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A Location Intelligence System for the Assessment of Pluvial Flooding Risk and the Identification of Storm Water Pollutant Sources from Roads in Suburbanised Areas

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Received: 8 May 2018; Accepted: 5 June 2018; Published: 7 June 2018

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Abstract: The interplay of an ever-growing number of inhabitants, sprawl development, soil sealing, changes in urban traffic characteristics, as well as observed climate trends gives rise to more frequent pluvial flooding in cities, a higher run-off of water, and an increasing pollution of surface water. The aim of this research is to develop a location intelligence system for the assessment of pluvial flooding risks and the identification of storm water pollutant sources from roads in newly-developed areas. The system combines geographic information systems and business intelligence software, and it is based on the original Pluvial Flood Risk Assessment tool. The location intelligence system effectively identifies the spatial and temporal distribution of pluvial flood risks, allows to preliminarily evaluate the total run-off from roads, and helps localise potential places for new water management infrastructure. Further improvements concern the modelling of a flow accumulation and drainage system, the application of weather radar precipitation data, and traffic monitoring and modelling.

Keywords: location intelligence; pluvial flood risk assessment; road run-off management; storm water pollutant sources; green infrastructure; blue infrastructure; urban climate adaptation

1. Introduction

Urban growth and climate change will be the main drivers of the deterioration of water resources in the near future. These processes affect both water quality and water quantity in urbanised catchment areas [1]. As the number of inhabitants in cities is expected to keep growing, negative consequences such as urban sprawl [2–4] and soil sealing [5] will also become increasingly significant. Urbanisation will lead to additional changes in the characteristic of urban traffic, as the volume of traffic and subsequent patterns of congestion increases. As a consequence, larger amounts of pollutants will build up on road surfaces [6].

Simultaneously, global climate change is expected to induce a transformation in pluvial spatiotemporal distribution and magnitudes [7–9]. The increase of high-intensity rainfall frequencies and patterns is predicted [10]. The interplay of growing impervious areas with extreme and high rates of precipitation will lead to the occurrence of local pluvial floods, and, consequently, higher surface water run-off [11–14]. Increasing flooding trends result in evenly increasing trends in economic losses [15]. In the future, pluvial floods could generate more cumulative damage than fluvial flooding events [16]. The direct and indirect impacts of extreme weather include losses in economic terms [17], the damaging and destruction of private buildings and urban infrastructure [18], the loss of human lives and the degradation of safety [19], and the deterioration of water quality [20].

The water quality on the watershed scale is notably related to the percentage of the impervious surface area [21]. Road dust deposit is one of the main sources of urban pollutants. Because of low leaching ratios, these pollutants are mainly transported in particulate forms [22]. Sealed surfaces provide a sink for road sediments, which tend to accumulate during dry periods. After each dry period, the built-up urban sediment and bound pollutants get detached and washed off by rainfall [23]. The wash-off process is either limited by road-deposited sediments or limited by transport [24], depending on the road's slope, the geometry and layout of curbs, and street sweeping [25], as well as the road surface's material (i.e., asphalt, concrete), and its characteristics (i.e., its roughness and texture influence on run-off quality) [26]. Storm water run-off from traffic areas contains zinc (Zn), copper (Cu), lead (Pb), chromium (Cr), suspended solids, as well as Polychlorinated Biphenyls (PCBs), Petroleum Hydrocarbons (PH), Polycyclic Aromatic Hydrocarbons (PAHs), and many others, which can degrade and pollute surface waterways [27–30]. Moreover, run-off contains readily soluble salts of potassium (K), cadmium (Ca), sodium (Na), magnesium (Mg), chloride (Cl), and sulfate (SO_4) [31]. There is a total of 1100 identified organic pollutants, which can be potentially transferred from road-related sources to the environment.

The mean concentrations of pollutants in run-off waters are dependent on rainfall characteristics and land use. Rainfall depth, mean intensity, and max 5-min intensity play a crucial role in so-called pollutant loading [32]. British research on integrated urban wastewater systems, which was carried out using the SIMBA5 simulation tool, showed that rainfall depth has a more significant impact on the surface water quality than the rainfall intensity [1]. Then there is the effect of first flush, which described the observation of higher concentrations of pollutants in run-off water at the beginning of a storm event [33].

There is a strong correlation between high traffic intensities and the levels of pollutants. Berndtsson [34] recorded particularly high rates of heavy metals and total phosphorus (P) in storm water in places where traffic intensity reached 7000 vehicles per day. Numerous studies on rainwater pollutants that have washed off the roads include the evaluation of seasonal variability of physical and chemical parameters [35], research on the partitioning and mobilising of inorganic chemicals and trace metals [36], analyses of particle size distribution [37], biotoxicity assessments [38], as well as impact assessments on the immune function of aquatic biota [39], and the examination of spills of hazardous compounds during traffic accidents [40].

As the pluvial flood risk (understood as a combination of hazards and damages) is forecast to increase in the future [41,42], cities and suburbs should become more resilient and adapted to new climatic and socio-economic conditions [43]. For a rational decision-making process in adaptation and spatial planning, the assessment of pluvial flood risk is essential [44]. Studies on the spatiotemporal dynamics of pollutants in run-off waters, as well as information on urban patterns and drainage systems, should help urban designers and decision makers to mitigate the rising impacts of urbanisation on aquatic ecosystems [45]. One of the challenges is to recognise the major pathways of heavy metals to the build-up on roads in order to protect the receiving aquatic environment [46].

Low-Impact Development (LID) and Green Infrastructure (GI) are effective measures to collect, infiltrate, and remove heavy metals, solid particles, and other pollutants loading from storm water run-off [47]. Among the most effective LID and GI practices are green roofs [48], permeable or porous pavements, rain gardening [49], application of water-absorbing geocomposites [50], and bioretention systems [8]. Waste waters derived from small settlements or produced in service areas located along major roads can be treated using aquatic plants and hydroponic systems [51,52]. At the catchments scale, water pollution removal can be provided in so-called Nature-Based Treatment Systems (NBTS) [53].

Locating and designing flood management facilities can be supported by modelling, risk evaluation, as well as decision making and monitoring systems. It is necessary to properly estimate their capacity in relation to changing water levels [54,55]. Decisive information could be complemented by simulations of land use changes and land take impact assessments [56,57] or the indictor-based spatial multivariate analysis [57,58].

Yin et al. [59] proposed an integrated methodology, which incorporates flood inundation modelling, traffic management, and risk assessment, to measure the impact of pluvial flash floods on intra-urban road networks in the city centre of Shanghai, China. They used high-resolution Flood Map (2D hydro-inundation modelling) to simulate overland flow and flood inundation for various flood return periods. Shorshani et al. [60] developed an original modelling tool that integrates simulations of traffic rates, gas emissions, and air and storm water pollution: they used a combined methodology of COPERT4, Polyphemus, and the United States Environmental Protection Agency Storm Water Management Model (USEPA SWMM) in order to predict the road traffic impact on the contamination of surface waters. The SWMM was also applied in the Urban Rainfall-Runoff Water Quality model developed by Gong et al. [61], which was used to simulate the load of suspended solids washed off a university campus in Beijing, China. In some studies [12,49,62], the SWMM is used to evaluate the effects of LID on run-off reduction. Fraga et al. [27] developed their own MEDUSA (Modelled Estimates of Discharges for Urban Stormwater Assessments) modelling framework. This tool calculates the pollutant build-up and wash-off from impervious surfaces such as roofs, roads, and car parks. Simulations can be made of single rain events, different land use patterns, and rainfall parameters. In addition, Trenouth and Gharabaghi [63] applied artificial neural networks to predict the mean concentration and the mean daily unit area load of highway pollutants. They accounted for traffic characteristics as well as meteorological factors of severe rainfalls, and their results supported the design of roadside ditch treatment systems and helped protect sensitive aquatic environments. Chen et al. [8] developed a planning support model that combines rainwater management with Computer-Aided Design (CAD) software. Finally, the City Catchment Analysis Tool (CityCAT) by Bertsch et al. [64] can be applied for better urban drainage designing and locating storm drain inlets. Overall, integrated systems combine pluvial flood risk mapping with water management tasks, as well as the economic effectiveness of flood control and adaptation measures [14].

The state of the art of flooding risk assessment, pollutant transfer modelling as well as planning and designing support systems shows some gaps in knowledge and practice:

- Research on pluvial events loss modelling and quantification is relatively rare [15,16];
- Modelling should take spatiotemporal variability from rainfall and flooding distribution into consideration [42];
- There is a lack of support tools for designers and policy-makers, which would benefit landscape management [8];
- Decision support systems should be developed for larger areas and should provide an assessment of the capability of new adaption practices [49].

2. Aims

The aim of this research is to develop the location intelligence system which will support:

- Pluvial flooding risk assessment;
- Spatial identification of potential diffuse road pollutant sources,
- Locating and dimensioning of the GI facilities.

The main assumption was that the system should be user-friendly and accessible for non-technical experts. Policy makers, architects, and designers are expected to use the system without any extra computer or database operational skills. This study is a continuation of previous research presented by Szewrański et al. [65].

3. Methodology

The methodological framework encompasses a combination of software integration of location intelligence systems, spatial data geoprocessing and weather data extraction, field inspections, and finally pluvial flood risk assessment and testing of the location intelligence system.

3.1. Location Intelligence System

The core element of location intelligence system is the original Pluvial Flood Risk Assessment (PFRA) tool, developed for supporting the urban adaptation to climate change [65]. A workflow model that was coded using the Python language is a combination of Geographic Information System (GIS) geoprocessing and land use spatial assessment, elevation and hydrologic analyses, as well as the application of climate change modelling and weather forecasting. The model can be used for various area sizes. Modelling results are stored in a tabular, spatiotemporal database, and are connected to a business intelligence system, responsible for visual data exploration (Figure 1). The location intelligence system is based on actively connected ArcGIS and Tableau software [66,67].

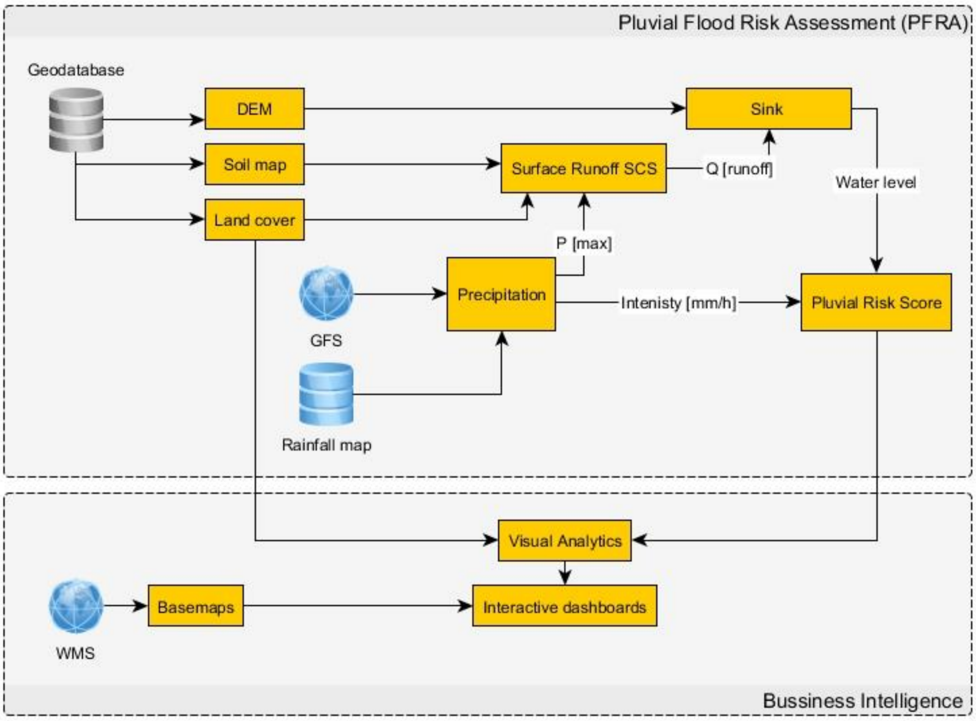


Figure 1. A schematic overview of the location intelligence system.

3.1.1. Data

Digital elevation data were received from Light Detection and Ranging (LiDAR) measurements. The spatial resolution of the Digital Elevation Model (DEM) used in the model was 1.0 m × 1.0 m. Soil data were retrieved from administrative databases based on an Institute of Soil Science and Plant Cultivation (IUNG) map with a reference scale of 1:25,000. Land cover data were taken from the Urban Atlas repository. The location intelligence system operates based on the Global Forecast System (GFS) produced by the National Centers for Environmental Prediction (NCEP). The rainfall data subsets stored in grib2 files are made available in time steps of 3 h each. In this study, the GFS dataset was used for the 24 and 25 July 2017. Weather data were analysed and visualised with use of zyGrib software. Field inspections were carried out in order to discover manmade changes to the watershed and to examine the hydrographic system.

3.1.2. Pluvial Flood Risk Assessment

Spatial data were processed with GIS tools in order to obtain pluvial flood risk distribution. Analytical workflow, assumptions and limitations were described in detail by Szewrański et al. [65]. The most important limitation at this stage was the model does not incorporate the underground storm water system. The run-off volume was calculated with use of Soil Conservation Service Curve Number (SCS-CN) hydrological model [68]. Calculations were provided for different land use scenarios and values of surface permeability. The SCS-CN methodology incorporates the water balance formula, based on the main assumption that the ratio of surface run-off to the total precipitation equates the ratio of actual infiltration to the potential maximum retention. The SCS-CN model is expressed by Equation (1).

$$Q = \frac{(P - I)^2}{P - I + S} \tag{1}$$

where:

Q—direct run-off [mm]
P—total precipitation [mm]
I—initial abstraction [mm]
S—potential maximum retention [mm]

The potential maximum retention can be calculated with Equation (2).

$$S = 25.4\left(\frac{1000}{CN} - 10\right) \tag{2}$$

where CN is the curve number related to the soil characteristics, land cover and the antecedent moisture condition.

The SCS methodology can be successfully applied in Polish hydrometeorological conditions as shown by previous research [69]. Basing on methodology applied by Ignar [70], the soils were classified into four groups of different infiltration capabilities : A, the highest; B, above the mean; C, below the mean; and D, the lowest. The areas covered by these groups were delimited. A soil map was combined with the Urban Atlas map: that way, CN values could be assigned to different land covers and soil classes with the use of US Department of Agriculture (USDA) tables [68].

The location and extent of impounded areas were evaluated with use of the hydrologic sink geoprocessing tools.

The Pluvial Risk Score (PRS) was calculated as a multiplication of hazard, vulnerability, and exposure values. The hazard assessment incorporates the amount of effective precipitation and the level of impounding water. The mean hazard varies from 0 to 100 points. When the rainfall exceeds 25.0 mm, the hazard value equals 100 points. The vulnerability assessment is based on the percentage rates of damage to buildings and their interiors. Based on a review of the literature [16], it was assumed that for every 1.0 cm of additional flood water, an increase in the damage of buildings of 3.37% is observed, and an increase of 5.88% for interior equipment. The exposition valuation is simplified: for each flooded area, the parameter equals 100. The final thus PRS varies from 0 to 100. The maximum valid value for rainfall is 400 mm.

3.1.3. Business Intelligence

Spatial and temporal data processed in GIS were stored in a geodatabase, which was directly connected to a business intelligence tool. All operations on data files, such as filtering, extraction, aggregation, and table calculation, can be provided within the graphical interface. The main output of the system was an interactive and dynamic dashboard, which contained land use information, pluvial flood risk maps, as well as effective rainfall and a spatiotemporal distribution of the surface runoff.

3.2. Study Site

The location intelligence system was tested for use in the suburban settlements of the city of Wrocław, Poland. As one of the largest and most rapidly developing Polish cities [71], Wrocław is impacted by uncontrolled suburbanization [72,73], farmland degradation [74,75], and landscape deformation [76,77]. As a consequence, there are many negative effects of rapid urbanization, such as rising low emission and environmental pollution by traffic flow [78–80], changes in biodiversity and ecosystem services [81], thermal stress [82,83], as well as numerous economic and social implications [84,85]. Wrocław and its suburbs are mostly lying in the valleys and floodplains of the River Odra and its tributaries. This region is affected by regular pluvial and fluvial floods events [86–90]. Simultaneous hydroclimate changes and urbanisation processes generate new challenges, that should be managed within the framework of strategic adaptation planning and decision making [91–93].

The experimental study site was located in the village of Kamieniec Wrocławski (51°04′43.7′′ N 17°10′36.0′′ E), 10 km from the centre of Wrocław (Figure 2). The total surface area of the study site was 0.85 km^2. A discontinuous urban settlement that was characterised by a soil sealing level of 50–80% occupied 28.7% of the total area. A continuous urban fabric with more than 80% of impervious surfaces shares 19.5% of the total area. Arable lands took up 21.4%, and pastures occupied 18.6% of the land. About 6.1% of the site was occupied by roads and associated lands, whereas industrial, commercial, and public places took up 2.3%. Grounds covered by water made up less than 1.0% of the area. The total length of watercourses located in the study site is approximately 3400 m.

Figure 2. The study site in the village of Kamieniec Wrocławski.

The southern part of the village is developed as a traditional discontinuous settlement, built up along the main road. A new housing area is located in the centre of the study site. The filed inspections showed some environmental aspects, typical for urban sprawl and unsustainable land development. The mean width of the inner road corridor is about 10.0 m, so the pavement is used by inhabitants as parking places (Figure 3a). Rain run-off from impervious traffic lanes that gets collected by surface gutters is released directly to watercourse (Figure 3b). The rainwaters drained by an underground system are treated in the same way (Figure 3c). As a consequence, the flowing waters are polluted, and water-dependent ecosystems are degraded (Figure 3d). Rainwaters are not stored or recycled. There is no green or blue infrastructure in the study area in Kamieniec Wrocławski. Moreover, no technical facilities for the treatment of road rainwater are in place.

Figure 3. Environmental aspects of unsustainable land development (**a**) Soil sealing; (**b**) Run-off released to watercourse; (**c**) Drainage system outlet; (**d**) Water-dependent ecosystems degradation.

3.3. Climate and Meteorological Conditions

The pluvial and thermal conditions in the Wrocław agglomeration were described based on the climate dataset from the years 1981–2010.

The mean annual air temperature was 9.1 °C. The maximum daily air temperature was 37.4 °C. The minimum record temperature was −30.0 °C. The mean annual total precipitation was 536.9 mm. The record daily precipitation was 115 mm. The mean amount of monthly rainfall varied from 25.2 to

81.0 mm. July remains the rainiest month. In 1997, when Wroclaw was affected by an extreme fluvial flood, the total annual precipitation reached 238.1 mm.

The pluvial flooding simulations in this study were based on GFS meteorological forecast for period between 24 and 25 July 2017. The total forecast precipitation was 39.7 mm, which would be almost 50% of the average total monthly rainfall. High rainfalls totals could be generated by cyclonic weather (Figure 4) and occurred during a frontal passage (Figure 5). The highest forecast rainfall rate was 13.6 mm per hour.

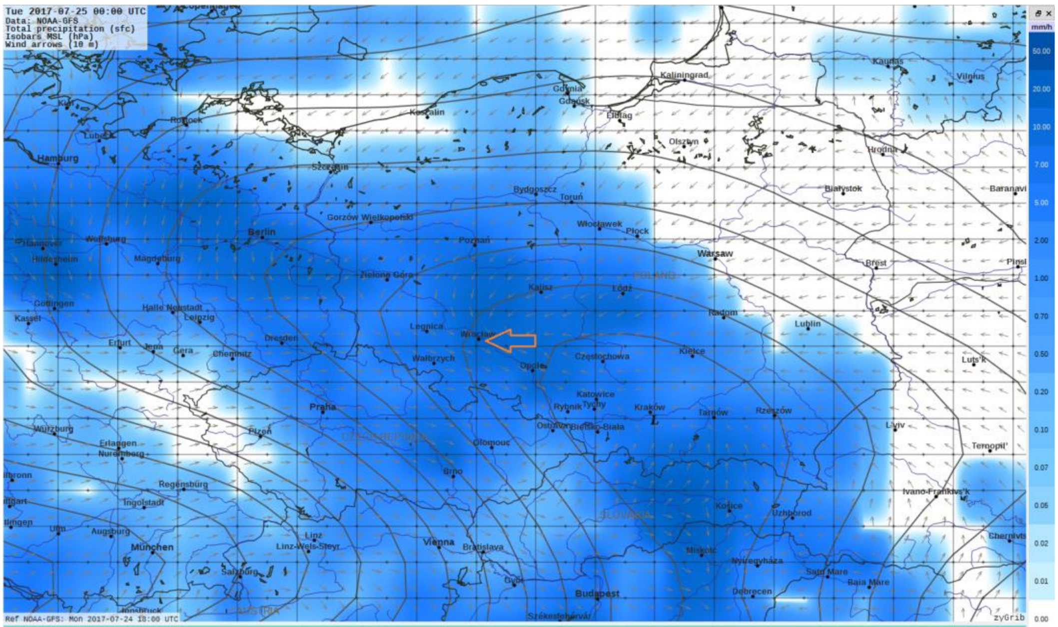


Figure 4. Weather map on 25 July 2017. Based on the GFS dataset, the center of low pressure is located in Southern Poland. The red arrow indicates the study site.

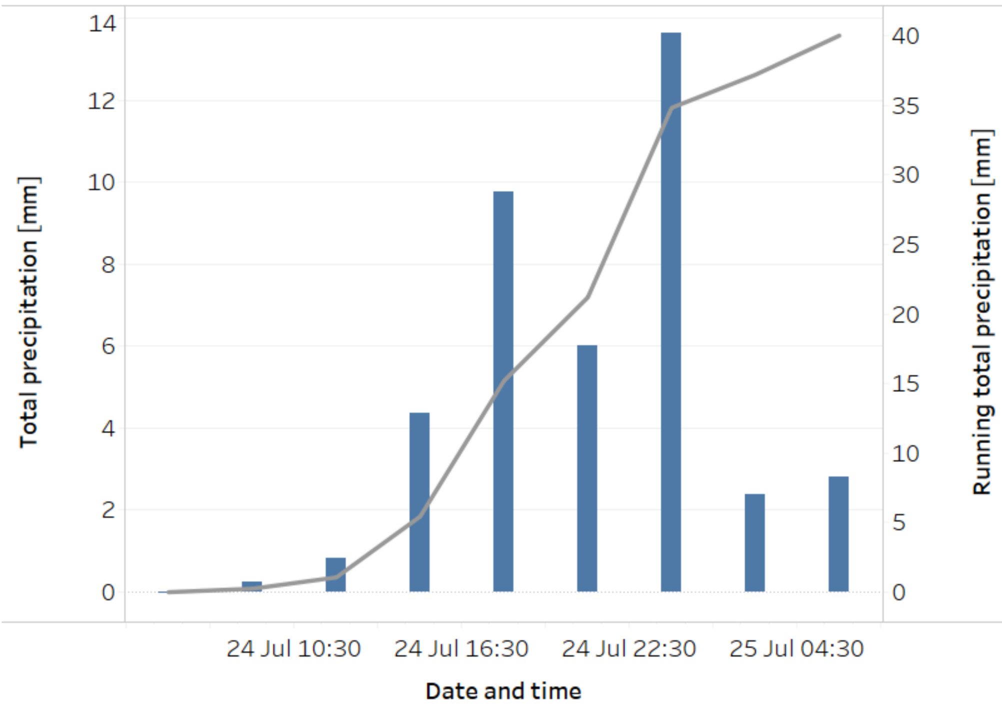
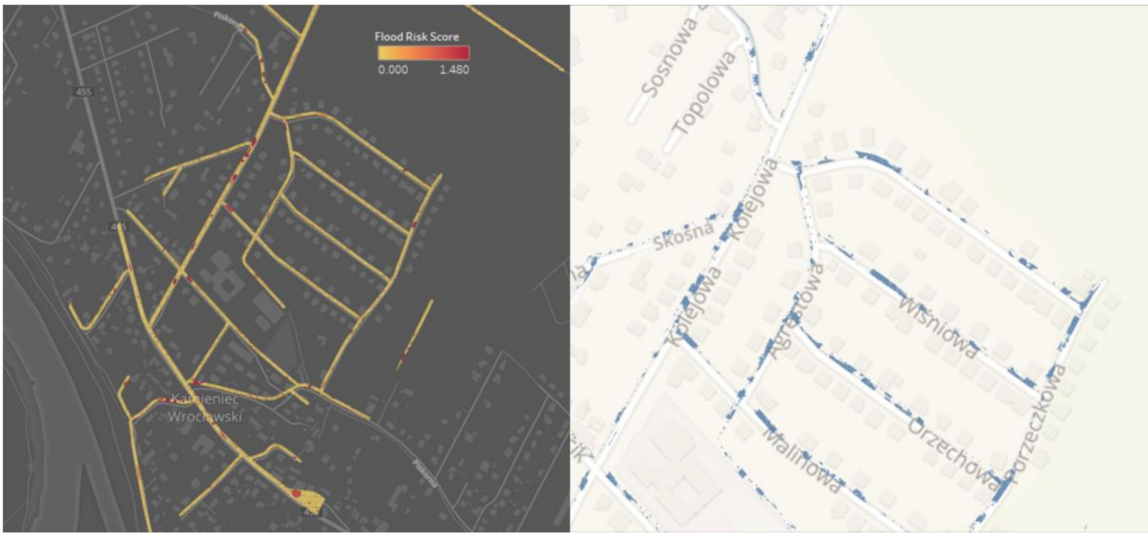


Figure 5. Forecast of weather conditions in study site from 24 to 25 July 2017 basing on GFS datasets.

4. Results: Simulations and Location Intelligence Tests

The simulations provided during this research allowed for the assessment of the spatial distribution of pluvial flood risk (Figure 6a). The maximum risk score was 1.48 points. More than 4% of the road surfaces were classified by a risk of over 1.40. The places which could be affected by rainwater impounding were located along the main road in the western and southern part of village, as well as in the new housing area in the eastern part. The vast majority of the roads (90.1%) was not subjected by water impounding.

The pluvial flooding risk assessment allowed for the identification of the hydrologic sinks (Figure 6b). As the sinks collect and store the rainwater run-off, green or blue infrastructure could be located strictly in these places. We assumed that the microtopography of the road surfaces indicate the potential localisations of water management facilities.



(**a**) (**b**)

Figure 6. (**a**) Pluvial flood risk map; (**b**) Hydrologic sinks location (zoomed map).

The location intelligence system allowed for the calculation of the area of micro-watershed of the sinks. There are more than 2000 m^2 of sinks with a flooding risk level surpassing 1.40. More than 2900 m^2 are characterised by a risk level of 0.20 to 1.40 points. A combination of the area and effective rainfall gives the total volume of the road run-off, which could be captured by green or blue infrastructure.

The final analyses can be shown through the use of the location intelligence dashboard (Figure 7). This dashboard is an interactive decision support tool that combines all results of modelling. The system allows the determining and adjusting of acceptable risk levels, filtering land cover class, and using the spatial and temporal filtering. Finally, it calculates area and volume of run-off for selected sinks. The results were presented on the maps of the flooding risk, the sinks' locations, the pluvial conditions, and the total run-off charts.

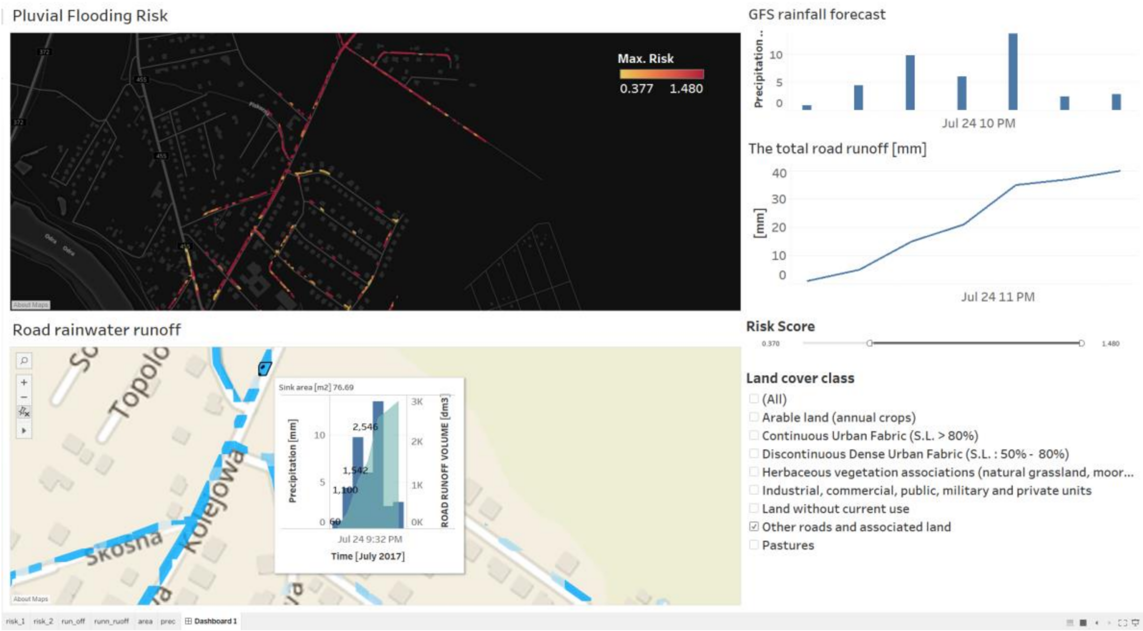


Figure 7. The location intelligence system's dashboard (screen capture).

During the tests, four potential locations were identified for the new GI. All sinks were located in places characterised by pluvial risk scores higher than 1.40 points. The total area of micro-watersheds was 79.1 m^2, 177.5 m^2, 191.6 m^2, and 263.2 m^2 for each of the four potential locations. Simulated run-off volumes during a pluvial event were 3077.5 dm^3, 6905.8 dm^3, 7454.4 dm^3, and 10,240.1 dm^3, respectively. In these places, the devices improving the quality of rainwater discharged into natural basins should be located. At the stage of designing new road networks, the implementation of infiltration trenches should be incorporated in order to provide natural purification processes. In case the road network already exists, the problem of contamination of discharged rainwater can be solved by installing a GI supporting the treatment of precipitation. Among such solutions could be the design and construction of bioswales or rain gardens with hydrophyte filters. In case of the test area, there were locations enabling the use of the aforementioned solutions without the need to reconstruct the road system (Figure 3b). The use of GI solutions increases retention, improves the quality of discharged rain waters, as well as influences the aesthetic values of the environment in a positive manner.

5. Conclusions and Future Work

The main research purpose was to develop a location intelligence system that would support a pluvial flood risk assessment and the identification of water pollution sources from the roads. The developed interactive tool allowed for the adjustment of the risk level, the calculation of run-off volume, and the identification of the places where the water treatment facilities could be located. The intention was to develop the tool which could be used in existing built-up areas. The application of this location intelligence system could be helpful for the adaptation to climate change at the local level in an already developed country. Data were visualised as pluvial flood risk maps, sink locations, the total precipitation, and the total runoff charts. The location intelligence system has some limitations that should be overcome in future research and development efforts.

Due to many uncertainties and assumptions of risk calculations, the model should be used as a preliminary evaluation tool. The same approach was considered by Sperotto et al. [13]. At this moment, the model cannot be used to process data on an existing drainage systems and flow accumulation. The functionality of the system could be improved by incorporating information on water velocity, flow rate, and its erosivity. Uncertainties concerning the soil and surface hydraulic parameters are among the challenges for future work and extension of the model. Proper hydraulic modelling is essential for a valid pluvial risk assessment and should be based on the high quality Urban Atlas and the accurate high resolution rainfall distribution [7,94]. Although the model incorporated LiDAR data into the modelling, the rainfall information was taken from the low-resolution GFS datasets. Based on the research results, it was decided to enhance the system by weather radar data processing. This should increase the accuracy of the spatial analyses significantly. At this moment the possibilities of using the 'wradlib' open source library are being examined [95].

At this stage, the location intelligence system is not able to model the transportation of pollutants. The core element of the PFRA tool was originally designed as a planning support tool, which simulates the water impounding in depressions in a certain a terrain. PFRA is an original script and can therefore be combined with any spatial model. As the storm run-off quality depends on the traffic density, in future research, the identification of storm water pollutant sources from roads will be enriched by real-time traffic monitoring or traffic modelling component with use of graph theory [67]. PFRA also needs to be enriched by flow accumulation modelling.

The results of the tests showed that the pluvial flood risk scoring should be more adjustable. At this stage, the maximum risk score is representative for the rainfalls amount of 400 mm. There are plans to modify the script in the near future so that the maximum risk level is to be a used as a parameter in decision-making.

The most significant problems relate to the technical and computational limitations. Geospatial analyses are mainly based on layer intersections; these analyses produce many spatial data. As geodatabases can store up to two billion number of records in the tables, the studied area needs to be divided into smaller parts. GIS modelling should be conducted separately for each subarea. Separate modelling results can be easily re-joined within a location intelligence system, which includes a BI tool. As Tableau is originally designed to operate using big data databases, it allows for effective analyses and data exploration. A detailed dissection on technical aspects of PFRA functioning is given by Szewrański et al. [65].

According to the limitations outlined above, the intelligence system can be used as an indicator-based planning support tool for the localisation of the surface water treatment and small retention systems. It can be used as a scenario-based decision support system for local development, which enables the identification of the environmental risk assessment of a specific weather event before its occurrence.

The main findings of this study are that a location intelligence system can effectively identify the spatial and temporal distribution of pluvial flood risks, can be used to evaluate the total run-off from the roads, and can help localise potential places of new water management infrastructure.

Author Contributions: The article was drafted by all authors. Data curation, S.S., J.C. and M.Ś.; Investigation, J.K. and M.Ś.; Methodology, S.S., J.C., J.v.H., J.K., K.T.-D. and R.Ż.; Software, S.S. and J.C.; Supervision, K.T.-D. and R.Ż.; Visualisation, S.S.; Writing—original draft, S.S.; Writing—review & editing, J.v.H. and J.K. S.S. is the corresponding author, the subsequent names are given in alphabetical order.

Acknowledgments: Land Cover data: European Union, Copernicus Land Monitoring Service 2018, European Environment Agency (EEA) [https://land.copernicus.eu/local/urban-atlas]. GFS datasets were retrieved from the repository of the National Centers for Environmental Prediction (NCEP) [https://www.ncdc.noaa.gov/data-access/model-data/model-datasets/global-forcast-system-gfs]. Regional Climatic data were obtained from the Institute of Meteorology and Water Management—National Research Institute [http://www.pogodynka.pl/polska/daneklimatyczne].

Conflicts of Interest: The authors declare no conflict of interest.

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