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Original Research Article

RIVER PARK ASSESSMENT: 2D HYDRAULIC WATERCOURSE MODELING FOR NATURE-BASED SOLUTIONS IN URBAN AREA

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Abstract

Over time, fragmentation of semi-natural habitats in urban areas has become a pressing concern, disrupting ecological processes within cities. The focus on preserving open ecosystems has grown, highlighting the need to enhance resilience in urban riverside areas for effective ecosystem restoration. Comprehensive studies on river valleys, considering both hydrology and ecology, play a crucial role in urban river ecosystem development. Our article explores the potential of protective zones with urban vegetation and watercourses as Nature-based Solution within Krakow's ongoing riverine park system development. The study's cross-sections in the River Park area revealed dominant velocities ranging from 0.67 to 2.0 m $s^{-1}$for SWQ (mean annual maximum flow) and below 0.67 m $s^{-1}$for Q1% (1% annual exceedance probability flow). The hydrological analysis accurately captured the natural river bed channels' curvature, providing the basis for a two-dimensional mathematical model to visualize the hydraulic structure of protected sites. Integrating water and greenery management systems in urban areas offers significant potential for adapting to climate change, mitigating extreme weather events. Our research's novelty lies in applying 2D hydraulic modeling, demonstrating how River Parks can serve as climate change mitigation solutions in urban environments.

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Keywords: 2D modeling; hydraulic properties; urban climate resilience; linear buffer park

1. INTRODUCTION

Living conditions in cities are closely linked to the health of their natural environment, which offers numerous advantages, as it forms the foundation for sustainable urban development [1]. However, urban ecosystems often suffer from low biodiversity due to rapid expansion and excessive resource consumption, particularly water and energy [2]. In recent years, there has been a notable increase in environmental awareness, especially in highly developed countries, leading to greater attention being paid to ecosystem services within urban spaces [3]. Nevertheless, humanity remains fully dependent on nature, and understanding city inhabitants as part of nature necessitates viewing urban nature components within the context of a global network of ecosystems. Urban ecosystems services (UES) are generated by both natural (e.g., city forests producing oxygen) and human-made (e.g., suburban croplands producing food) activities [3]. The management of city green-spaces requires significant care and regular watering [4], emphasizing the importance of efficient natural resource management [5]. Moreover, integrating nature with technology can reshape the relationships between the environment, the economy, and society, potentially leading to the creation of modern services [6]. Furthermore, ecosystem services provided by urban environments can play a critical role in pollution mitigation [7]. The concept of ecosystem services has gained rapid popularity and has been adopted to protect urban environments worldwide [8]. Recognizing the beneficial impacts of ecosystem services on both the environment and humanity, the implementation of blue-green infrastructure (BGI) has been proposed as a means to counteract climate change [9, 10]. BGI offers diverse solutions to environmental, societal, economic, and political challenges [11], ranging from biodiversity conservation and climate adaptation to water drainage and the creation of green areas [12]. Additionally, BGI can lead to job creation and an increase in real estate market value [13, 14]. While traditional grey infrastructure remains necessary, integrating natural processes through green infrastructure can offer simultaneous solutions to multiple issues [15]. For instance, the natural water absorption capacity of plants and soils can be harnessed to reduce rainwater, especially stormwater, runoff to lakes, rivers, and streams [16]. The strategy for green infrastructure fully incorporates green infrastructure into the EU policy, making it a standard approach for land use planning across the European Union. This strategy highlights that green infrastructure can contribute to achieving several EU policy objectives through natural process-based solutions and remote sensing. This study aims to develop an appraisal method for the restoration of protective buffer zones, specifically willow-poplar floodplain forests (*Salici-Populetum*), as blue-green infrastructure within public spaces. The central focus is on a nature-based solution (NBS) in the form of a River Park located in an urban area, where 2D hydraulic modeling is utilized to address temperate climate changes in Central Europe. The dimensioning aspect of CCHE2D surpasses other 2D models due to its consideration of both longitudinal and transverse flow. Furthermore, in urban stream scenarios characterized by intricate alterations in channel morphology and flow patterns, the 2D methodology tends to be more suitable compared to one-dimensional models. Furthermore, urban areas often encounter rapid shifts in weather conditions, including significant localized rainfall events, which serve as a rationale for selecting this model. The specific goals of this paper are as follows:

1. Utilizing 2D hydraulic modeling to illustrate the degradation of urban streams within river channel corridors.

2. Evaluating specific hydrodynamic parameters in an urbanized river.

2. MATERIALS AND METHODS

2.1. Study site

The research was carried out in a River Park (Wilga River) located in Kraków, and included small-scale studies and field work (Figure 1). The river bed is 660 m long, while the valley is 570 m long. This gives brick's tortuosity coefficient of 1.15, which classifies the bed as sinuous. Field survey revealed that the riparian zone of River Park serves as a habitat for the proliferation of invasive species. The significant spread of Japanese knotweed (*Reynoutria japonica*), Small balsam (*Impatiens parviflora*), Wild cucumber (*Echinocystis lobata*), and Policeman's helmet (*Impatiens glandulifera*) poses a threat to the native flora. Additionally, the presence of *Acer negundo*, introduced from North and Central America, exacerbates the local ecological issue. For the analysis a 2D hydraulic model was developed and publicly available GIS databases were used. During the field work, measurements of the discharge, velocity and water depth in the watercourse were carried out. Furthermore, communities of invasive species on the river banks were inventoried. Additionally, climatic data for the period of 1981-2010 were obtained, including the average year temperature and the annual sum of rainfall for the city of Krakow, Poland.

Fig. 1. River Park – elevation of terrain and park boundary

2.2. 2D modelling

Numerical modelling was performed using the CCHE2D model developed by The National Center for Computional Hydroscience and Engineering (NCCHE), University of Mississippi, USA. The software is used to simulate turbulent flows in open channels under steady and variable conditions, bed-load and suspended sediment transport and changes in the river bed morphology. The model is based on a 2D mesh, on which the results are presented averaged parameters (2DH type). The water flow is calculated using the Finite Elements Method (FEM) and the Finite Volume Method (FVM) algorithms [17-20].

The model is based on the continuity and moment equations, as shown below.

Continuity equation

$$\frac{\partial Z}{\partial t}+\frac{\partial (hu)}{\partial x}+\frac{\partial (hv)}{\partial y}=0 \tag{2.1}$$

Moment equations:

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-g\frac{\partial Z}{\partial x}+\frac{1}{h}\left[\frac{\partial (h\tau_{xx})}{\partial x}+\frac{\partial \left(h\tau_{xy}\right)}{\partial y}\right]-\frac{\tau_{bx}}{\rho h}+f_{Cor}v$$
$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}=-g\frac{\partial Z}{\partial y}+\frac{1}{h}\left[\frac{\partial \left(h\tau_{yx}\right)}{\partial x}+\frac{\partial (h\tau_{yy})}{\partial y}\right]-\frac{\tau_{by}}{\rho h}+f_{Cor}u \tag{2.2}$$

where:

u, v – averaged speeds in the x and y directions, g – the value of acceleration due to gravity, Z - water table level, h – local water depth, ρ – water density, f – Coriolis parameter, τ_xx, τ_xy, τ_yx, τ_yy – Reynolds stress averaged over depth

2.3. Climatic data

The source data included average monthly values of the air temperature and monthly sums of precipitation for the Kraków-Balice station (49 ° 58 '59.182' 'N, 19 ° 54' 13.754 '' E) from the period of 1981-2010, published and archived by the Institute of Meteorology and Water Management National Research Institute in Poland. The headers of even pages should include the authors' surnames, the headers of odd pages should include (in the place of "Instructions to authors") an expression related to the text of the paper (e.g. the whole title of the paper or its part).

3. RESULTS AND DISCUSSION

3.1. Modeling steps

The model mesh was generated from geodetic data obtained from two sources. It was collected by geodetic measuring the cross-sections and the longitudinal profile of the river bed with using the TOPCON GTS-226 total station. While for the flood plains, the Digital Terrain Model (DTM) was used. At the beginning, the geodetic data was saved in the database file *.mesh_xyz, in which each point was characterized by its x, y coordinates and z height. The program creates a model mesh that is a real reflection of the terrain by reading the database file. The next step is to define the boundary conditions and initial parameters of the model. The defined flow conditions are the water surface level and the roughness of the channel described by the Manning roughness coefficient. The relevant model parameters are the simulation duration (1 h) and the time step (0.1 s).

a. Model calibration

In order to perform the calibration, the velocity and the water surface level were measured in the field with a known flow rate Q = 0.53 $m^3 \cdot s^{-1}$. Then, the same flow rate was applied to the model, comparing the velocity and the water surface level values with value parameters obtained from field measurements. If these values were significantly different, attempts were made to equalize them by changing the Manning roughness coefficient. The field data was compared with the modelling results using the Nash-Sutcliffe efficiency coefficient (NSE) [21], the value of which was NSE = 0.94 for the water velocity and NSE = 0.89 for the water surface level, which proves a very good fit of the model to real conditions [22].

b. Proper simulation

After calibrating the model, appropriate simulations were made for the flow rates: SNQ = 0.03 $m^3 \cdot s^{-1}$, SSQ = 0.40 $m^3 \cdot s^{-1}$,and SWQ = 7.82 $m^3 \cdot s^{-1}$, Q1% = 30.53 $m^3 \cdot s^{-1}$ and Qbankfull = 91.00 $m^3 \cdot s^{-1}$.The characteristic flow rates were calculated using statistical methods, on a basis of the data measured by the water gauge on the Wilga River in Golkowice. The paper focuses on the flows: SSQ, SWQ and Q1%.

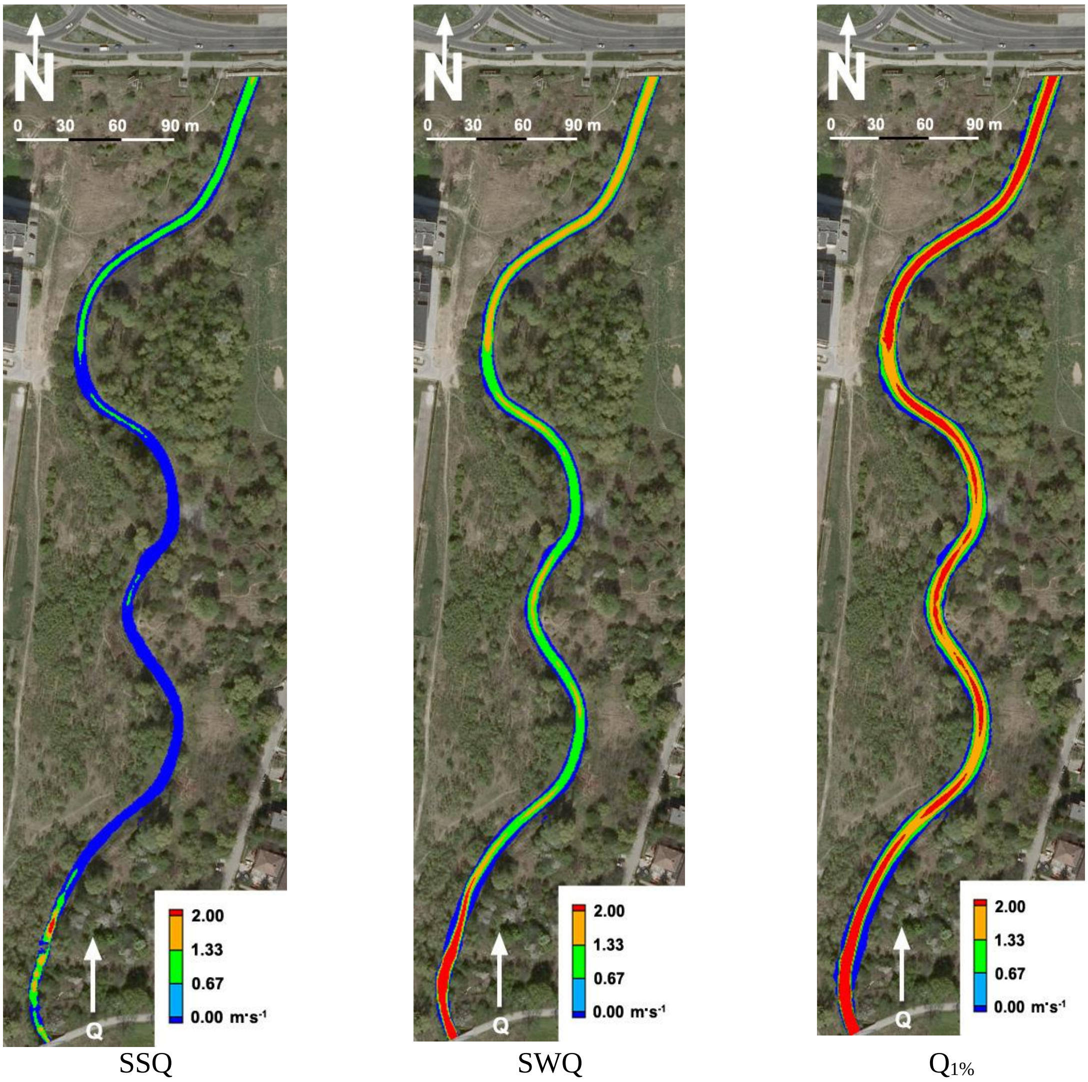


Fig. 2. The velocity in the watercourse for the multiannual mean low flow (a) and mean annual maximum flows (b)

In the riverbed, the highest water depth can be observed in places where the velocities are the lowest. Thus, for SWQ, in the central part of the analyzed section, it ranged from 0.37 to 1.1 m (Figure 3). In the area of the upper bridge, where the speed was higher than under the lower bridge, the water table was h = 0.4–0.7 m. In the area of the lower bridge, the depth was h = 1.0 m. The upper section is characterized by a lower water level, not exceeding h <0.4 m, while in the lower section it ranged between 0.4 and 0.7 m for flows SWQ.

3.2. Hydraulic 2D modeling

During the SWQ flow, the highest velocities were found near the inlet (V> 2.0 $m \cdot s^{-1}$) to the park and in the area of its outlet (V> 1.5 $m \cdot s^{-1}$). This is caused by the increased slope of the longitudinal profile of the river bed, shaped this way as a result of the construction of bridges. The bridges do not narrow the watercourse, because the water, even with the SWQ flow, does not leave the river channel and also water damming is not observed. After passing under the bridge (V> 2.0 m s^{-1}), the velocity of the water decreases, reaching the value within a range of 1.0–1.5 m s^{-1}. This value is maintained up to the lower section of the bed, where it increases again before the bridge to over V> 1.5 $m \cdot s^{-1}$. The flow velocity reaches a considerable level, especially in the vicinity of bridges, also because the riverbed is deeply indented (at 3.5–4.5 m below the floodplain terrace). In consequence, even with significant swells, no water is spilt over the floodplain (no valley retention), and thus the flow is speeded up. In this section, bank erosion can be observed (especially in the central part of the section, where the flow velocity is much lower than at its beginning or end, but the banks are reinforced with paving slabs only up to 0.5 m above the bed). Bed erosion can also be observed in the studied river section. Although the river bed is lined with stone paving, it is often damaged, with concrete cubes torn out, leading to further destruction of the paving (destruction of successive cubes), lowering of the bed and the formation of deep depressions in these areas.

When we observed SSQ and SNQ flow, the velocity distribution is similar to that for SWQ flow, except that the values are much lower. In areas with the SSQ flow, in the initial section of the bed (near the bridge), the velocity values (Figure 2) range from 1.0 to 2.0 $m \cdot s^{-1}$. In the final section, the velocity values are 0.7 to 1.3 $m \cdot s^{-1}$. In the middle section, they usually do not exceed the values of V <0.7 $m \cdot s^{-1}$. Only in the area of the left bank slope the velocity reaches the value of 0.7 $m \cdot s^{-1}$. In the case of SNQ, the velocities in the vicinity of the bridges reach the value of 1.0 $m \cdot s^{-1}$, and in the central section they are significantly below V <0.7 $m \cdot s^{-1}$.

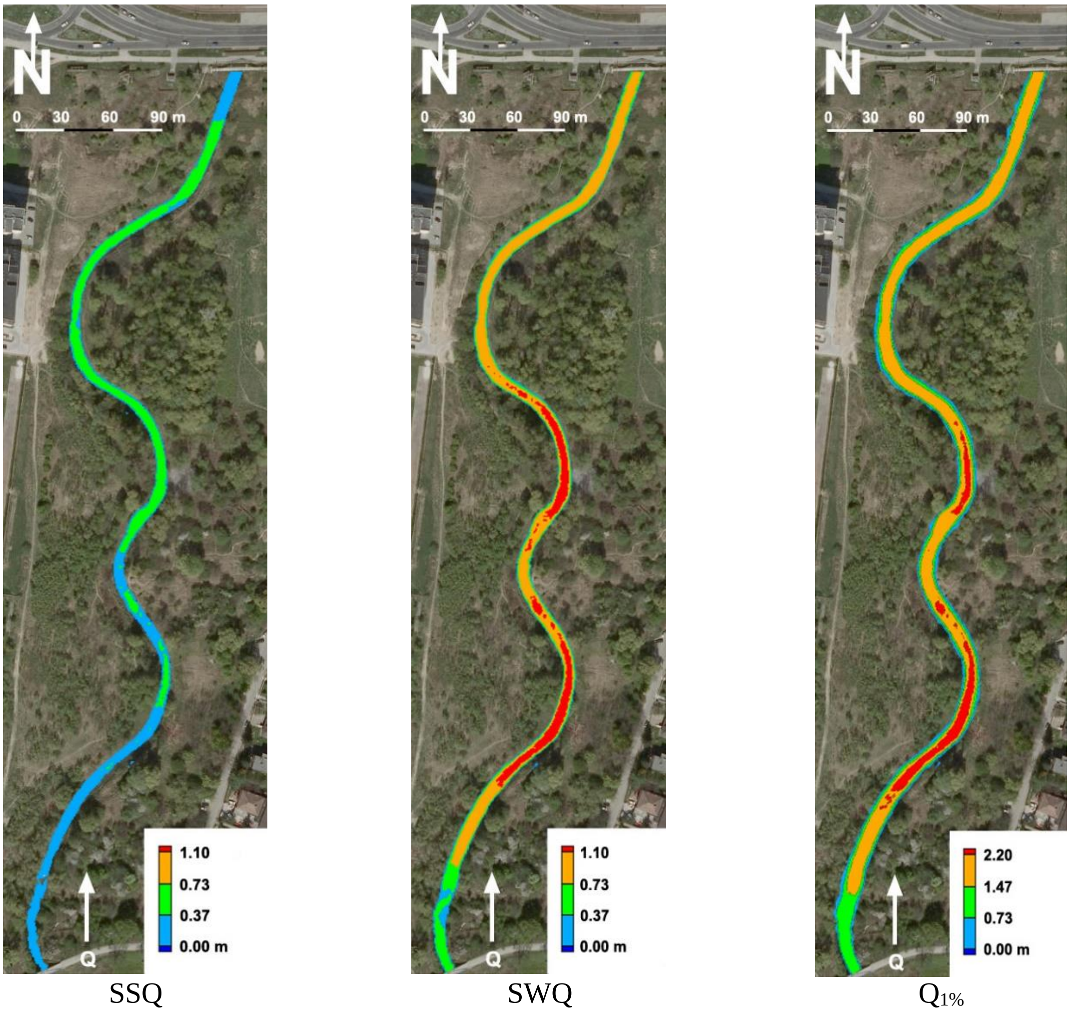
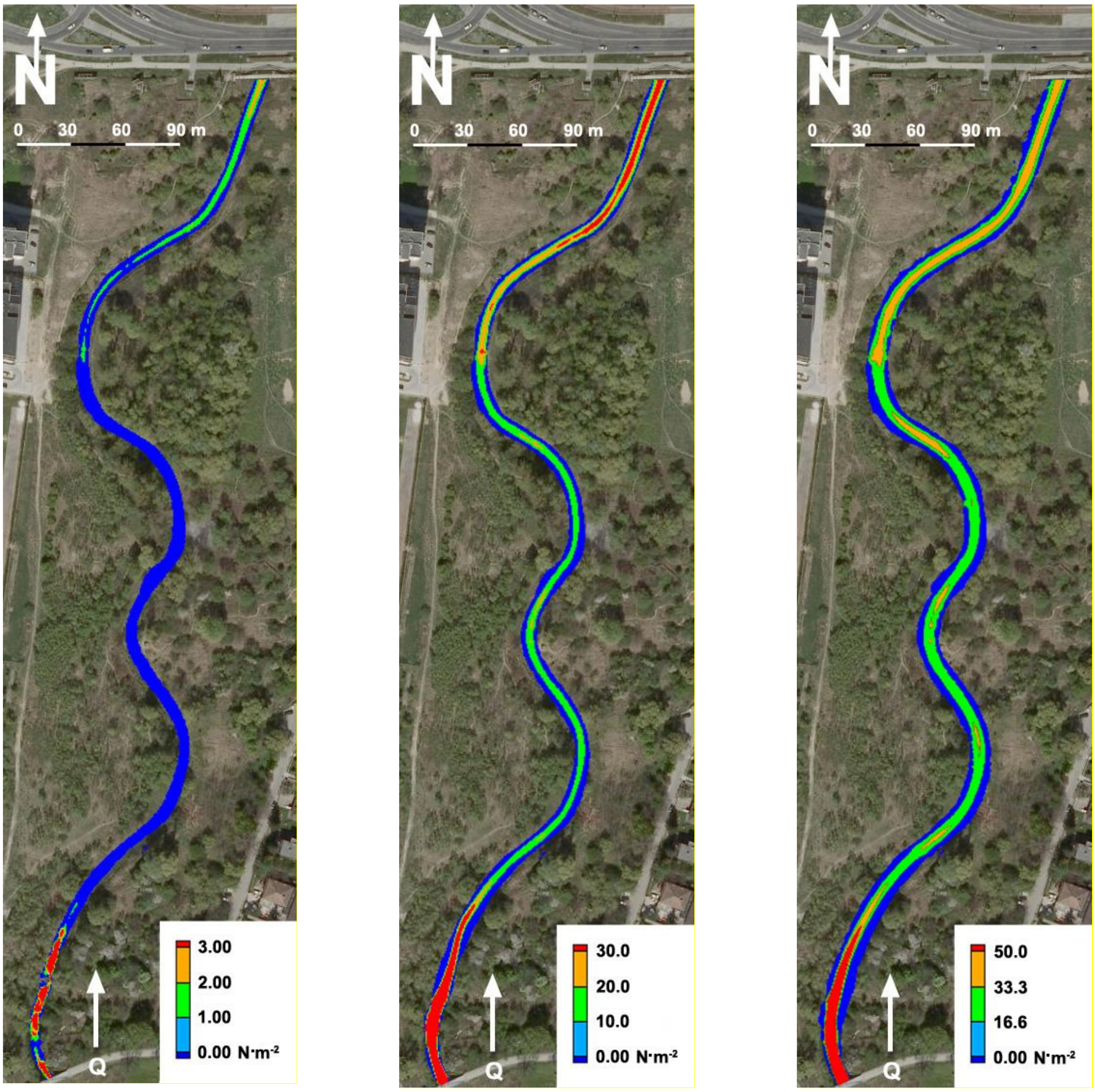


Fig. 3. The water depth in the watercourse for the multiannual mean low flow (a) and mean annual maximum flows (b)

During the SWQ, the highest shear stresses (Figure 4) are concentrated in the vicinity of bridges. The upper bridge area exhibited the highest values, reaching 15 $N\cdot m^{-2}$. In the lower bridge area, the values were slightly lower but remained substantial at 10 $N\cdot m^{-2}$. In both cases, within the central part of the river channel, stress levels did not exceed 0.01 $N\cdot m^{-2}$. Specifically, at the upper bridge, the stress measured <0.11 $N\cdot m^{-2}$ for SSQ.



SSQ SWQ $Q_{1\%}$

Fig. 4. Shear stress in the watercourse for the multiannual mean low flow (a) and mean annual maximum flow (b)

The value Fr exceeding 1 at this point indicates the occurrence of the supercritical motion. In the remaining sections of the channel, the value of the Froude number was Fr <1, which proves the occurrence of sub-critical motion. During the SNQ, the distribution of the Froude number value was similar to that of the previous flows, except that in the upper bridge region, the value of this parameter reaches Fr = 1 only in certain points, due to a low flow (Figure 5).

For all analyzed flows, the greatest decrease in the water surface level is found in the area of the upper bridge. This is related to the high slope of the longitudinal profile of the river bed. Even for flood flows (SWQ), the water does not spill out onto the flood plain.

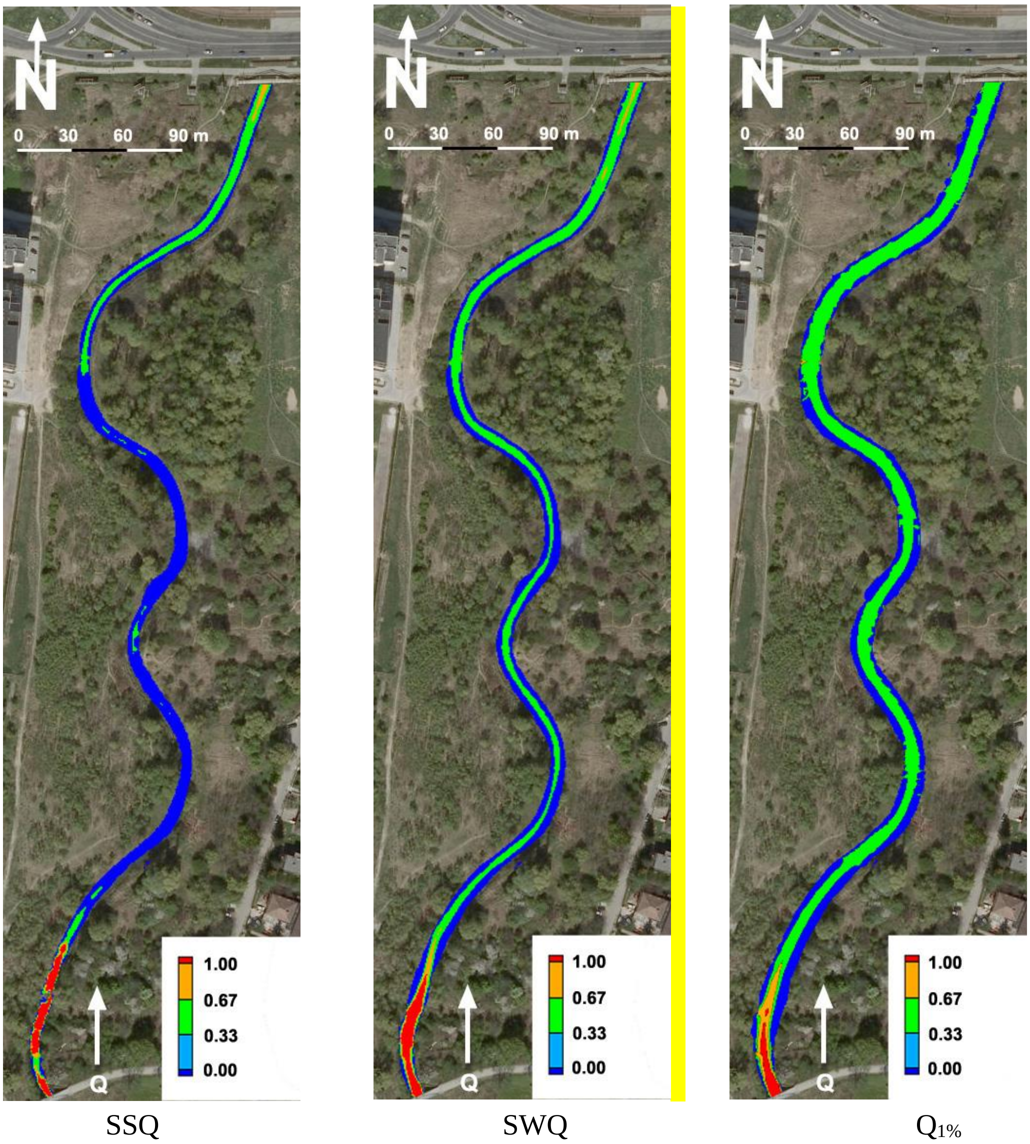
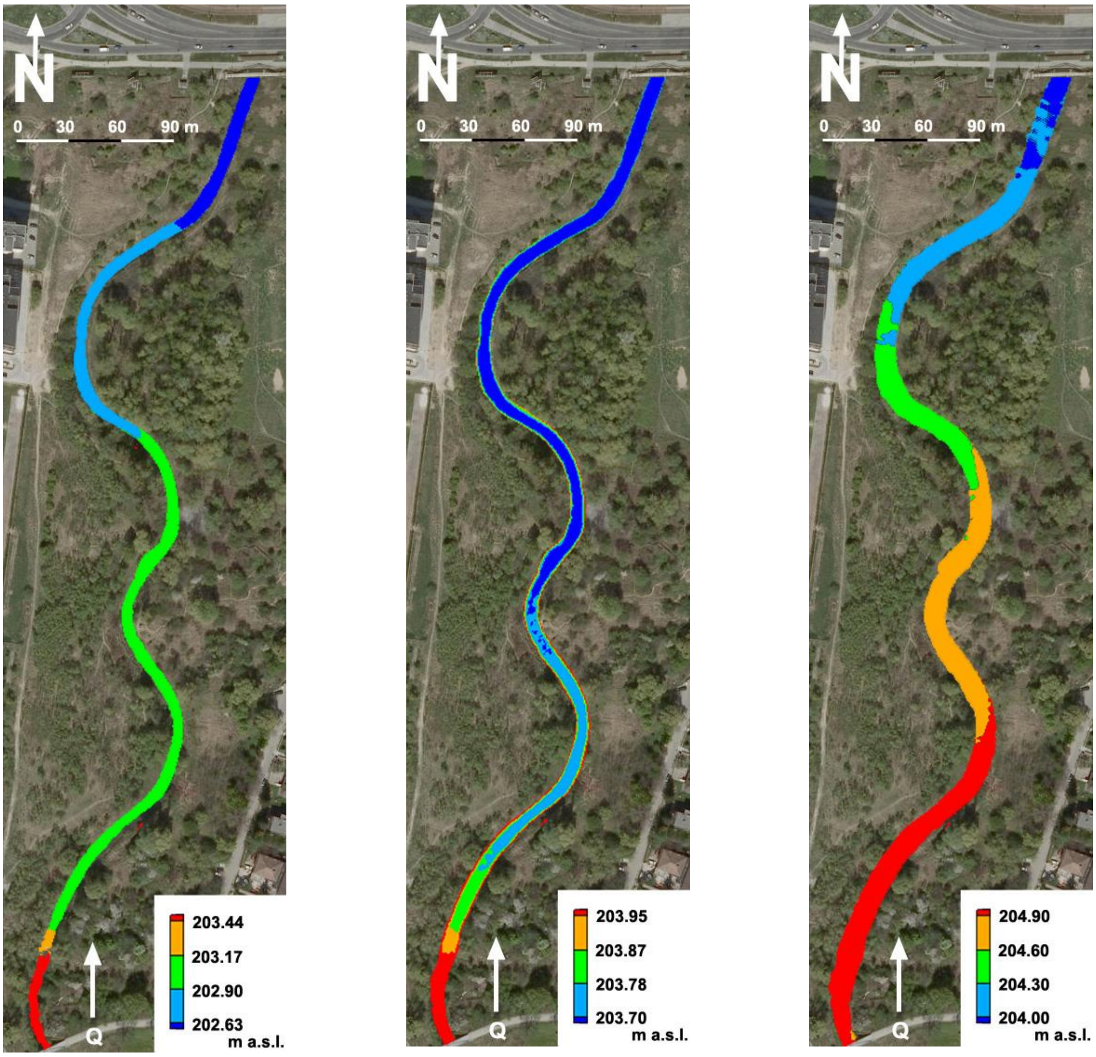


Fig. 5. The Froude number in the watercourse for the multiannual mean low flow (a) and mean annual maximum flows (b)

The results of the 2D model indicated the time-space variability in the hydraulic characteristics. With the increasing SWQ flow, the water level in the riverbed and the water table height were higher (Figure 6.) The magnitude and the time of the Q1% and SWQ flows are strictly dependent not only on the geomorphologic, but also on other parameters. Those fluvial processes include the shear stress, which reflects the catchment's response to water swirls in a river channel. In the studied section of the riverbed, the shear stresses were low for SWQ.



SSQ SWQ $Q_{1\%}$

Fig. 6. The surface water table in the watercourse for the multiannual mean low flow (a) and mean annual maximum flows (b)

3.3. River Park as an example of a Nature-based Solution in an urban valley

In recent years, public green spaces have attracted attention [23]. Despite numerous studies on public spaces, greenery in those areas is rarely examined. Studies focused on the functioning of green areas in urban spaces have shown the strongest relationship between the use of the potential of green and blue infrastructure and ecosystem services [24]. The green infrastructure is an important element of the functional and spatial structure of the city. It is a component of the public space system, and shapes urban architecture, separating areas with different expansion and facilities [25]. Plant protection products and fertilizers are not used on flower meadows, which also makes them "clean", environmentally-friendly areas. Therefore, they can be used to design environmentally-friendly and natural systems. The introduction of individual synanthropic plants in the future can influence preferences of local people. Therefore, the access to the natural environment has become one of the main components in assessing the quality of life as a new development model that is friendly to people. A buffer zone within a green area will enable the balanced land management and a functional connection with surroundings and with other green areas. Furthermore, it may contribute to the appropriate development and a functional urban surface water flood modeling [26]. A rational urban policy in the sphere of sustainable development is a key issue for two-dimensional unsteady hydraulic models for applications in floodplain forest ecology. The appropriate use of these resources can reduce investments and expenditures, and increase greenery aesthetics, as well as botanical, hygienic and utility values of existing vegetation [27].

Urban green areas and water bodies should be connected with ecosystem service for assessing effects of land use policy [28]. In this study, selected hydraulic parameters were averaged using a 2D model. At the higher SWQ, the water moves with a supercritical motion [29]. Physical mappings of hydraulic phenomena were developed using the Froude number. The Froude number increased only locally over one section, due to a higher water level. For the entire length of the river channel, the Froude number assumed a similar value both for Q1% and SWQ. For the sections examined, the flow was smooth, with Fr below 1. The results indicate that at the depth of > 0.73m for both Q1% and SWQ, an increase in the velocity of water flows was noted. The average air temperature in Kraków has increased over the past 30 years (Figure 7). The research on extreme events (precipitation, runoff) occurring in hydrological catchments, in cities, should include development of regional research methods and methods for the analysis of observational data, obtained primarily from observations in studied catchments and studies on the anthropo-pressure impact on the hydrological regime of watercourses [30]. In the analysis of the symptoms and effects of global warming in Poland, attention should be paid to the last decades of the 20th century and the first decade of the 21st century, when an increased rate of warming is visible [31, 32]. Regardless of the region, an increase in the average annual air temperature is observed. The intense increase in the air temperature may directly affect the well-being of people and their surrounding environment. The average annual air temperature values in the successive decades of the period of 1981–2010 in Kraków amounted to 8.1, 8.5, and 8.7°C. The average annual air temperature increase per decade was 0.33°C in the analyzed 30-year period, and was statistically significant at the level of $\alpha = 0.05$.

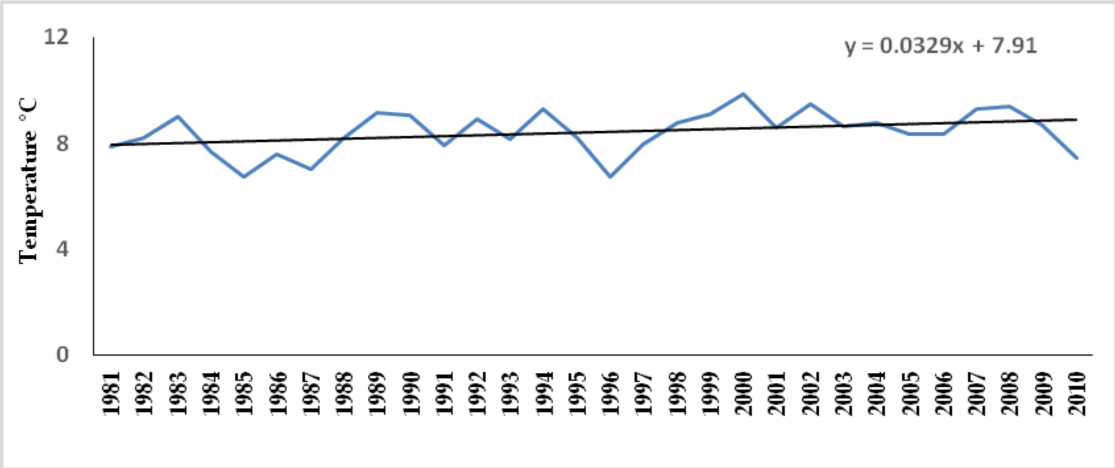


Fig. 7. The course and trend for the average annual air temperature in Krakow in 1981-2010

The analysis of changes in precipitation in Poland in the period of global warming does not show clear trends. In the period of the 20th century, they show a slight decreasing trend of -1.49 mm / 10 years, and in the second half of the 20th century - a growing trend of 2.85 mm / 10 years [33]. In the analyzed forty years of 1971–2010, the annual sum of rainfall in Kraków was 672 mm. In individual years, the amounts of annual sums were characterized by high variability. The driest year was 1993, with a total of 470 mm, and 2010 was the wettest, with a total of 1,020 mm. Drier periods occurred in the first half of the eighties and the nineties. In the second half of the 1980s and at the end of the analyzed period, there is a clear upward trend in rainfall totals. The analysis of the precipitation trend shows an increase by 5.65 mm / year (Figure 8).

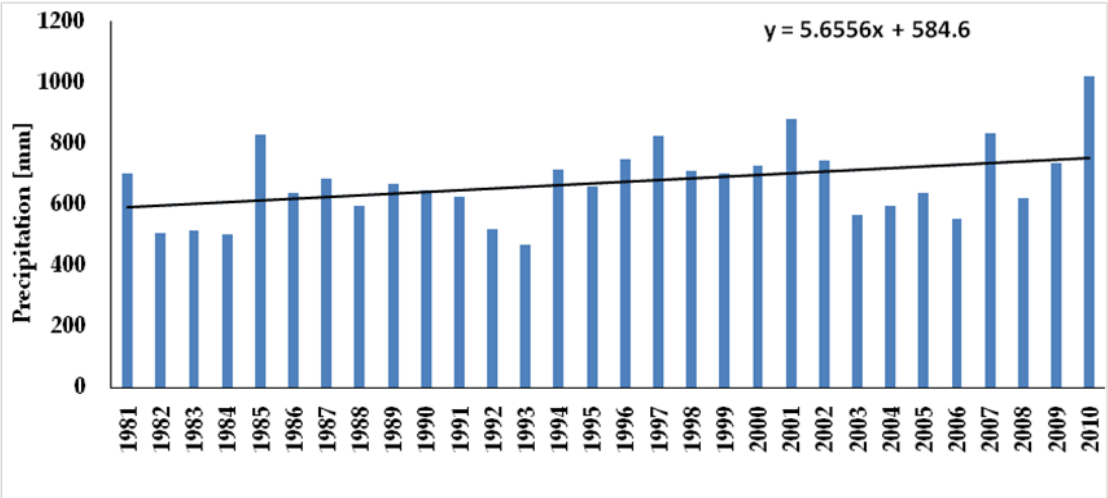


Fig. 8. The course and trend for the average precipitation in Krakow in 1981–2010

Extreme temperatures are of great practical importance, because they pose various real threats both to the environment and to economic activities. The average number of days with tmax ≥30° C per year in Kraków was 7.5 in 1981–2010. In the course of many years, an upward trend of 2.25 days per decade can be noted. At the end of the 20th century and the beginning of the 21st century, the average number of days with tmax ≥30° C in certain years reached extreme values, e.g. 18 in 1994 and 22 in 2006 (Table 1).

Table 1. Long-term averages and the lowest and the highest values for various elements of the climate in Krakow in 1981-2010

Selected climate indicators	mean	min	max
Annual temperature [°C]	8.4	9.9	6.7
Annual sum of precipitation [mm]	672	470	1020
Annual number of days with tmax ≥ 30 [°C]	7.5	0	22
Annual number of days with tmax ≤ -10 [°C]	1.8	0	11

Source: Institute of Meteorology and Water Management

The meteorological data presented in Table shows that for the multi-year period, the average number of frosty days was 1.8 days a year. Additionally, no frosts were recorded in one season. On the other hand, for hot days (≥30° C), the annual average for Krakow was 7.5 days per year, and the maximum number of hot days was 22 days during one year.

3.4 Urban planning system for ecohydrological practices

The variety of greenery facilities was assumed to be a specific criterion for the ecological systems [34] Urban planners should consider the urban greenery system in their designs. The spatial design for construction of residential roads is considered as a solution for street greenery [35]. The majority of landscape architects and urban greenery engineers use synanthropic vegetation in public urban spaces. Nevertheless, synanthropic communities are an element that contributes to the urban landscape. [36]. The development of green areas in the city should proportionally accompany the expansion of settlement areas [37]. The implementation of such measures should also result in an improvement in specific urban green indicators. Therefore, it is recommended to ensure that green areas are appropriately introduced into the functional and spatial structure of the city. The urban space may be covered with synanthropic plants in flower meadows. The naturalistic design using this plants is important for social acceptance. New trends in the planting design should be supported by specialists [38]. However, very often local city authorities are cautious about introducing environmentally-friendly designs. A special attention should be paid to invasive species that pose a high risk [39]. According to environmental activists, the use of synanthropic must be supported by a scientific research. Both the horizontal intensity of vegetation and the species structure have an impact on the assessment of the functionality of vegetation at exposed places in the city [40]. The green infrastructure and Nature based-Solutions (NBS) can be introduced into areas designated to be city green areas, such as city gardens and parks and surrounding recreation places and other sites. Scattered elements of a city's ecosystem, such as trees and lawns, provide numerous important services including absorption of pollutants [41], reduction of water runoff from the city and therefore relieving the stormwater system and reducing costs of its operation, as well as contributing to temperature control [42]. Ecosystem services have a value that can be estimated in financial categories, and the obtained results can be used for evaluation of the environmental impact of business activities or planned investments. This applies to services of both usable and non-usable nature [43]. The value of ecosystem services can be estimated using different methods. In this study, we attempted to focus on evaluation of water retention in soil. Finally, the green infrastructure is based on the EU strategy for protection of biodiversity. However, it is much more than just a tool for protection of biodiversity [44]. Studies have shown that solutions for green infrastructure are less expensive than grey infrastructure and provide an extensive range of additional advantages for the local economy, social issues and the environment [45].

The green infrastructure contributes to alleviation of negative effects of extreme weather phenomena and other consequences of climate changes, which belong to the most expensive and dangerous natural hazards in Europe and worldwide [46]. This solution will improve the quality of city life, not only by enabling exploitation of the recreational potential of the environment, but also by creating conditions for development of environmentally-friendly transport passing through green corridors [47]. In particular, ecohydrological approaches are important for the functioning of the urban environment (restoration, ecological corridors, protection of biodiversity, and increased water retention). The protection of a green zone should cover a larger area with a hydrography network [48-50]. Natural ecosystems function and within the urban space, even if they are only fragmented, and play an indisputable role in shaping of public space and improvement in the quality of life of the citizens. Such a solution may reduce the need for costly infrastructure of an underground stormwater system. River Park is connected to undeveloped land within the riparian buffer zone. In many cities worldwide, green areas are an element of urban composition, influence the character and the appearance of streets and squares, and shape and organize the city interior and whole watershed.

4. CONCLUSIONS

Research has shown that 2D hydraulic modelling can be applied to visualize the channel change of an urban watercourse. The geometric pattern of the hydraulic structure showed significant degradation of the canal. Average velocities and the water depth of the stream revealed low variation in measured and calculated cross-sections. The Froude number displayed a slight change in the mean annual flow in the riverbed. The differences observed between SWQ and Q1% may suggest that the river valley close to River Park has no mitigation capacities and protects neighbouring areas against the effects of negative climate change. Regardless of the value of the flows, the water remained in the riverbed due to the large indentation of the river valley. This helps to protect the neighbouring areas against flooding, and on the other hand, causes quick water outflow and low water retention capacity of the catchment area. Any River Park should become a protected site and vegetation buffer zone facilitating adaptation to the climate change. Urban watercourses and channels must be designed to increase the retention capacity of the riverbed and valley. Hydrological 2D modeling can be developed as approach to integrate ecological and hydrological research. Nature-based Solutions may be implemented in the water area in the city. Studies have shown that a River Park can be a part of a Nature-based Solution. This way, the synergy effect will be achieved in the management of the greenery of river valleys in cities.

additional Information

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