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City and Water Risk: Accumulated Runoff Mapping Analysis as a Tool for Sustainable Land Use Planning

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Abstract: The complex integration of water and flood risk management, climate change adaptation, and sustainable planning requires advanced, dynamic tools that are unavailable to most planning offices. This paper aims to demonstrate that the available GIS technologies and large, variable, and diverse datasets (big data) already allow us to create effective, easy-to-use, and, most importantly, cross-sectorial and holistic tools that integrate issues related to planning, flood risk management, and adaptation to climate change. Resulting from an interdisciplinary study of districts in Kraków, Poland, which have been heavily affected by pluvial floods in recent years, the accumulated runoff mapping analysis method proposed in this paper can be considered an effective planning tool that can be used at the initial stage of pluvial flood risk assessment and, above all, for spatial planning analysis and urban design. The proposed tool accounts for a correlation of development, land cover, and hydrological conditions, as well as their impact on vulnerability and the urban climate, while integrating environmental, urban, and social amenities. Intended for preliminary planning phases, it uses open-source software and data, which, although giving approximate runoff volumes, do not require advanced hydrological calculations or costly and time-consuming field research. The method allows studying alternative scenarios that can support the cross-sectorial, inclusive, and interdisciplinary discussion on new developments, sustainable planning, and adaptation to climate change. Most importantly, it can reduce, if not eliminate, issuing decisions that may have negative impacts on urban areas and enhance their resilience before more sophisticated, detailed, and advanced methods are ready for implementation.

Keywords: runoff assessment; GIS tools; adaptability to climate change; sustainable urban planning; water resources management; pluvial flood risk management

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1. Introduction

The frequency and magnitude of pluvial floods are on the rise, along with globally intensifying precipitation for many regions [1,2]. In Europe, twice as many flash floods of a medium to large magnitude have been registered as of the late 1980s. The European Commission has already recognized the need to better understand and account for pluvial flood risk through a detailed modeling assessment. In practice, however, flood risk management plans are still primarily oriented towards fluvial flood risk despite pluvial floods emerging as a crucial problem under conditions of progressive urbanization combined with climate change.

At the same time, climate change and its accompanying heavy rains negatively verify the years of neglect in developing comprehensive strategies that integrate urbanization, natural resources management, the conservation of urban and suburban ecosystems, and risk management. As emphasized by Bosseler et al. [3], due to ongoing urbanization and climate change phenomena, which will increase flooding event magnitude and frequency, existing flood management techniques and plans with the aim of making cities more resilient to urban flooding must all be updated. However, in Poland, as in many other countries, developed and developing alike, cross-sectorial factors and tools are still searched for in vain, regardless of the call for new guidelines and approaches [4]. Planning tools are often too limited, and their tight framework prevents the consideration of complex and dynamic natural phenomena. As a result, planning systems fail to catch up to the potential offered by the full application of the latest environmental research findings, planning procedures are multi-year operations, and many instruments are not up to date at the time of their enactment.

Easy-to-use tools are highly valuable when facing flash floods and can be a step in the right direction in terms of legislation. Small-scale, nature-based, neighborhood-level retention measures were investigated by Barnaś et al. [5] as a part of a thermal retrofit strategy tailored to post-communist housing estates. A portion of the findings became part of an experimental implementation of a series of detailed solutions as a part of a climate standard for public buildings in Kraków [6]. This document considerably extended the array of retention-aiding elements and considered land cover, substrate thickness on green roofs, and ancillary green elements, such as façade gardens. Increasing control via planning instruments is the only viable option for change. Land development conditions in Poland essentially only stipulate the Ratio of Biologically Vital Area (RBVA) values, which are generally rather low. In the case of multi-family housing, it is rarely possible to secure more than 30% RBVA. In other use types (apart from green spaces), this is much lower. Other ecosystem services, such as shading, remain in the sphere of promoting specific projects, with the actual impact remaining marginal.

One of the aspects that intrinsically binds flood risk and urbanization is that the latter irreversibly changes the hydrogeological cycle. Surface sealing results in decreasing infiltration capacity and increasing runoff, which increases flood risk in urban areas [7–11]. This applies not only to fluvial flood risk but also to pluvial and flash floods, the risks of which are increasing as much as they are still underestimated.

Problems associated with pluvial floods and rainfall-runoff dependencies attract increasing attention. For this reason, analyses are undertaken, and methods are developed to integrate aspects that influence flood occurrence and intensity, which could also be used in planning. The methods used depend on the objective, the accuracy, and the scale required. GIS tools allow us to develop and implement a method for measuring and monitoring various parameters of the environment, and their integration with the rainfall-runoff model makes it possible to analyze the consequences of various processes and/or decisions.

Previous studies have proven that the accumulated runoff analysis allows for the identification of potential flood risks in developed areas and planning for suitable action to remedy potential risks. For instance, Manchado et al. [12] developed a method using ArcDrain to estimate the cumulative peak runoff based on map analyses (digital elevation model, land cover map, hydrogeological map, and precipitation). The aggregated peak runoff in 247 sub-basins in the city of Santander in northern Spain shows that not only are heavily sealed areas critical but also those that receive runoff from higher sub-basins. Based on the analysis, catchments were selected and simulated, and of these, flood risk minimization measures were identified [12]. Similar analyses were presented by Kumar et al. [13], who analyzed runoff changes using spatial data and the SCS-CN method (a similar approach to Manchado et al. [12]). The analysis was performed to support the effective management of water resources.

Xu et al. [14] simulated the impact of different scenarios for the development of the city of Munich by calculating surface runoff using the SCS-CN method and data on land use and land cover. Various scenarios of the city's further development were analyzed, the total surface runoff from the entire city was estimated, and the effectiveness of such an approach in planning sustainable development was demonstrated. A similar scope and approach were used by Sjöman and Gill [15], who analyzed various scenarios for the development of low, medium, and high-density residential areas in three cities in the Höjeå River catchment in southern Sweden. Jahan et al. [16] assessed the impact of changes in land use (1994–2020) on runoff in South Kingstown in southern Rhode Island, USA. The analysis was carried out using an approach that integrated the Remote Sensing (LULC changes according to LANDSAT), GIS, and SCS-CN methods.

SCN-CN has a range of disadvantages as it was developed for agricultural areas, and it has been criticized for giving inaccurate readings for other types of areas, such as forests [17,18]. Assessment accuracy was also observed to be affected by the precision of a range of initial parameters (soil texture and land use change) [19] and by the use of a lumped model [17]. Comparative studies for a range of rainfall-runoff models that determine the design hydrograph were also performed [18–21], and considerable differences were found. Despite these disadvantages, it is a widely used method due to its many advantages, as listed by Ponce and Hawkins [17]: (1) its simplicity; (2) predictability; (3) stability); (4) its reliance on only one parameter; (5) and its responsiveness to major runoff-producing watershed properties.

As with many others [18,22–27], the aforementioned studies model rainfall-runoff dependencies under different climate conditions and developmental changes using SCS-CN. Such impacts are also assessed using other methods that are based on rational runoff assessment methods [28], runoff path balances [29], or global water balance analyses [30]. The direct impact of land use/cover changes on runoff has been assessed in studies [10,11,31–35], in addition to runoff coefficient assessments [36–40] and prognosticating changes as a result of further changes in land use/cover and their impact on runoff and other hydrological components (e.g., groundwater recharge and evapotranspiration) [10,36,41]. The impact of agricultural areas on green or forested areas and the volume of annual runoff were also estimated [8,42–45].

Waterlogging determination studies were performed using both hydrologic modeling and other approaches. Their main trajectories have included multicriteria decision-making analysis (MCDM, combined with Geographic Information Systems), such as Analytic Hierarchy Process (AHP) [46–48], AHP-TOPSIS [49], TOPSIS [50], VIKOR [50], machine learning (ML), such as Fuzzy AHP [51,52], the ANN model [53], and maximum entropy [54–56]. Other approaches either tested other techniques or combined several, such as random forest (RF), boosted regression trees (BRT), extreme gradient boosting (XGBoost), the boosted generalized linear model (GLMBoost), and naïve Bayes [50,57–59].

Among the disadvantages of the methods described above, which may limit their applicability, is the need for algorithms and software that may not be available to local planning authorities. In this study, we propose a simplified method that can be used to assess a major parameter that can affect the occurrence of inundation–accumulated surface runoff. This method can also be used alongside MCDA and ML as a criterion and/or a property. This analysis utilizes precipitation levels [50,54,57], whose localized variability may not be significant in a small-scale case study, or the runoff modeled–which requires the additional use of hydrological models, such as the Storm Water Management Model (SWMM) [56,60]. The surface runoff estimated using the proposed method informs us of potential threats arising in upstream catchments, which can pose a greater threat than the parameters for the given area alone.

The method can be used to identify critical locations (districts with the highest accumulated runoff) and upstream source subcatchments in which reparatory actions should be taken first. In addition, this method displays how simple mapping analyses can allow us to transition from basin areas to cadastral plots, which are used in spatial planning. This information can provide urban planners with the necessary knowledge about potential threats in individual cadastral units, the sources of these threats, and simulate trans-formation strategies. Information about elevated areas that generate increased risks due to changes in land development can inform correct reparatory strategies. The method also allows for simulating vulnerability remediation strategies by limiting surface runoff for both protected areas and intervention sites.

The study's aim is to provide tools that inform potential local problems (inundation) and aid in coordinating retention control in planning.

The proposed estimation method can be a practical tool for planning, as presented below in Section 3.2. The tool allows for simulating remedial action scenarios by changing the runoff coefficients for selected surfaces or by subtracting a part of the runoff (e.g., as a result of the building rainwater retention devices). These changes can be applied to the Topographic Object Database (BDOT) and, after geoprocessing, allow us to simulate the effects of remedial measures.

2. Materials and Methods

GIS and Cumulative Runoff Analysis Methodology

The proposed quantitative surface runoff analysis method is intended to support spatial planning. The method's use does not require specialist hydrological knowledge, as it consists of basic spatial analysis operations that can be executed in GIS software. For analytical purposes, the authors used data sets (open data) that are publicly available in Poland and cover the country's entire territory. Version 3.28 of QGIS was used to perform the analysis. The flowchart of the proposed method is shown in Figure 1.

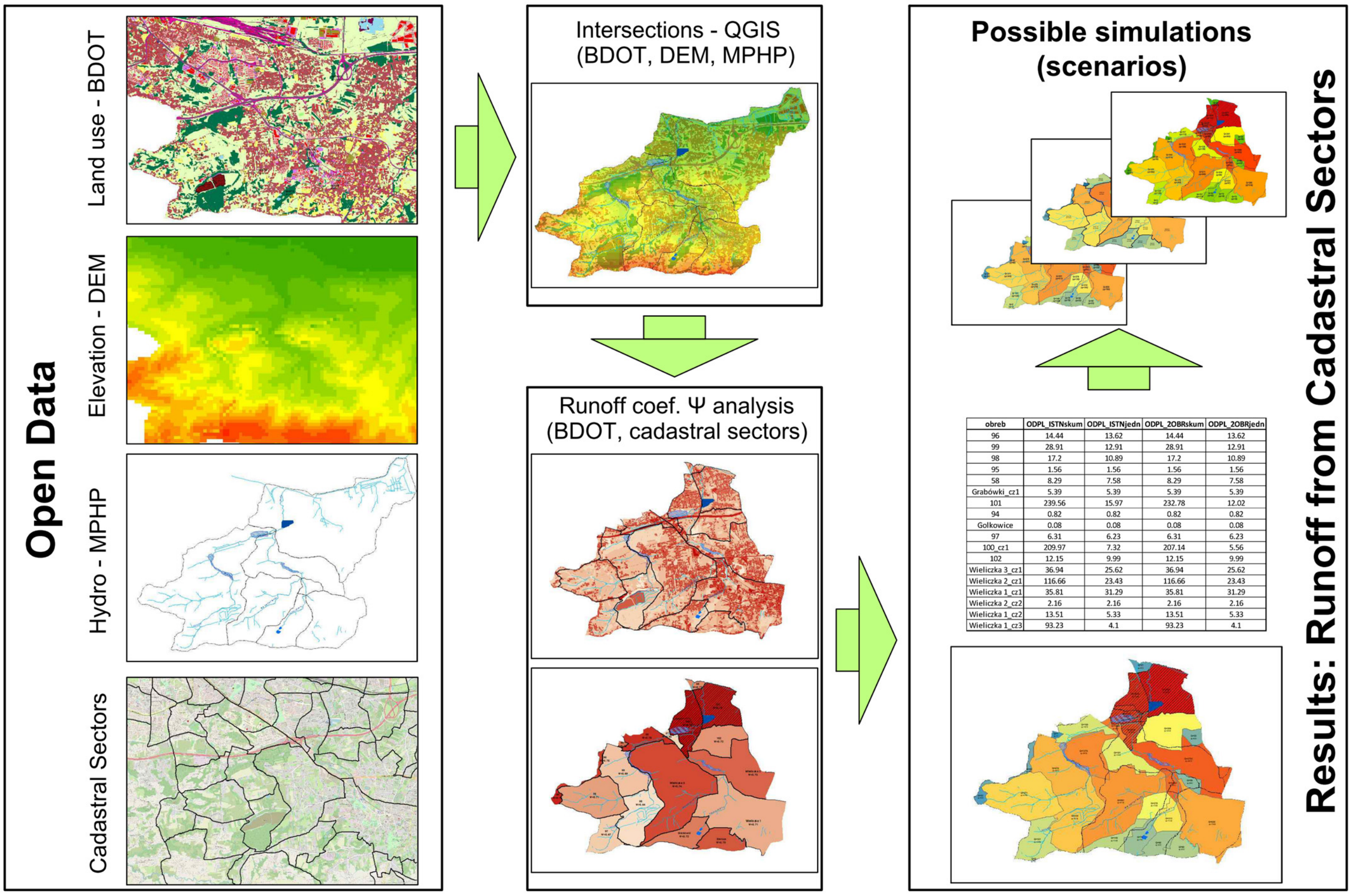

Figure 1. Flow chart showing the stages of surface runoff estimation using GIS tools.

The accumulated runoff mapping analysis method presented in this paper uses open-source software and data. To estimate the runoff, it uses runoff coefficients, which, although giving approximate runoff volumes, do not require advanced hydrological calculations or costly and time-consuming field research.

The GIS software operations were used to obtain the surface runoff values for the analyzed areas. The land use BDOT database, the current digital elevation model with a 100 m resolution (DEM), and hydrographic data of watercourses and their catchments (Map of the Hydrographic Division of Poland MPHP) were obtained for the study in early 2022 for the entire area under study from Polish state institutions—the Central Office of

Geodesy and Cartography (https://www.geoportal.gov.pl (accessed on 17 January 2022)), Open Data Service, and WMS Baza Wody Polskie (https://dane.gov.pl (accessed on 17 January 2022)). First, the areas under study and their characteristics were isolated based on land development. It is suggested to use as much information contained in the features of individual polygons and lines of land development objects in the BDOT database as possible, including materials, vegetation type, and use. Altitude data were assigned to the database using geoprocessing tools, which were the basis for estimating the slope of the surface of each object. This enabled the assignment of runoff coefficients. Standard runoff coefficients used in Poland were used to describe the sealing of land use and land cover classes in the area [61–64].

The proposal to transfer from hydrographic units—river catchments—to cadastral units was intended to simplify decisions for planners regarding changes to existing and planned future developments. Cadastral sectors are units that usually include entire districts within their boundaries, whose borders are usually transport routes (roads and train tracks).

The BDOT database, when enhanced with additional detailed information on existing runoff coefficients, allows the calculation of surface runoff within selected areas, as well as cumulative runoff. At this stage, the use of calculation formulas and built-in statistical tools allowed for the calculation of averaged runoff coefficients for a given area (catchment, cadastral precinct). We can calculate the approximate surface runoff for the given precipitation (event, the sum of annual precipitation, the annual average over many years, etc.). The surface runoff from a divided cadastral unit, e.g., between two catchments, was calculated in proportion to its area. The cumulative runoff was calculated on the basis of the direction of the runoff, determined using the average elevation and slope for the designated cadastral sectors.

Map-based analyses were performed while accounting for both administrative divisions into cadastral sectors and those of the watershed system. Contrary to catchments, the cadastral sector is the fundamental unit of Poland's administrative division and is used in spatial planning. This complies with the intended goal: to develop a tool for application in more than one sector of planning—water management, spatial planning, and greenery development.

As mentioned in the introduction, runoff and the runoff coefficient are often used to assess changes in land cover [24,30,32,34,42,44]. This effect can be analyzed for accumulated runoff in subcatchments [12,24]. In this study, a rational method of calculating the runoff was used based on the intensity of rainfall in the form of [28,65–67]:

$$Q_{sp} = \Psi \cdot P \cdot A \tag{1}$$

where:

Q_{sp}—runoff volume from a given area (m^3/unit time);

Ψ—runoff coefficient;

A—analyzed area (m^2);

P—peak (or daily or annual) rainfall (mm/unit time).

The product of rainfall volume and the runoff coefficient expresses the runoff from the area under study. Some of the rainfall is absorbed into the soil, stops at the surface, or evaporates; hence, not all rainfall flows into stormwater drains. The runoff coefficient, which is also called the drainage basin imperviousness coefficient, is the relationship between the volume of runoff from a given surface and the amount of rainfall that falls onto said surface. The Ψ value is directly dependent on land cover and development, with terrain incline also heavily impacting its value. In simplified estimates of runoff volume, runoff coefficient values were taken from the literature. For watersheds with multiple land-use classes, a composite (area-weighted average) runoff coefficient, Ψ_{av}, can be estimated [14,28,68]:

$$\Psi_{av} = \frac{\sum_{i=1}^{n} \Psi_i \cdot A_i}{\sum_{i=1}^{n} A_i} \tag{2}$$

where:

i—subarea i with a specific land use type;

n—total number of land use classes in the catchment;

Ψ_i—literature-based runoff coefficient for land use class i;

A_i—subarea size for land-use class i in the watershed.

As mentioned above, runoff coefficients (Ψ) that demonstrate the imperviousness of different land cover types (Table 1) were determined to assess climate change resilience. Based on data included in the Topographic Object Database, the Ψ coefficient was corrected to account for the type of surface material, development density, and plant cover. This dataset allowed for an in-depth characterization of the entire area. This approach is much more reliable than land cover aggregation, which ignores materials and biologically active surface types.

Table 1. Runoff coefficient Ψ values for various types of surfaces [61,62,69,70].

Surface Type	Surface Incline [%]					
	0.5	1	2.5	5	7.5	10
Roofs	0.85	0.9	0.96	0.98	0.99	1
Impervious pavement	0.7	0.72	0.75	0.8	0.85	0.9
Typical pavement	0.5	0.52	0.55	0.6	0.65	0.7
Footpaths	0.2	0.22	0.25	0.3	0.35	0.4
Parks and gardens	0.1	0.12	0.15	0.2	0.25	0.3
Fields	0.05	0.08	0.1	0.15	0.2	0.25
Forests	0.01	0.02	0.04	0.06	0.1	0.15
Compact development	0.8	0.82	0.85	0.9	0.95	1
Loose development	0.6	0.62	0.65	0.7	0.75	0.8
Villa development	0.4	0.42	0.45	0.5	0.55	0.6

Each individual polygon that was extracted from the BDOT database was described using attribute characteristics that detail its development. These include information about the object's class, land use (e.g., yard, roadway, agricultural crops, forest areas, cultivated areas, building roofs, transportation, industrial and residential complexes, etc.), the type of development (e.g., dense, compact, or loose), the type of vegetation (e.g., forest, coppice, tree canopy, shrubbery, orchard, trees, grasses, bushes, etc.), and the type of material used (e.g., concrete, asphalt, ballast, gravel, natural ground, etc.). In addition, individual polygons were characterized using elevation and slope data. Each characteristic affected the base runoff coefficient Ψ given in Table 1, modifying it up or down.

3. Results

3.1. Study Area

The accumulated runoff mapping analysis was investigated based on alternative remedial solutions for the Serafa River watershed and Bieżanów—a southern district of Kraków, Poland, marked in (Figure 2), that regularly suffers from flooding.

The area is located in the Lesser Poland Voivodeship, in the southeast part of Kraków, and the Serafa is the right-bank tributary of the Vistula River. The total length of the Serafa River is 12.7 km, and the catchment area is 72.4 km^2, the river in the section enclosing the Bieżanów district has a length of 6.57 km, and the catchment area is 26.76 km^2. The area developed rapidly in the mid-twentieth century, losing its natural character due to uncontrolled urbanization, flood prevention regulations, and the takeover of land adjacent to the river. These are universal problems that enhance the vulnerability of many urban areas worldwide. The area of study is large enough to present a variety of issues, properties, factors, and characteristics and small enough to make the results comprehensible.

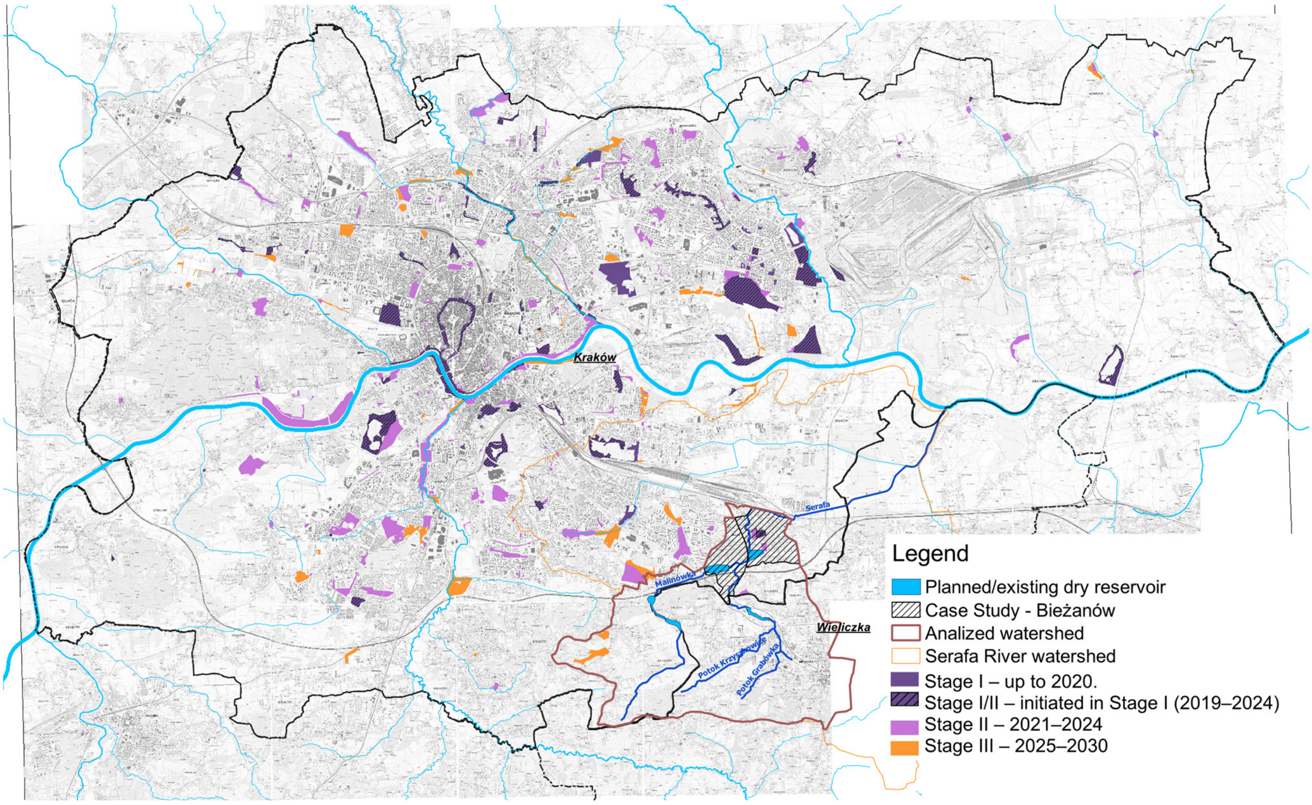

Figure 2. Staging of projects in green areas following an updated ranking list with the area under study marked [70].

Flood protection for the Bieżanów district is based on a dry reservoir (the Bieżanów reservoir, with a capacity of 130 dam^3) and embankments along the Serafa, which do not provide adequate flood protection, as shown in Figure 3. Additional reparatory measures intended to prevent flooding in the Bieżanów area focus only on the temporary reinforcement of the river's banks and the construction of makeshift levees. A steady increase in flood event numbers and scale has been observed in recent years, as presented in Figure 3, and the scope of damage caused has resulted in increasing discontent among citizens, which makes a community–municipal dialogue difficult.

The unfavorable situation in Bieżanów is largely the result of a sectoral approach to planning, e.g., there being no integration of water management plans, spatial planning, and green development plans. In the section of the area under study (spanning between the boundaries of the Serafa catchment to the section of the Bieżanów district) that is administered by Kraków, there are 78 applicable local spatial development plans (LSDPs), with another 18 being drafted, while in the section within Wieliczka, there are three approved LSDPs. Most of the LSDPs were approved before the latest (2022) update to the main water management plans: the River Basin Management Plans (RBMPs) [71] and the flood risk management plans (FRMPs) [72]. This stems from the fact that LSDPs in Kraków do not contain the latest flood hazard findings.

Water management plans (RBMPs and FRMPs) are drawn up on a macro scale—that of entire river basins—and are usually unable to address problems that are important on a micro-scale, e.g., a city district. In addition, unfortunately, Polish FRMPs do not take into account pluvial floods due to the lack of data and the inability to model this phenomenon [73]. As a result, FRMPs designate areas exposed only to fluvial floods and plan measures to counteract them. Planning problems that arise from urbanization, zoning changes, and urban flash floods are usually not addressed. In the case of Bieżanów, the FRMP took into account local problems and local solutions, but unfortunately, this is an exemption rather than the norm. When preparing FRMPs, available studies are queried and also carried out locally. This is how flood prevention projects for the Serafa River watershed were included in the flood risk management plans. Local plans to increase flood protection in the Serafa catchment indicated the need to build five dry reservoirs (two on the Serafa River and three along its tributary, the Malinówka River) [74]. These projects were accepted in the first and then the second update of RBMPs and were also listed as urgent to be implemented in FRMPs. The first Bieżanów reservoir on the Serafa River was put into operation in 2015, while the others were unfinished as of the writing of this study (March 2023).

Figure 3. Kraków-Bieżanów; consequences of a pluvial flood combined with a levee breach on the Serafa River, August 2021. [Andrzej Banaś/Polska Press (2021)].

One planning document that could have covered pluvial floods, local inundations, and other threats of climate change was the 2030 Kraków Climate Change Adaptation Plan [75]. However, the plan was not based on modeling, as the hazard of fluvial floods was assessed based on flood hazard maps, flood risk maps, and flood risk management plan provisions that applied solely to fluvial floods. In the case of measures planned in the Serafa watershed, they repeated the projects planned in the FRMPs—five dry reservoirs in the Serafa River watershed. The plan, while declaratively promoting comprehensive solutions that consisted of technical and non-technical action, education, dynamic monitoring, prognostication model development (including rainfall-runoff models), defining good practices, and the development of warning systems, is undoubtedly a step in the right direction. However, due to lacking a quantitative diagnosis and failure to include an expert assessment of its measures, it can be seen as ineffective.

This was demonstrated by a cross-analysis of the climate change adaptation plan and the green area development and management guidelines for the years 2019–2030 [70], which were drafted in 2019 after the approval of the adaptation plan. At the time, efforts were initiated to develop a proposal for a green area system in a mixed network-wedge layout in the form of river parks and densely tree-covered areas. The document highlighted the potential and significance of green and blue ecosystems [70] and indicated that the low class of water in waterways and a lack of systemic flowing-, standing-, and groundwater management protection systems were a weakness of Kraków's green areas. It also did not propose any reparatory measures.

The integration of the urban greenery network with the strategy of flood protection and climate change adaptation was not listed as a priority in any of the documents mentioned. Certain aspects linked with blue-green infrastructure can be found in specifications for goal four of the green areas' development and management guidelines, namely in valuable wildlife area conservation or making the city's development more spatially and ecologically sustainable, in addition to rationally managing natural assets, including water. The document mentioned river valley conservation by the successive purchase of areas included in river parks, the surveying and elimination of illegal sewage discharge outlets, and the development of a cohesive flowing-, standing-, and groundwater management strategy to effectively conserve hydrological assets and maintain proper hydrological conditions in green areas and precious wildlife habitats. River parks also appear as an element of achieving goal two: integrating the city's scattered and fragmented greenery structure into a continuous system of open areas connected with bicycle and pedestrian paths and green strips.

The document specified that such parks would be aquatic and ecological land corridors intended to ensure the continuity of the city's wildlife system and the protection of high-biodiversity habitats. This is why the fragmentation of this system, displayed in graphical appendix 23 to the Kraków public green area system proposal, which also covers the Serafa River valley, is even more surprising. The area itself was not assigned priority status; most projects for Bieżanów were planned for Stages II and III, which corresponded to the years 2021–2024 and 2025–2030, respectively (Figure 2).

Another document that is crucial to the strategy for managing natural assets in Kraków, the Kraków Powiat Forest Cover Extension Program for the Years 2018–2040 [76], plans to increase forest cover in the area under study and its contiguous areas only marginally. However, the plan highlighted the existence of drinking water sources in the Bieżanów area that supply the waterworks in Wieliczka [76]. Groundwater in Kraków is poorly isolated from the soil surface and is thus not resistant to penetration by pollutants. Effective groundwater quality and asset protection must be a crucial task and issue featured in local spatial development plans. However, this study showed that the co-dependency of grey, blue, and green infrastructures was merely declared, and individual strategies veered towards doctrinal atomization. Meanwhile, climate change adaptation requires more holistic methods and tools that make better use of new technologies and large, variable, and diverse datasets (big data).

3.2. Accumulated Runoff Analysis

As mentioned above, the analysis operates with units shared across planning natural asset and flood risk management, which enhances the applicability of the method and its suitability in formulating climate change adaptation strategies. Land cover data accounting for retention potential and present threats was documented based on the open-source systems of the Head Office of Geodesy and Cartography (Topographic Object Database—BDOT) [77]. The development of the area of the Serafa River watershed with aggregated land cover and primary watercourses is presented in Figure 4. The spatial analysis of the watershed's land cover showed that the watershed was urbanized—almost 42% of the area consists of anthropogenic forms. Grassland and agricultural uses also predominated, as they formed slightly over 40% of the area, in addition to forests and tree-covered areas (10.6%). A more precise division into land use subclasses was used for the analysis, as well as information contained in the BDOT database on the materials used (e.g., sealed surfaces: concrete, prefabricated pavers, bitumen mass, concrete slabs, and stone pavers) and type of greenery (forests, tree-covered areas, groves, grasslands and scrublands, fields, orchards, allotment gardens, ornamental plant nurseries, and plantations). Eventually, the watershed was divided into unique polygon types with different use and land cover in QGIS (143 in total). Individual areas were characterized as a combination of detailed information contained in the BDOT database used (object class: land use or type, type of development, type of vegetation, or type of material used).

Information on the land incline for the entire area was accounted for based on the digital elevation model with a grid of 100 m presented in Figure 5.

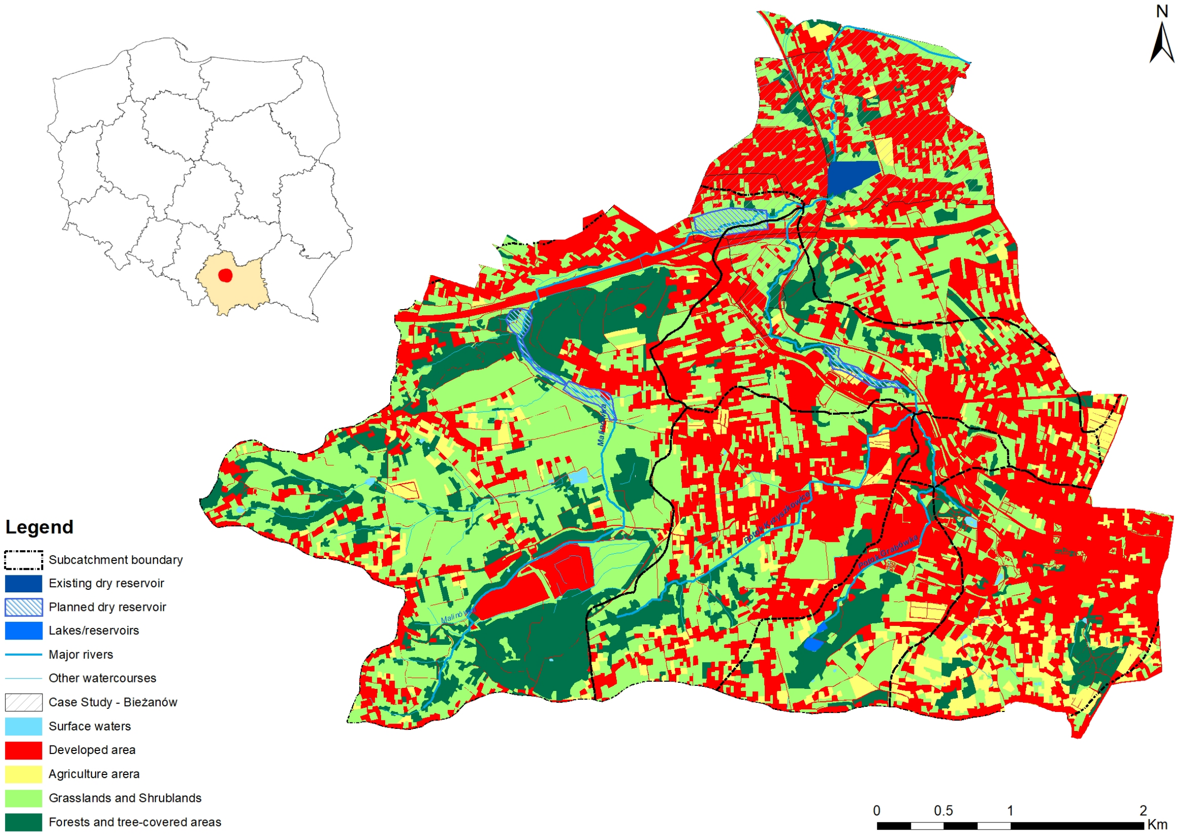

Figure 4. The land use and land cover (the main classes) in the Serafa River watershed.

3.3. *Accumulated Runoff Mapping Analysis as a Tool to Assess Urban Area Vulnerability*

Due to the extensive size of the watershed and significant differences in land cover, the land incline for the entire area was accounted for based on the numerical terrain model with a grid of 100 m. The watershed under investigation was divided into 143 separate areas, each with a different land cover. Based on data included in the Topographic Object Database, the Ψ coefficients were estimated and presented in Figure 6.

Figure 6 illustrates runoff coefficients and thus shows the degree of urbanization, as highly urbanized areas are significantly sealed (darker color), while natural, undeveloped areas have lower coefficient values (lighter color). Green crosses mark the locations of interventions by the State Fire Service (PSP) aimed at eliminating pluvial and fluvial flooding recorded in the years 2018–2020. During the time period under analysis, the highest flood density (62 interventions) occurred in the subcatment of the Serafa to the Grabówka Creek. It is a source catchment but heavily urbanized (the average runoff coefficient for this subcatment, as presented in Figure 6, amounts to Ψ = 0.48) with an active stormwater drainage system that drains water from a significant area of the catchment directly to the source section of the Serafa River. The analysis showed a significant number of dense residential areas (>60% of the area) and insufficiently developed biologically active areas for the entire Serafa catchment. This, combined with the lack of a watercourse to receive runoff from the central area, confirms the high number of pluvial floods. The highest number of river and pluvial floods—84 floods—was observed in the area of Bieżanów, in the western part of the Serafa from the Malinówka to the Drwina Długa catchment. It is an area in the central section of the Serafa River and is equally heavily urbanized (the average coefficient runoff for this subcatment was Ψ = 0.43) carrying the waters of the Serafa, after merging with the tributary of the Malinówka, from heavily urbanized upstream catchments.

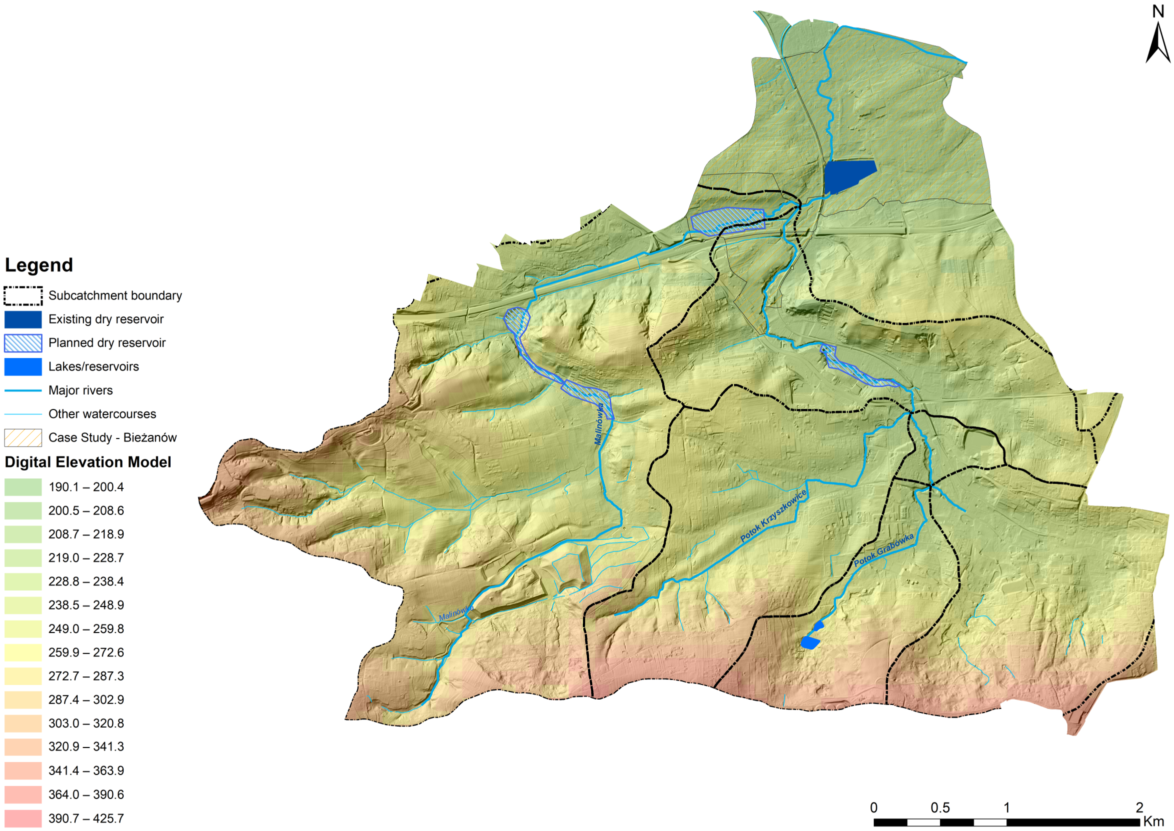

Figure 5. The digital elevation model in the Serafa River watershed.

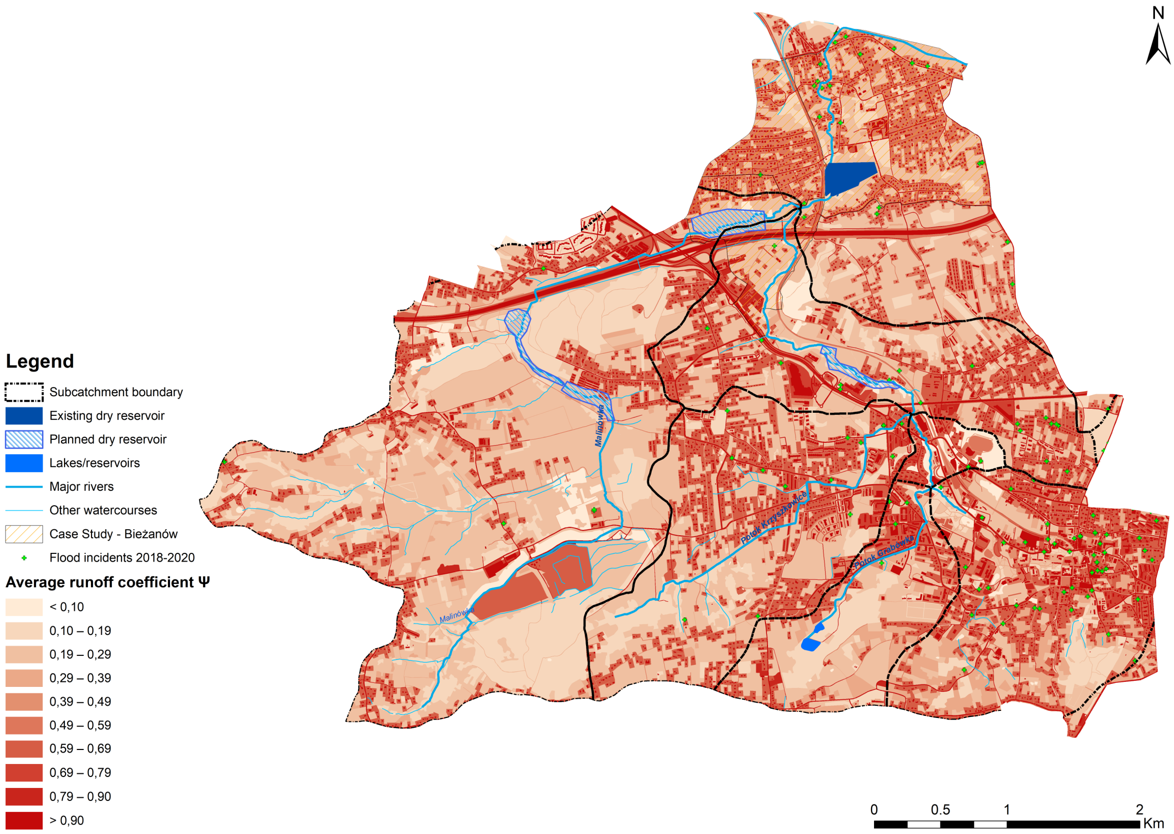

Figure 6. Estimated runoff coefficients in the Serafa River watershed.

Based on the aggregated data, actual Ψ runoff coefficients were calculated for each cadastral sector (Figure 7). This showed a serious problem with the land cover of the Serafa River watershed ($\Psi > 0.43$ in 19 cadastral sectors), which mostly stemmed from low material perviousness. One case of an incorrectly developed and highly impervious ($\Psi > 0.49$) sector was the source catchment of the Serafa, located almost entirely within the borders of cadastral sector Wieliczka 1, which registered the highest occurrence of floods in the years 2018–2020 despite being located upriver. This sector is serviced solely by the stormwater drainage grid, which can be seen as having insufficient capacity and is unable to receive all surface runoff safely.

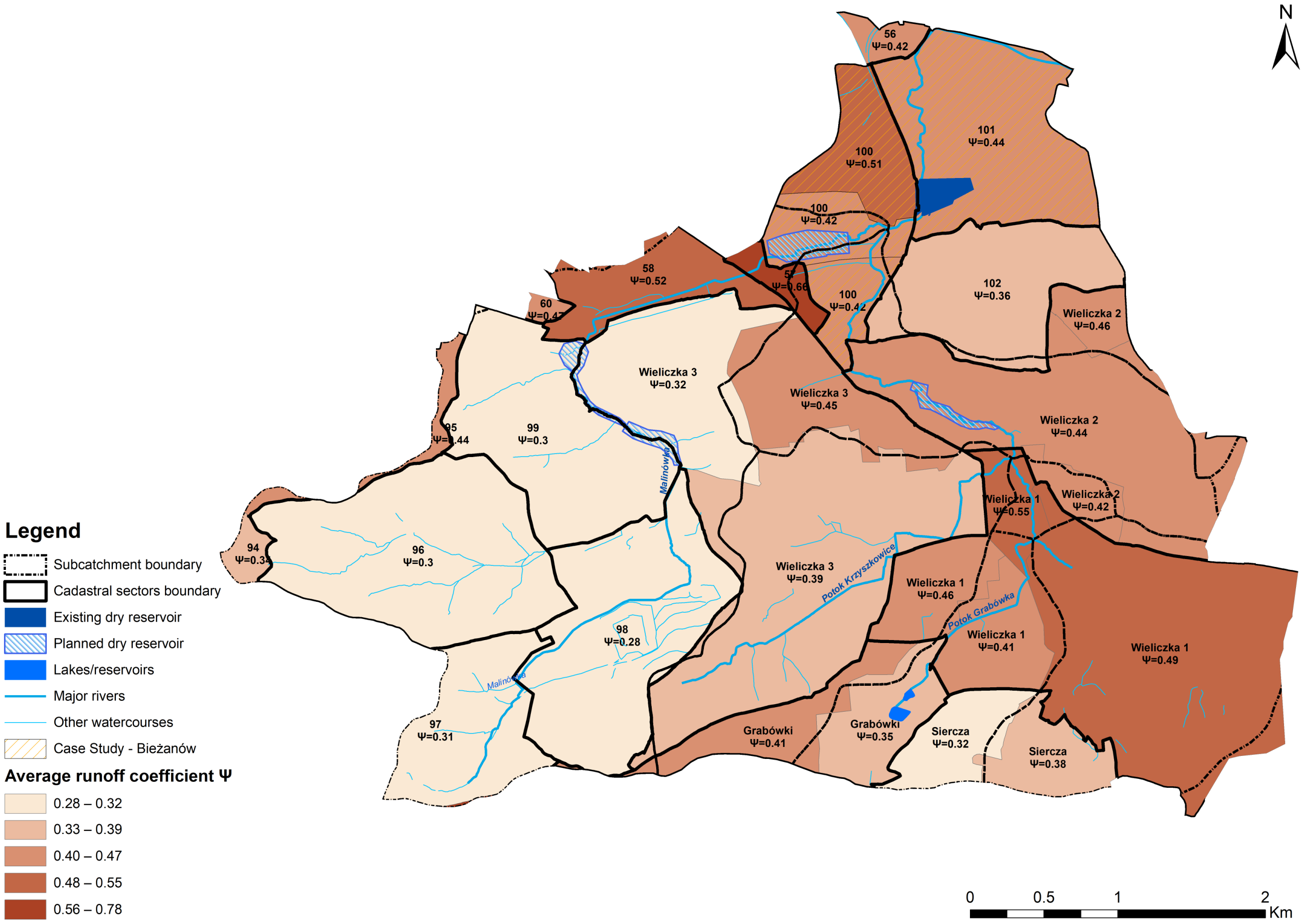

Figure 7. Average runoff coefficients in cadastral sectors of Serafa River watershed.

The effect of transferring the results of the hydrological water balance from the sub-basin to the administrative units (cadastral plots) is shown in Figure 8. The map shows the estimated accumulated runoff from the cadastral sectors, taking into account all water flows from upstream plots and specific runoff from each cadastral sector (in parentheses). This view of the catchment area, divided into administrative units, allows a direct reading of the runoff load of each cadastral sector from the areas upstream and the runoff generated on its surface.

Using cadastral sector-based surface runoff analysis, spatial and urban institutions will gain insight into the amount of surface runoff that reaches areas with lower average a.s.l. elevations.

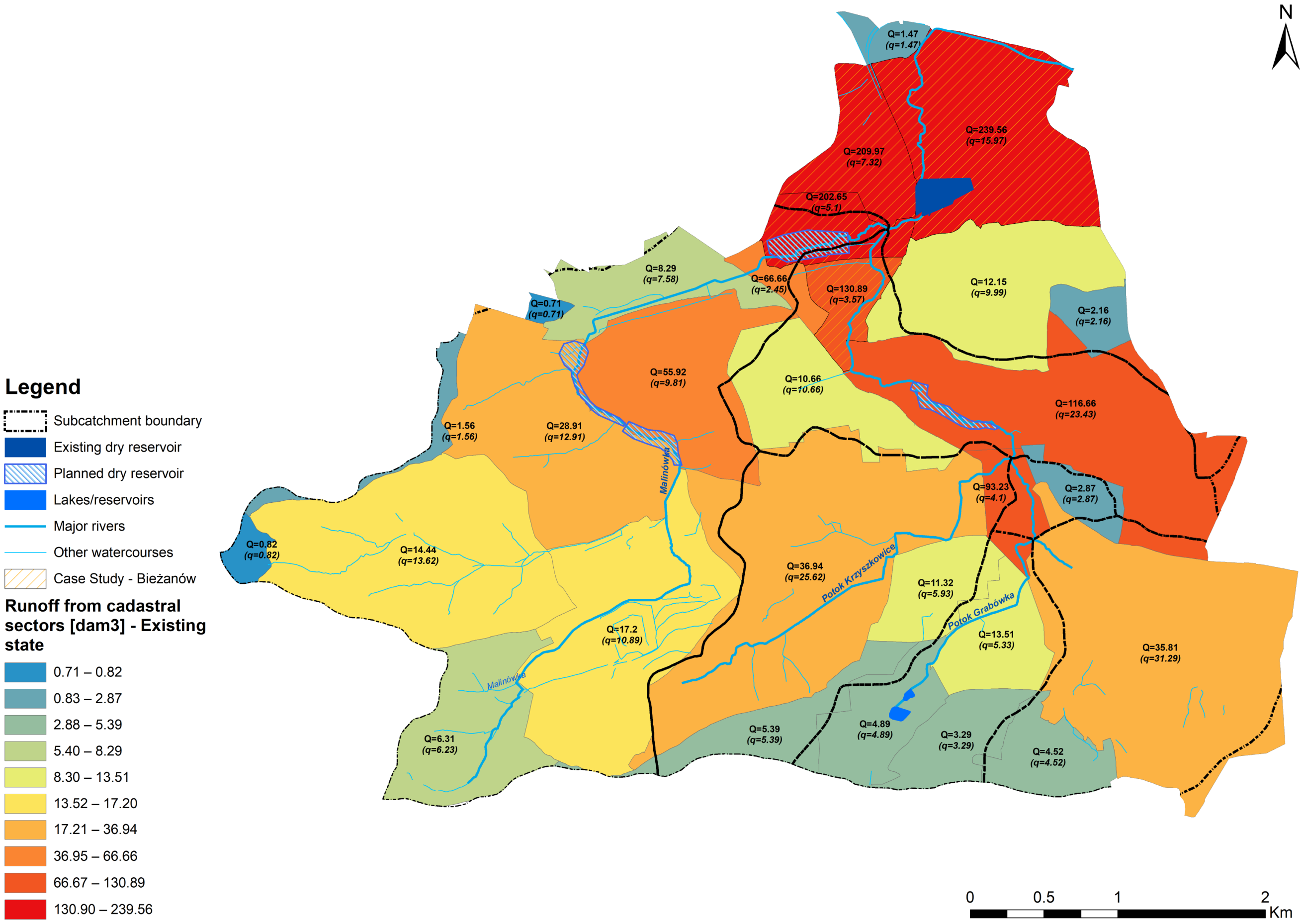

Figure 8. Accumulated (Q) and specific (q) runoff [dam^3] in each cadastral sector.

The color scheme used in Figure 8 reflects the specific runoff (q) generated on individual cadastral plots and the cumulative runoff (Q), which includes the total volume of water generated on the surface of a given cadastral sector and all rainwater that flows into it, factoring in the slope of the terrain from cadastral plots located upstream. The results of the calculations shown in Figure 8 should be compared with the current average runoff coefficient Ψ (Figure 7). The proposed method can be used to determine the actual scale of the problem in an analyzed area. High values of the runoff coefficient Ψ cause significantly higher runoff via surface roads based on terrain incline. They contribute to local flooding and increase the danger and risk of flooding in downstream cadastral sectors. The color scheme used in Figure 8 expresses the transfer of the burden of flood risk from a catchment's upstream areas to those downstream. The stronger the shade of red, the greater the runoff volume a given cadastral sector is threatened by. Cadastral sectors 100 and 101, for which the estimated runoff coefficient Ψ was lower than that of the Wieliczka 1 area in the upstream catchment area, are shown in intense red. The rapid inflow of rainwater to the Serafa River from the Wieliczka 1 cadastral sector (an urbanized and extensive area equipped with a large-diameter drainage system) is the reason for the greater hazard in the Wieliczka 2 area and below in the area under study, which is the recipient of all the cumulative hazard from the rapid diversion of rainwater towards it via surface roads.

The analysis clearly showed that heavily sealed cadastral sectors with high averaged Ψ runoff coefficients generate a local hazard and have a significant negative impact on the cadastral plots located downstream. This rule also becomes apparent from the other side, i.e., the relatively poorly sealed cadastral plots located in the western part of the catchment area do not significantly affect the increased surface runoff of rainwater and thus do not generate a hazard downstream. This clearly points to the cause of frequent flooding in the area, which is attributed to the cadastral sectors located upstream of the Serafa River.

Therefore, such an analysis allows for the spatial planning of possible runoff paths using green and grey infrastructures and shall facilitate surface water flow balancing in the entire watershed. The potential applications of this tool have been presented in Section 3.2.

3.4. Local Protection Strategies and Reparatory Scenarios

The application of accumulated runoff maps is shown in the example of the densely developed part of Bieżanów, which is exposed to high flood risk. The Bieżanów district is located in the middle course of the Serafa River and includes two cadastral plots numbered 100 and 101 (marked in Figure 8 using black hatching). Figure 8 shows all the cadastral plots that lie in the catchments located upstream relative to Bieżanów, from which runoff flows towards this area. The risk of flooding in Bieżanów results from the dense development and significant land surface sealing in Bieżanów itself (cadastral sectors 100 and 101 have some of the highest runoff coefficients Ψ, amounting to 0.44 and 0.51–see Figure 7) but also, as mentioned, from the runoff of water from the areas located along the tributary. The results of two hypothetical reparatory strategies that employ grey and green infrastructures and an increase in retention combined with the replacement of surface materials to lower key area vulnerability have been presented below. Afterward, a simulation of two reparatory scenario proposals was conducted:

- Scenario 1, presented in Figure 9, assumed that any measures would be confined to areas where flooding events were recorded (cadastral sectors 100 and 101).
- Scenario 2, presented in Figure 10, encompassed measures in cadastral sectors located upstream, for which the runoff coefficient Ψ is at least 0.4, identified to have an impact on the hydrological situation in critical and highly vulnerable sectors.
- Simulated measures for both scenarios:
    1. Replaced 50% of footpaths (concrete, prefabricated pavers, bitumen mass, concrete slabs, or stone pavers) with modern mineral courses infiltrating into the ground;
    2. Replacement of 50% of the surfaces of squares and parking spaces with impervious surfaces from bitumen mass, concrete, concrete slabs, stone and prefabricated pavers, and polyurethane with modern mineral courses that allow water infiltration into the soil;
    3. Managed 50% of rainwater from local and access roadways with impervious surfaces from concrete, concrete slabs, and prefabricated and stone pavers via bioretention or infiltration measures or other green infrastructure measures;
    4. Increased by 20% the number of trees in current shrublands, orchards, and grasslands, as well as on private properties and fields, in the form of rain gardens, parks, and planting new trees;
    5. Implementation of runoff micro retention from existing single-family building roofs and the roofs of buildings with two residential units to rain barrels or tanks within the cadastral sector. The main scope of the micro retention is to apply minimum tank volumes, which are estimated at 3% of the annual rainfall and are equivalent to capturing a steady rainfall of 273.3 $dm^3/s*ha$ (p = 20%, t = 15 min) [65].

The simulation for Scenario 2 resulted in a ca. 11% decrease in accumulated runoff (from 239.56 dam^3 to 214.08 dam^3) at the level of the Bieżanów district, whereas Scenario 1 would have resulted in a reduction of only 2.8%. This is due to the fact that 90% of the total runoff carried by the Serafa in the Bieżanów area is from upstream subcatchments. The action presented in Scenario 2 is more time-consuming and requires greater financial expenditure, yet it can significantly minimize flood risk and thus reduce damage.

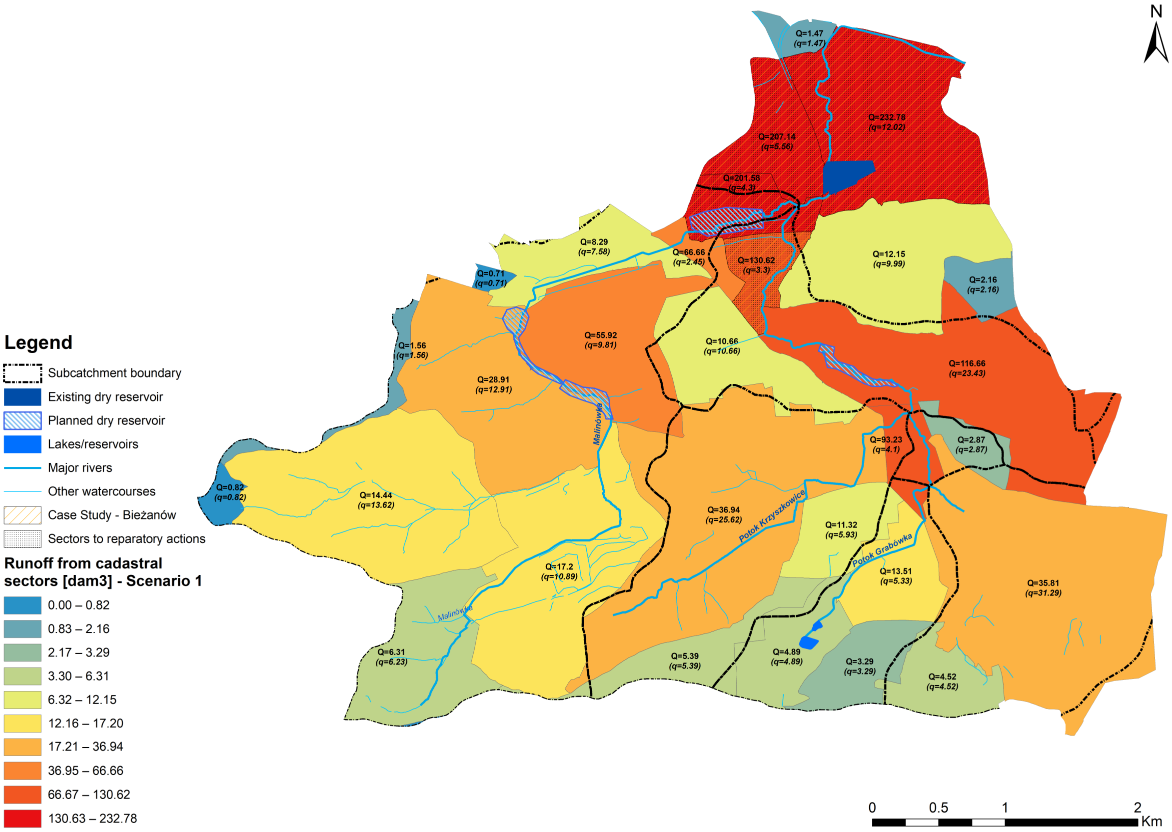

Figure 9. Accumulated (Q) and specific (q) runoff [dam^3] in cadastral sectors 100 and 101, for which reparatory measures compliant with Scenario 1 were assumed.

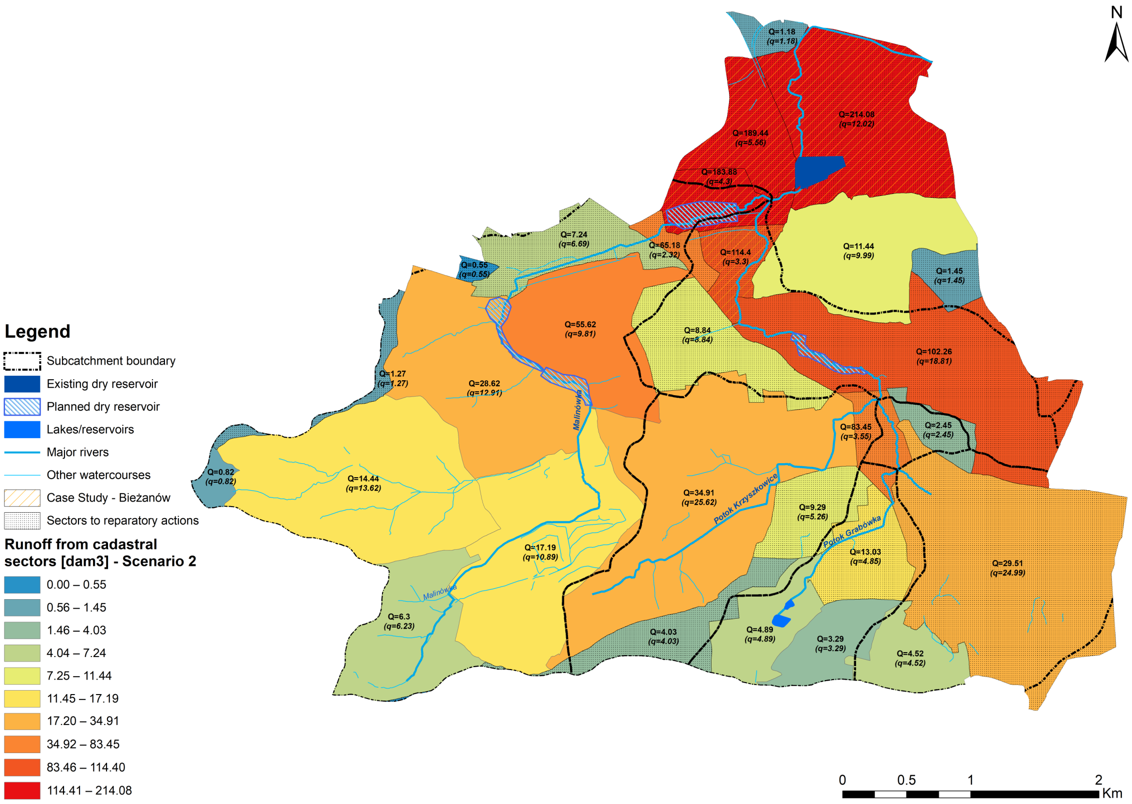

Figure 10. Accumulated and specific runoff [dam^3] in cadastral sectors 100 and 101, for which reparatory measures compliant with Scenario 2 were assumed.

4. Discussion

The proposed method for determining the cumulative runoff using the GIS technique allows for estimation for the purposes of planning analyses:

- Characteristics of cadastral sectors in terms of development intensity by determining the runoff coefficients, which can identify sectors with a high degree of sealing, where remedial actions should be taken first;
- Estimation of the surface runoff for the selected precipitation, which allows, for example, to determine the estimated capacity of devices that can retain the runoff for the selected precipitation (or its part);
- Calculation of the cumulative surface runoff for the selected rainfall allows us to visualize approximately how the runoff increases along the river's course and increases flood risk downriver;
- Information on sealing in individual cadastral units and runoff from their area allows us to select the location, type, and capacity of remedial actions both in the units at risk and in the units located above, which may actually be the source of existing threats;
- The possibility of simulating remedial actions can be a tool for formulating initial concepts of action programs, formulating appropriate recommendations, and provisions in local spatial development plans, obligations of investors and property owners in the field of stormwater management, the mandatory share of biologically active areas, location of city parks, and other urban planning recommendations.

The runoff coefficients determined for individual cadastral units ranged from 0.28 to 0.66, reaching the highest values in units with dense development: 0.66 in unit 57, 0.55 in Wieliczka 1, 0.52 in unit 58, and 0.51 in the Bieżanów district (in cadastral unit 100). The lowest average runoff coefficients were determined for districts with a significant share of forests–units: 96, 97, 98, and 99. The impact on the amount of runoff (and runoff coefficient) of afforested areas was discussed by, among others, Sriwongsitanon and Taesombat [38] and Bai et al. [42]. In the case under study, surface runoff determined on the basis of average runoff coefficients for cadastral units was also high in highly urbanized areas, although the area of the unit is a factor, and high runoff also occurs from units with less dense development but with a large area. Higher runoff coefficients and higher runoffs for areas with dense development were also reported by Sjöman and Gill [15], who analyzed various scenarios for the development of low-, medium-, and high-density residential areas in three cities in the Höjeå river catchment in southern Sweden, for precipitation of 24 mm for the city of Lomma for low-intensity residential areas. Here, the runoff coefficient was 0.60, and for high-density areas, it was 0.84. These results concern housing estates; in the case of the Serafa catchment, some units, such as 57, 58, 100, and 101, are typical housing estates, where the estimated runoff coefficient range was 0.44–0.66. Other units have a significant share of grassland, forest, and other land cover categories, so it is impossible to compare the values obtained.

As mentioned earlier, a similar division into larger areas, as used in this study, was applied by Manchado et al. [12], where the highest peak runoff values were recorded in the city's center, which had the densest development. A similar observation was made in this study. Manchado et al. [12] showed that critical areas include not only those with a high degree of sealing but also those that receive runoff from upstream subcatchments. In the case of the Serafy catchment, the risk in the area of the Bieżanów housing estate also has its source in the units located above; approximately 90% of the accumulated runoff in the section of the Serafy estate comes from the upper catchment. In [12], the simulated countermeasures included four scenarios involving the replacement of 10%, 25%, 50%, and 100% of the area of selected built-up land cover classes with permeable surfaces. Modeling and additional analysis showed that a potential flood resilience strategy for Santander could be to replace 25% of the roads and densely urbanized areas with permeable pavements and GI in identified watersheds that generate risk.

Sjöman and Gill [15] analyzed the impact of various solutions (including sedum cover on garage roofs, permeable paving, and tree cover) on the reduction of runoff in areas of different densities. Depending on the location, they pointed to permeable paving materials and tree cover as the best strategies for reducing surface runoff in housing estates, but the results obtained were highly dependent on the soil type. Two scenarios were analyzed for Bieżanów: Scenario 1 included taking remedial actions in the Bieżanów district (cadastral sectors 100 and 101), where flooding occurs, and Scenario 2, which also covers upstream districts. Due to the scale of measures, Scenario 2 led to a greater reduction in runoff (11%) and the risk of flooding in the Bieżanów district.

From the standpoint of Polish cities, the threat of flooding is the most crucial hydrological problem and is still treated in a non-comprehensive manner [78–81]. Risk plans and flood protection strategies do not account for pluvial floods due to a lack of data and difficulties in modeling this complex phenomenon [71,72,81]. The result of FRMPs is delineating areas under the threat of fluvial floods and a list of preventative measures. The problems that cities face that are caused by urbanization, changes in land development, and the generation of conditions that facilitate urban flash floods are not accounted for in these plans. Unfortunately, spatial development strategies, local spatial development plans, and the development of Kraków's green areas also do not contain effective remedial action in these areas [73,82].

We are aware that an in-depth analysis of topography, use, land characteristics, land cover diversity, and buildings should become the basis for modern plan design. Also, importantly, dynamic adaptation to changing conditions. In the meantime, planning procedures are many years old, and the instruments introduced when they were fully legislated are, in some ways, no longer up to date. Future measures should include the modification of plans to include new instruments and consideration of changing conditions. The Polish Spatial Planning and Development Act is currently in the process of amendment and will feature a new, coherent strategic document that will act as local law–the General Plan. There are currently no detailed regulations concerning it, which can serve as an opportunity to propose the inclusion of large-scale, comprehensive flood risk assessments as a standard flash flood prevention measure.

In our opinion, simplified hydrological analyses presented on hydrographic division maps, together with administrative divisions, could become an effective tool in drafting plans and strategies and in decision-making, as well as a valuable source of information about hydrological processes. This study demonstrates that during conceptual and analytical stages, cadastral sectors should be treated as interdependent. Any planning action taken for cadastral plans should account for terrain incline and the direction of surface runoff to local terrain concavities and surface water channels/waterways. Each area with distinctive land cover should be adapted to climate change so that the greatest possible water volume can be directed towards biologically vital surfaces (with a bio-retention capacity) and minimize runoff directed to stormwater drainage grids. The planning of biologically active areas and planting greenery (especially trees) should comply with a sector's topography and those of downstream sectors to which runoff will flow in accordance with the natural terrain incline and the incline transformed via land development.

5. Conclusions

The proposed tool that transfers hydrological process characterization from the hydrographic to the administrative division is flexible and simple enough that it can be applied to all of a city's watersheds in a relatively short and uncomplicated spatial analysis. At the local level, using effective and generally accessible hydrological tools and GIS and open-access databases, the provisions of higher-level programs (for the area under study, these are RBMPs, FRMPs, and others) would likely produce effective rainwater management plans at the cadastral sector level. The results of analyses should, as plans and clear guidelines, be made a part of mandatory LSDP provisions, spatial development condition and direction studies, planning permits, and other local documents.

The actual potential to modernize existing land cover will differ by sector and could be detailed further, for instance, by using a 1 m numerical terrain model, a detailed site plan, a survey of existing stormwater collectors, and the use of hydrological, hydraulic, and meteorological simulation modeling. Such a model could be used to simulate both threats and remedial measures in alignment with the assumptions of this or others that reflect local technical, economic, and societal determinants.

As mentioned before, the accumulated runoff mapping analysis method presented in this paper uses open-source software and data. To estimate the runoff, it used runoff coefficients, which, although providing approximate runoff volumes, do not require advanced hydrological calculations or costly and time-consuming field research. While in the analysis of the final result these limitations must be taken into consideration, the method is intended for the initial phases of planning and decision-making processes.

The advantage of the method presented here is the use of open-source software and data. Its efficiency can be achieved without advanced hydrological calculations that require time and resources often unavailable to local planning units and stakeholders. The method can be used to identify critical locations (district areas with the highest accumulated runoff) and upstream source subcatchments in which reparatory actions should be taken first. In addition, this method displays how simple mapping analyses can allow us to transition from basin areas to cadastral sectors, which are used in Polish spatial planning. This information can provide urban planners with the necessary knowledge about potential threats in individual cadastral units, the sources of these threats, and simulate transformation strategies. Information about elevated areas that generate increased risks due to changes in land development allows for drafting suitable reparatory strategies. The method also allows for simulating vulnerability remediation strategies by limiting surface runoff for both protected areas and intervention sites while informing about potential local problems (inundation) and coordinating retention control in planning.

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