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# The Impact of Impervious Surfaces on Ecohydrology and Health in Urban Ecosystems of Banská Bystrica (Slovakia)

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**Abstract**

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The risks of accelerated runoff and its larger amounts brought by urbanisation include increased flood flows and pollution of downstream ecosystems. One of the most significant permanent effect of urban sprawl is soil sealing, which alters natural infiltration and runoff. In addition to imperviousness, the increased runoff from sealed and compacted surfaces results in increased sedimentation of stream ecosystems with contaminants. In most urban planning strategies, water related ecosystems have already become the fundamental components of the integrated urban landscape management, but still have been referred to as objects of protection or rehabilitation; not as management tools. This paper shows how soil sealing significantly affects urban environment and urban ecosystems health. It also demonstrates significant impacts of a city on downstream ecosystems. Data obtained from orthophotomap vectorization showed that the model urban catchment is relatively highly urbanized. 45% of model area is sealed mainly with buildings (40.41%), streets (31.01%), and parking lots (25.28%). Compared to natural basins, urban runoff is 64 times higher and carries a significant amount of pollutants.

**Keywords**: built environment; runoff; soil sealing; urban catchment; urban hydrology

Urbanized areas covered to a high extent by impervious surfaces (IS) can be perceived as a part of a basin or as enclosed gravitational units (urban catchments – UC), where the cities are protected from rural area waters by a network of retaining ditches (Price & Vojinović 2011). Compared to natural basins, UC are spacious areas with IS extensively affecting ecohydrological (EH) processes in a city. Soil sealing (SS) related to imperviousness results in reduced or completely suppressed infiltration and disruption of natural ecological links, especially urban water interfaces (Gessner *et al.* 2014). In UC, the direct runoff (mostly the surface runoff – SR) dominates over the base runoff, resulting in the most adverse ecological and environmental impacts, even in the wider catchment area (Verworn 2002). Urbanization brings about the risks of accelerated SR and their larger amounts, which may lead to increased flood flows. The lack of vegetation and faster and larger SR contribute to the reduction of evapotranspiration (ET), which affects the energy balance of cities. The ET within the soil-vegetation system can create oases, which are by 2–8°C cooler than their built-up surroundings (Oke 1987). The warm IS increases the rainfall temperature and the UC runoff is up to 15°C warmer than the natural one (James 2002). In the built-up area covered by IS and semi-impervious surfaces, soil and vegetation lose the abilities to perform their ecological functions (Novák *et al.* 2010) and therefore their capacity to provide ecosystem services (Costanza *et al.* 1997) is decreased as well. Reduction in vegetation brings along an increase in strongly limited ability of microclimate regulation, infiltration, creating of noise barriers, and reduction of recreational and cultural values (Bolund & Hunhammar 1999). Most urban soils are artificially created and have strong tendencies to become contaminated (Galušková *et al.* 2011), acidified, salinized, and also the tendencies towards soil erosion and excessive occurrence

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of pathogenic organisms. Soil environment is often extremely skeletal or heavily compacted, which leads to the low ability of infiltration. Natural filtering and buffering capacity of soil causes a high content of heavy metals, dust and other pollutants (Craul 1992).

Summarizing, the urban development leads to the weakening of landscape hydric potential (Lepeška 2010), the ability of its components to decelerate, retain, and infiltrate precipitation. It refers to direct influence of urbanisation on the amount, quality, distribution, and accessibility of water resources. The resulting change in climate, water, and air quality can consequently jeopardize environmental safety and health of urban ecosystems. Despite this, only a few studies concentrate on the assessment of urbanization impacts on hydrological systems and their ecological consequences.

### Options of application ecohydrological principles within urban catchments

The capacity of the UC to provide various ecosystem services depends on its ecological integrity, its appropriate natural organizational order, expressed by structural completeness and connectivity, coherent dynamics, functionality, and resilience (Sabo 2004). Therefore, these services are determined and limited by both an expansion of cities and the state of ecosystem itself (Wagner & Breil 2013). Regarding a spatial expansion, a sensitive urban planning reducing the external impacts on UC ecosystems, could be of a great help. Expected benefit of their influence is the reduction of SR, which leads to the improved conditions of ecosystem functioning. The state of ecosystems can be improved in various ways of remediation, renaturation, and revitalisation.

These approaches, especially if implemented simultaneously, contribute to the improvement of the ecological state or urban streams and their ecological potential demonstrably. The reinforcement of the functional approach to ecosystems is one of the principles of ecohydrology (Zalewski 2002) as well as of the concept of preserving or strengthening the landscape hydric potential (Lepeška 2010). Ecohydrology is used within the framework of "reciprocal regulation"; the regulation of biological processes by means of hydrological ecosystem properties management and the control of hydrological processes by means of managing biota. It is a great challenge to apply the experience of ecosystem management to the management of highly dynamic UC. If we consider the rapidly growing influence of human activities on ecosystems and limited space for implementation of mitigation policies, a potential reinforcement of the ecological integrity of urban semi-natural ecosystems and of the wider catchment area, as a basis of their resilience and ecological carrying capacity, may seem to be an interesting option.

The aim of this paper is to determine the total area of IS within Banská Bystrica city and to quantify the amount of SR during individual rainfall events and also the amount of the selected pollutants in the area. The starting point of the analysis of disturbances and changes of keystone ecological linkages resulting from the urbanization will be a concentration of available data about IS in one complex geodatabase.

## MATERIAL AND METHODS

The city of Banská Bystrica is the fifth largest city in Slovakia with the population of 77 375 (year 2014). It is situated in the part of the Zvolenská hollow around the River Hron arch that contributed to a rapid development of industry and population migration in the second half of the 20$^{th}$ century. Despite

Figure 1. Banská Bystrica city urban area (scale 1 : 50 000)

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the continuing decrease in the population since the 1990s, the urban area keeps spreading. The best resources to get an overview of the soil sealing in the UC include detailed cartographic documentation. We have used orthophotomaps of Banská Bystrica city taken in 2011 that have been updated by field survey. As reference data, the images from the Google Earth© have been used and georeferenced for further processing in the program ArcGIS 9.3. The borderline of Banská Bystrica urban area (Figure 1) was vectorized according to cadastral data.

The methodology of mapping real areas, shapes, and spatial distribution of IS was chosen on purpose. In some other published theses dealing with this subject, the area of IS is determined on both the estimation of the IS areas percentual coverage in a mapped square and on their allocation into individual categories (Yuan & Bauer 2007). The advantage of this methodology is easy and fast data processing, which allows processing of larger areas or several UC and creating comparative analyses eventually. One of the main disadvantages of the coverage percentage estimation of IS is the lower accuracy, of about 85% (Yang *et al.* 2003). The presented methodology allows much higher precision, but in comparison to other methods it is disproportionately time consuming. We have chosen it to pinpoint the areas and the spatial distribution of IS within the model UC. The resulting geodatabase will be used for further analyses of IS.

The IS have been divided into five categories. The first category includes roads and pavements. The second one encompasses buildings. The third type of IS are larger area structures such as parking lots or squares. The fourth category includes areas under construction. The last category covers the areas that could not be classified into any of the former categories. They include mainly industrial sites and built-up areas around buildings.

The IS data have been taken from the orthophotomaps in the scale of 1 : 1000, sufficient enough for a detailed vectorization of objects. The minimum mapped area of objects was 10 $m^2$. Each type of IS was assigned the corresponding runoff coefficient – *c*, which indicates the percentage of precipitation that occurs as SR. Then the UC runoff for total model precipitation events was calculated based on the runoff coefficients for individual types of IS. Table 1 presents the *c* values of selected IS types according to individual authors. For further calculations, the value of *c* was chosen according to Hvitved-Jacobsen *et al.* (2010). The areas under construction were assigned the common *c* coefficient of 0.8. Uncategorized areas including mostly concrete industrial site surfaces were assigned the runoff coefficient within the range of 0.70–0.95. The calculation of SR followed the rational method (Thompson 2006):

$$Q = c \times i \times A$$

where:
$Q$ – runoff amount (l/s)
$c$ – runoff coefficient (–)
$i$ – average precipitation intensity (mm/h/ha)
$A$ – drainage area (ha)

The ET and losses of the model UC have been replaced with the total initial losses (interception, surface water logging, and evaporation – Amaguchi *et al.* 2012). We have considered the range of 3 mm (the highest possible value of the initial lump losses) for the whole UC. For reference, the model torrential rain of 23 mm/h was determined. The average annual precipitation (AAP) of 819 mm is reported within the model UC.

To evaluate the pollution, in this case contamination by heavy metals carried by the SR, we have evaluated dry and wet depositions of Pb and Cd. The average annual deposition of Pb is 3.39 g/ha/year

Table 1. Runoff coefficient (*c*) values

| Author | Streets, pavements, parking lots | | | Buildings roofs |
|---|---|---|---|---|
| | asphalt | concrete | cobbles | |
| Hvitved-Jacobsen *et al.* (2010) | 0.70–0.95 | 0.70–0.95 | – | 0.90–1.00 |
| Regulation No. 397/2003 Coll. | 0.90 | 0.90 | 0.40 | 0.90 |
| Maindment (1992) | 0.70–0.95 | 0.70–0.95 | 0.70–0.85 | 0.75–0.95 |
| NZIE (1980) | 0.85 | 0.85 | 0.60–0.80 | 0.90 |
| Viessman and Lewis (2003) | 0.70–0.95 | 0.80–0.95 | 0.70–0.85 | 0.75–0.95 |
| Mark and Marek (2011) | 0.85–0.95 | 0.90–0.95 | 0.70–0.85 | 0.75–0.95 |

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and of Cd 1.74 g/ha/year within the model UC (Miňďáš & Tóthová 2004).

## RESULTS AND DISCUSSION

According to cartographic analyses, the reduced urban area of 1767.73 ha within the model UC has been outlined for detailed analysis. The parts of the area covered by the individual types of paved surfaces in the UC can be found in Table 2. Figures 2 and 3 present the part of the UC with mapped objects and segments. Roads are highlighted grey, buildings red, paved surfaces yellow, sites under construction white, and other built-up areas are highlighted brown.

The total area of mapped IS (and/or SS) is 789.05 ha, referring to 44.6% of the model UC. The rest of the UC includes permeable or semi-permeable surfaces (however, these were not a subject of this contribution). According to the ranges of runoff coefficients (Table 1) and the considered AAP of 819 mm, the amount of the average annual SR from the UC is 5.007–6.251 mil $m^3$. The values of the average annual runoff of evaluated IS and their percentage to the total SR are presented in Table 3. The amount of the speeded-up SR within the UC during the torrential rain of 23 mm/h is 118 000–148 000 $m^3$ (133 000 $m^3$ on average).

Regarding pollution by heavy metals, the SR from the model UC transports potentially 2674.87 g of Pb and 1372.95 g of Cd into a water body per year. These heavy metals are mainly the result of both dry and wet deposition.

The fact, that almost 45% of the surface of the model UC is impervious, would not seem to be of a great importance at the first sight. To compare the outcomes of the similar theses may be complicated not only due to the different approaches used. The methodologies that present specific area of IS, considered the small cuts of larger agglomerations only and IS cover varied from 15–98% (Boyd *et al.* 1993) or 44–46% (Miller *et al.* 2014). There was just one case where the area of a greater UC part was evaluated (Bauer *et al.* 2004) and the proportion of IS varied from 37 to 58%. The percentage of the IS cover of the UC is an important environmental indicator. The strong correlation between basin imperviousness and its drainage basin was described (Todd 1989). If the IS proportion is higher than 25%, the environmental quality of water reservoir is considered as degraded (Arnold & Gibbons 1996).

The reduced perviousness of UC leads to the reduction in infiltration and increased SR. When 35–50% of UC is covered by the IS, the SR is 3 times higher in comparison to the forested basins (calculated with the 10% SR from the forest) and 5.5 times higher when the coverage varies from 75 to 100% (Arnold & Gibbons 1996). However, if we consider more precise direct measurements of forest SR, the runoff from UC becomes significantly higher. The SR in the broad-leaved forests (which dominate in natural potential vegetation of the model UC) represents 1.52% of the precipitation amount in an open area (Midriak 1993). With the IS area of 789.05 ha within model UC and the AAP of 819 mm, the annual amount of precipitation is 6.46 mil $m^3$.

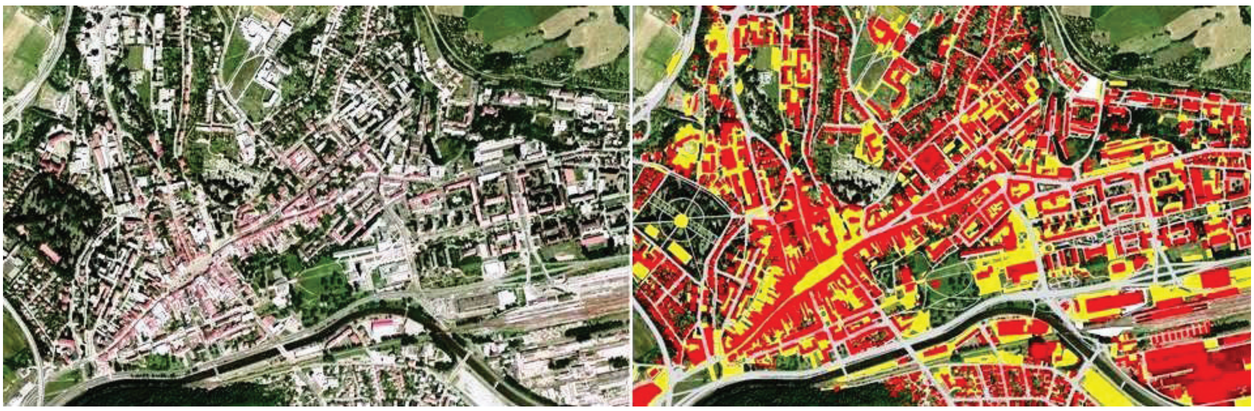

Figure 2. Mapped urban area of Banská Bystrica city (cut-out, scale 1 : 10 000)

Table 2. Area of the main impervious surfaces types

| Area | Roads | Buildings | Parking lots | Construction sites | Uncategorized | Σ |
|---|---|---|---|---|---|---|
| (ha) | 259.42 | 291.95 | 210.09 | 6.35 | 21.24 | 789.05 |
| (%) | 32.90 | 37.00 | 26.60 | 0.80 | 2.70 | 100.00 |

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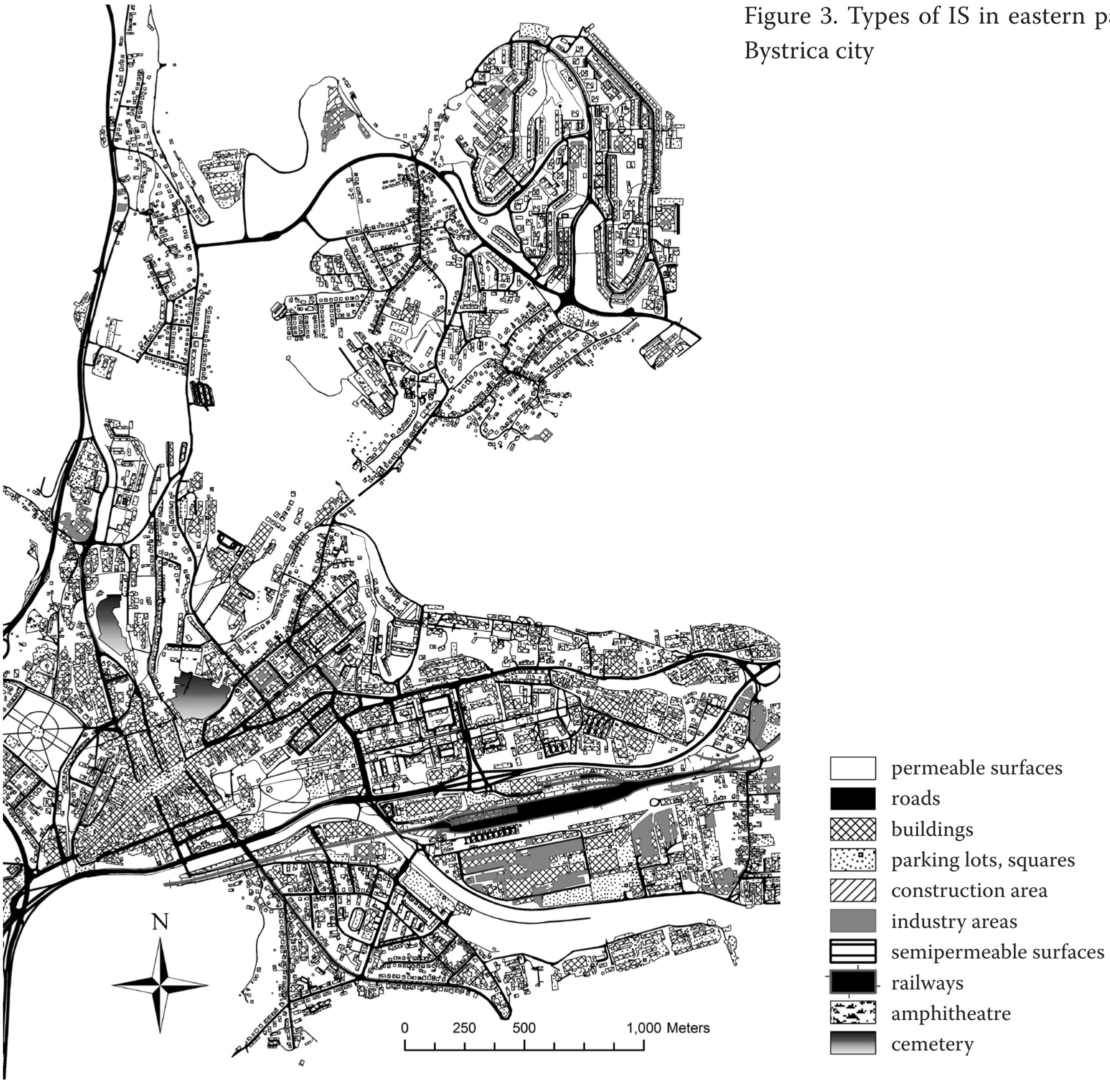
Figure 3. Types of IS in eastern part of Banská Bystrica city




Hypothetically, if the same amount fell onto the forested catchment of the same size and with the same AAP (considering the SR of 1.52%), the annual amount of only 0.098 mil $m^3$ would drain off the area. Since also the IS have a certain retention capacity, although very small, the amount of 5.007–6.251 mil $m^3$ per year flow off the model UC. It represents 51–64 times higher SR compared to the forested catchment. Such a water loss becomes most evident in the insufficient supply of groundwater and surface water reservoirs (in the model UC just further away from the alluvial plain). In general, this phenomenon results in a decrease of groundwater resources and the streams disappearance (Elmore & Kaushal 2008). The vast area of IS results in increased SR, both concerning its speed and amount, thereby the risk of flooding of the urban areas increases significantly (Douglas *et al.* 2007).

During the model torrential rain, the amount of SR could reach up to 148 000 $m^3$. Torrential rain carries the risk of such an amount of SR which can result in forming either a flood wave (Douglas *et al.* 2007) or increase of both its size and speed of movement. In

Table 3. Average annual runoff ($\bar{x}$) from individual impervious surfaces types

| Runoff | Roads | Buildings | Parking lots | Construction sites | Uncategorized | Σ |
|---|---|---|---|---|---|---|
| (mil $m^3$/year) | 1.48–2.01<br>$\bar{x}$ = 1.74 | 2.15–2.39<br>$\bar{x}$ = 2.27 | 1.20–1.63<br>$\bar{x}$ = 1.42 | 0.0416<br>– | 0.121–0.165<br>$\bar{x}$ = 0.143 | 5.007–6.251<br>$\bar{x}$ = 5.62 |
| (%) | 31.01 | 40.41 | 25.28 | 0.75 | 2.55 | 100.00 |

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case of rainless periods, pollutants originating from dry deposition accumulate mainly on IS. During the next rainfall event, the formed SR is typical for its high concentration of pollutants (Hvitved-Jacobsen *et al.* 2010). Consequently, the low-lying ecosystems are exposed to the acute impacts of SR pollution. Urban terrestrial ecosystems are affected by urbanization also in other ways. Along with the spatial growth of cities and the increase of IS density, they become smaller, gradually losing their linkages to the surrounding ecosystems (Scalenghe & Marsan 2009) and their ecological integrity. Their biocenoses suffer from heat and drought, and, on the other hand, from occasional floods (Douglas *et al.* 2007). Compared to natural conditions, urban biocenoses and habitats are exposed to stronger pollution originating from various sources. As a consequence, the degradation of ecosystems and their services may be observed (Zhao *et al.* 2013). The water-related ecosystems are exposed to physical and chemical changes of inflowing water. The increased risk of the water quality is related to the IS runoff, especially after longer periods with no rain. Pollutants tend to load in the river bends and they may reach the water body during intense rainfalls (Hvitved-Jacobsen *et al.* 2010). Another risk to the water ecosystems is related to the long-term and multiplied influence of pollutants originating mainly from dry and wet deposition, as are especially persistent organic pollutants and heavy metals. Calculated potential long-term load of SR results in 2674.87 g of Pb compound and 1372.95 g of Cd compound per year. For living organisms, Cd is both carcinogenic and teratogenic with the lethal effects at even low concentrations (Eisler 1985). Unlike Pb, Cd accumulates at all trophic levels of living organisms (Sindayigaya *et al.* 1994). Although Pb as well has highly negative effects on organisms, the biomagnification for the whole trophic segment has not been confirmed. The problem may occur with long-term exposure to higher Pb concentrations. In such a case, the capacity of the Pb buffering mechanisms may be exceeded. Since the elements are composed of highly toxic compounds, the possible occurrence of contaminated SR within the river ecosystem or soil matter (Friedlová 2010) represents a serious environmental threat. Over the period of time, pollutants are accumulated in sediments from which they may be mobilized by means of sediment disturbance, change of pH, etc.

Comparing data in Table 2, we may conclude that the settlement area of approximately 300 ha was built up to serve the needs of about 77 000 residents. In order to provide the residents with human and material transportation, the area of 260 ha had to be covered with IS. Another 210 ha are occupied by parking lots and other large paved areas. Put it simply, we may say that the 100% construction of buildings requires extra 89% of the surface to be covered with roads and 72% with parking lots. These data must be taken into account in further development of cities.

## CONCLUSION

The urban sprawl brings about a number of ecological and environmental risks. In case of the model UC, we have highlighted only a few of those related to high proportion of the IS. One of the most serious findings is that the real coverage of SS represents 45% of the city with the annual SR of 6.251 mil $m^3$. Compared to natural basins, the urban SR is 64 times higher and it carries a significant amount of pollutants.

The reduction of environmental threats in Banská Bystrica city depends directly on the ability of the environment to infiltrate and retain rainfall. Therefore, the identification of EH services is the key to the development and execution of several policies at the river–catchment–city level. The starting point should be the harmonization of the existing infrastructure with the potential of ecosystems to absorb the impact of human activity.

The main risks associated with the implementation of the EH principles within UC is related to the proper choice of appropriate adjustments of EH policies, the options of their regulations, and their proper localization within the area as well. Although scientific ecological approaches emphasize the importance of the functional aspects of ecosystems, applied water management regulations have still not been able to implement them into a planning practice. The restoration of ecosystem functions is usually the result of the revitalization measures performed, and are seldom planned as a primary intention. Moreover, EH solutions should be managed and monitored similarly to the supply of drinking water or sewage water treatment. We must be aware of the importance of rainfalls within the UC and do not consider them to be a threat, but a valuable resource.

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