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GIS-based Flash Flood Risk Estimation in Urban Areas. Kaunas City Case Study

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The climate change is continually creating new challenges for researchers from various fields because it affects rainfall pattern and consequently the runoff and river flow over the world. The unpredictable flash floods of the last summer make it necessary to adjust the methods used in urban hydrology. On the other hand, intensifying urban development takes place without respecting the principles of sustainable development, which inevitably leads to unexpected problems, which cannot be solved without research. Flash floods causing inundation of relatively small urban areas localizing the damage to both the population's assets and the city's infrastructure. To reduce the damage, it is first necessary to identify it, assess the extent of its and distribution in the city's territory and reveal the causes. The new achievements of remote sensing technologies in the last decade enables the rapid and timely acquisition of spatial information that can be used to identify potentially inundated areas and estimate their geometric parameters. The aim of this article is to determine potentially inundated areas by screening of local depressions using conventional GIS technologies and LIDAR data and develop a digital map for decision makers to maintain the sounder urban planning process.

Total number of local depression with area > 1 ha is 256 (the smaller one were not accounted) and total area of them 981 ha, average depth of depresions - 1.2 m. Probably inundated streets length are 11 km and total number of buildings at risk – 4221. We cannot estimate whether all of 256 depressions determined here present the real danger, as this could be checked if street floods were registered and respective data was collected on such events. However, having compared several cases described in the press with provided images and dates, the determined locations of depressions are quite precise have been found

Keywords: flash floods, remote sensing, urban drainage.

Introduction

The exhaustive and thorough flood risk assessment is necessary in order to create an integrated damage mitigation system. Flood is one of natural disasters that occupies different places in the range of damage magnitudes caused by other natural phenomena – hurricanes, earthquakes, tsunamis, etc. in different climatic zones and countries. According to the data of statistics portal www.statista.com, the highest losses globally (including Europe) in 2016 were caused by natural disasters of hydrological nature (high level of ground water, high level of rivers, flash floods, etc.); the natural disasters of meteorological and geophysical nature take the second place in Europe. Without going deep to the statistics details, it should be noted that the problem of floods is very important in the European Union and attention given to this is confirmed by the respective directive on floods adopted in 2007 (Europos parlamento, 2007), which had to be implemented by all countries until 2013. According to this document, Lithuania has prepared flood risk maps and created the plan of risk mitigation (Flood hazard and risk maps, 2018). However, these maps and the created plan for flood risk mitigation do not include local flash floods caused by the so-called "flash" storms in urbanized areas. The floods of hydrological nature are divided into separate groups. According to the research (Kreibich and Dimitrova, 2010) carried out in valleys of Danube and Elbe rivers, four groups of floods of hydrological nature were distinguished, which are provided here in the order of the highest damage caused: 1– break of dikes; 2 – high water level caused by water coming by the river; 3 – flash storms causing local flash floods; and 4 – high level of ground water. Of course, this order may be different in different locations, because it is related with both nature of floods and the characteristics of objects located in flood areas.

Attention to floods caused in cities by storms constantly increases with an increasing fraction of population in cities, and the forecast is that two thirds of population will live in cities in 2050 (Sörensen et al., 2016). Seeking to reduce the expansion to the new agricultural areas, cities become more densely populated and better quality of life requires higher percentage of impermeable paving (Perry, 2008); furthermore, urbanization processes in most cases do not meet sustainable city development principles (Wong, 2012). Due to such processes, the traditional engineering solutions where municipal wastewater networks are also used for rainwater run-off become ineffective. Climate change processes cause both changes of river flood start/finish dates and changes of precipitation seasonality, which in turn leads to additional uncertainties when applying existing codes of hydrological calculation (Freni, 2010); therefore, new researches are necessary due to the development of cities and climate change, which would allow adjusting and adapting the current calculation codes and regulations (Redfern et al., 2016). All this encourages seeking for new and advanced research methods which would allow estimating the situation promptly and taking decisions that would mitigate the damage caused (Wicht and Osinska-Skotak, 2016; Albano et al., 2014).

There are literally hundreds of models (most known – DR_3M–QUAL; HSPF; MIKE–SWMM, QQS; SWMM and other) developed by academic institutions, regulatory authorities, government departments and engineering consultants that are capable of simulating storm water quality and quantity in an urban catchment (Zoppou, 2001). The models are capable of simulating flows in common infrastructure components, such as pipes, open channels, retarding basins and natural channels and other infrastructure components (Elliott and Trowsdale, 2007). Most of the models simulate water quality and quantity of urban storm water run-off and combined sewer overflow. Wash-off is simulated as a simple function of run-off or as a first-order decay relationship. Sewer flows are generated using land use, population density and other factors. Infiltration into the sewer system is dependent on the sewer condition and groundwater levels. Flows and pollutants are routed through the sewer system using a modified kinematic wave approximation and assuming complete mixing (Chen et al., 2016). These models are very advanced laceration, but these methods also require detailed information (urban infrastructure data and collection of data in real time), and collection of this information greatly increases the price of future projects. This is the reason why these models are difficult to implement in big urban areas.

The summer of 2017 clearly confirmed the relevance of these issues for the largest cities in Lithuania when the local press was focused on the drowning areas in one or another city at least for several months. Most cases did not get qualified explanation why this happened, because scientific research in Lithuania is not practically carried out in this area. We could find only several publications on creation of methodologies on intensities and calculations of storms.

A quick and easy practical solution, which does not evaluate the exact quantitative results of the damage, but allows quick evaluation of potential risks and, on this basis plan, the need for more detailed research, is proposed in this article.

This research is intended to provide the simplified risk estimation of local flash floods in urbanized areas at a micro level by using the known GIS technologies (Albano et al., 2014; Maidment, 2002) and the information obtained using the remote sensing methods such as satellite images or laser scanning of the surface.

The result of the research is the digital map created for Kaunas city areas subject to the risk of flash flooding caused by heavy storms, which can be further used to plan the flash flood risk mitigation measures and when creating city development plans. This will allow substantiating necessity and development of researches combining methods of urbanistic hydrology, remote sensing, and spatial analysis.

Methods

The object of the research is Kaunas city territory according to the current administrative boundaries (Fig. 1) provided in the spatial data set of Georeference base cadastre (hereinafter referred to as GRBC), version 2017. The data used for the research is the following: the data of digital spatial laser scanning points of earth surface LIDAR and a layer of GRBC areas for estimation of permeability of surfaces.

The research aims to determine the local depressions of the terrain and their geometrical and hydrological characteristics: volume, average depth of a depression, catchment of a depression, index of water permeability of catchment, length of streets and number of buildings falling into a depression area, as well as index of shape of the terrain of depression catchment.

The digital terrain model based on the above mentioned LIDAR data was used to determine these characteristics.

The following software was used: ArcGIS 10.6, ArcGIS tools ArcHydro (Maidment D.R., 2002), and LassTools (Rapidlasso, 2018).

The following workflow was applied in the research:

- the initial LIDAR points were filtrated using LasTools in order to eliminate accidental errors and converted to the format supported by ArcGIS;
- by using ArcGIS, the arrays of points were transferred to the united data base and the digital terrain model (DTM) of the selected cell size (1 m) was generated.

Then the work was carried out using ArcHydro package:

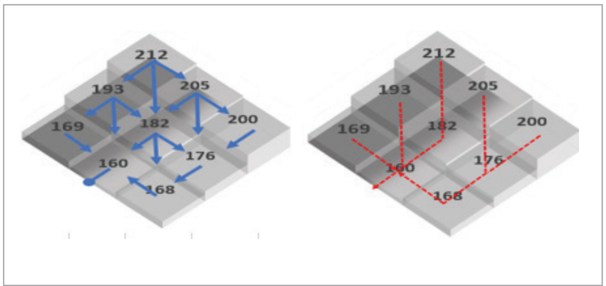
- the generated DTM was aggregated to the cell size of 5 m and hydrologically correct surface was created;
- waterways and catchments were defined;
- depressions and their local and global catchments were defined and the above mentioned geometrical characteristics of depressions were determined;
- depressions of the area smaller than 1 ha were rejected and the final layer of depressions was generated.

ArcHydro principal scheme of algorithm is such that heights of terrain cells are analysed and the outflow direction from the cell is determined together with relative value of differences of heights between the cells, which is then used to determine the direction of flow (Fig. 1, blue colour). By connecting vectors, continuous lines of waterways are obtained (Fig. 1, red colour). If directions of adjacent cells are opposite by 180 degrees, it means that this place is the divide between these cells or the centre of depression, which is then used to distinguish boundaries of catchment (Maidment, 2002).

In this case, we use the “hydrologically correct” surface, i.e., where the local depressions are “levelled”. The same algorithm is also applied for determination of boundaries of depressions and their local catchments, but here we come back to the original model

Fig. 1

Simplified scheme of ArcHydro algorithm



of terrain. When the number of depressions, their location, and geometrical characteristics (area, volume, average depth) are determined, we estimate the risk of each depression based on the impact of various flooding risk factors by using the following equation:

$$R = \frac{K_1 * w_1 + K_2 * w_2 + K_3 * w_3 + K_4 * w_4 + K_5 * w_5 + K_6 * w_6}{w_1 + w_2 + w_3 + w_4 + w_5 + w_6} \quad (1)$$

where: R – risk index in unit fractions; normalised variables are used for risk assessment: K_1 – ratio between area of depression and local area of depression catchment; K_2 – global area of catchment; K_3 – score of surface permeability; K_4 – number of buildings falling into the area of depression; K_5 – length of streets falling into the area of depression; K_6 – index of shape of local terrain of depression;

$w_1 ... w_6$ – weights.

All variables included in the equation are normalized by converting their values to a unit fraction based on the maximum. Values of weights were determined with positive and negative signs; for example, the higher surface permeability reduces the flood risk, but the higher number of buildings falling into the area increases the risk, etc.

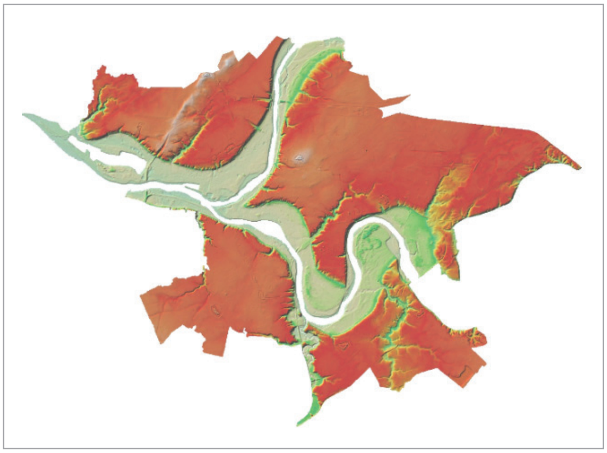
Results and Discussion

We followed the following principle for assessment of the risk of flooding of streets and other infrastructure: what would happen in case of failure of a wastewater system (blockage or failure of part of equipment) installed in areas of catchment and depression during a storm, which should normally operate well and ensure good drain of run-off water. The second assumption is that irregularity of a storm in space and time is not assessed, because we do not model the surface run-off in this case.

After the assessment of the quality of the created digital terrain model (DTM) was performed (Fig. 2), it was noticed that the required precision could not be achieved in certain areas occupied by trees or buildings. In the latter case, the heights were interpolated based on the heights determined according to the building contour line. As mentioned above, the two DTM were generated: the first with a cell size of 1 m and the second with a cell size of 5 m, which also underwent elimination of the closed depressions in order to satisfy the requirements of ArcHydro method.

Fig. 2

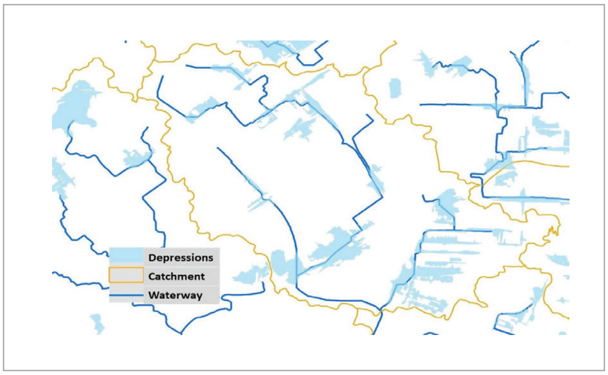
Digital terrain model of Kaunas city



Both the generation of DTM and the determination of global and local catchments and depressions and of their geometrical parameters consume much computer run time. Calculations of individual phases took up to 10 days for a computer with a 8-core processor. Catchments were distinguished into the global (based on 5 m DTM) together with waterway lines and the local (based on 1 m cell DTM), which determine the water intake area to the specific depression (Fig. 3). The global catchment may contain several local depressions. When the one located upstream is filled up, the overflow water runs to the one located at a lower level despite the fact that the latter could be already filled up fully or partially from the local catchment area. This is estimated by parameter K_1.

Fig. 3

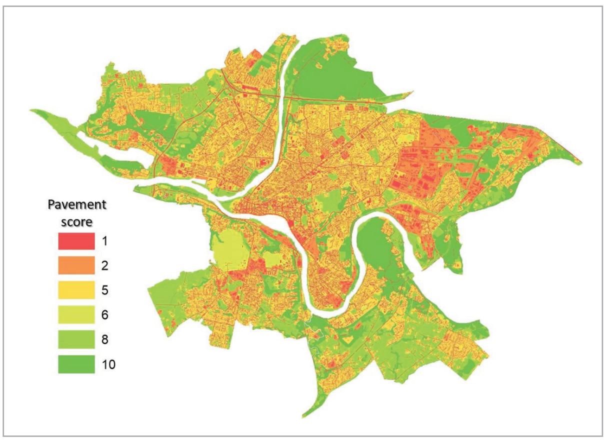
Catchments of depressions and waterways (a fragment of one catchment)



Probably the most important factor for flood risk estimation is the type of surface paving, determining the capability of rainwater permeation into the ground. For this reason, 6 groups of paving based on the layer of GRBC areas were distinguished and the scores were assigned to them (Fig. 4).

Fig. 4

Spatial distribution of paved/unpaved areas (higher number indicates less paved areas)



It has to be mentioned that this layer should be detailed for blocks of single-store buildings in the future, because the area in this zone is divided only into two categories: the plot part occupied by a building and the rest part of the plot, which usually contains lawn, paving of concrete blocks or other, garden, asphalt, etc. This would allow more precise estimation of distribution of water permeability.

By using the previously created GIS layers, calculations of the parameters required for risk estimation with the help of standard spatial analysis tools of ArcGIS were carried out: by overlaying the areas of depressions with layers of streets, it was found out what maximum length of a street could be flooded and how many buildings fall into this zone. Both parameters are very important in estimating potential damage as flooding of the streets disturbs traffic, and buildings falling into the zone allow to assess the potential damage to population's assets (in the case of residential single-store or multi-store buildings) or to public and private companies or institutions. We also estimated one more factor which, in our opinion, is also important. According to DTM, terrain shapes were distinguished (Jenness, 2018). First, the topographic index was generated and, based on its classification results, the layer of terrain groups was obtained, which was used to estimate that the depressions located in valleys would create less trouble with regard to the fact that run-off water here can be drained at smaller expenses, in comparison with large, relatively flat areas.

Based on the generated layer of characteristics of depressions, the risk index was calculated using the formula provided above, and after classification, the final map of areas subject to potential flooding by dividing into the five classes was created (Fig. 5). As expected, the most risky depressions were located mostly in flat areas with the densest building development; however, there are exceptions as well. Based on such selected values of weights, the riskiest group also includes Marvelė street, which is assumed as a single large depression, because it has an embankment border with the River Nemunas. This was determined by the particularly large number of residential houses and, despite of a good permeability index, there is a large catchment area from high slopes here.

Total number of local depression with are > 1 ha is 256 (the smaller one were not accounted). Total area of them 981 ha. The average depth of depresions - 1.2 m. Total length of probably inundated streets 11 km and total number of buildings at risk – 4221.

Fig. 5

Spatial distribution of depressions by the risk index

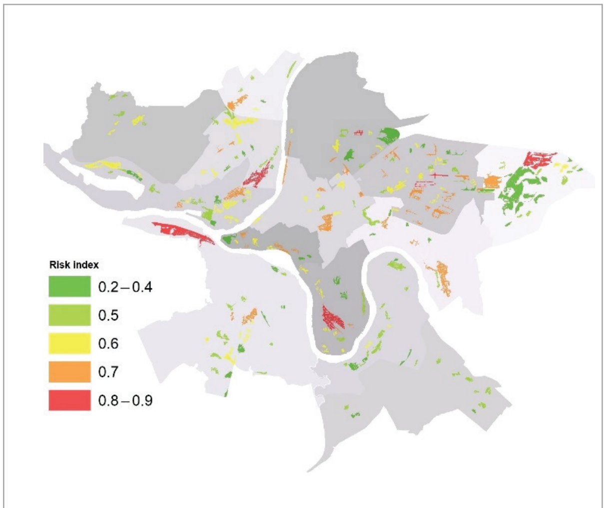


Fig. 6

Inundated Kovo -11 street and Krėvės street (source: "Kas vyksta kaune") and inundation map

The major value of the created map is such that it can be used for planning the city development, selection of possible flood mitigation measures, variety of which is not discussed in this article due to the limited scope of text.

We cannot estimate whether all of 256 depressions determined here present the real danger, as this could be checked if street floods were registered and respective data was collected on such events. However, having compared several cases described in the press with provided images and dates, the determined locations of depressions are quite precise have been found. For example, depression at the crossroad of Kovo -11 street and Krėvės street is quite often flooded due to its small volume, but high value of K_1 parameter (Fig. 6).

Conclusions

1. The created map of local floods could be used for more sustainable urbanistic development and creation of a flood risk mitigation plan as a preliminary risk assessment document; however, surface run-off modelling is necessary in order to further develop this subject.
2. The defined waterways, depressions, and boundaries of catchments will allow estimating the rationality of arrangement of the existing wastewater network and, if necessary, making the required adjustments.
3. In order to create Kaunas city DTM according to LIDAR data, the more elaborated mechanisms for elimination of possible errors are required.

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GIS metodais grįstas urbanizuotos teritorijos lokalių poplūdžių identifikavimas Kauno miesto atveju

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Vykstanti klimato kaita nuolat kelia vis naujus iššūkius įvairių sričių tyrėjams. Pastarosios vasaros netikėti ir žaibiški poplūdžiai verčia koreguoti ir urbanistinėje hidrologijoje taikomus metodus. Spartėjanti ir intensyvėjanti miestų plėtra vyksta neprisilaikant darnaus vystymosi principų, kas neišvengiamai sukelia netikėtas problemas, kurias išspręsti neatliekant mokslinių tyrimų bus vis sudėtingiau. Viena iš ypač paaštrėjusių problemų – dėl intensyvių ir gausių liūčių, užtvindomi lokalūs atskirose miesto teritorijose esantys nedideli plotai ir padaroma atitinkama žala tiek gyventojų turtui tiek ir miesto infrastruktūrai. Norint žalą mažinti, pirmiausia reikia ją identifikuoti, įvertinti jos išplitimo mastą miesto teritorijoje ir nustatyti priežastis. Ypatingai spartus pastarojo dešimtmečio nuotolinių tyrimų technologijų vystymasis leidžia operatyviai gauti daug ir tikslios erdvinės informacijos, kuria pasinaudojus, galima atlikti potencialiai apsemiamų teritorijų identifikavimą ir jų kiekybinių parametrų nustatymą. Šio straipsnio tikslas – naudojant žinomas GIS technologijas ir nuotolinių tyrimų metodais gautą erdvinę informaciją, nustatyti Kauno miesto potencialiai rizikingus plotus dėl jų apsėmimo intensyvių liūčių metu, sudaryti jų skaitmeninį žemėlapį, kuriuo vadovaujantis būtų galima planuoti poplūdžių rizikos mažinimo priemones, bei vadovautis kuriant miesto plėtros planus. Atlikus modeliavimą nustatytos 256 įdubos, kurių plotas didesnis nei 1 ha (mažesnės nebuvo vertinamos), bendras šių įdubų plotas siekia 981 ha, o vidutinis gylis apie 1,2 m. Užtvindomų gatvių atkarpų bendras ilgis siekia 11 km ir pastatų patenkančių į rizikos zoną skaičius – 4221. Negalime įvertinti, ar visos iš čia nustatytų 256 įdubų tikrai yra keliančios realų pavojų, nes tą patikrinti galėtume, jei gatvių užtvindymai būtų registruojami ir kaupiami duomenys apie tokius įvykius. Palyginę keletą aprašytų spaudoje atvejų (su pateiktomis nuotraukomis ir datomis) matome, kad įdubų vietos nustatytos pakankamai tiksliai.

Raktiniai žodžiai: poplūdžių rizikos vertinimas, nuotoliniai tyrimai.