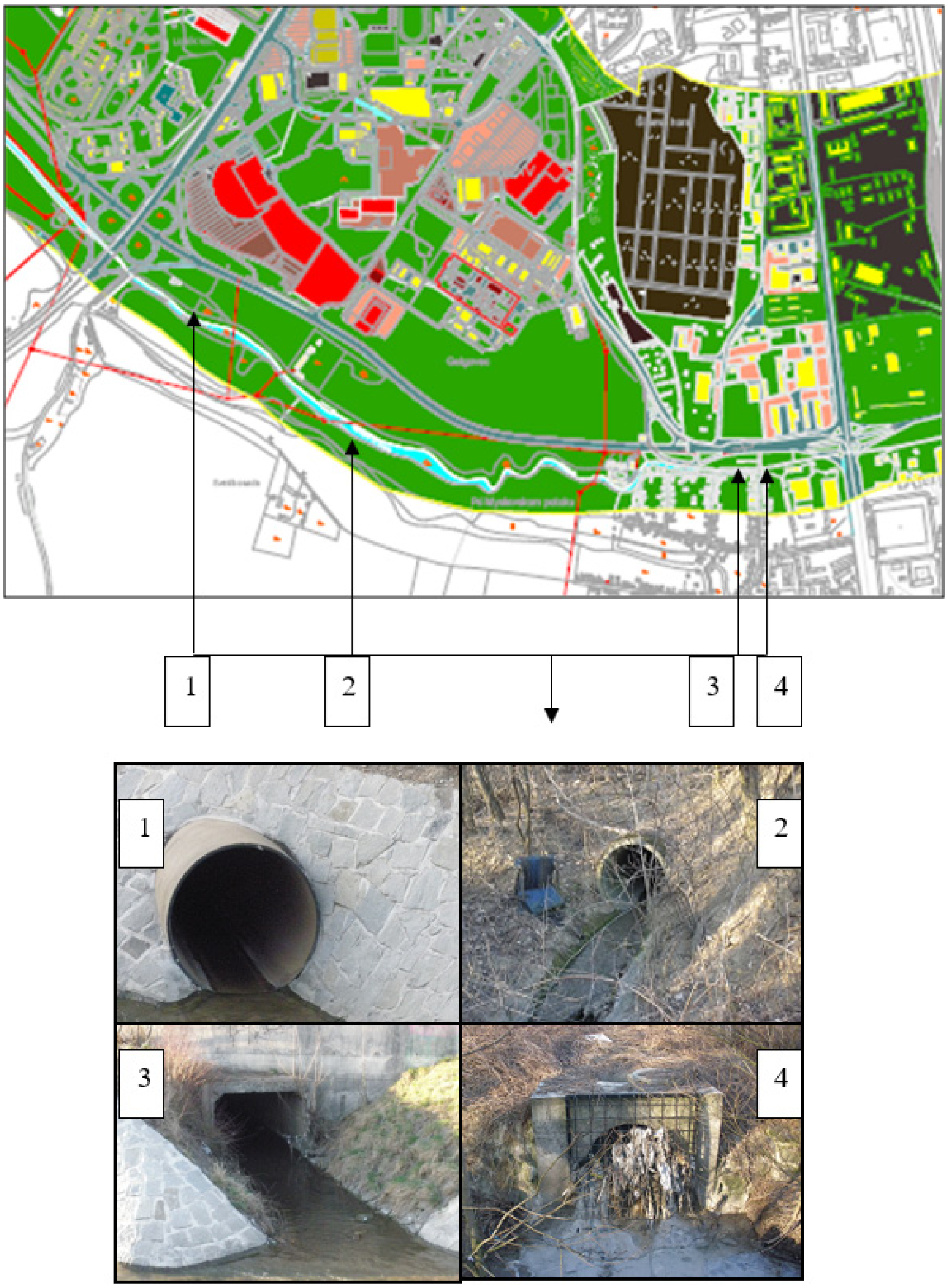

Figure 7. Drainage outlets to Myslavsky Creek

Conclusion

The world's population nowadays is concentrated in urban areas. This change in demography has brought land-use and land-cover changes that have a number of documented effects on streamflow. The most consistent effect is an increase in impervious surfaces within urban catchments, which alters the hydrology and geomorphology of streams. In addition to this, runoff from urbanized surfaces as well as municipal and industrial discharges result in increasing floods in urbanized areas as it decreases river bed capacity for flow. Nowadays, when the urbanization and expansion of urban settlements are at the forefront, much attention must be paid to water management, in particular, rainfall-drainage processes from the basin. One of the appropriate tools for managing these processes in a river basin is the SWMM precipitation-out model, which is widely used to model various situations that occur in urbanized locations. This model, as well as the rational method, was used in the current study. The SWMM can be used to model the amount of drainage from the basin from different underlying surfaces, and model design values for precipitation, sewerage and other phenomena associated with precipitation-drainage processes. The model can be used either in the scientific sphere or directly in designing rainfall-drainage processes in cities.

This paper presents the current state of runoff condition in the study area of Myslavsky Creek Basin, taking into account the urban development in the last 30 years, mainly of newly built hypermarkets. The goal of the study was an evaluation of the surface condition, calculation of the runoff coefficient and propose potential measures to stabilize conditions in the drainage basin of Myslavsky Creek located in the Eastern part of Slovakia.

The drainage ratios of the monitored area were compared based on two time periods, for 1980 and 2010, and two land use maps for both years were processed. From the processed land use map, total drainage factors were found, which varied considerably, because in 1980 the area was not as urbanized as it is today. The runoff coefficients for the different time periods 1980 and 2010 were compared. For 1980 the runoff coefficient was calculated of 0.2412, and for 2009, the runoff coefficient was calculated of 0.3404. Such a difference between the runoff coefficients results from the differences in the built-up area of the river basin in 1980 compared to 2010. The state of build-up area in the river basin at present is the same to 2010. In the past, rainwater has been filtered into the land surface directly into the soil, and so extensive flooded areas have not occurred. The situation is different nowadays because in 30 years the number of built-up and reinforced areas has increased enormously and all the rainwater is captured and discharged by rainwater drainage through the drains into the Myslavsky Creek. Due to the fact that almost all of the rainwater is diverted to Myslavsky Creek as well as the rainwater from selected objects in the monitored area, the flow of the Myslavsky Creek is increasing, and therefore its flow capacity for the corresponding amount of rainwater discharged is not satisfactory.

Based on the changed outflows of the Myslavsky Creek, it is necessary to propose potential measures to stabilize the runoff in the catchment area of the Myslavsky brook, thus increasing the flood protection in the lowland areas. Measures may be environmental (removal of obstacles) as well as organizational (compliance with water management decisions, design of retention areas). Such potential measures can help in saving money and the life of people.

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