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Extreme weather layer method for implementation of nature-based solutions for climate adaptation: Case study Słupsk

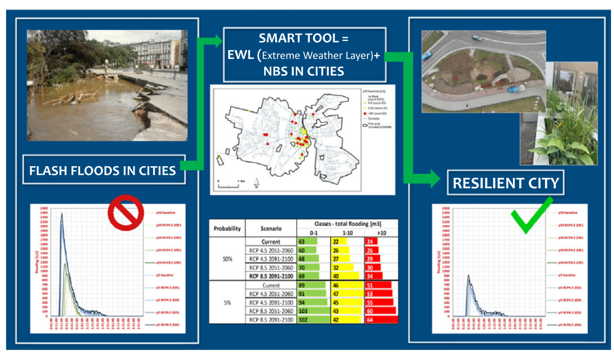
Karolina Fitobór [a], Rafał Ulańczyk [b], Katarzyna Kołecka [a,*], Klara Ramm [c], Iwona Włodarek [c], Piotr Zima [a], Dominika Kalinowska [a], Paweł Wielgat [a], Małgorzata Mikulska [d], Danuta Antończyk [d], Krzysztof Krzaczkowski [d], Remigiusz Łyszyk [d], Magdalena Gajewska [a]

[a] Department of Water and Wastewater Technology, Faculty of Civil and Environmental Engineering, Gdańsk University of Technology, Narutowicza St. 11/12, 80-233 Gdańsk, Poland
[b] Institute of Environmental Protection, National Research Institute, Kolektorska St. 4, 01-692 Warszawa, Poland
[c] Economic Chamber Polish Waterworks, Jana Kasprowicza St. 2, 85-073 Bydgoszcz, Poland
[d] Water Supply Company Słupsk, Elizy Orzeszkowej St. 1, 76-200 Słupsk, Poland

HIGHLIGHTS

- Stormwater quality and quantity in climate scenarios
- Stormwater management needs to be resilient, robust, flexible and attractive.
- Integrated Stormwater Management should be applied in future urban development.
- Stormwater management before grey pipe by means of green retention
- Extreme Weather Layer combined with nature-based solutions is a smart tool.

GRAPHICAL ABSTRACT



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ABSTRACT

One of the most severe climate risks that is expected to affect all regions is related to stormwater. Climate models, constructed based on long-term trends, show that extreme weather events such as storms, cloudbursts and a large rise in sea level will be significant in the coming decades. Moreover, even the frequency and intensity of "normal" rainfall events, such as microbursts, are expected to be remarkably higher than today in some regions.

The efficiency of urban drainage systems is affected by the land use in its whole catchment. In addition to the climate stress, there is ongoing continuous densification of urban space, resulting in more buildings and larger areas being covered with impervious surfaces. Planning decisions today approving such compaction do not consider the impacts beyond the close proximity of the land parcel. As a result, by following the current planning practices, cities are becoming extremely vulnerable to stormwater flooding (flash floods).

This study presents a holistic and dynamic planning method – the Extreme Weather Layer (EWL) – that makes it possible to analyse the impact of a single development (e.g. paving a gravel parking lot with asphalt or turning an area of urban greenery into a shopping centre) on the performance of the urban drainage system and therefore on the flooding risk of the whole catchment. The EWL is based on a widely accepted drainage modelling engine coupled with GIS system and other databases which provide spatial information.

Thus, the EWL combined with the systemic approach of turning from grey to green infrastructure could be a smart tool for implementing NBS solutions for stormwater management in climate adaptation in urban areas. This smart tool could indicate how much more green infrastructure is needed and which places in the city the mitigative NBS measures would help significantly.

* Corresponding author.
E-mail address: katkolec@pg.edu.pl (K. Kołecka).

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1. Introduction

Over the last century, there have been significant changes in the water cycle, which are closely linked to climate change. The Intergovernmental Panel on Climate Change (IPCC) has been providing data since 1988. In 2008, it was projected that the water cycle will be severely impacted by climate change and subsequently generate challenges in cities such as droughts, floods, water resources pollution and heat waves (Stefanakis et al., 2021).

As long-term observations show (IPCC), one of the most severe climate risks that is expected to affect all regions is related to stormwater. Numerous climate models, constructed based on just such long-term trends, show that extreme weather events such as storms, cloudbursts and a large rise in the sea level will be significant in the coming decades. Moreover, even the frequency and intensity of rainfall events, such as regional microbursts, are expected to be remarkably higher than today. The fragmented, plot-based urban planning approach widely applied in many countries does not currently consider these facts.

In addition to the climate stress, there is ongoing continuous densification of urban space resulting in more buildings and larger areas covered with impervious surfaces. Planning decisions today approving such compaction (detailed plans, building permit procedures, etc.) do not consider impacts beyond the close proximity of the land parcel. As the efficiency of the urban drainage systems is affected by the land use in its whole urban catchment, influencing very long distances downstream, this is very short-sighted.

Cities interrupt the natural water cycle by creating impervious areas, which prevent infiltration and increase surface runoff. As a result, cities provide rainwater management services in the form of sewer networks that drain the city, to protect the inhabitants from floods. However, this type of urban drainage has proven insufficient during extreme (sometimes even during slightly stronger than average) rain events, which result in surface runoff that cannot be entirely drained by the sewer network. As a consequence, we are witnessing frequent pluvial floods in cities, erosion, pollution in downstream watercourses due to combined sewer overflows (CSOs), and malfunctioning of hydraulically overloaded wastewater treatment plants (Atanasova et al., 2021).

Floods can affect not only the quality of surface waters but also groundwater, and can mobilise hazardous substances from urban areas. As a consequence, they can have a negative impact on ecosystems and raw water quality, carrying suspended pollutants, diluted pollutants and microorganisms. In addition, when CSOs occur after dry periods, their environmental impact is more severe. Such an overflow is the worst event for sewage system operators (EurEau, 2020). Therefore, rainwater should be discharged to open (natural) receivers to reduce the amount of rainwater in the combined sewage system. However, if the rainwater becomes contaminated, simple solutions can be insufficient.

According to many authors, the concept of Nature-Based Solutions (NBS) has been in the spotlight recently, because of its strong potential to address several urban challenges such as climate mitigation, air quality, water management, participatory planning, and governance. One of the most appreciated characteristics of NBS is their co-benefits and multifunctionality. Despite being designed for a specific purpose (e.g. urban drainage), NBS can deliver several ecosystem services at the same time (e.g., treatment, evaporative cooling, and biodiversity). A single element can serve as retention and mitigation of the heat island effect in the city (Raymond et al., 2017; Pearlmutter et al., 2020; Oral et al., 2020; Kisser et al., 2020; Skar et al., 2020; Katsou et al., 2020). NBS such as rain gardens, green roofs, bioretention swales, and green walls and many more are elements of blue-green infrastructure (BGI), which are "before the pipe" facilities and elements that are an important part of water-sensitive urban design (WSUD). Thus, many questions arise: how can WSUD be created in already-existing city infrastructure, what are the tools that help introduce NBS for stormwater retention before grey infrastructure, and to what extent do we need to introduce BGI to protect water bodies against spillages from CSOs?

This study presents the layout and implementation of a holistic, dynamic planning method called the Extreme Weather Layer (EWL) which makes it possible to analyse the impact of a single development (e.g. a single building notice – paving a gravel parking lot with asphalt; or a broader detailed plan – turning an urban greenery area into a shopping centre) on the performance of the urban drainage system and therefore on the flooding risk of the whole catchment. The method is based on a widely accepted drainage modelling engine coupled with GIS system and other databases that provide spatial information. The EWL was developed in 2021 in collaboration with authors within the NOAH project (Annus et al., 2021; Truu et al., 2021), and tested in eight European cities including one large-scale application in the City of Słupsk – presented in detail in this paper.

The EWL can be used to analyse the resilience of urban areas using different climate and future development scenarios. Moreover, it can be used by a municipality and/or water utility to pre-design adaptive measures such as blue-green infrastructure and smart stormwater systems. Specific technical requirements and descriptions for procurement documentation can be derived from these results. The EWL applied in Słupsk and described in more detail in the next section is based on widely used components linked together, which are 1) the SWMM model, 2) rainfall, stormwater and wastewater quality monitoring, 3) climate projections including short and intensive rainfall events, and 4) GIS layers serving as a background for the presentation of flood and pollution risk and for the presentation of the risk itself. Integration of these tools to provide new inputs for the decision-making aimed at the protection of receiving waters from pollution, and at adaptation of urban drainage systems to projected rainfall intensities is not demonstrated and used widely enough, which is confirmed by recent studies (Chu et al., 2019; European Union, 2000; Ranasinghe et al., 2021) which is further discussed in the "Results and discussion" section. The presented pilot application is the first of its kind in Poland and one of only a few in the world. This study is not limited to the flood risk assessment based on hydraulic modelling, but presents what information the end-users (municipalities, decision-makers) should be provided with to plan the most efficient climate adaptation measures. The proposed measures are aimed not only at minimising the urban flood risk but also at minimising the forecasted loads of pollution that pose a risk to receiving waters – the Słupia river and the Baltic Sea. The measures proposed for Słupsk include NBS, which are still under-recognised and under-invested in urban planning and development not only in Poland but also in many other places in the world (Dodman et al., 2022).

The systemic approach of the city of Gdańsk, which is one of the more advanced cities in Poland regarding NBS for stormwater management, was applied as adoptive and mitigative measures in the presented Słupsk case study.

2. Material and methods

2.1. Pilot site description

Słupsk is located in north-western Poland, 20 km from the Baltic Sea. The area of the city is 43.15 km^2. Urban areas take up approx. 17.40 % of this space. The pilot site does not include the entire sewer system operated by Słupsk Water Supply, but the most densely built-up area of 22.03 km^2 where both separate and combined sewer systems exist. Just before the main pumping station (which serves as an outfall in the pilot area), there is an overflow, which separates any excess wastewater and directs it to the Słupia River. The pilot area is the main source of inflow to the Wastewater Treatment Plant (WWTP) of which 30 % is stormwater. Therefore, it is necessary to assess sources of pollution in the inflow to the WWTP and in the overflow, and to prepare tools that will provide a basis for the wastewater and stormwater control system.

A monitoring system was set up in the Słupsk Pilot Site, which consisted of the following devices (Fig. 1):

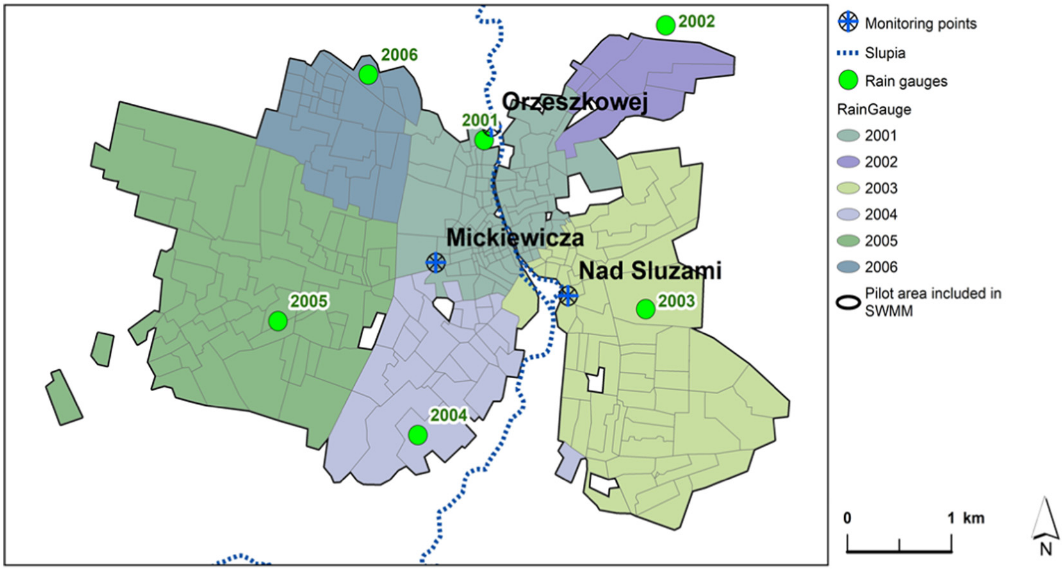

Fig. 1. Catchment area with locations of sampling and monitoring points (Orzeszkowej Street, Mickiewicza Street, Nad Śluzami/Wiejska Street; Słupsk, Poland).

- Devices for measuring the amount of precipitation (rain gauges) – 6 pieces.
- Devices for measuring the water level at the main sewers with a system for automatic data archiving, remote transmission, and visualization – 12 pieces.

Calibration measurements of the devices installed in the sewage network were carried out. The research consisted in measuring the flow rate and determining the flow curves. Monitoring was launched in 2019 and continued until the end of 2021.

2.2. Sample collection and quality of stormwater methodology

Samples were collected during rain events (at least 1 h after the start of rain) or directly after heavy rainfall. Then they were immediately transported to the laboratory and subjected to quality tests. It should also be mentioned that the samples taken for basic quality indicators were not fixed and were not frozen. Whenever possible, mixed subsamples were collected by an autosampler. In exceptional circumstances, grab samples were taken.

Samples were collected from December 2019 to May 2021 (nine sampling series). All samples (and corresponding results) collected up to December 2019 should be regarded as pre-investment (before pilot change). While the samples taken from 2020 should be regarded as the results obtained after the investment (after pilot change).

In each series, samples were collected from the same three points, as presented in Fig. 1. The diagram also includes the locations of the rain gauges that are a part of the monitoring network in the city.

The first point, SP 1 (Orzeszkowej Street; geographic coordinates: 54°28′35.4″N, 17°01′48.6″E), is located in the north-eastern part of the city of Słupsk, where residential and service buildings dominate, as well as facilities of technical infrastructure. Moreover, this sampling point is located at the end of the sewage network, therefore it can be assumed that domestic wastewater is transported to this point throughout the city. Sampling point SP 2, located in the city centre (Mickiewicza Street; geographic coordinates: 54°27′54.5″N, 17°01′19.8″E), is an area of residential and service buildings, while the eastern part of the city (SP 3: Nad Śluzami/Wiejska Street; coordinates: 54°27′45.4″N, 17°02′30.9″E) consists mainly of residential and green areas of the catchment structure.

All determinations (BOD_7, TSS, TN, TP, COD) were conducted according to the laboratory procedures recommended by the Polish Committee for Standardization and were consistent with European and International Standards. What is more the determination of BOB_7 has been fixed for all partners in the NOAH project. The procedures used are presented in Table 1.

2.3. Hydraulic component of the EWL

A spatial planning method called the Extreme Weather Layer (EWL) was developed as part of the climate city adaptation in the city of Słupsk (NOAH, 2021). The EWL system in Słupsk integrated the digital representation of the city's stormwater system, catchments and surface infrastructure (e.g. roads and buildings) which are potentially at risk of urban flooding. This integration was aimed at enabling (1) the quantification of urban flood risk and risks posed to receiving waters by heavy rainfalls (incl. those resulting from climate change), and (2) the assessment of the efficiency of mitigative measures. Such aims were achieved by including a hydraulic model in the EWL system that is capable of simulating the stormwater and wastewater stage and flow rates.

The SWMM (Storm Water Management Model) (USEPA, 2020) was applied to prepare the model of the sewer system. The selection of this software was justified by its accessibility, well-proven worldwide applicability, and functionality corresponding to the needs of the EWL, i.e.: simulation of long-term scenarios; numerical representation of mitigative measures (e.g. retention tanks, dry ponds, green roofs and other types of retention, flow control devices, changes in the surface roughness and perviousness); and its ability to run a large number of simulations, preferably without a graphical user interface, thus making it possible to run the model as a hidden layer of a spatial information system such as the EWL (Rossman and Huber, 2016; Rossman, 2017). The model structure was parameterised using inputs described in more detail in the Supplementary material (Table S1). In addition to the static inputs to the model, four

Table 1
Determinations and corresponding standard laboratory procedures.

Determination	Polish Committee for Standardizations	European and International Standards
Total suspended solids (TSS)	PN-EN 872:2007	EN 872:2005
Biological oxygen demand (BOD_7)	PN-EN ISO 5815-1:2019-12 and PN-EN 1899-2:2002	ISO 5815-1:2019 and ISO 5815-2:2003
Total nitrogen (TN)	PN-EN ISO 11905-1:2001	EN ISO 11905-1:1998
Total phosphorus (TP)	PN-EN 6878:2006	EN ISO 6878: 2004
Chemical oxygen demand (COD)	PN-ISO 6060:2006	EN ISO 6060:1989

types of dynamic inflows were added and applied to specific locations according to the type of sewer system – combined or separated: (1) runoff entering the combined system directly; (2) runoff entering the sanitation system via unsealed manholes; (3) wastewater entering the sanitation system; and (4) infiltration of groundwater. The methods of calculating the inflows are described in more detail in the Supplementary material (Table S1). The hydraulic model was the only part of the EWL subject to validation. The remaining main inputs that could be considered to be potential sources of uncertainty were the rainfall projections, however, these inputs were subjected to validations reported elsewhere, which is mentioned in the "Results and discussion". The validation was based on hourly outflows from the sewer system measured over one month (January 2019). The prediction accuracy was assessed with the use of Pearson's correlation coefficient (R) and the Nash-Sutcliffe efficiency coefficient (NSE). Validation was performed separately for dry periods and wet which included six days with precipitation. For the dry season, the accuracy of prediction was assessed at $R = 0.74$ and $NSE = 0.55$, while for the wet days, the coefficients equalled 0.83 and 0.63, respectively.

2.4. Estimation of current and future rainfall intensity

20 min of rainfall with a frequency of 2 years (probability = 50 %) and 20 years ($p = 5$ %) was analysed. The rainfall volume representing the current climate scenario was estimated using the empirical (regional) probability functions used in Poland (Bogdanowicz and Stachy, 2002; Banasik et al., 2017). The main source of the inputs used for the preparation of the projected rainfall events were statistically downscaled EURO-CORDEX simulations (Struzewska et al., 2020). Four projected rainfall datasets were used in the presented study, i.e. the RCP4.5 and RCP8.5 scenarios, and the 2051–2060 and 2091–2100 horizons. More details on the preparation of the rainfall data for the EWL in Słupsk can be found in the Supplementary material (Table S1).

2.5. Assessment of impacts of climate change and mitigative measures on the flood risk and pollution loads

The EWL was used for the following purposes: (1) identification and quantification of the flood risk and the risk of a CSO (combine sewer overflow) as a result of heavy rainfalls and climate change, (2) assessment of pollution loads that may flow out of the sewer system via flooded manholes and the CSOs, and (3) evaluation of the efficiency of measures aimed at the retention of runoff before entering the sewer system.

In the EWL, the flood risk has been categorised using three classes: high (red), moderate (yellow) and low (green). The risk was defined using two output variables, i.e. flooding flow rate and flooding volume. The threshold values between classes were defined based on the 33rd and 67th percentiles of all manholes at risk. In the case of a CSO, there were no classes defined to indicate the risk – the outcome was presented in the EWL directly as a comparison of the current and expected volume of overflow to the Słupia river.

Pollution loads were calculated based on simulated volumes of flooding and overflows multiplied by the concentrations of pollutants measured in Słupsk during rain events. Loads in urban flooding were calculated based on the average concentrations observed during the most intensive rainfall event at three sampling points. In the case of loads in the discharge (CSO), only the sampling point closest to the CSO was used (more details regarding the observed concentrations can be found in Section 2.2).

The mitigative measures scenario assumed that 30 mm of runoff will be retained. Such a retention goal was applied in the model of the Słupsk sewer system, but it was limited to impervious areas in combined sewer system catchments only. The retention of 30 mm may be considered to be quite an ambitious scenario, but it is based on plans currently being implemented in other cities located in coastal areas, e.g. Gdańsk (Poland), where all new investments are obliged to prove that the development plan includes measures aimed at the retention of 30 mm of rainwater. Compliance with these requirements is verified based on a checklist that includes all roof, communication and semi-permeable areas, and a list of capacities of various water retention methods to be applied, e.g. retention and detention ponds, rain gardens, green roofs, drainage and soakaway systems, and underground retention tanks. For the areas not connected to the city's stormwater system, it is advised to have a retention capacity of not 30 mm, but 60 mm of precipitation (http://www.gdmel.pl/dla-inwestorow/wytyczne-dla-projektantow).

3. Results and discussion

3.1. Stormwater quality

The results of the quality tests are presented in Tables 2 and 3. Table 3 contains the minimum, maximum and average values of selected quality indicators for individual sampling points (SP 1–SP 3), as well as for the reference samples (pure rainwater). Generally, for pure rainwater (Table 2), the concentrations of all tested parameters were very low. The content of biodegradable organic substances, expressed as BOD_7, was highest in the spring and autumn, and lowest in the winter. The highest concentrations of TSS were recorded in the spring season and the lowest in the winter. The TN values were highest in the spring and lowest in the autumn. Similarly, the TP values were highest in the spring and lowest in the autumn and winter. In the case of the wastewater samples (mixture of rainwater runoff and domestic wastewater), a significant deterioration of all quality parameters was observed in relation to the background (pure rainwater). Nevertheless, contact with pollutants washed from hardened surfaces of the catchment (such as roads, streets and car parks) also had an impact. The obtained results of the determinations were highly variable – depending on the sampling period, method of collection (grab sample or mixed subsample) and sampling point. For almost all indicators, higher values of determinations were observed for single samples (grab samples) than for composite representative samples (mixed subsamples taken with the autosampler). On the other hand, the average values of the parameters for all sampling points remained at a similar level (except for COD). Without taking into account the extreme values and deviating from the other results, it was noticed that the samples collected at SP 2 were of relatively good quality, while the worst quality were the samples collected at SP 3. The highest BOD_7 values were obtained for samples from SP 3. The extreme values (the lowest and the highest BOD_7 values) were recorded for the SP 1 sampling point, respectively, 360 mgO_2/L (series I) and 658 mgO_2/L (series VII). As mentioned, slightly higher values were observed for grab samples,

Table 2
Pure rainwater quality tests – control samples (Słupsk, Poland).

Parameter	Unit	Pure rainwater (control sample)					Overall results		
		Sampling series					Min	Max	Aver.
		I (12.2019)	II (05.2020)	VI (10.2020)	VII (11.2020)	X (5.2021)			
BOD_7	mgO_2/L	2.37	2.94	x	3.20	3.10	2.37	3.2	2.90
COD	mgO_2/L	x	x	27.6	x	x	–	–	27.6
TSS	mg/L	<2.0	33	16	<2.0	8.3	2	33	15.33
TN	mgN/L	<1.0	2.18	6.92	0.37	2.17	0.37	6.92	2.53
TP	mgP/L	0.087	0.097	0.258	0.081	0.15	0.081	0.258	0.135

x – parameter was not tested in the sampling series.

Table 3
Summary of the pure rainwater quality tests and the stormwater runoff quality tests conducted from December 2019 to May 2021 in Slupsk (Poland).

Parameter	Pure rainwater			Sampling point								
				SP 1			SP 2			SP 3		
	Min	Max	Aver	Min	Max	Aver	Min	Max	Aver	Min	Max	Aver
BOD_7 mgO_2/L	2.37	3.2	2.90	360	658	502.5	452	549	493.75	435	547	508.25
COD mgO_2/L	–	–	27.6	866	1596	1213.4	942	1769	1348.5	885	1331	1132.8
TSS mg/L	2	33	15.33	215	792.45	400.24	174	560	404.28	245	745.45	394.42
TN mgN/L	0.37	6.92	2.53	42.5	145	90.04	60.5	133	99.11	73.4	148	108.67
TP mgP/L	0.081	0.258	0.135	5.05	14.5	11.22	8.41	19.6	12.16	9.64	18.4	12.04

especially in the case of COD. Among all sampling series, the highest value of COD was recorded for a grab sample collected in series V at SP 2 (1769 mgO_2/L), while the lowest was for a mixed subsample taken from SP 1 (866 mgO_2/L) in series IV. The general trend observed for TSS determinations in all series and for all sampling points was that the lowest values were for samples collected in May. The samples collected in the autumn and winter periods also returned relatively low values. The lowest suspension concentration was recorded for the samples collected in May 2020 from SP 2 (174 mg/L) and in December 2019 (215 mg/L) from SP 1. The highest TSS values were noticed in October 2020 for samples taken from SP 1 (792.45 mg/L) and SP 3 (745.45 mg/L). The lowest recorded value of TN was found at SP 1 (series I: December 2019; 42.5 mgN/L). The highest value was also found at the same sampling point (series VII: November 2020; 145 mg/L). An equally high value (148 mgN/L) was obtained in tests of series V for samples collected from SP 3. It should be noted that it was a single/grab sample. In the case of the results of total phosphorus determinations, a similarity was observed with the results of the total nitrogen determinations. Increased values of total phosphorus occurred at the same sampling points and in the same sampling series as increased values of total nitrogen concentrations. Overall, for all series, the values of TN and TP determinations were the highest for SP 3, and the lowest for SP 1. All results are presented in the Supplementary Materials (Tables S2, S3 and S4).

The quality of stormwater runoff is mainly related to the type of catchment, precipitation parameters, length of rainless periods, but also the degree of surface sealing and intensity of traffic. Depending on the place of origin and environmental conditions, the chemical and physical composition of the runoff varies significantly. According to Eriksson et al. (2007), over 700 different types of pollutants have been found in stormwater. Runoff formed in residential areas and non-urbanised areas is relatively less polluted, whereas runoff from industrial areas and city centres is highly contaminated and can even be hazardous. It should also be taken into account that part of the sewage system in Słupsk is a combined sewage system. Therefore, in the event of heavy rainfall, the emergency/storm overflows transport a mixture of sewage and rainwater to the receiver (i.e. the Słupia river). It is therefore reasonable to assume a wider range of control parameters than for pure rainwater. Moreover, such research

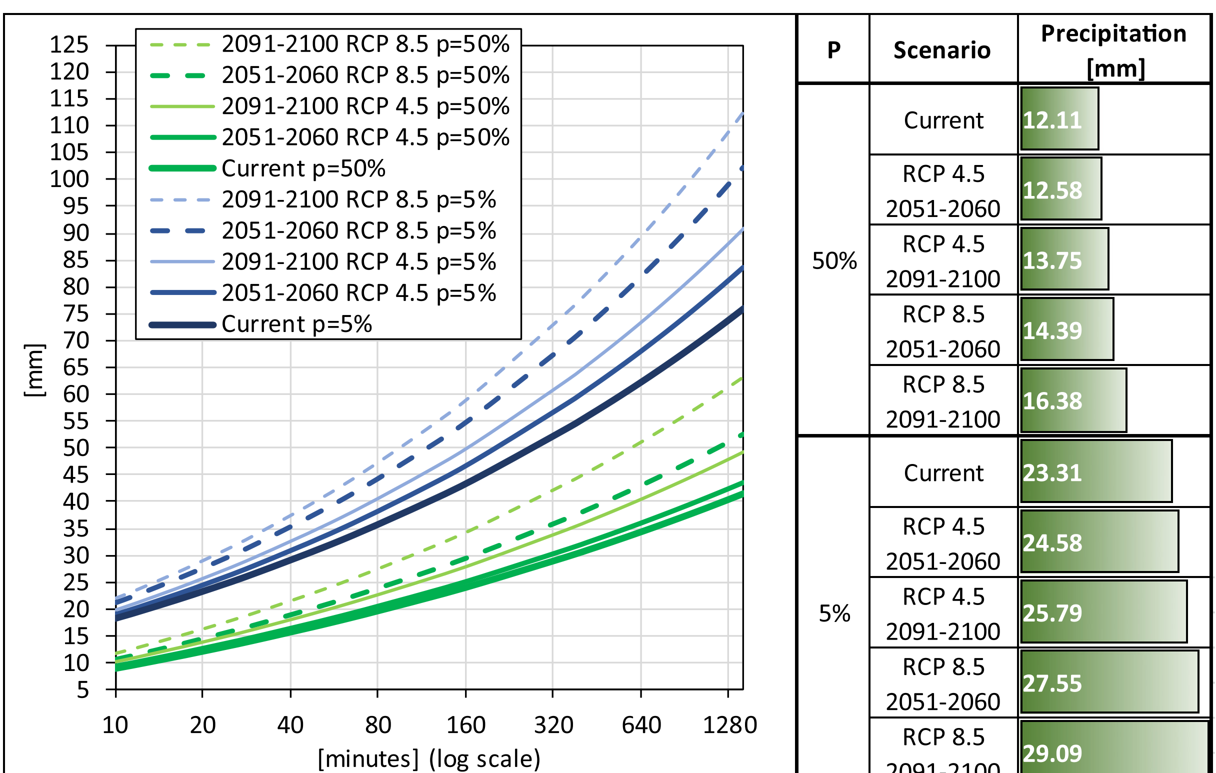

Fig. 2. Calculated intensity of a 20-minute rainfall in current and future scenarios.

material is very challenging to process (generally, stormwater is characterised by a high concentration of suspensions). Hence, stormwater runoff should be treated as a unique type of sewage, but certainly not as pure, raw water.

3.2. Rainfall intensity and impacts of climate change on the flood risk

The flood risk was estimated for both the current climate scenario and for the four climate change scenarios presented in Fig. 2. Even in the current climate conditions, it was estimated that every two years there is a rainfall event expected to cause flooding of 108 manholes in the city (Fig. 3). When less frequent rainfall events are considered (a 20-year rainfall), nearly twice as many manholes are at risk. The inclusion of any of the analysed climate change scenarios leads to an increase in the flood risk, understood both as the number of flooded areas and the intensity of flooding. The intensity of flooding was classified as low, moderate and high based on the flooding flow rate in manholes. The threshold values for the classes were one and ten cubic metres per second (Fig. 3).

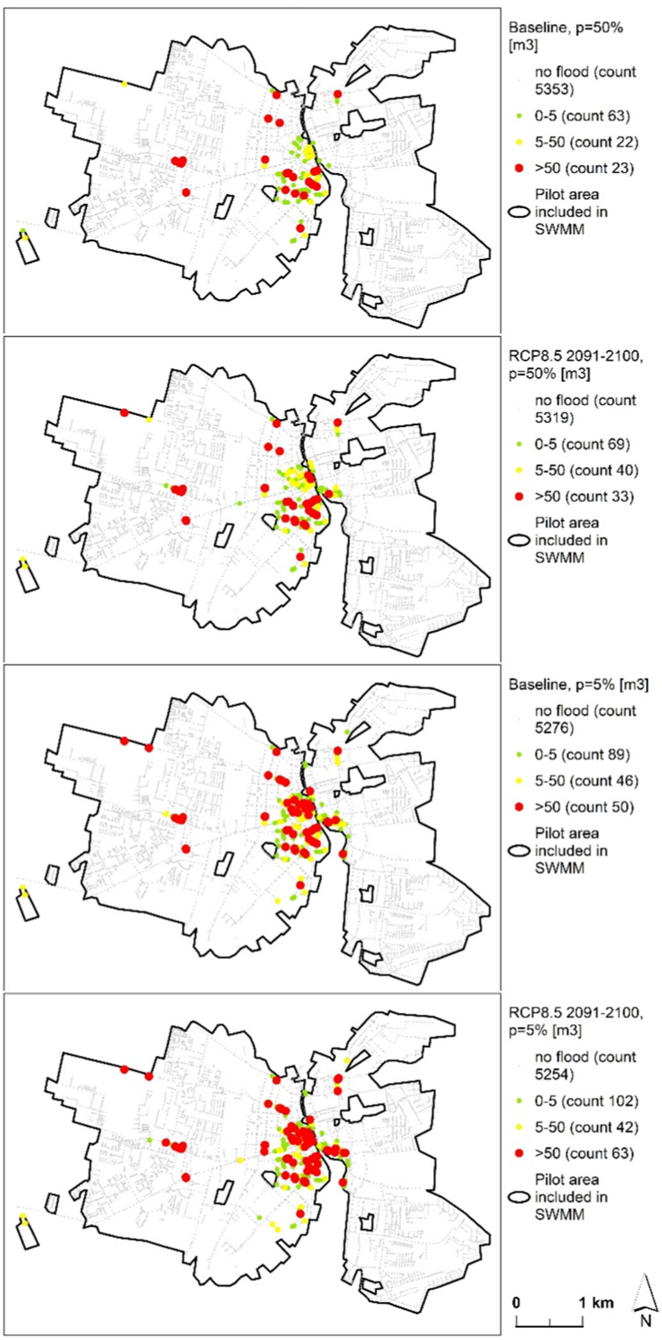

Fig. 3. EWL maps presenting the flood risk classes in various rainfall scenarios.

Even the less severe scenario (RCP4.5 for the 2051–2060 horizon) is expected to increase the number of flooded manholes by 3 % in the case of rainfall events of both analysed probabilities – 5 and 50 %. The most severe climate change scenario (RCP8.5, 2091–2100) resulted in an increase in the number of manholes at risk by 31 % and 12 % for the 2-year and 20-year rainfall events, respectively (Fig. 2). The flood risk classes mostly affected by climate change are the moderate class for the more frequent rainfall events ($p = 50$ %) and the high-risk class for the less frequent ones (p = 5 %). The estimated change in the volume of flooding attributed to climate change is much greater (approx. threefold) than the change in the number of locations at risk. At present, the flooding volume may reach 6700 m^3 per event with a 2-year frequency and 27,000 m^3 per event with a 20-year frequency. In the case of more frequent events, the volume increases by 11 %, 36 %, 50 % and 95 % as a result of the following climate change scenarios: RCP4.5 2051–2060, RCP4.5 2091–21,000, RCP8.5 2051–2060 and RCP8.5 2091–2100, respectively. In the case of rainfall with a 5 % probability of occurrence, the relative change is not as much as mentioned above. It was estimated at 9 %, 17 %, 29 % and 40 %, respectively. However, it should be noted that the absolute change expressed by the volume of flooding is greater and reaches nearly 10,000 m^3 in the case of the RCP8.5 scenario for horizon 2091–2100.

The impact of climate change on the volume of a CSO is of the same magnitude as the impact on urban flooding as far as the percent change and rainfall event with a frequency of 20 years are concerned. The percent change in relation to the current scenario is much greater where the 2-year rainfall is concerned. The relative change ranges from 23 % in scenario RCP4.5 2051–2060 to 169 % in scenario RCP8.5 2091–2100. The volumes of estimated overflows, together with the flow rates and durations, are presented in Table 4

3.3. Impacts of climate change pollution loads

The water excess causing flooding and CSOs is only a part of the adverse effects of heavy rainfalls, but it is the effect to which the functioning of cities is most sensitive (Revi et al., 2014). There is, however, a group of effects which to a lesser extent (and indirectly) impact the functioning urban areas and human health–pollution (Müller et al., 2020). Based on the concentrations of pollutants observed in the stormwater and wastewater during and after heavy rainfalls (described at the beginning of this chapter) and based on simulated flooding and sewer overflows, the load of pollutants has been estimated for the current climate scenario and future scenarios. Depending on the character of the city's stormwater system, the excess of polluted stormwater or a mixture of wastewater and stormwater can pollute 1) areas near the flooded manholes, and 2) the surface waters that receive the CSO. In the case of the city presented in this study – the city of Słupsk – both pollution risks are valid. Most of the excess water causes urban flooding, i.e. submerging of manholes and adjacent areas, which are usually impervious. In the case of Słupsk, the volume of urban flooding was estimated at 93 % of the total stormwater/wastewater excess, while the remaining 7 % enters the receiving waters (Słupia river) directly via the sewer overflow. The estimated loads of pollutants that are spilled into the city in various climate scenarios are presented in Table 4 as "pollutants in urban flooding". These pollutants may reach the surface water by re-entering the sewer system, via runoff or by passing through the soil or into an aquifer. The pollution of surface waters may thus be delayed and decreased. In contrast, the pollution load at the outflow from the stormwater system and in a CSO affect the quality of surface waters directly. This part of the pollution load is summarised in the table as "pollutants in CSO". The sum of both types of pollution in Table 4 ("pollutants in urban flooding" and "pollutants in CSO") gives the total pollution load directed to the environment instead of the treatment plant. Climate change was estimated to increase the total pollution load released from manholes and a CSO by 11.9 % and 37.4 % in 2051 and 2091, respectively, when

Table 4
Summary of estimated sewer overflows and loads of pollution in urban flooding and in the sewer overflow.

	Rainfall event probability 50 %					Rainfall event probability 5 %				
	Base-line	RCP4.5		RCP8.5		Base-line	RCP4.5		RCP8.5	
		2051	2091	2051	2091		2051	2091	2051	2091
Sewer overflow										
Total [m^3]	411	506	714	817	1108	1963	2102	2260	2501	2692
Average [m^3/s]	0.31	0.32	0.40	0.44	0.50	0.46	0.44	0.47	0.47	0.48
Duration [min.]	22	26	30	31	37	71	79	81	89	94
Peak [m^3/s]	0.60	0.67	0.88	0.94	1.18	1.92	2.00	2.05	2.12	2.29
Estimated loads of pollutants in urban flooding [kg/rain event]										
BOD_7	3024	3368	4101	4521	5895	10,859	11,819	12,671	14,059	15,196
COD	9456	10,534	12,827	14,139	18,437	33,960	36,962	39,627	43,968	47,523
TSS	1753	1953	2378	2621	3418	6297	6853	7347	8152	8811
TN	453	504	614	677	882	1626	1770	1897	2105	2275
TP	54.16	60.33	73.47	80.98	105.60	194.49	211.68	226.95	251.81	272.17
Estimated loads of pollutants in CSO [kg/rain event]										
BOD_7	148.3	183.2	257.0	294.5	399.6	707.4	757.1	813.6	900.0	969.8
COD	657	812	1139	1305	1772	3136	3356	3607	3990	4300
TSS	88.6	109.4	153.5	175.9	238.7	422.5	452.1	485.9	537.5	579.2
TN	17.5	21.6	30.3	34.8	47.2	83.5	89.4	96.1	106.3	114.5
TP	2.08	2.57	3.61	4.13	5.61	9.92	10.62	11.41	12.63	13.60

less intensive rainfall events ($p = 50$ %) and less intensive climate change (RCP4.5) are considered. For rainfall of the same probability (50 %) and the more intensive climate change scenario (RCP8.5), the increase in the total pollution load was estimated at 51.8 % and 98.4 % for the years 2051 and 2091, respectively. The impact of climate change on the pollution load for less frequent rainfalls ($p = 5$ %) was estimated to be much smaller. The increase in load compared to the current climate scenario was 8.7 % (RCP4.5, year 2051), 16.6 % (RCP4.5, year 2091), 29.3 % (RCP8.5, year 2051) and 39.8 % (RCP8.5, year 2091). Based on these results, it can be concluded that the less intensive but more frequent rainfalls may pose a much larger risk to the receiving waters. Such an assumption is correct if the existing sewer system cannot cope with the water excess during both

Fig. 4. Examples of simple NBS solutions for stormwater retention from Gdańsk.

the less frequent (e.g. 20-year) and more frequent (e.g. 2-year) rainfalls. For example, the climate change-driven increase in the total load of COD ranges from 1233 to 10,096 kg per 2-year rainfall event and from 3222 to 14,727 kg per 20-year rainfall event. The "from – to" ranges depend on the climate change scenario. However, regardless the scenario, it is evident that the pollution load caused by a 20-year rainfall will not exceed the pollution load caused by less intensive rainfalls which will occur more frequently.

3.4. Impacts of mitigative measures on the flood risk and loads of pollution

In our work, we tested the EWL, most likely for the first time, as a tool for simulating the effects of increased rainfall retention at the real and relatively large scale of a city. The same approach that was introduced in 2016 in the city of Gdańsk was assumed, which aims to retain up to 30 mm of precipitation in so-called green retention in the area with already-existing grey infrastructure (Kasprzyk et al., 2022). Such an approach is called retention "before the pipe" and could be implemented by applying nature-based solutions (NBS). NBS in this case is understood as defined by the IUCN (International Union for Conservation of Nature) as "actions to protect, sustainably manage, and restore natural or modified ecosystems, that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits" (https://www.iucn.org/commissions/commission-ecosystem-management/our-work/nature-based-solutions, access 21.04.2022). Some of the above-mentioned added values of applying NBS for green retention were investigated in a paper by Kasprzyk et al. (2022). For such retention, different types of NBS solutions could be applied, such as: rain gardens set up both in soil and in containers, through the creation of specially formed green troughs, trenches or retention basins as well as simply diverting water into a green area and transforming it into a green infrastructure for retention. All such simple examples for Gdansk are presented in Fig. 4 and could be easily applied in any town and in any development.

The percent area of these catchments where mitigative and adaptive measures were applied in the model are presented in Fig. 5. In this case green retention is limited to impervious areas in combined sewer system catchments only, thus indicating how the approach to the retention of stormwater before the pipe using NBS green retention will act on reducing the overflow spillage to the river and decreasing flash floods for the two tested rain events and the two selected climate scenarios (Figs. 6 and 7).

P	Scenario	Decrease in the flooding volume [%]	
		Urban flooding in Słupsk	Overflow to the Słupia River
50%	Current	77	100
	RCP 4.5 2051-2060	75	100
	RCP 4.5 2091-2100	71	100
	RCP 8.5 2051-2060	69	100
	RCP 8.5 2091-2100	64	100
5%	Current	55	84
	RCP 4.5 2051-2060	53	79
	RCP 4.5 2091-2100	52	75
	RCP 8.5 2051-2060	51	69
	RCP 8.5 2091-2100	49	60

Fig. 6. Percent change in the volume of urban flooding and CSO as a result of the measures aimed at the reduction of runoff inflow to the combined sewer system.

Simulation of the considered changes in the spatial development resulting in a decrease in runoff reaching the combined sewer system indicated that the less severe rainfall events ($p = 50$ %) would cause no overflows to the Słupia river and that the urban flood volume would be decreased by approx. 70 % compared to the scenario with the current spatial development plan. The more intense the rain event, the smaller the impact of the flood prevention actions is expected. For a 20-year rainfall event, the planned measures are likely to decrease the overflow by approximately 72 % and the urban flooding by 52 % (Figs. 6 and 7).

3.5. Potential and future of smart tool

The research presented in this paper was aimed at improving urban spatial planning in terms of mitigation of floods and pollution resulting from heavy rainfalls. When it comes to the application of new methods and tools, such as the EWL, the achievement of the planned objective should be validated on multiple scales, starting from the local one – the case study area – and ending in a larger one, e.g. regional or national. The local scale is required to confirm that the methods are beneficial and thus

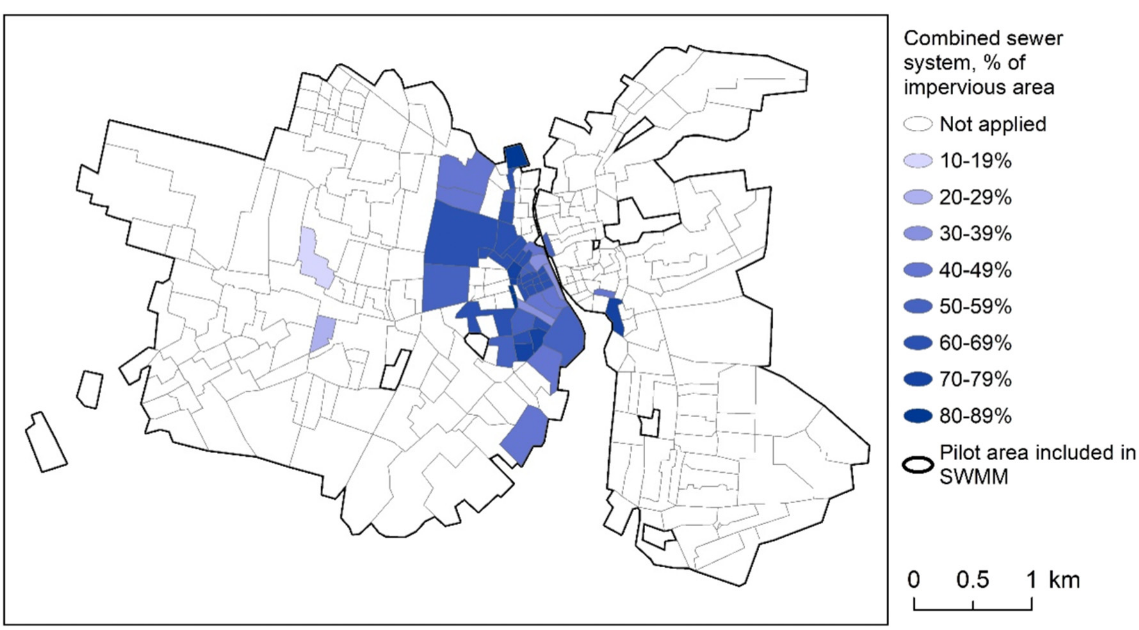

Fig. 5. The percent area of catchments, where the 30 mm rainfall retention was applied in the model.

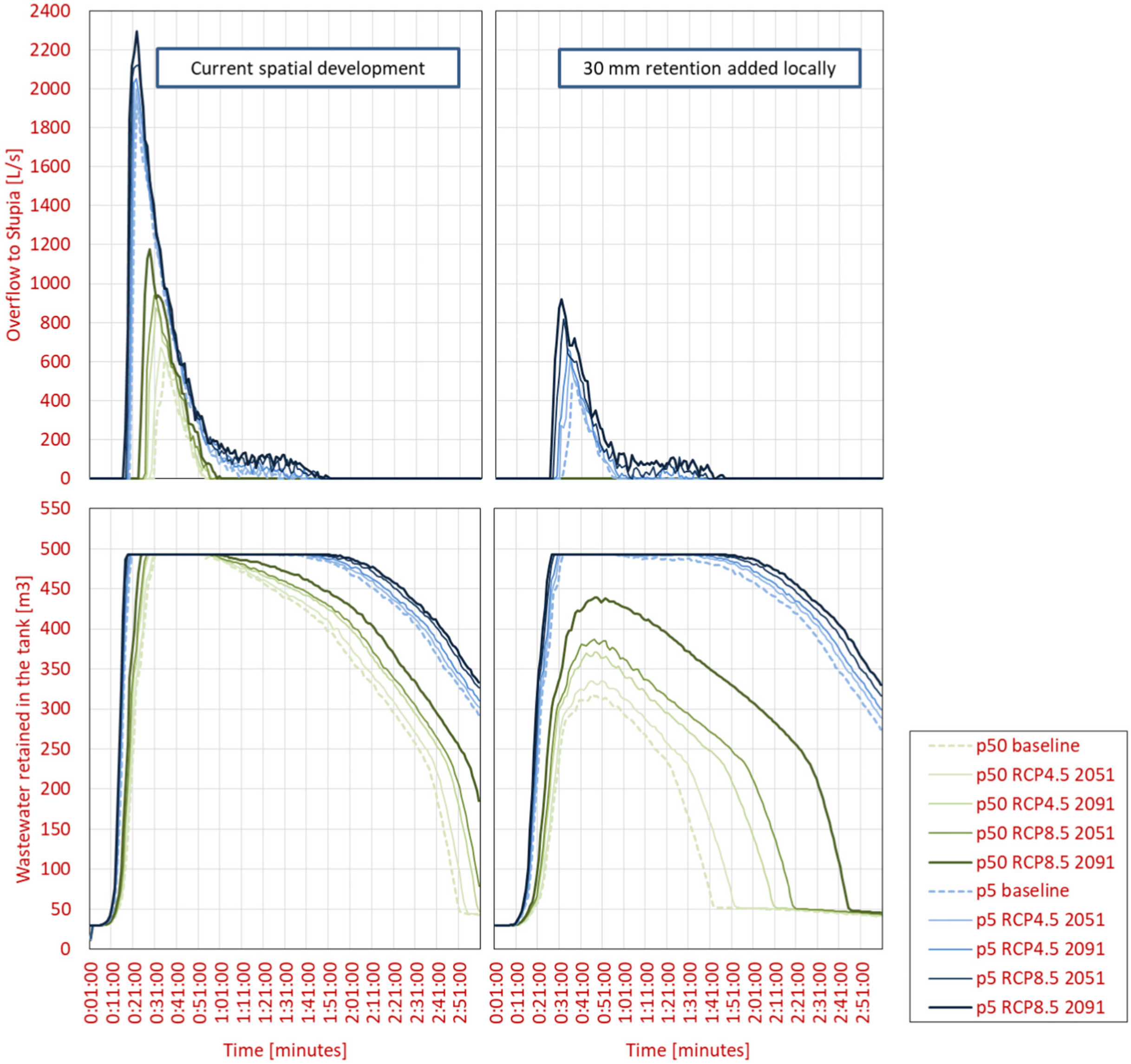

Fig. 7. Impact of changes in spatial development based on stormwater retention scenario on the CSO.

acceptable by end-users (municipalities and companies responsible for the stormwater and wastewater management), while the larger scale is required to confirm the applicability of the proposed methods and the possibility to support more ambitious objectives, such as the protection of surface waters.

In the case of the presented study, the local impact can be confirmed relatively easily. The increase in flood risk as a consequence of projected climate change and the decrease in risk as a result of mitigative measures (stormwater retention before pipe) were proven using the hydraulic model calibrated beforehand based on the observed flow rate in the sewage system. The costs of the mitigative measures investigated can be estimated and compared to the achievable results (savings) in terms of the decrease in the flooding and pollution risks. Therefore, it can be concluded that tools such as the EWL are useful and beneficial (can help to optimise climate adaptation measures) when evaluated on a case-by-case basis. Unfortunately, the number of cases (applications of similar tools) is not large but is growing, e.g. Price et al. (2016), Sharma et al. (2016) and Roseboro et al. (2021) who presented a study of similar scope to that presented here.

At this point, we come to the large-scale evaluation issue, which is more complex – depending on many more factors than the cost-effectiveness. As mentioned above, the applicability can be a limiting factor, and both the technical aspects of the application of the supporting tools should be taken into account as well as the end-user acceptance. The former should not be a significant limiting factor, which is confirmed by numerous applications of model-based and GIS-based decision support systems and reviews of urban runoff models including those dating back to the 1990s and including many already addressing adaptation to climate change (Knapp et al., 1991; Elliott and Trowsdale, 2007; Hu et al., 2020; Wijesiri et al., 2020; Rio et al., 2021; Ferrans et al., 2022). The latter aspect of the applicability – acceptance – seems to be the main limiting factor. This hypothesis was confirmed in November 2021 on a national scale by potential users of the EWL (36 representatives of institutions responsible for stormwater and wastewater management in cities, and of companies offering consultation services/support on this subject) – responders to a questionnaire regarding model-based tools for spatial planning. Over 80 % of the respondents stated that the limiting factor for the wider application of EWL-like tools is the lack of knowledge (awareness) on such tools, and over 60 % of respondents considered the lack of proven accuracy and the uncertainty as limiting factors. The lack of knowledge is what the presented study addresses directly; it includes a successful demonstration of the new tools and dissemination of the knowledge in cooperation with end-users, governing institutions and the municipality, which aims to ensure safe and economically advantageous spatial development. Such a bottom-up approach seems to be appropriate not only to increase awareness about solutions dedicated to spatial planning and adaptation to climate change, but also in a wider context to design smart, sustainable cities (Kuzior and Kuzior, 2020). Therefore, the lack of knowledge is something that quite rapidly becomes meaningless. It is then obvious to bring up what was considered to be a limitation to technology transfer in environmental studies and mathematical modelling from decades ago. First, it was the lack of knowledge and tools available (Orlob, 1979, 1983). At present, most of the interviewed potential end-users of model-based tools stated the same thing, and this is confirmed at a global scale (e.g. by Ranasinghe et al., 2021; European Union, 2020). The tools (mathematical models and model-based spatial tools) are readily available, and similarly, the knowledge has been disseminated by a huge number of guidelines, technical documentations, user manuals and reports, and scientific papers describing case studies. It can therefore be concluded that the lack of knowledge/awareness is caused by the lack of need, or rather the lack of knowledge about the existing need to apply advanced tools capable of optimising urban spatial planning.

The second most important limiting factor specified by the interviewed end-users was the uncertainty of the systems such as the EWL and the inputs used. An analysis of uncertainties related to climate change projections is out of the scope of this study. EuroCORDEX-based projections have been the subject of numerous validations and downscaling exercises (Halsnæs and Kaspersen, 2018; Padulano et al., 2021) including those done as a part of the KLIMADA 2.0 project – a source of data used in the reported study (Struzewska et al., 2020). To ensure that the analyses include the full range of possible climate changes, the mid-range and the long-range forecast were taken into account, as well as two Representative Concentration Pathway (RCP) scenarios, i.e. RCP4.5, which can be considered as reflecting the current commitments according to COP21 and COP22 – the moderate climate change scenario, and RCP8.5, which reflects the ongoing greenhouse gas emissions (Halsnæs and Kaspersen, 2018) and can be considered to be the severe climate change scenario. The uncertainty related to climate projections can be relatively large and has to be taken into account, however, this can (or needs to be) accepted by decision-makers because climate projections are officially adopted in national and regional policies and action plans (Adger et al., 2018), (e.g. “White paper – Adapting to climate change: towards a European framework for action”, “An EU Strategy on Adaptation to Climate Change” and “Guidelines on developing adaptation strategies” by the European Commission), and national documents such as: “Polish National Strategy for Adaptation to Climate Change with the perspective by 2030” and “Urban Adaptation Plans for cities with more than 100,000 inhabitants in Poland”. Given the foregoing, if the applicability of EWL-like tools is limited by the unknown accuracy of the results, the sources of uncertainty to be minimised or explained in the dissemination activities may result mainly from the inadequate models used or inadequate method of applying the model and from the poor quality of insufficient input data. These sources of uncertainties are known to experienced modellers and are addressed by numerous publications and guidelines aimed at improving the efficiency of decision support tools (e.g. D'Erchia et al., 2001; Calder et al., 2018; Moges et al., 2021).

Regardless of all of the factors that may, to some extent, limit or delay the application of model-based tools capable of including climate change risk assessment in urban spatial planning, there is a need for such tools. Such a need is articulated both by governing institutions such as the European Commission and the research institutions that provides the tools, expertise and a knowledge-base on the problem to be solved – in this case, large-scale pollution by urban runoff which can be the main source of selected pollutants in surface waters (Pistocchi, 2020).

4. Conclusions

The Extreme Weather Layer (EWL) presented in this study demonstrated the capability of supporting urban spatial planning by including the aspect of climate change-driven risks posed to urban drainage systems in the decision-making process. The EWL proved to be useful in estimating the current and future flood risk which will increase considerably taking into account even the least severe climate change scenarios. The tool, combined with runoff quality measurements, also made it possible to estimate the pollution load discharged during the current and forecast rainfall events in the form of spillages (urban flooding) and CSOs to surface waters. These loads may be considered to be insignificant when one city is analysed, but on a larger scale, the urban runoff can be considered to be a primary source of individual pollutants. Thus, the EWL combined with the systemic approach of turning grey into green infrastructure could be a smart tool for implementing NBS solutions for stormwater management in climate adaptation in urban areas. This smart tool could indicate how much more green infrastructure we need and in which places of the city the mitigative NBS measures would help significantly.

It is important to remember that stormwater quality parameters are unique and valid only for the specific catchment. Therefore, validation of the results should be carried out only for this specific catchment area.

Further activities aimed at the optimisation of the urban stormwater and wastewater systems, and the spatial planning are required above all else. What is still needed, however, is for awareness to be raised not about the EWL, but about its potential and the need to apply such tools.

CRediT authorship contribution statement

Karolina Fitobór – Methodology, Formal analysis, Investigation, Writing - Original Draft, Writing - Review & Editing
Rafał Ulańczyk – Methodology, Software, Validation, Formal analysis, Visualization, Writing - Original Draft, Writing - Review & Editing
Katarzyna Kołecka – Resources, Writing - Original Draft, Writing - Review & Editing, Project administration
Klara Ramm - Writing - Original Draft, Writing - Review & Editing, Funding acquisition
Iwona Włodarek - Writing - Original Draft
Piotr Zima – Methodology, Supervision
Dominika Kalinowska - Investigation
Paweł Wielgat - Investigation
Małgorzata Mikulska - Investigation
Danuta Antończyk - Investigation
Krzysztof Krzaczkowski - Resources
Remigiusz Łyszyk - Project administration, Funding acquisition
Magdalena Gajewska – Conceptualization, Writing - Original Draft, Writing - Review & Editing, Project administration, Supervision, Funding acquisition

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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