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Review

Stormwater Management in the City of Warsaw: A Review and Evaluation of Technical Solutions and Strategies to Improve the Capacity of the Combined Sewer System

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Abstract: Urban flooding is an increasingly common phenomenon around the world. The reasons are usually attributed to the insufficient capacity of the combined sewer system and its inability to adapt to the changing dynamics of rainfall. This is also the case in Warsaw (the capital of Poland), where the sewage system was designed in the 1960s. The aim of the article is to highlight possible hydrological solutions that would significantly improve Warsaw's situation in terms of rainfall runoff. The article looks at some solutions that were previously mentioned in the literature and presents an assessment of the possible changes in land use/land cover on the hydrological processes and improvements in the general hydrological situation of Warsaw. In addition, the article points out the need to update the programme and spatial approach to the discharge of water from specific watersheds in Warsaw, as well as to establish a single manager for stormwater drainage in the city of Warsaw. An important issue is the restoration of natural retention basins in the city and the construction of artificial basins in places with frequent local flooding. The article emphasises the importance of building individual detention basins (as well as low-impact developments) for newly planned investments. Other important aspects are as follows: the construction of suitable underground or open channels, the need to disconnect Ursynów's stormwater runoff from the catchment area of the Służewiecki Stream and to channel it along the southern bypass for Warsaw (S-2) to the dry lakes and ponds in Wilanów. Finally, the article discusses the application of Sustainable Drainage Systems (SuDS) and Real-Time Control (RTC) in urban drainage systems as a possible solution to improve wastewater management in urban areas.

Keywords: urbanisation; urban flood; rainfall run-off process; stormwater management; Służewiecki Stream Catchment; real-time control (RTC); Sustainable Drainage Systems (SuDS); Water-Sensitive Urban Design (WSUD)

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1. Introduction

Rapid urbanisation is contributing to an increase in flood risk in large cities by impeding their stormwater runoff [1–5]. In some cases, urbanization has led to a several-fold increase in the volume of surface runoff [3–5]. A natural consequence of urbanization is an increase in the size and frequency of floods. In other words, the consequences of urban development are a higher peak runoff and higher flood frequency [3]. Kanclerz et al. [5], for example, showed the impact of urbanisation of the suburbs of the city of Poznań on water conditions in the catchments of the "Dopływ spod Lusówka" and "Przeźmierka" watercourses. In these catchments, a fivefold increase in urbanised areas was observed for the catchment area of the "Dopływ spod Lusówka" and a ninefold increase for the catchment area of the "Przeźmierka". As a result of the increasing impermeability of the catchment area, the effective amount of precipitation increased, leading to a rapid runoff of rainwater and an approximate doubling of the discharge in the watercourses.

The higher intensity of rainfall runoff being experienced in the city of Warsaw at present is a consequence of the urbanisation process of the catchment areas, which is obviously accompanied by an increased proportion of impervious and channelised surfaces [6]. The capacity of the sewage network is reaching its limits and, as a result, local flooding is becoming more frequent in the catchment area [7]. As a result, heavy rainfall leads to flooding, which causes traffic problems and material losses for some Warsaw residents.

One of the most important causes of flooding in cities is the change in rainfall patterns. Rainfall is often torrential, as 3/4 of the average monthly rainfall can fall within 30 min. In general, rainfall can be said to occur less frequently but in greater amounts. The city's rainwater collection systems are not equipped to handle such intense rainwater flows. The high percentage of concreted areas in the city is also an important factor. The water that now flows over streets and pavements would normally infiltrate and feed groundwater. Squares and courtyards where paving stones or asphalt driveways have been laid do not allow for water to percolate (see also Figure A2 in Appendix A). Instead, they cause rapid runoff towards the lowest lying areas. The water supply system in Warsaw is over 4000 km long, but is not capable of draining this amount of water. A number of investments have already been made in this direction, but more are needed. For example, the "Czajka" retention basin (i.e., the local wastewater treatment plant) has already been built (and has been operational from 2020), which can hold an additional 80,000 L of water [8]. In addition, huge transmission and retention collectors are being developed. These will improve water retention in the coming years. Investments have also been made in a wastewater network management system that will enable the diversion of rainwater.

Due to the increasing frequency of local floods, which are usually accompanied by heavy rainfall [9–12], solutions should be considered that will effectively minimise the risks of their occurrence, and thus protect the inhabitants of Warsaw (and other major cities) from transport difficulties (which usually accompany such phenomena), material and environmental losses.

The article is structured as follows. In Section 2, we discuss the risks associated with the possibility of flooding or inundation in Warsaw from the Vistula River in connection with smaller watercourses such as the Służewiecki Stream. Furthermore, in this section we identify uncertainty factors associated with climate change and set the context for the adopted standards for the design of wastewater systems (in Poland). Section 3 presents the historical and legal background of the Służewiecki Stream. The Służewiecki Stream is one of the smaller watercourses that cause frequent and most severe flooding in the southern part of Warsaw, more specifically in districts such as Mokotów, Ursynów and Wilanów. In this context, Section 3 also addresses some accusations of negligence on the part of those responsible. Section 4 is devoted to discussion and presents some solutions that the authors believe can contribute to the better management of stormwater drainage in Warsaw.

It is worth mentioning that there is a whole range of technical measures (technical and engineering devices/facilities) and various activities (including organisational ones) that make it possible to reduce (slow down) the problem of stormwater runoff and the occurrence of floods in large cities such as Warsaw.

Please also note that, in addition to the references to a large number of publications, we have also included Table A1 in Appendix A, which, in a sense, summarises the most important studies dealing with the hydrological problems of the city of Warsaw. Our aim is to briefly characterise these works and show their contribution to the understanding and analysis of Warsaw's hydrological problems, thus further expanding the literature in this field.

To illustrate a number of problems related to the city's water management and the resulting problems presented in the study, we will use various case studies (Praski Harbour, Fort-Bema, Lake Zgorzały, Służewiecki Stream Catchment, etc.) and Pierce's abductive reasoning to develop the best explanation [13]. In other words, we will prove the scientific problem raised in the introduction in the form of various case studies and stylised facts, which is in line with scientific principles and this type of research method [14].

2. Materials and Methods

2.1. Risk of Flooding from the Vistula River

The flood risk in Warsaw is twofold. On the one hand, the greatest risk is the possibility of flooding due to the large volumes of water from the Vistula. In this case, the area at risk of flooding (p = 1%) is about 75 km^2 [15]. The flooded area is located on both banks in the river valley. The second type of risk is associated with the other watercourses, which have a much lower flow compared to the Vistula, but can also cause major flood damage due to dense development and the solidification of the catchment area (i.e., the process of solidification) as a result of urbanisation. For example, the area of the Długa River in the Białołęka district, which floods with a probability of p = 1%, is over 9.575 km^2. Other watercourses that may cause flood damage are the Służewiecki Stream with the Wolica Canal, the Regułka River, which has been converted into the U1 drainage ditch, the Wawerski Canal and other smaller watercourses.

As far as the danger of flooding by the great masses of water in the Vistula is concerned, the factor that determines the degree of flooding danger is the flow of the river. The Vistula in the Warsaw section is characterised by floods caused by precipitation as well as by snowmelt and damming floods. Theoretically, we can estimate the risk of the river overflowing by estimating the extent of a ten-year, hundred-year or even a thousand-year flood (water).

The water is kept in check by dikes, which, in Warsaw, are prepared for a thousand-year water, i.e., with a flow $Q_{p0.1\%} = 9960$ m^{3}s^{-1} [16]. However, there is always some uncertainty about their durability. If the flood wave in the river lasts for only a relatively short time, the danger is usually rather negligible (low). However, if it lasts for a long time, or, as in 2010, two flood waves come one after the other, the water can seep through the levee body. It should be remembered that the dikes were built in the 19th century and the technology and foundation of the dikes still date to that time [15]. In their study, Magnuszewski et al. [17] presented the flood levels (i.e., flood stages) observed in the Warsaw section of the Port Praski profile over the last 200 years. In the studied period, the maximum discharge occurred during the flood of 1844 and was 8250 m^{3}s^{-1}. Theoretically, the 2010 flood was caused by a flow of 5899 m^{3}s^{-1}, which was preceded by a dike breach in four places on a section of the upper Vistula [17].

The risk is very high when houses are located in a flooded area. The situation is worse in the lowest lying areas, i.e., Czerniaków, Wilanów, Saska Kępa and Gocławek. For years, there have been disputes about the spatial plans for these areas in connection with flood policy. This is undoubtedly a major dilemma and local authorities have different positions on these issues. There was an idea to make the 100-year flood boundary mandatory in the local plans as an area with limited development. This was strongly protested by the communities. Nevertheless, new housing estates are constantly being built in these areas (both in Wilanów and Gocław).

In the last five years (i.e., 2016–2021), investments in flood protection to prevent flooding in flowing waters have significantly slowed down. They are now to be carried out by the State Water Holding Company Polish Waters with the money collected from companies and private individuals for water and wastewater [18]. These funds, which are borne by every owner of a fortified plot of land over 1000 m^2, are considerable, but from the perspective of national necessities, investments in flood protection in the Warsaw area are hardly to be expected [18].

Between 2011 and 2015, 1314 km of dykes were built in the country, and between 2016 and 2019, only 119 km were built. Data for 2020 are not yet available. The quantitative distribution of built and modernised dikes (the Central Statistical Office summarises this and does not provide separate data for newly built and modernised dikes) is shown in Figure 1.

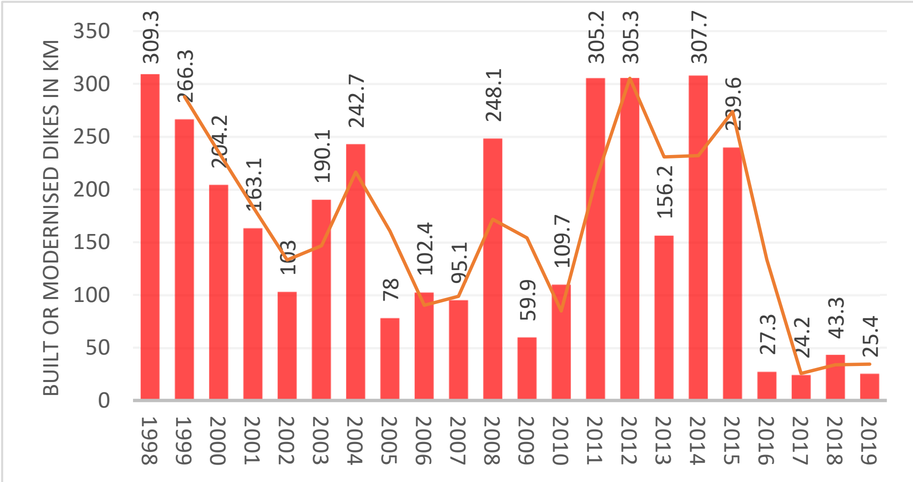

Figure 1. Built and modernised flood dikes (in kilometres) (source: own elaboration based on Central Statistical Office data).

In turn, local authorities allocate less funds for investment because there have been additional burdens, e.g., expenditure on health care, education, and expenditure related to COVID-19 [19]; there is also less tax revenue from Warsaw-based companies and revenue from property and real estate tax [18]. The policy of the central government, which reduces the revenues of local governments from year to year, is also significant [18]. Therefore, citizen initiatives and social pressure are necessary to obtain EU funds for the development of stormwater infrastructure, to which developers, municipal enterprises and residents will also contribute through their own property management. Planning infrastructure investments with the participation of the various stakeholders is a multi-year process.

Considering the regulations on the financing of flood protection infrastructure by municipalities, joint actions with the State Water Holding Company Polish Waters require decisions on the introduction of expenditures into the strategy, long-term investment plans and budgets for individual years. This process takes at least 2–3 years from the moment of defining joint actions [18]. Despite the many obstacles, this seems feasible. The implementation of such investments would be much easier if there was a single administrator and a single body responsible for water facilities in a city such as Warsaw. Proof of the city's ability to engage in water investments is the construction of a flood gate with a chamber and a navigation sluice head at the entrance to Praski Harbour (The construction of a floodgate with a sluice chamber at the entrance to Praski Harbour in Warsaw was chosen as the Construction of the Year 2020 by the Polish Association of Civil Engineers and Technicians. It is part of the hydrotechnical infrastructure of Praski Harbour in Warsaw), built with money from private investors [20,21]. The developer of the housing estate was only a cash intermediary [21]. It is worth noting that this investment had been planned for many years, as the 100-year-old water threatened large parts of the Prague district. There were never enough budgetary funds for its implementation [21]. Thanks to the flood control sluice at the entrance to the harbour, the risk of flooding was minimised by reducing the fluctuations in the water level in the harbour [21].

After the dams in Powsin, Wilanów and Białołęka were extended, the city of Warsaw became safer from the Vistula. The flood embankments along the Wał Miedzeszyński and the Białołęka on the Długi River side still need to be rebuilt [22]. Larsen truss walls must be installed there to strengthen the embankments on sandy soil in urban areas, because the floods in recent years have shown that intense rainwater (after accumulation) tends to break the embankments by washing away the soil or by infiltration into beaver nesting channels [23].

According to Goździewski and Giżejewski [23], beaver activity in the immediate vicinity of watercourses can cause damage to spread over longer stretches of watercourses or water meadows. There will undoubtedly be negative environmental impacts if beaver constructions weaken dikes, which can lead to flooding, with catastrophic effects on the environment. Such activities have been observed in the floodplains of the Vistula River, which were not only weakened by waterlogging, but also led to local scouring and collapse of the soil.

Larsen truss walls are particularly suitable for reinforcing dams in hydraulic engineering and for direct foundations on waterlogged soils [24,25]. They can also be used to regulate rivers and canals and to seal flood embankments [24]. An example of the implementation of appropriate engineering and structural protection in the form of Larsen sheet piles is presented in the work of Sondaj and Górecka-Żwirska [24].

In addition, there are still flood protection requirements in individual districts that are complicated to implement in the current legal system, as the example of the Służewiecki Stream, addressed in this article, shows.

2.2. Risks Related to Other Watercourses

As previously mentioned, in addition to the threat posed by the large waters of the Vistula, flood hazards from smaller watercourses also pose a significant risk. Measures taken by Warsaw authorities to identify flood hazards from smaller watercourses are as follows [15]:

- Reconstruction of the hydrological system comprising the Służewiecki Stream and the Wolica Canal to secure the lower section of the Służewiecki Stream against flooding [26,27];
- Programme and spatial concept for the reconstruction of the Długa estuary [22];
- Construction of the spillway between the Brzezinski Ditch and the Bródnowski Canal;
- Construction of a stormwater drainage system in the catchment area of the U-1 ditch.

As far as these smaller watercourses are concerned, the Służewiecki Stream causes the most problems [15]. In the catchment area of the Służewiecki Stream, excluding the "Okęcie" airport, an area of 19.95 km^2 is drained by stormwater drains, which corresponds to 37% of the catchment area; the length of stormwater drains is 220.7 km. The valley of the lower Służewiecki Stream is not protected from flooding to an appropriate extent, considering the land use. The maximum water emerges from the banks with a probability of less than 50%, causing flooding and waterlogging. The capacity of the Wolica Canal is less than the potential outflow of the stormwater channel and there is a risk of dams overflowing. The area at risk of flooding is 1.6 km^2 with a probability of 1%. The risk of flooding is assessed by simulating the probability of flooding (determining the probable flows), which is unfortunately a very complicated task. Performing this type of calculation (simulations) is associated with a high risk of error, related to the lack of homogeneity in the runoff for a large catchment area. In this context, Barszcz [6] points out the high index of area variability in runoff for the catchment area of the Służewiecki Stream, which is characterised by an area of 59.73 km^2 [27] (see Figure 2).

Barszcz [6] particularly points out the mosaicism (land use/land cover) of the subcatchments, which vary with their discharge rate. The problem of the lack of homogeneity of the drainage areas lies in the fact that each sub-basin has a different specificit and, thus, different runoff rates (see Figure 3).

In addition to the mosaic character of the land surface, there is a high degree of urbanisation of the catchment area, as well as its facilities (infrastructure), which slows down runoff (mainly retention basins, but also natural ponds or dams) and the specificity of the sewer network itself, whose purpose is to ensure the flow of rainwater [6,26,27].

Barszcz [6,28–30] has thoroughly analysed the case of the urbanised catchment of the Służewiecki Stream and carried out a corresponding simulation based on the Storm Water Management Model (SWMM) and the conceptual model, called Santa Barbara Urban Hydrograph (SBUH) [31,32], and developed forecasts for discharges with a certain probability of exceedance.

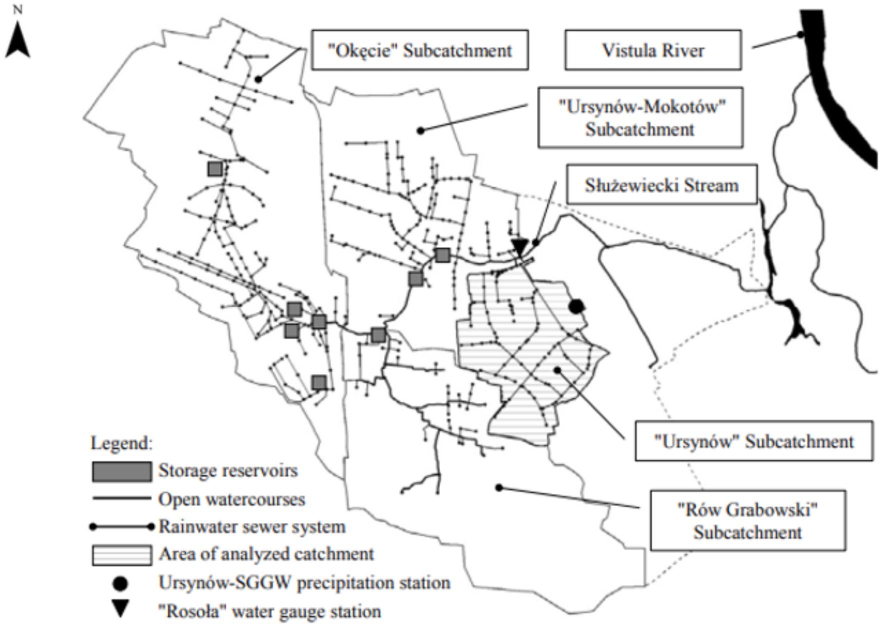

Figure 2. Catchment area of the Służewiecki Stream up to the "Rosoła" measurement profile (Source: M.P. Barszcz).

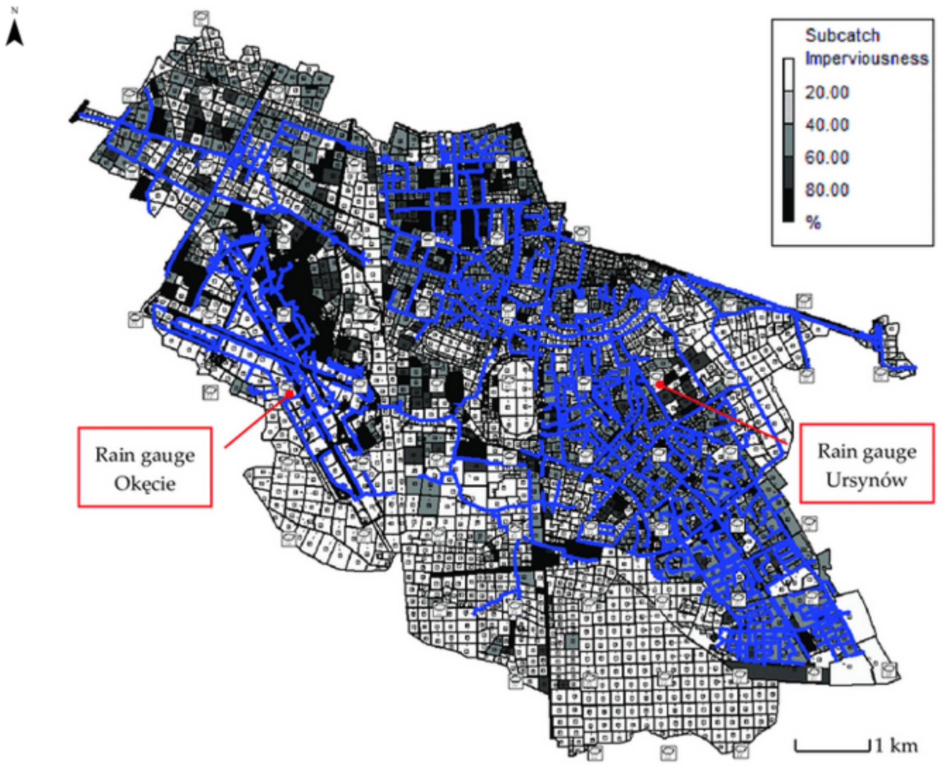

Figure 3. Służewiecki Stream Subcachments (note: stormwater sewer system and channels are marked in blue).

2.3. Climate Change Risk

Extreme climatic phenomena have increased in recent years. Precipitation events occur either unexpectedly or over many days (accumulation) and lead to flooding and, subsequently, to sewer flooding. These increasing natural phenomena lead to measurable economic losses. To remedy (counteract) this, appropriate measures should be taken, prepared and implemented in good time.

According to climate scientists, weather anomalies are steadily increasing [33,34]. Rapid urbanisation and climate change make urban communities more vulnerable to natural hazards, and weaken the resilience of cities [35]. It is recognised that an excessively rapid urbanisation process significantly contributes to climate change by, among other things, altering the carbon cycle and other biogeochemical processes [36]. As far as Warsaw is concerned, the maximum precipitation amounts, i.e., the amounts during the heaviest rainfalls, are constantly increasing. Moreover, the highest daily precipitation falls in the outskirts of the city (and not in the centre); more precisely, in the southern part of Warsaw, in the areas of Mokotów, Wilanów and Piaseczno (see Figure 4).

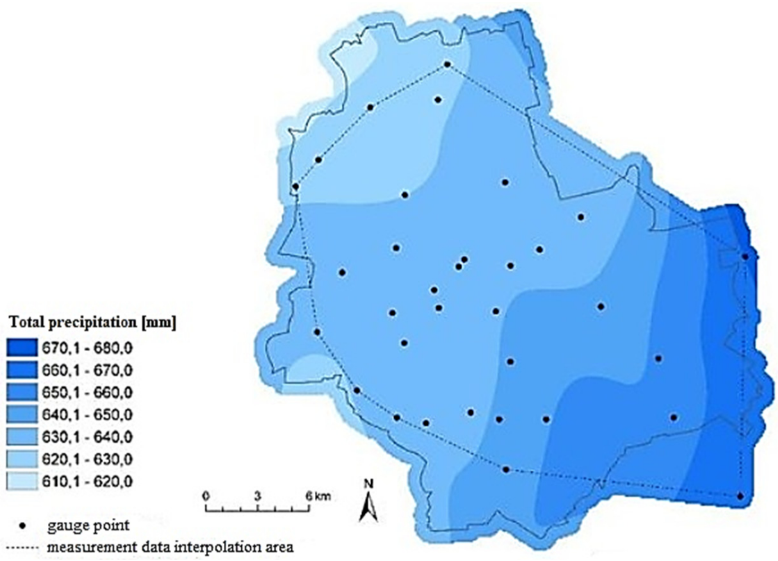

Figure 4. Total annual precipitation in the city of Warsaw—averaged over the period 2008–2014 (Source: Department of Geoecology and Climatology IGiPZ PAN).

This phenomenon can be defined as a precipitation jump. The city becomes a heat island due to the nature of the soil and the degree of urbanisation, i.e., the increasing number of buildings from year to year. This can be associated with convection clouds and the impingement of heated air masses on the city; the extra energy reaching the city is released at the city boundary. Therefore, designers of drainage systems should address these climate issues and create systems that can withstand rainfall runoff.

Figure 5 shows daily precipitation for the period from January 1952 to May 2022 for the measuring station at Okęcie Airport (precipitation in mm). Due to missing data, the data for the period from January 1964 to December 1972 are not included in this graph.

It should also be made clear that the weather in Poland in recent years has been exceptionally favourable compared to the scale of flood damage in northern Germany, the Netherlands, Belgium and France in 2021, although it has not been without some localised flooding in southern Poland and some summer storms that have not spared Warsaw. More specifically, in 2021, there were some local floods in Warsaw districts such as Mokotów, Ursynów, and Wilanów. Streets, metro stations, the railway tunnel across the city and the basements of residential buildings were flooded [10,12]. One such significant heavy rainfall occurred on the evening of 12 July 2021, when a very strong thunderstorm front arrived over Warsaw in the evening and the intense rainfall caused localised flooding. The districts of Ursynów and Wilanów were the most affected. Part of the Służewiecka Valley was underwater. The measuring station at Okęcie Airport recorded 26 mm of precipitation and the water level of the Służewiecki Stream was very high, causing local flooding. According to the Institute of Meteorology and Water Management (IMGW), daily rainfall exceeded the monthly norm. The previous year was no different, when there were also numerous local floods in districts such as Mokotów, Ursynów and Wilanów [9,11]. This suggests that it would be worth taking some significant investment measures to prevent such incidents in the future. However, under the current legal system, it is difficult to implement investments in stormwater drainage in large municipalities such as the city of Warsaw, as responsibility for individual water facilities in Warsaw is divided [18]. Investments to protect the Vistula River, the Służewiecki Stream, the Wawerski Canal, the Długa River, and other watercourses classified as flowing waters, fall under the responsibility of the State Water Holding Polish Waters, established in 2016. The State Water Holding Polish Waters was formed from the melioration and water institutions of the provinces and the regional water management offices [18]. Stormwater drainage in the city is the responsibility of the Municipal Water Supply and Sewage Company, as well as the independent managers of housing cooperatives, housing associations, municipal and private companies, and private property owners. It is, therefore, difficult to identify the culprit for the floods in a particular area of the agglomeration, especially in the catchment area of the Służewiecki Stream.

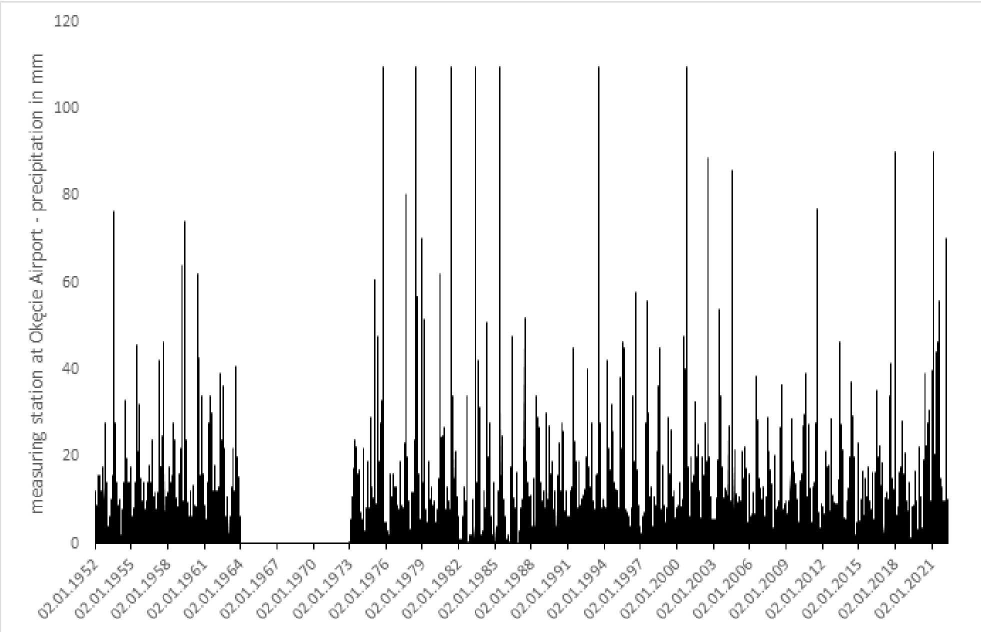

Figure 5. Warsaw Okęcie Airport measuring station—Daily Precipitation in mm (source: own elaboration).

Long-term climatology and forecasting are addressed by experts and scientists working within the Adaptacity project [37]. As far as the climatological findings of the Adaptacity Project are concerned, both trend analysis and simulations indicate that more precipitation can be expected in the future, while the length of the dry periods remains unchanged. The overall picture shows that the annual amount of precipitation in Warsaw has increased by more than 100 mm over the last 40 years, although the number of rainy days has remained the same. This means that the number of heavy rainfalls has increased, and more water falls on Warsaw in the same period. As Figure 6 shows, the projections until 2090 indicate a significant increase in annual precipitation (especially in the southern part of Warsaw, where the catchment area of the Służewiecki stream is located) [37]. The fact is that both the number of days with intense precipitation (over 10 mm of water/m^2) and higher individual precipitation values (over 90 mm of water/m^2) are increasing. Analysts predict that this trend will continue in line with climate change scenarios in the city. In particular, the number of short-term, heavy precipitation events that cause flooding will increase (Figure 6). This will not only cause traffic problems but will endanger the property and lives of people who are within the reach of rapidly rising water.

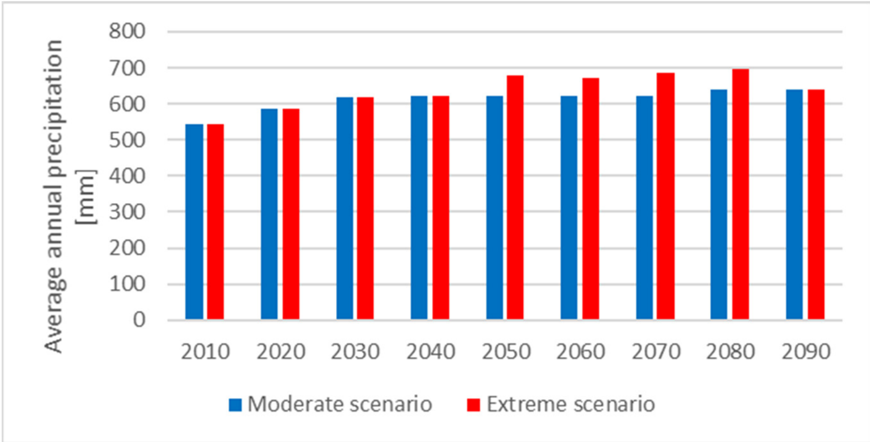

Figure 6. Precipitation projections to 2090 under an extreme climate change scenario (measuring station Bielany).

There are an increasing number of precipitation events where more than 10 mm of water per square metre falls in less than an hour. For example, in June 2010, 80 mm of precipitation was recorded in Warsaw on a single day. The Adaptacity project identified the most vulnerable districts in Warsaw. This analysis shows that the central districts of the city seem to be spared from the most extreme rainfall, as it passes by the central part of the city; in these central districts, rainfall is more frequent but less intense. Most of the rain clouds pass over the city from the northwest; however, even so, the heaviest rain falls on the opposite side of the city to the east and southeast (as shown in Figure 4). This is the picture that emerges from a comparison of the annual rainfall totals.

There are many factors that can influence these precipitation characteristics in Warsaw. One of the factors is the surface topography, which is reflected in the digital elevation model (DEM) and slope (% rate) in Figure 6. In this context, it is worth noting that the districts on the left bank are both higher in elevation and have higher built-up areas compared to the districts on the right bank. This means that the clouds move laterally around them, as is the case in mountainous regions. However, one should not ignore, for example, the issue of air circulation or air pollution, which could also be reflected in the overall precipitation pattern. In this context, it should also be noted that large quantities of pollutants over the city can exacerbate the precipitation phenomenon if clean air masses form around them in which there is no precipitation. In addition, there is the stack effect (a.k.a. chimney effect), i.e., the different air temperatures in the different regions of the city. As a rule, hotter air forms in the centre and cooler air forms in the surrounding areas, resulting in a strong upward pull of air mixed with raindrops. This phenomenon causes the precipitation to be flung into the outer districts of the city.

There is a lot of impervious surface in Warsaw, and about 40% of the capital's surface does not allow for 80% of rainwater to pass through, which is why heavy rainfall is particularly dangerous in this city. The water does drain into the sewage system, but since this was designed in the 1960s, it does not have sufficient capacity. This is the reason that there is so much local flooding and inundation in this city due to flash floods. Heavy rainfall events are thought to occur when the total rainfall exceeds 50 mm per day. Such weather events occur several times a year in Warsaw. They lead to numerous floods. The probability of their occurrence is p = 1.5%. This is visually confirmed in Figure 5.

Of course, there is a whole range of water installations to solve the problem of excess water during heavy rains. For this purpose, in addition to sewers, there are gutters, drainage ditches, etc. However, both the drainage ditches and the smaller watercourses flowing through Warsaw are often insufficient to cope with the excess water in the city. In addition, the combined nature of the city's sewage system leads to problems with wastewater treatment during heavy rainfall (see Figure A1 in Appendix A). In critical situations, the responsible bodies are forced to discharge the wastewater directly into the Vistula. However, there are also solutions, which mean that all rainwater does not necessarily have to be discharged into the Vistula through the sewage system or drainage ditches. Such solutions include absorption basins, permeable asphalt, green roofs, lawns lowered in relation to the streets or rain gardens. The concept of the so-called sponge city is also becoming more popular [38–40]. This type of solution retains water, preventing street flooding, but also allows for it to be used during periods of low rainfall.

Of course, there are other climate characteristics besides rainfall that are important when conducting a flood risk analysis. For example, the variation in rainfall-induced runoff over long-term changes. To explain this, it is important to refer to hydrographs. The issue of hydrographs has already been addressed by many other scientists [41–43]. In total, there are seven parameters that influence the occurrence of floods [44]. Apart from rainfall intensity, the other factors include the following: runoff accumulation, distance from the river network, elevation, land use, surface slope and geology. To illustrate some of the above parameters, we display professional maps: DEM, slope (% rate) (Figure 7), a real satellite image and land-use classes in the legend (see Figure 8). Please note that the catchment area of the Służewiecki stream is clearly marked with a red line against the background of the entire Warsaw urban area.

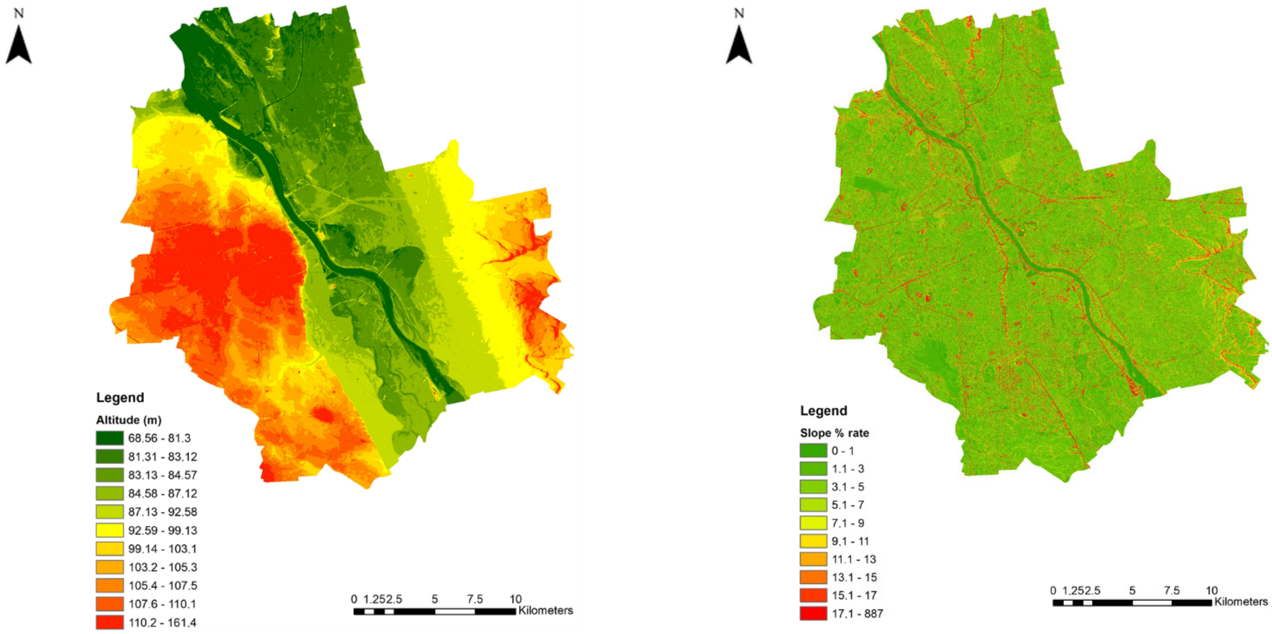

Figure 7. Digital Elevation Model (DEM) and slope (% rate) map for the city of Warsaw.

The digital elevation model and the slope (% rate) maps for the Służewiecki catchment are presented in Figures A3 and A4 in Appendix A.

In this article, we not only look for studies and papers that have already addressed Warsaw's hydrological problems, but also for possible solutions, and conduct an analysis that can contribute to further public discussion that will stimulate decision-making by local authorities and the State Water Holding Polish Waters.

2.4. Standards for Sewage Systems

Ongoing urbanisation and changing climatic conditions necessitate an appropriate review (stress testing) of existing wastewater systems (in terms of the need to upgrade them) regarding to the hydraulic capacity of networks and facilities. In particular, based on suitable hydrodynamic models, the overflows of the sewers need to be examined, considering various parameters (time and space) with regard to the load of variable precipitation.

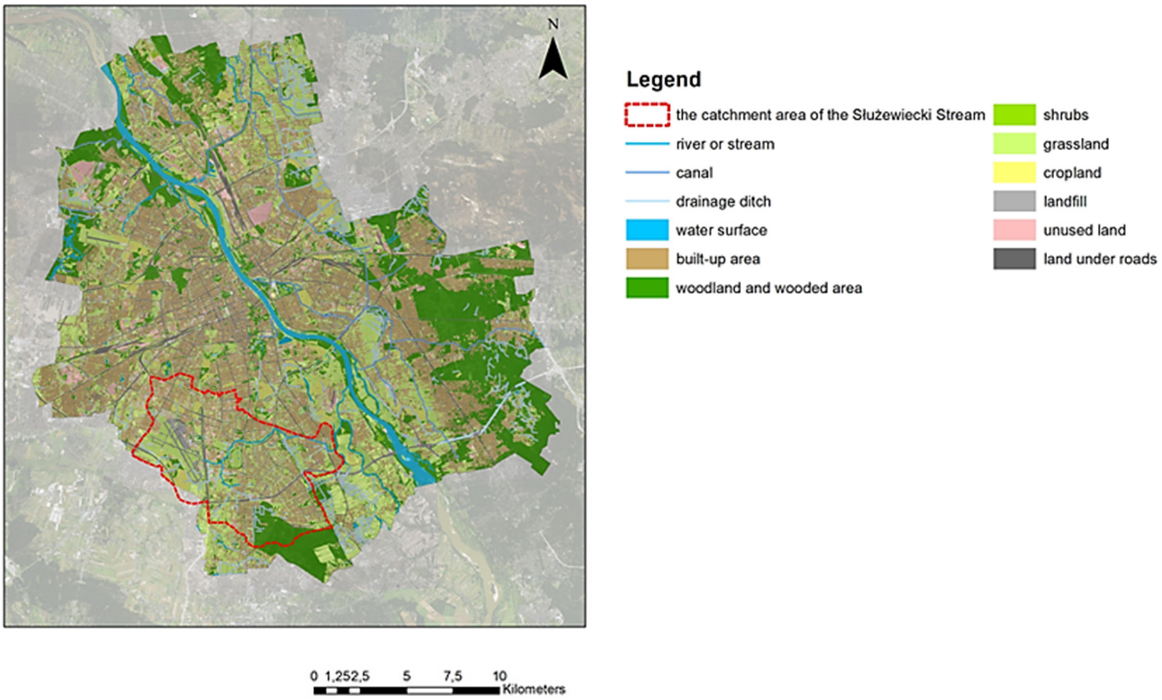

Figure 8. A real satellite image and land use classes for the city of Warsaw.

The standard: PN-EN 752:2008 describes the recommendations (and procedures) for reviewing the frequency (of stormwater overflows) and sewer overflows in the context of the reliability of the functioning of sewage systems [45–48]; such a review is required and enshrined in Polish law, which is dealt with in the Order of the Minister of Environment of 2014, (*Ordinance of the Minister of the Environment of 18 November 2014 on the conditions to be met when discharging wastewater into water bodies or into the ground and on substances that are particularly harmful to the aquatic environment. Official Gazette. Republic of 16 December 2014, item 1800*) although it has not been put into practice.

Automatic rain gauges used by water and wastewater companies allow for the production of model rainfall hyetograms and intensity–duration–frequency (IDF) curves [49]. The latter show the relationships between rainfall duration, rainfall intensity (or rainfall layer) and the frequency of their occurrence. Model rainfall hyetograms make it possible to simulate the operation of drainage systems in hydrodynamic simulation programmes such as SWMM or GoldSim.

In the modernisation and expansion of a drainage system, it is necessary to use appropriate computer software [50]. However, the lack of suitable input data (including flows in the drainage systems and rainfall) and of a suitable modelling methodology, is cited as the reason that this scheme is not applied in practise. In any case, the already existing methods are considered not quite adequate (not meeting expectations) [7].

As the nature of precipitation introduces an uncertainty factor (random/stochastic) and cannot be predicted (over long-term horizons), it is acknowledged that storm sewers and combined sewers (i.e., entire drainage systems of urbanised areas) are subject to periodic disturbances or interruptions in their function (i.e., they are not and cannot always be completely reliable) [7].

The standard currently in force in Poland for the drainage of urbanised areas (safe design) is the standard PN-EN 752:2008. In short, the consideration of a reasonable, socially acceptable frequency of maximum stormwater flows per specified area is recommended when designing drainage systems. These maximum frequencies of water flooding are specified in more detail in this standard. For residential areas, the frequency is assumed to be 1 (flood/overflow) in 20 years (for urban areas 1 in 30 years as shown in Table 1). One way to protect against flooding is to safely size wastewater.

Table 1. Computational rainfall and flood occurrence.

Design Rainfall Frequency (1 in C Years)	Land Use	Frequency of Occurrence of Floods (1 in C Years)
1 in 1	Rural areas	1 in 10
1 in 2	Residential areas	1 in 20
1 in 5	City centres, service and industrial areas	1 in 30
1 in 10	Underground transport facilities, street crossings, etc.	1 in 50

It is becoming common engineering practise to integrate insights from the field of probabilistic and statistical (econometric) modelling into traditional urban hydrology modelling. A generally accepted principle of design is that a reasonable rainfall frequency is assumed, for which runoff is calculated, and the capacity of the designed wastewater system cannot be less than the correspondingly determined runoff. The principles of designing wastewater systems, considering their dimensioning according to the frequency of calculated rainfall, are presented in the works of Błaszczyk [51,52], Błaszczyk et al. [53], and Kotowski [54,55], among others.

Wastewater systems are designed so that, when completely filled, the discharge frequencies recommended in the standard (PN-EN 752:2008) are not exceeded. Nowakowska and Kotowski [7] point out that, due to the non-linear movement of fluid in the closed channels of a sewage system, it is impossible to explicitly address the relationship between the frequency of incoming precipitation and the frequency of overflow events. Depending on the depth, diameter and slope of the sewer bottom, there is a possibility that the flow rate will increase even after the sewer is filled due to a further increase in sewage backfilling. Therefore, hydrodynamic modelling is performed for a given sewer system to determine the potential increase in capacity.

To determine (verify) the proper operation of sewage systems, appropriate calculations are made to indicate the overload condition that leads to flooding (in terms of the frequency of overflow to the water table) [7]. However, it is only when water exceeds a certain level (i.e., when roadsides are crossed and water enters adjacent properties or the basements of buildings) that flooding can have serious consequences [7,56].

The basics of the safe design of property drainage are described in Kotowski [6,55]. In Polish conditions, the following methods are used for stormwater drainage systems: constant intensity (MSN) and maximum intensity (MGN) [47], which are based on the precipitation model developed by Błaszczyk in 1954 [57,58]. This model is criticised for assuming too-low rainfall intensity values (according to some researchers, they are underestimated by about 40%). The calculations found in Bogdanowicz and Stachý [59] also indicate that the results obtained with Blaszczyk's model (for C = 2, 5 and 10 years) are significantly overestimated (by about 50%) [59].

The conclusion is that the adoption of incorrect assumptions and the underestimation of certain risk factors (uncertainty factors) have largely contributed to the inappropriate dimensioning of sewage systems in many large cities (such as Warsaw), which has led to a higher number of sewer overflows in recent years [60].

2.5. Sustainable Drainage Systems (SuDS) and Water-Sensitive Urban Design (WSUD)

Although we refer to sustainable drainage systems (SuDS) at various points in our study, it is worth devoting a separate section to this topic, as the concept has gained in importance in recent years [61–63]. Fletcher et al. [61] state that, as cities have become more urbanised, the management of urban stormwater has become considerably more complex, and the terminology associated with urban drainage principles and practises has been greatly enriched by the introduction of a number of different terms, such as SuDS. In short, SuDS are different types of drainage solutions that mimic the natural environmental processes associated with stormwater retention to minimise the negative impacts of urbanisation on surface water management [62,63]. The best-known SuDS solutions are natural vegetation, trees, permeable pavements, bioswales, wetlands, detention basins and green roofs. They allow for stormwater management that resembles the processes found in nature, which greatly facilitates runoff management and volume control, and reduces pollutants entering groundwater. In other words, SuDS is a system for stormwater management in urban areas that complements traditional methods of direct discharge of surface water (via a network of suitable pipes and channels) into the sewer system. Importantly, SuDS solutions reduce negative impacts on the climate, including the urban heat island effect [61,63]. The positive impacts of SuDS are mainly due to the influence of reduced surface runoff, infiltration and increased evapotranspiration [61]. As an environmentally friendly approach, SuDS has many environmental, social and economic benefits [64–67]. Godyń et al. [63] analysed the concept of implementing sustainable stormwater management (SuDS) for a housing estate in Krakow, Poland. In their study, the authors discussed the most popular SuDS solutions for reducing surface runoff, i.e., permeable surfaces, infiltration swales, rain gardens or infiltration basins. The results of their study show the significant effectiveness of SuDS solutions in reducing runoff, but also potential financial savings of up to 10% resulting from reduced stormwater charges (at both national and municipal levels). According to the authors' calculations, the investment for such an exemplary housing estate can pay for itself within 12 years.

Another similar concept, Water-Sensitive Urban Design (WSUD), is also worth mentioning in the context of SuDS and green and blue solutions (as a countermeasure to reduce environmental damage caused by urbanisation). WSUD is a type of stormwater management that focuses on minimising environmental degradation and improves the recreational attractiveness and aesthetics of the city [68]. It can be seen as a somewhat holistic approach to engineering and spatial design that integrates the urban water cycle into the context of urban planning and incorporates the different areas of stormwater management, including groundwater management, wastewater management, water recycling, water storage and water supply, into the design of integrated management of the urban water cycle [63]. The main objective of WSUD is to reduce the impact of urbanisation on the natural urban water cycle. Godyń et al. [63] argue that the commonality of these two concepts is solving the problems of stormwater management in the context of ecological challenges and providing live solutions that are compatible with the natural processes in the environment [63]. The author emphasises that, thanks to the new Water Act of 2017 in Poland, solutions to increase water retention in urban areas are promoted, which is also a new opportunity for Warsaw. This new law aims to support the implementation of solutions that increase groundwater retention, but also the use of rainwater, which should support sustainable urban water management.

Regarding the implementation of SuDS and WSUD in Warsaw, there is no comprehensive study that examines the knowledge on this topic. The knowledge is very fragmented and scattered. Only a few papers by different authors contain topics on this issue [69–72]. However, some sources suggest that Warsaw is not a leader in promoting this type of solution [73]. Although there is no lack of SuDS infrastructure projects in Polish cities, Gdańsk and Wrocław are most often mentioned as pioneers in the implementation of stormwater capture and storage solutions, i.e., in the creation of small-scale retention systems in the form of rain gardens, retention parks and basins. Gdańsk, for example, is increasingly introducing various innovative solutions of this kind, e.g., sedum mats instead of lawns around sports facilities, and has adopted appropriate regulations for the introduction of such solutions, i.e., the so-called Gdansk Urban Detention Policy. Similar activities are also taking place in Wrocław with the Grow Green project (in the Ołbin settlement), which aims to adapt the inner-city areas of Wrocław to climate change with nature-based solutions, i.e., by introducing alternative forms of green spaces and creating a system of small-scale retention. As far as Warsaw is concerned, the "Climate Change Adaptation Strategy for the City of Warsaw until 2030 with an Outlook to 2050", which addresses the issue of SuDS, was adopted relatively late—in July, 2019. This document states that to mitigate climate change, investments in green spaces, water storage and renewable energy sources are necessary.

The document points out that from the perspective of climate change and ongoing urbanisation, it is necessary for the city to properly manage stormwater and maintain and develop green and blue infrastructure such as parks, forests, lagoons and ponds. Considering the provisions of the above-mentioned adaptation strategy, appropriate documents and spatial plans still need to be prepared. Therefore, there are many indications that Warsaw still has to make extensive investments related to SuDS and WSUD.

In the context of specific scientific work, mention should be made, for example, of the study by Bus and Szelągowska [72], who presented concrete calculations of the ecological and economic benefits of water retention by green roofs and carried out an analysis of the social-cost benefits for the entire life-cycle of green roofs. Their results showed that water retention and measurable environmental and economic benefits are the highest in cities such as Warsaw, Kraków and Wrocław, as these cities have the highest number of green roofs. The average ecological and economic impacts for the studied area were 507,000 per year and $621,000 per year, respectively. Barszcz [69], on the other hand, showed how the use of appropriate facilities to improve stormwater infiltration and retention parameters at the plot and catchment level of the Służewiecki stream in Warsaw can influence surface runoff and retention and infiltration depths. The results of Barszcz [69] indicate that the most promising effects at the plot level are for solutions with infiltration trenches and permeable soil and gravel layers. At the catchment level, the greatest reduction in runoff was achieved through a combination of solutions: "permeable soil layers" and green roofs. In another study, Wojnowska-Heciak et al. [71] investigated the possibility of using structural soils under pedestrian and yard areas as a promising SuDS solution that could be applied in Warsaw. According to these authors, such a solution can help increase water retention capacity in urban areas. In their study, Wojnowska-Heciak et al. [71] adopted the parameters of the heavy rainfall peaks recorded in 2013 in the western part of Warsaw in Bieleany (heavy rainfall for one of the extreme storm events, where almost 40 mm of rain fell within 1.5 h). The authors were able to determine that about 6500 m^3 would have fallen in the area that was the subject of their study. Their results showed that the proposed method of using 100 mm of structural soil under pavements and yards (these soils have an average porosity of 30%) would significantly increase stormwater retention in the study area (about 2200 m^3 of water could be stored) and would be an important countermeasure against local flooding

2.6. Real-Time Control (RTC)

RTC is a management system for the combined sewer network that allows for optimised control of the entire network in real time to improve its efficiency. In other words, with an appropriate intelligent system that analyses data and controls the available infrastructure (gates, pumps, valves, weirs, other equipment, etc.) to improve its performance. As Beeneken et al. [74] and Maiolo et al. [75] have noted, RTCs significantly contribute to improving the hydraulic performance of the entire water-management system and to achieving its operational objectives. In this respect, a RTC is a valid and cost-effective solution to urban stormwater management [75]. With RTCs offering greater flexibility in control systems, it is possible to improve the utilisation of the combined sewer network, to more easily achieve operational objectives, and also to reduce environmental impacts [74]. It is worth noting that the first RTC solutions were introduced in the United States as early as the late 1960s [76]. The benefits and potential of these solutions soon started to be discussed in scientific publications [77]. However, the real breakthrough that led to the popularisation of these solutions came with the development of microprocessors in the 1990s [76].

One of the most comprehensive studies in this area seems to be the work of Ly [78], who refers to real-time control (RTC) as a suitable strategy for optimising the capacity of sewer networks to reduce combined sewer overflows (CSOs). The advantages of this method are the higher adaptability of the network to changes, no need to build additional detention volumes, higher environmental friendliness of CSOs and improved cost-efficiency.

In short, RTC is a way of optimising the capacity of wastewater networks. RTC can be based on real-time control based on hydraulics (HBR), but can also be based on the real-time control of water quality (QBR). In his study, Ly [78] presented a simple QBR strategy to appropriately influence the amount of CSO loads in flood risk situations (if necessary). Ly [78] highlights that the performance of the HBR and QBR strategies (the latter uses mass–volume curves for prediction) can be comparable. The author also retested the QBR method for a small catchment (205 ha) and the catchment of Louis Fargue in Bordeaux, France (7700 ha). The results showed that this method reduced CSO loading from 3 to 43% for more than one third of the rain events (31 rain events over 2 years were tested). The implementation of this strategy in the Louis Fargue catchment has proven that the use of QBR as a stormwater management method has tangible benefits in terms of efficiency.

For 17 heavy rainfall events (19 such events were tested over a 15-month period), a reduction in CSO load of between 6 and 28.8% was observed. The study also addressed the question of the extent to which the performance of the QBR method depends on the uncertainty of the sewer network curve prediction, which was demonstrated for one particular storm event. A sensitivity study was also carried out to estimate the range of uncertainty and the results showed what should be considered when choosing between QBR and HBR. As it turned out, the volumes of the basins, as well as their specific location in the catchment, are important in this regard. Assuming that there is a system with certain degrees of freedom and certain operational constraints, the control is used to track these constraints with reference to the constraints of the whole system, i.e., its degrees of freedom. In the context of stormwater management, the temporal dimension represents one such degree of freedom [79]. Therefore, let us assume that there is a combined sewer network defined by the corresponding wastewater processes (the combined sewer network is defined by these processes) with which variables such as water quality, water level and flow are associated. According to Schütze et al. [79], to claim that a given combined sewer network is controlled/managed in real time, it is necessary for the corresponding wastewater processes to be continuously monitored in real time for the defined points of the network actuators, from which the relevant data should be collected. The positions of the actuators are determined based on this. The latter can influence and change certain processes.

Knowing the setpoints of all actuators and the corresponding predefined control targets, to be able to implement RTC, one has to apply a suitable control strategy that refers to the corresponding time sequences with respect to the previously mentioned actuators or, more precisely, to their setpoints. Schütze et al. [80] identify the specific situations of an exemplary wastewater network operator for which it is advisable to implement an RTC-based system. One of these situations is the repeated, frequent flooding of the sewer system and the need to counteract such situations. Other situations that justify the use of an RTC are the high pollutant loads discharged into the receiving water, relatively high operating costs for network operation, e.g., due to energy or chemical costs, or high investment, transport or storage costs. As the combined sewers in Warsaw are notoriously overloaded, it is worth considering the solutions presented in works by Schütze et al. [80], Ly [78] or Gimenez-Maranges et al. [62] and looking for unconventional solutions to minimise the negative impacts of the most extreme storm events. The use of any of the RTC strategy can have a significant impact on the performance of a combined sewer network [78]. The fundamental difference between RTC and conventional approaches is that, unlike the latter, RTC considers the dependence of stormwater management strategies on the assumption that the designed system, whatever it may be, is constantly subject to certain stresses, which are dynamic in nature [76]. Conventional methods, however, are based on certain static conditions that are considered for a specific (extreme) design event (i.e., the assumption of certain boundary conditions, such as the aforementioned Błaszczyk model from the 1950s [57,58], used for the design of the sewage network in Warsaw) [81]. To take this even further, RTC considers the variable of the temporal dimension related to stormwater management and allows for more flexible management, which basically boils down to the ability to quickly respond to all kinds of disturbances and external problems in the system [82].

In this context, the savings associated with the introduction of RTC systems should also be highlighted. That is, compared to conventional strategies for managing combined sewer networks, RTC shows itself to be clearly superior. More specifically, there is a body of research that has already provided evidence that RTC-based management offers measurable cost benefits compared to conventional strategies for increasing the capacity of the wastewater network [62,74,78,80]. An important practical demonstration of the effectiveness of RTC is the study by Beeneken et al. [74], in which the authors use the concrete example of the city of Dresden to show the economic benefits of applying RTC over a 10-year period, reducing chemical oxygen demand (COD) by almost 40% and saving up to about 60 million euros. In the case of Dresden, one alternative that the engineers and planners of the wastewater network considered when designing the combined sewer network was the implementation of solutions such as the construction of retention basins. On the equipment and technical side, the implementation of an RTC strategy includes controllers, sensors, actuators and appropriate data transmission systems [78,82,83]. In their study, Schütze et al. [83] describe an exemplary RTC system and emphasise its control loop character. As can be seen in Figure 9, the scheme of the RTC method takes the form of a control loop in which the relevant elements in the data flow framework are as follows: the relevant sensors for the sewer network (rain gauge, radar, flow metre, water level metre and water quality metre), a controller (to operate the actuator), an actuator (to control relevant system elements, such as pumps, valves or weirs) and a variable processor (toprocess the data).

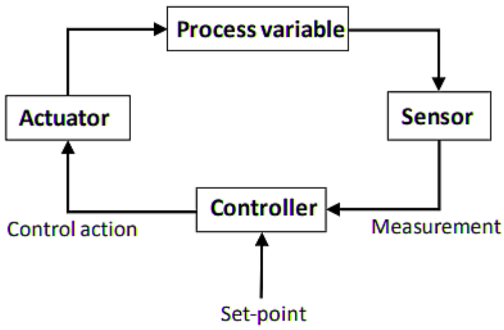

Figure 9. Data flow in a RTC control loop (source: based on Ly [78]).

The goal of the whole RTC system is to minimise any deviation from the desired state. In short, this type of correction of deviating states from the desired (i.e., predefined) state is achieved by appropriate control loops, i.e., feedback or feedforward control loops [84]. There is a very extensive literature that deals very thoroughly with the subject of actuators [78,85]. As mentioned earlier, the actuators of RTC systems are: (1) Gates, which regulate flows and accordingly allow for the storage or diversion of flows (from more heavily loaded to less heavily loaded) between differently loaded elements of the system; (2) Pumps, which assist in the transfer of water between different points in the sewer network and, in particular, allow for gravity to be overcome, releasing reserves from downstream areas; (3) Valves, which, among other things, control flows; (4) Weirs that serve as overflow devices and provide sufficient storage volume, e.g., to reduce the overflow volume in combined sewer overflows; (5) Devices that serve other purposes, e.g., flow dividers or dispensers of appropriate chemical substances or aeration devices to remove pollutants.

It is also worth noting that there are different criteria for categorising the different methods of controlling sewer networks [86,87]. These issues are discussed in detail in the work of Meirlaena [86], Lund et al. [87] and Ly [78]. In his work, Ly [78] highlights the criterion based on control objectives and considers it relevant in the context of the water quality-based real-time control strategy (QBR), which this author proposed and compared with the hydraulic-based real-time control strategy [HBR], taking into account their performance and efficiency. One of the most popular control methods is model predictive control (MPC), which has been used for more than half a century in many engineering fields, including the automotive, aerospace and energy sectors. More precisely, MPC is used in automatic control systems. Traditional feedback loop controllers work by adjusting their operation in response to changes in the system's output. In predictive control, the controller adjusts its operation in advance as the output of the system changes. This is a method of controlling dynamic systems that consist of cyclically solving an optimal control task in which the initial condition is equal to the current estimate of the object state. The initial part of the solution (control function) is given to the input of the object, and then the whole procedure is repeated for the new, currently determined state of the object. MPC is particularly useful for RTC because it allows for the modelling of many constraints and the consideration of system constraints, including but not limited to actuators, so that many sewer network management problems can be solved [88]. MPC enables, among other things, the recursive repetition of control actions over a finite control time interval and the corresponding optimisation. MPC uses a statistical process model to anticipate the future states of the system. Furthermore, thanks to a suitable performance algorithm, MPC enables the optimisation of network costs based on relevant preset performance indicators. Such a control method has an advantage over other methods that, thanks to recursive optimisation, it can easily adapt the system to a changing environment, which is the case when new weather data (precipitation) and data on the state of the wastewater network arrive. As an example of one of the earliest RTC systems functioning in practice, and based on the MPC method, Schütze et al. [79] refer to the global RTC forecasting system of the city of Québec, whose implementation started at the end of the last century.

Intelligent RTC System for Combined Sewer Network Control in Warsaw

To date, Warsaw does not have an intelligent RTC system, such as those used in some cities around the world, e.g., Dresden, Philadelphia, Tokyo or Minneapolis. However, there are indications that the municipality has looked into this issue and plans to follow the path that leading cities have already taken in the field of real-time sewer network control. The deadline for the introduction of such an intelligent, self-learning control system for the combined sewer network of the Polish capital is scheduled for January 2023 [89]. This introduction is taking place at present as part of a project to expand and modernise the wastewater transport system. Of course, the task is not easy, because the combined sewer network in Warsaw is one of the longest in Europe. It consists of a system of pipes and pumping stations controlled by automated processes. In response to the challenges described in the adaptation strategy document, and against the backdrop of climate change, the city authorities (together with MPWiK) have taken on the difficult task of modernising the entire system and implementing modern, environmentally friendly solutions [89]. This is all the more important as it allows for the automation and centralisation of the entire management of wastewater infrastructure across Warsaw—something that has been lacking in stormwater management in such a large and constantly developing city as the capital of Poland.

It is worth mentioning that the combined sewer system in Warsaw is served by three treatment plants, namely “Czajka”, “Południe” and “Pruszków”. The latter is responsible for the disposal of wastewater from the Ursus district. The entire system consists of over 4000 km of sewers (4200 km to be exact) and over 120 pumping stations. Every day, about 530 million L of wastewater flow through the combined sewer system; during heavy rains, this number increases fourfold or more [89].

As mentioned above, the new system, which is currently under construction, will aim to integrate the control of the sewer system throughout the city (hence its centralised nature) and fully automate all related processes. In this way, the municipality hopes to significantly reduce the risk of flooding during the most extreme storms, which have increased in recent years. The centralisation of the sewer system in Warsaw was an absolute must, because such a system makes it possible to collect all the necessary data on the congestion of the entire network and its performance in real time. This is especially important during extreme storms, when large amounts of rainwater quickly accumulate in different sections of the network.

The implemented modern RTC system, based on the dynamic retrieval of data, enables the control of the wastewater flow and a quick response in situations of sudden extreme weather events. Furthermore, thanks to this modern solution, it will be possible to minimise the risk of local flooding, e.g., through more effective water storage in collectors and retention basins, effectively reducing the previously frequent rain overflows from the combined sewer system. When we talk about real-time dynamic data-processing (the basis of this new system), we mean capturing, collecting and processing the most up-to-date data in real time. This includes not only information coming from different points of the sewer network itself and its facilities, but also the latest weather radar forecasts. With such solutions, in the future it will be possible, among other things, to predict the intensity of rainfall and determine the exact location(s) of combined sewers, which could potentially become a bottleneck in the entire system.

The new RTC system will be based on artificial intelligence (machine learning methods) and will collect, process and analyse as much data as possible, based on which it will then find the most optimal solutions. If necessary, the system will control all hydrological devices and equipment, i.e., the pumping stations, the various distribution chambers and the storage basins mentioned in Section 2.3, resulting in optimal management of the rainwater that flows into the sewer system from various locations. In this way, it will be possible to respond to weather extremes up to two hours in advance, and the measures taken will become increasingly accurate and precise thanks to the work of the self-learning algorithm—which will form the basis of the system. The newly introduced system will also make it possible to make future investments to more efficiently expand the entire combined sewer system.

It is worth mentioning that, in addition to the control system for the combined sewer network, work is also being conducted on the construction of large collectors: “Wiślany”, “Lindego Bis” and “Mokotowskie Bis”, which should additionally support the capacity of the whole system [89]. The point is that the solutions that are introduced should have a comprehensive and integrated character. These solutions will additionally significantly increase the capacity of the entire combined sewer network.

3. Służewiecki Stream

3.1. Historical Background

The Służewiecki Stream is the longest watercourse feeding the Wilanów district at present and flows into the Lake Wilanów. It carries industrial and environmental pollutants from sources in its catchment area. The Służewiecki Stream continues to function as a collector within the municipalities from which it discharges water, being open in some places and covered in others [90].

The current state of the Służewiecki Stream has been influenced by the fact that it has changed hands over the last 50 years:

- Until 1997, the Służewiecki Stream was formally a sewage treatment plant and was managed by the Municipal Water and Sewage Company (MPWiK), which pursued investment goals set by the city [27];
- In 1997, the stream was classified as a “running water” by the Minister of Environment, and until 2017 it was managed by the Marshal of Mazowieckie Voivodeship through the Voivodeship Land Reclamation and Water Management Office (WZMiUW) [18];
- Since 2017, the flowing waters have been managed by the State Water Holding Polish Waters [18,91].

To describe the characteristics of the Służewiecki Stream Catchment area, it is necessary to point out that there is a combined sewer system in Warsaw that extends to Woronicza Street and Wilanowska Avenue (see Figure A1 in Appendix A). In the south, up to the border with Piaseczno, there is a distribution sewer network. In the area of the distribution network, wastewater is connected to the municipal sewage system. Rainwater is drained into the Służewiecki Stream via the storm sewer system.

Regular flooding caused by the overflow of the Służewiecki Stream affects the inhabitants of Mokotów and Wilanów [9–12]. The situation is the worst for the residents of the residential area of Arbuzowa and Miasteczko Wilanów or Służewiecka Valley, which are located in the immediate vicinity of the stream that repeatedly overflows its banks [27,90]. One of the authors, who lived in Śródziemnomorska Street, 200 m from the Służewiecki Brook, was also repeatedly affected by the effects of its overflows. In this part of the Mokotów district, basements are frequently flooded by overflows from the sewage system. The cause is the inflow of rainwater into the sewer system (through so-called "unaccounted" connections) and the overflow of the sewer system and the Służewiecki Stream at its various sections, e.g., Służewiecka Valley (Dolina Służewiecka)—Sobieski Avenue.

During the following heavy rains, the underground houses near the Służewiecki Stream, e.g., between Wilanowska Street and the Służewiecki Stream, are systematically flooded (such a situation occurs no less than twice a year) [9–12]. In particular, the famous residential building "Residence by the Brook" (also known as "Under the Wolves"), where the two-storey underground car park was flooded up to the ground floor until the water flowed out of it onto the flooded streets [9,11].

From this point of view, given the investments related to the Slużewiecki Stream and the delays in the works over the last 20 years, we are trying to explain the existing administrative and technical obstacles and to stimulate citizen actions that will put some pressure on the responsible decision-making centres. To reach reasonable conclusions, it is necessary to go through the last 76 years of history, also analysing possible technical solutions and the current system of managing and financing water investments.

What has resulted from changes in ownership and what investments have been made to deal with the rainwater in the southern part of Warsaw? The biggest mistake made by the Warsaw authorities was the planning of the housing estates in Ursynów. Considering the urban planning and transport solutions that were developed, the problem of water management was left unsolved, as no direct rainwater collector was planned for this area to channel the water into the Vistula River, or at least into the Wilanówka River [26,27], after it was cleaned of oily substances and sludge. Ursynów is inhabited by more than 150 thousand people at present [92]. The simplest solution was chosen, i.e., stormwater from Ursynów was connected to the Służewiecki Stream without estimating the impact of runoff accumulation for Wilanów and without estimating the absorption capacity of the Ursynów North and South areas for residential, commercial and parking development and roads [27]. In the 1990s, when there were repeated nuisance floods in the areas adjacent to the Służewiecki Stream, attempts were made to remedy the situation and preparations were made for the development of the Wilanów fields, where the Wilanów municipality is located at present, which is home to about 40 thousand people. In 2003, for the purposes of urban planning in Wilanów, a hydrological study was prepared [26,27], according to which, after an 8-h rainfall during storm events, the water from the catchment area of the Służewiecki Stream in the cross-section of Przyczółkowa Street was calculated to be 42.4 m^3s^{-1}. This water accumulates in the section below Rzymowskiego Street and in the area of the Arbuzowa Housing Estate and East Wilanów. Successive floods occurred in 2002 and 2010 [90]. The extent of the floods can be seen in the photo shown in Figure A5 in Appendix A. The impounded runoff backs up in front of the Przyczółkowa Street culvert and on the existing water facilities of the Wilanów Park complex, where the capacity of the section from St. K. Potocki Street to Wilanów Lake totals about 4 m^3s^{-1} (p 168, [27]). The scale of the facilities is shown in Figure A6 in Appendix A, which shows that the stone waterfall in Wilanów Park.Banasik's calculations [26] were confirmed in studies conducted in 2006–2009 at the Department of Hydraulic Engineering and Environmental Rehabilitation of the Warsaw University of Life Sciences in the work of Barszcz [6]. In the study entitled "Prediction of maximum probable runoff due to heavy rainfall in the urbanised catchment of the Służewiecki Stream", storm runoff in the section from Rosoła

Street to Wilanów Lake (about 50% of the catchment) was calculated to be 23.0 m^3s^{-1}, with 24 mm/m^2 of precipitation during the storm event [6]. This estimate does not refer to the precipitation of 15 August 2008, which was 81.5 mm during a one-day rainfall. A precipitation like that of 2008 is a precipitation that occurs with a probability of once in 100 years. It was already known at the time that such heavy rainfall would occur a few more times in the coming decade (years 2010–2020), but this was not seriously considered by anyone. Indeed, such heavy precipitation has occurred several times (e.g., on 3 June 2010 and 13 July 2016), most recently in 2021 and the year before [9–12].

The comparison of the above-mentioned discharges from the catchment area of the Służewiecki Stream with the capacity of the facilities in the Wilanów Park complex also leads to many interesting conclusions. It is worth mentioning that the construction of the Wilanów Palace-Park complex in the 17th century was accompanied by extensive hydrological works [93]. A 0.8-km-long canal called the Sobieski Canal was built to drain water from Lake Wilanów into the Vistula, and it has fulfilled its function for 250 years. The last section of the Sadurka River (which flowed in parallel to Rzymowskiego Street) was reconstructed for the purposes of the park designed by the architect Augustine Locci and channelled into the park [93]. This solution with a stone waterfall is a permanent element of history and culture under the protection of the Monument Conservator [94].

The protection of the Wilanów Palace and Park complex precludes the possibility of rebuilding this section—in the 1990s, a method was sought to reduce the intensity of runoff by building a parallel water system [27]. In 2003, the existing water facilities were inventoried and the necessary scope of investment was determined, which was presented in the document "Programme and spatial concept of water drainage from the Służewiecki Stream basin", commissioned by the Marshal's Office of Mazovia [27]. This document presents possible solutions to the flooding problem in Wilanów. Proposed solutions include the construction of retention basins on the grounds of Okęcie Airport, the revitalisation of retention basins (which has been partially realised in the last 20 years) and the construction of pumping pipelines with a capacity of Q—24.4 m^3s^{-1} that would lead directly into the Vistula River in the strip of land designated for the A2 route (S8) [26,27]. During the construction of the pumping pipelines, a shunting valve was provided in the Arbuzowa Housing Estate as well as a discharge of the dammed water of the stream in the Arbuzowa settlement through a parallel channel to the planned A2 route [27].

Although the study was positively reviewed by the Warsaw authorities at the level of the districts in the catchment area, i.e., Ursynów, Mokotów, Wilanów, as well as by the MPWiK and Warsaw City Hall, the proposed solution could not gain acceptance among the respective administrative authorities, because (according to the living planners) Warsaw City Hall did not coordinate the adaptation of the local plan for West Wilanów [27]. For this purpose, it was also necessary to separate and acquire the land for the retention basin with an area of 5000 m^2 [27]. However, due to the lack of funds and the unwillingness to finance these investments, the MPWIK did not agree to the adaptation of the Wolica Canal [27]. The total cost of the scenario, which envisaged the construction of a parallel canal, was calculated at PLN 541.94 million [15,26,27]. The corresponding agreement between the Mayor of Warsaw and the Marshal of the Mazowieckie Voivodeship had also not been signed [27]. The Ministry, which had commissioned the planning of the A2 on the Warsaw section, opted for the alternative solution, without the possibility of solving the city's water management in this area [27], as there was no specific agreement. The rainwater from the A2 route was drained directly into the Vistula, which was accepted after a long process of agreements [27]. In the first version, the route was to be drained into earth evaporation basins and into the Wilanówka River. Although this solution was considered more expensive, it was still preferable, as the rainwater would feed the drying lakes in the western part of the Vistula after purification. The location of the planned pumping station along the completed A2 route is shown in Figure A7 in Appendix A.

The discussion on flooding had a positive outcome at the time, namely, the introduction of requirements by the Służewiecki Stream administrator for a stormwater retention basins to support newly designed facilities. These requirements have already been considered in the construction of Galeria Mokotów and the buildings in the Służewiec Przemysłowy Industrial Estate, which forms an exclusive office zone. The airport "Okęcie" was included in the construction of the reservoirs [90]. By 2006, five reservoirs with a total capacity of 42,490 m^3 had already been completed, including reservoirs above the airport with a capacity of 8000 m^3 [6]. According to the water permit, the maximum discharge from the airport into the stream is 5.31 m^3s^{-1} [6].

3.2. Some Remarks on Proper Stormwater Management

It must also be acknowledged that Warsaw City Hall began revitalising the reservoirs in Ursynów and Mokotów after 2005 [90]. At that time, 11 reservoirs were rehabilitated under the Small Reservoirs Programme [95], including: Berensewicza Pond [96], Wyścigi Pond, Krosno Pond, Kądziołeczka Pond, Moczydło Ponds; reservoirs: No. 1, No. 2 and No. 3, Czyste Pond, Pozytywka Pond, Wąsal Pond, Zgorzała Lake, Zabłocki Pond, and Grabowski Lake [95]. A dam was also built on the Służewiecki Stream above Puławska Street, which is explained in more detail in this article. The recultivated reservoirs create a scenic "wilderness" in their surroundings, which is invaluable for the inhabitants. Figure A8 in Appendix A shows the view of Lake Wąsal, located on the Katarynki Road near Piaseczno. The 25,000 m^2 water reservoir called Priest's Pond ("Księży Staw"), located at the intersection of Wilanowska Avenue and Dolina Służewiecka (Służewiecka Valley) Street, is also being considered for revitalisation. The reservoir has an unregulated legal status. The deterioration of the reservoir is documented in Figure A9 in Appendix A. Photo evidence presented in the article shows the neglect of the aforementioned reservoirs (Figures A7 and A8 in Appendix A). In connection with what has already been said, the question arises as to whether the revitalisation of the reservoirs has been properly carried out properly. A positive answer applies to the reservoirs where the inflow of rainwater was maintained. A negative answer applies to the reservoirs where the inflow of rainwater was not properly maintained (conserved). The revitalisation of Zgorzała Lake, located 500 m from Puławska Street behind the church in Pyry, is an example of the latter (see Figure A10 in Appendix A). After the revitalisation of the lake, which cost 8 million zloty (PLN), the water returned to Lake Zgorzała (about 1.5 thousand trees and bushes that "grew in the lake" were cut down to "make room for the water"), but only for a few years [97]. Over time, the lake began to dry up again. The situation is similar to that of other reservoirs without surface water supply in the area, such as Krosno Pond or Wingerta Lake.

The authors conducted a field survey and visual hydrological assessment and concluded that progressive development has a cut-off surface water recharge. The lack of surface runoff inevitably leads to an overgrowth of vegetation known as "land cover". It can be concluded that the hydrological system of the Służewiecki Stream is not properly managed. Moreover, no one properly maintains this. However, whenever there are complaints about the unpleasant stench of the stream, the Warsaw authorities carry out a piecemeal clean-up. It is worth asking where mistakes were made. There has been no hydrological analysis of the clean-up project, no reliable accounting of inflows and evaporation of water, and no appointment of a single manager and administrator who would also be responsible for maintaining the entire system. How and what needs to be fixed? The area around Lake Zgorzała is not yet fully developed. However, due to its attractive location, it is possible that suitable residential and commercial properties are already planned in this area. The clean rainwater from the new housing estates would have to be diverted into this reservoir.

3.2.1. The Fort Bema Housing Complex Example

It is worth referring to the example of the construction of one of the largest housing estates in Warsaw, namely, the construction of the Fort Bema housing complex in the Warsaw-Bemowo district [98,99], which took place in 1999–2011, where an area of 1,480,000 m^2 (i.e., 148 hectares) was allocated for urban development and land use, and residential buildings were constructed (approximately 200,000 sqm of usable and residential space + services) [18,98–100]. This area is located on the edge of the Vistula basin and outflows into the Bemowo forest and further into the Kampinos primaeval forest. In this area, there is a separate system for sanitary and storm water drainage. The solution to the management of rainwater in this project was worked out with the municipality (now district) of Bemowo, with the participation of the MPWiK and the authorities of the City of Warsaw, by diverting rainwater into the ditch of Fort Bema, which is part of the 19th century fortress complex with an area of 222,000 m^2 (i.e., 22.2 hectares). Before the relevant works were carried out and the stormwater was diverted, the ditch was "dry" and degraded, with illegal dumping of municipal waste and rubble and demolition material. The drainage area covered several dozen hectares, which were bordered by Obrońców Tobruku Street, Osmańczyka Street, Gen. Maczek Street, Księcia Bolesława Street and Route S8; it also included roads, car parks and pavements of housing estates, the roofs of the buildings of the "Leśne Estate I ÷ V", the "Fort Bema Estate", the "Green Flatlet II and III" and the housing estate of the "Ideal Flat" workers' housing cooperative, as well as the WZL-4 facility and the Air Force Institute of Technology. Naturally, sand traps and separators were installed at the outflow of these water bodies into the reservoir to ensure there was clean water in the reservoir (a ditch around Fort Bema). The width of the ditch surrounding the fortifications reached up to 30 m, including a 12–15-m-wide water area. A fragment of the ditch in its present state can be seen in Figures A11 and A12 in Appendix A. How were the project preparations carried out?

- In the area of the housing estates affected by the ditch revitalisation project, the local spatial development plan was approved by the resolution of the Municipal Council of Warsaw-Bemowo, No. XIX /127/01 of 6 December 2001, in which the revitalisation of the ditch with rainwater from the housing estates is noted as a suitable solution [18,98,99];
- The drainage system was constructed by the developer after consultation with the Voivodeship Conservator and the Bemowo Municipal Office, having previously replanned the stormwater catchment area for 14,980,000 m^2 (i.e., 1498 hectares) and reached an agreement with the MPWiK. The realisation of such a scenario was possible because the interests of the state-owned enterprises, the Bemowo municipality and the developer were combined (a new stormwater and storm sewer system, a sewage system, electricity supply and modern road infrastructure were developed at a significantly lower price per usable area than the construction of comparable infrastructure elsewhere in Warsaw) [99].

Apart from the necessary investments in the further revitalisation of the detention basins, the question arises as to whether there is a system for managing the existing water facilities. Limiting stormwater runoff in Wilanów requires targeted runoff management during stormy rains. The following examples, i.e., the Służewiecki Pond—a flow-through basin—and the Wolica Canal and its discharge of stormwater from Ursynów, provide a better insight into whether and how the city of Warsaw manages its water facilities.

3.2.2. Służewiecki Pond—A Flow-Through Reservoir

To evaluate the retention capacity of the existing reservoirs, we try to answer whether the installed facilities effectively reduce stormwater runoff in Wilanów. The answer to this question is provided by a hydrological assessment of the Służewiecki Pond near the tram terminus at the intersection of Puławska and Rzymowskiego Streets, covering an area of over 20,000 m^2 (i.e., 2.0 hectares), which collects water but does not slow down runoff. The stream valley was separated by a robust concrete dam with an embankment thickness of 1.74 metres. An Archimedean screw was installed in the river to generate electricity. During heavy rains, overflow of the dam is possible. Figure A13 in Appendix A shows a photograph of the reservoir, documenting its scenic value.

Assessment of the reservoir is as follows:

- The reservoir has scenic qualities, with a fountain in the middle, which has a positive effect on the climate and leads to aeration of the reservoir;
- The reservoir is rich in flora and fauna.

At the same time, it should be noted that the reservoir has no hydrological value, as it is a flow-through reservoir that does not retain water in the event of sudden rainfall and does not limit its discharge, which is due to the applied measures and the reservoir orders that are issued (i.e., damming instructions). Moreover, people are aware of the impact of the damming upstream of the reservoir.

According to a study conducted by environmentalists, after the construction of the reservoir, the water was dammed by at least 0.3 m at 400 m from the reservoir, making it impossible to maintain the installed separators at the outlets. Figure A14 in Appendix A shows an elevated water level in Wyścigowa Street near a multi-family housing estate. What should be done in this situation? The water level in the reservoir should be lowered by 0.3 m (under normal water flow) by placing an Archimedean screw at the outlet, which serves as a pressure pipe. Changing the reservoir level will allow for the retention of about 1500 m^3 of water during extreme rainfall.

3.2.3. Wolica Canal and Its Discharge of Rainwater from Ursynów

The Ursynów area is situated on terraced terrain about 10 m above the catchment area of the Służewiecki Stream and the Wolica Canal. It is worth mentioning that the capacity of the collection channel should have controllable discharges in flood situations in the catchment area. However, to determine by how much the retention capacity of the canal can be increased, separate expert opinions are required and must be paid for.

It is also necessary to determine the method of water retention in the Wolica Canal, which discharges rainwater from Ursynów at an intensity of 8 m^3s^{-1} into the Służewiecki Stream with its tributary to the Arbuzowa residential area. The scale of the water system can be seen in Figure A15 in Appendix A.

4. Discussion

4.1. General Issues

The city of Warsaw is exposed to two types of flood risk. The first relates to the Vistula River, whose occasional floods threaten up to 25% of the city's area [15]. This is a serious risk and, in this context, it is incomprehensible to reduce (by many times) investments in the construction and modernisation of flood embankments. However, the risk associated with the occurrence of flood waves on the Vistula can be controlled in advance to a certain extent; moreover, there are protective dikes that provide protection against 100-year or even 1000-year water [15]. The second type of threat is urban flooding, which is caused by intense rainfall and usually occurs in the summer season [34]. This is difficult to predict it because it is impossible to state with great accuracy where and at what time intense rainfall will occur and for how long it will last. It is, of course, possible to produce appropriate simulations and hydrographs, but carrying out appropriate stress tests on the relevant water infrastructures is a very multidimensional issue and, therefore, extremely difficult. There are some radar methods [41,101], but even these can only identify the most vulnerable areas a few hours before such heavy rainfall occurs. In the case of heavy rainfall in highly urbanised areas with high runoff rates, huge amounts of water cannot drain away, with inefficient sewage systems leading to street flooding and localised flooding.

Based on the operations and reports of local fire units, a corresponding map was developed to show the vulnerability to local flooding [102]. This map is based on the reports of rainfall in the period 2008–2013 and shows the locations of actual floods in the mentioned period and the related deployments (see Figure 10). The locations are marked with the corresponding GPS coordinates and their nature is described. This is very valuable material because it shows the actual extent of the phenomenon.

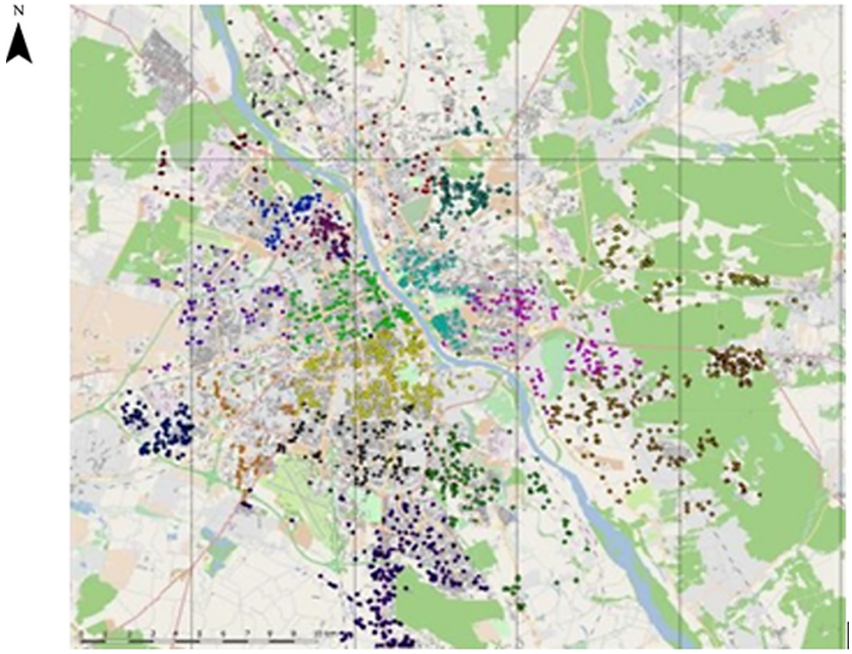

Figure 10. Fire brigade reports of interventions due to heavy rainfall in Warsaw in 2008–2013 (Note: different colours of the dots indicate different fire brigade units. The report shows that most of the operations took place in the southern part of Warsaw and covered the catchment area of the Służewiecki Stream).

As can be seen in Figure 10, the map is densely dotted. There were as many as 3128 such interventions in the five-year period [37]. It is worth remembering that the sewage system in Warsaw was designed back in the 1960s, according to the standards of the time [6]. Since then, 60 years have passed, the climate has changed, rainfall has increased, and land cover has changed. There is now much denser development and, therefore, many more concreted areas (see Figure A2 in Appendix A) [37,102]. However, there is no way to expand the cross-section of the entire drainage system. Many interesting alternatives were ruled out at the beginning of this century, when a hydrological operation study for the catchment area of the Służewiecki Stream was prepared [27]. They were discarded for various reasons. Either they were poorly evaluated by local authorities, required investments in ecologically protected areas or simply proved too expensive.

By far the cheapest solution is the introduction of retention elements and the construction of reservoirs that collect the water immediately after a heavy rainfall and then gradually discharge it through the existing sewage system. Many such retention basins have already been built, e.g., along motorways. However, there are many more possibilities, such as the creation of green roofs [69], i.e., permeable surfaces that absorb water. These are very important challenges for architects and urban planners.

4.2. What Comes Next?

The Route A2 outflow from the tunnel, together with the outflow from the stormwater collector in Płaskowicka Street, which has a diameter of 4.0 metres, forms a technical junction [103]. There is no possibility of reconstructing the collector according to the assumptions of the original design from 2002, i.e., assuming a specific location of the pumping station and pressure pipes with direct discharge into the Vistula [27]. Therefore, it is worth asking whether there are alternative scenarios for the catchment area of the Służewiecki Stream. A technical solution of the flood protection channel type (i.e., spillway/relief channel) is not possible/realistic to design. What options could be considered? After analysing the available technical studies and reviewing the water facilities along the Służewiecki Stream with the participation of engineers and experts, we can see the following viable solutions for technical and social discussion. Against the background of the considerations presented above, we see the following feasible options (measures), which will slow down the runoff in Wilanów (i.e., in the Wilanów catchment):

- Construction of a "dry reservoir" for flood protection, a so-called polder, in the Służewiecka Valley between Puławska Street, Rzeczypospolitej Avenue and Nowoursynowska Street (see Figure A16 in Appendix A).
- Construction of dams above Łączyna Street to slow down the runoff of the collector along the Radomska Railway and Okęcie Airport.
- Construction of an aboveground or underground retention basin in Rosoła Street at the confluence of the Służewiecka Valley.
- Further revitalisation of reservoirs, e.g., Priest's Pond.
- Reconstruction of stormwater runoff from Ursynów areas to increase retention in the channel during heavy rainfall, including the construction of a dam to retain stormwater in the Wolica Channel.
- Active management of water facilities.
- Designation of a single body that is responsible for the water facilities in the city of Warsaw.

4.3. Anticipated Difficulties

The construction of a dry reservoir (i.e., polder) in Dolina Służewiecka between Puławska and Nowoursynowska Streets with an area of 30,000 m^2 (3 ha) was considered and approved in the Master Plan for Wilanów (1,480,000 m^2), which was not supported and stopped by the residents of the Dolina Służewiecka residential area and the Mokotów district. The most appropriate solution seems to be the one described in the study on the conditions and directions of spatial development in the capital city of Warsaw [104,105].

The implementation of dry polders requires special agreements between the State Water Holding Polish Waters, the mayor of the capital Warsaw and the mayors of the districts, or the approval of a single body that would be responsible for the stormwater system flowing into the Służewiecki stream. In practise, however, this is difficult to achieve, as none of the above-mentioned authorities claim responsibility for these investments. Moreover, it is unlikely that these parties would be willing to share in the costs of these investments and the management of the entire system.

Is it necessary to introduce solutions such as those presented in this study? The reality is that the catchment area of the Służewiecki Stream is constantly expanding. In the south of Warsaw, near the border with Piaseczno, there is a large area adjacent to the Radomska Railway. Transport connections with these areas are fast (thanks to the metro system), and soon the passability of the S7 route (the so-called "Puławska Bis") will also be achieved within the "Airport" node (the Warsaw Express Ring Road) (expected in October 2022). The section between the "Airport" node and Lesznowola is already 80% completed. The section between Lesznowola and Tarczyn is the least advanced, but the new contractor has contractually committed to ensuring that the line is passable by October 2022. The completion of this section will attract the interest of developers who are interested in the area.

Rainwater from this area cannot be channelled into the catchment area of the Jeziorka River, as the existing sewer system cannot absorb the rainwater from the buildings in Piaseczno. The only solution is to connect the rainwater sewer to the Służewiecki Stream. The realisation of investments in water supply along the Służewiecki Stream clearly depends on adequate funding from the budget of the City of Warsaw and the State Water Holding Polish Waters, as well as from EU funds. The aforementioned institutions should cooperate, and the discussed water investments should be included in the priority list of these institutions, as they have significant resources.

It is worth initiating investments in this area through social and civil society circles. In the current situation, and with a view towards possible technical solutions, it would be advisable to consider setting up a relevant citizens' forum, to which representatives of the State Water Holding Polish Waters, the city of Warsaw, the MPWiK, the districts connected to the Służewiecki Stream, and professionals and experts would be invited to make concrete investment initiatives related to stormwater management.

Finally, the issues addressed in Sections 2.5 and 2.6, namely, SuDS and RTC, can significantly contribute to improving the hydraulic performance of the overall water management system and achieving its operational objectives.

5. Summary and Conclusions

The main problems have been set out in Section 4. Below, we provide a synthetic overview of the main issues that should be addressed to improve Warsaw's situation with regard to the local flooding caused by heavy rainfall:

- There should be a single manager for the stormwater system in the city of Warsaw; otherwise, responsibility will be diluted;
- It is necessary to update the programme and spatial concepts for the discharge of water from individual catchment areas in Warsaw (e.g., the catchment area of the Służewiecki Stream);
- Natural retention basins need to be restored in the city and artificial retention basins need to be built in places where overflows and local flooding occur;
- The system must be made more efficient by building appropriate underground or open channels;
- All new investments (including high-rise buildings) must be equipped with detention basins to accomodate the so-called excess stormwater that cannot be absorbed by the city's stormwater or combined sewer system;
- Ursynów's stormwater runoff must be disconnected from the catchment area of the Służewiecki Stream;
- Water from Ursynów needs to be channelled to the Vistula via the southern ring road from Warsaw (S-2) to supply the dry ponds and lakes in Wilanów;
- The expansion of the combined sewer system should precede the planned investments and be carried out with a considerable reserve capacity so that, in future, the currently unserved areas (undeveloped land; raw land) can also be connected without problems;
- Spatial development plans and studies on the conditions and directions of spatial development must provide space for the construction of retention basins to absorb excess rainwater;
- It is necessary to revitalise the flood-control dikes in the Warsaw section;
- Reserves of floodplains (so-called polders) should be created before Warsaw.
- The implementation of SuDS, WSUD solutions and a comprehensive RTC system (currently under construction), discussed in Sections 2.5 and 2.6, can significantly improve stormwater management in Warsaw.

Finally, a stormwater management system for Warsaw should be holistically designed and managed. This means that its proper functioning would consist of many elements, each important in its own way, and that all elements would be interconnected. Neglecting one area could lead to a malfunction of the entire system. Proper management should not only include the recommended technical solutions, such as new collectors, channels extending the length of the combined sewer system, and retention basins, but must also focus on the proper functioning of the already-existing water facilities (including their inspection and maintenance to avoid such neglect, as in the case of Lake Zgorzała, where the lake dried up a few years after the multi-million investments). Proper stormwater management must also include various SuDS solutions and the implementation of RTC-type systems. In this context, it should be emphasised that it is good that the Warsaw authorities, together with MPWiK, have finally recognised the need to implement the RTC system that Warsaw lacks. However, this came much too late and earlier work on such solutions could have avoided many problematic situations and material losses. It is worth continuing this work and developing the newly implemented system in the future (after it becomes operational in early 2023, perhaps also in conjunction with QBR strategies, instead of only HBR). Moreover, the City of Warsaw is not a leader in SuDS solutions, so it is advisable to intensify activities in this area. In this context, the solutions that have already been tested and implemented in other cities can be copied. From the conducted analysis, we can conclude that there is a lack of systematisation of knowledge about SuDS and environmentally friendly architecture, not only in Warsaw itself, but also in other major Polish cities, and that the existing knowledge is very scattered. Therefore, as a future research line, we propose to create an overview of all SuDS solutions, WUDS and low-impact developments.

Last, but not least, COVID-19 has led to a significant shift in the organisation of work, with long-distance work and the flight of many Varsovians to non-urban areas increasingly becoming the new norm. Hopefully, similar to the current ongoing de-globalisation, we will also see a form of de-urbanisation (after all, most processes in both natural and social sciences have their peak/turning point), which, in combination with a growing number of SuDS solutions, could reduce the proportion of impervious surfaces and improve the overall water management situation in Warsaw.

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Appendix A

Below, in Table A1, we provide an overview of the most important works/studies dealing with the hydrological problems of the city of Warsaw. Our aim is to briefly characterise these works and present their contribution to the understanding of the analysed hydrological problems in Warsaw.

Table A1. Scientific approach—various fragments (and water installations) of the Warsaw hydrological system.

Authors	Subject	Contribution
Sieradz et al. [27]	Programmatic and spatial conception of water drainage from the catchment area of the Służewiecki Stream in Warsaw, considering the development of the catchment area.	In this study, the geodetic documentation of the Sluzewiecki Stream was evaluated and its existing technical conditions were determined, with special attention to the areas impeding the flow of water. The existing flow capacity of the Służewiecki stream and the structures (at various sections) were determined in great detail (with complete calculations). In addition, the influence of the stream on the groundwater and its level, as well as the infiltration of this water, was determined and ascertained. The hydrology of the entire catchment area of the Wilnowka River was discussed in detail. For certain sections of the Służewiecki Stream and the Wolica Canal, the predicted discharges of large rainwater were determined for $p = 2\%$. The authors presented technical solution variants of the programme and the spatial concept of stormwater drainage from the Służewiecki Stream Catchment area (more precisely, 3 variants were presented, of which variant no. 2 was finally selected). Interestingly, many other technical solutions were also analysed, which were considered but eventually discarded for various reasons. Finally, an analysis of the water flow in the Wilanowskie and Powsinkowski Lakes was carried out in connection with the proposed solution variants.

Table A1. *Cont.*

Authors	Subject	Contribution
Banasik et al. [106]	The catchment area of the Służewiecki Brook—a comparison of the impact of urbanisation in different phases of urban development (i.e., 1970 and 2005) on stormwater runoff.	Banasik et al. [106] studied the influence of different precipitation events with different durations and at different stages of urbanisation on peak runoff and rainfall runoff in the catchment of the Służewiecki stream. They applied the hydrological approach based on the SCS-CN and IUH method and showed a significant correlation between the increasing urbanisation of the catchment and the increase in peak runoff and the required retention volume. The study showed that an increase in impervious surface from 15 to 21% resulted in a 38% increase in peak runoff and a 76% increase in required detention volume. At the time the study was conducted, the authors projected an increase in impervious surface area to 31% by 2020 (i.e., within 12 years), which, according to their analysis, would have resulted in an increase in peak runoff of up to 92% and required detention volume of up to 357%.
Barszcz [6]	Prediction of the most probable runoff caused by heavy rainfall in the urbanised catchment of the Służewiecki Stream.	Barszcz [6] points out the high index of area variability of runoff for the catchment of the Służewiecki Stream, which is characterised by an area of 59.73. More specifically, Barszcz [6] points to mosaicism (land use/land cover) of the sub-catchments, which vary with their run-off rate. The problem with the lack of run-off area homogeneity comes down to the fact that each sub-area has a different specificity and, therefore, different run-off rates.
Olesiński [107]	Służewiecki Stream—technical solutions to stormwater retention in the area of the catchment.	The article deals with the application of technical solutions for stormwater retention in the area of Wilanowska Avenue and adjacent streets. This refers to the stormwater drainage system project, which provides for the discharge of stormwater into the Służewiecki Stream in quantities not exceeding 10 L per second.
Barszcz [42]	Służewiecki Stream—analysis of precipitations; calculation of normalised precipitation depth distributions for different cumulative precipitation durations.	The author presented an analysis of precipitation measured at 3 different measuring stations (i.e., Ursynów, Okęcie and Pyry) in the experimental catchment of the Służewiecki stream. The analysis included a total of 71 precipitation episodes and dealt with the calculation of normalised precipitation depth distributions for different cumulative precipitation durations (for each nearest 10th percentile of the cumulative precipitation time). The results showed that the rainfall depths ranged from 1.0 to 81.5 mm and the times ranged from 20 to 1000 min. The author then performed statistical processing on the data and presented a synthetic result (using the median of all results) showing the normalised distribution of rainfall depths. This is important because the hydrographs in the studied catchment can be determined based on the results presented by Barszcz [42]. Another contribution of the analysis by Barszcz [42] is the finding that the synthetic normalised precipitation distribution calculated for the studied area is very similar to the results obtained in the USA and Germany (graphically, these distributions show great similarity). This information and the results of the analyses can be used for design analyses.
Magnuszewski et al. [17]	Hydraulic conditions of the flow of the large waters in the Vistula section in Warsaw (500–521 km) in the period before embankment and regulation. Hydraulic capacity of the current riverbed in the so-called Warsaw.	Magnuszewski et al. [17] described the problem of maintaining adequate hydraulic capacity of the current riverbed in the so-called Warsaw Corset and performed corresponding calculations of riverbed capacity for the conditions of $Q_{1\%}$ and $Q_{0.1\%}$ flow and different development scenarios of the riverbed. The authors reproduced the flow volume of the catastrophic floods, which are shown by the signs of the big water with the two-dimensional hydrodynamic model CCHE2D.

Table A1. *Cont.*

Authors	Subject	Contribution
Barszcz [108]	Służewiecki Stream	The author has conducted an analysis of the influence of the use of rainwater infiltration and retention systems on the runoff from the catchment area of the Służewiecki Brook in Warsaw. The paper presents a thorough analysis of how distributed stormwater infiltration and retention facilities (i.e., LID) in the urbanised sub-catchment of the Służewiecki Brook influence the characteristics of surface runoff and retention and infiltration layers in response to a single rainfall event.
Wawer [90]	Synthesis of water management problems with regard to the catchment area of Lake Wilanów and the Wilanówka River	Wawer [90] analysed the catchment area of Lake Wilanów and the Wilanówka River, evaluating the state of the water environment, and prepared a certain synthesis of water management problems. The author pointed out the reasons for the progressive deterioration in the city's water resources, citing, among others, the ongoing urbanisation of the catchment area and the construction of transport infrastructures without a proper stormwater drainage network (lack of comprehensive legal regulations on wastewater disposal and an effective control system).Important problems that have led to occasional local flooding and inundation in Warsaw are: (1) the conversion of the Służewiecki stream into a stormwater and industrial wastewater outfall, which has led to the complete ecological degradation of the entire stream system and the reservoirs in its network; (2) the failure to implement a separate stormwater combined sewer network; (3) the chaotic water and wastewater management in Warsaw, which means that the proposed solutions concerning only flood protection are ad hoc and do not comprehensively solve the problem; (4) mistakes in planning new investments and communication infrastructures; (5) the regulation works on the Wilanów section and the liquidation of the floodplain, which led to a local increase in the risk of flooding for areas located in a depression in relation to the maximum filling capacity of the Służewiecki stream; (6) the lack of adequate policies and decisions regarding Lake Wilanów and the Southern Pond, which should receive the protection they deserve and be prioritised when solving water and sewage problems; (7) faulty or too limited legislation in the field of water management solutions; (8) creating a situation where the bottoms of new and newly reconstructed reservoirs are silted up due to the rapid accumulation of organic matter as a result of eutrophication with organic sediments; (9) finding a situation where some reservoirs are not in good condition, e.g., the Wyścigi Pond, and are filled with a high proportion of organic material, which become water objects/facilities causing the secondary deterioration of flowing waters, as decomposition processes of organic matter take place at the expense of the content of dissolved oxygen in the water; (10) the absence of solutions to the retention of clean rainwater in the soil in areas where this is possible, which aggravates the processes leading to flooding in the catchment area of the Służewiecki Stream.
Jakubiak et al. [101]	Warsaw—precipitation analysis for 25 different rain gauges.	Jakubiak et al. [101] based their study on the relationship between radar reflectivity factor (Z) and rainfall rate (R), and analysed individual pixels of the radar image to estimate rainfall intensity. They then compared their results with those of rain gauges in Warsaw (accurate for 25 different rain gauges) and found significant discrepancies in the highest values of rain intensity. Their results are worth considering when using radar data in the hydrological modelling of catchments such as the Służewiecki Stream Catchment.

Table A1. *Cont.*

Authors	Subject	Contribution
Barszcz [69]	The impact of selected low-impact development objects (LID) in the catchment area of the Służewiecki stream (in Warsaw) on surface runoff (runoff) and retention and infiltration depths for different scenarios	The study was conducted to assess the impact of selected low-impact development objects (LID) in the catchment area of the Służewiecki stream on surface runoff (runoff) and retention and infiltration depths for different scenarios, including the selected property (shopping centre). The results show that LID objects increase the infiltration depth and decrease the surface runoff depth and volume. The study showed that the best results were achieved for scenarios with "permeable soil layer" and green roofs.
Barszcz et al. [30]	Służewiecki Stream and Wolica Ditch (Canal)	The authors' contribution consists of the development of a hydrodynamic Storm Water Management Model (SWMM) for different cross-section points in the catchment of the Służewiecki Brook and in the presentation of thorough calculations for discharges with corresponding exceedance probabilities, i.e., 50, 10, 2 and 1%. The calculations were performed for ten different design cross-sections, most of them for the respective sections of the Służewiecki Brook and two calculations for the Wolica Ditch, which is a tributary of the Służewiecki Brook.
Sobol [70]	Concept for implementing SuDS for the Siekierki area in Warsaw, which has been causing hydrogolgic problems for years.	Sobol [70] refers to new and effective ways of managing water in urban settings in the context of the rapidly growing population in urban areas. The author highlights that there are contemporary sustainable solutions for the more efficient management of urban stormwater, and that these are sustainable urban drainage systems (SuDS). These concepts contrast with traditional drainage infrastructures. Sobol [70] presents a concept for the implementation of such an SuDS solution for the Siekierki area in Warsaw (an area located in a bend of the Vistula River). In the hydrological and hydrogeological context, the Siekierki area is considered to be an area that causes many problems and hinders development planning.
Krajewski et al. [109]	Służewiecki Stream Catchment—prediction of sediment graphs in runoff from small detention basins in urban areas.	Krajewski et al. [109] used relevant data for 7 rainfall-runoff events with suspended sediment and developed a model of sediment concentration in stormwater runoff from a small detention pond in the catchment of the Służewiecki stream based on these data. The results showed a high degree of similarity between the estimated and observed discharges, which could allow accurate prediction of sediment graphs in the discharge of small detention ponds in urban areas.
Bartosik [15]	Review of the technical objects and water facilities that are part of the passive flood protection system of the city of Warsaw	Bartosik's [15] work examined the technical objects that are part of the passive flood protection system of the city of Warsaw, emphasising that they were built in the last one hundred and sixty years. These objects were developed to protect the city of Warsaw from flooding of the Vistula and Jeziorka floodplains, where the Warsaw agglomeration is located. The system consists of linear structures—flood embankments, a dam and point structures—the Żerań navigation lock, the Czerniakowska Gate, a series of pumping stations and dam sluices, and a syphon. The total length of the dike sections is just under 53 km. The protected area at risk of flooding from water draining with a probability of p-1% is over 75 km^2.

Table A1. *Cont.*

Authors	Subject	Contribution
Barszcz [41]	Relationship between rainfall intensity (R) from rain gauges (for certain rainfall cells with 1-km resolution) and radar reflectivity Z for the urban catchment of the Służewiecki stream in Warsaw.	The aim of the study by Barszcz [41] was to find the relationship between rainfall intensity (R) from the rain gauge (for certain rainfall cells with 1-km resolution) and radar reflectivity Z for the urban catchment of the Służewiecki stream in Warsaw. In the study, the author used five methods to determine the calculated radar reflectivity values (for specific precipitation cells with 1-km resolution) and different scenarios that included data from 2 existing rain gauges and 64 virtual rain gauges assigned to the corresponding precipitation cells in the catchment. In his study, Barszcz [41] achieved reasonable agreement between the measured parameters of the runoff hydrographs and the simulated parameters as a function of rainfall depth. His results regarding the Z–R relationships allow for a better estimation and understanding of the precipitation intensity (compared to the Marshall–Palmer relationship).
Barszcz [43]	Prediction of hydrographs of runoff from stormwater retention basins in the Służewiecki Stream Catchment.	Barszcz [43] evaluated the utility of using SWMM and SBUH models to predict hydrographs of runoff from stormwater detention reservoirs in the catchment of the Służewiecki stream, when controlled by appropriate valves. Assuming that the rainwater is retained in the reservoirs, and considering the effect of the delay in rainwater runoff from the catchment resulting from this retention, the author then proposed methods for determining the concentration time for a given rainfall event. The median absolute errors in terms of peak flows and hydrograph volumes for the events analysed indicate satisfactory simulation results with both the SWMM and SBUH models.
Nowak Da Costa et al. [110]	Assessment of the risk of flooding and inundation by floods in Warsaw.	Considering deterministic and stochastic aspects, Nowak Da Costa et al. [110] studied the possibility and risk of flooding and inundation by floods in Warsaw by referring to the issue of risk, the function of buildings and the number of inhabitants (especially considering the characteristics of buildings in terms of their capacity function). The study has shown the percentage of buildings that could be affected by a 500-year flood and what risks this potential event poses in quantitative terms.

In this section, we also present a more detailed map of the sanitary, rain and combined sewer system for the catchment area of the Służewiecki Stream (Figure A1), the concretisation and urbanisation of the individual districts (Figure A2), DEM and slope (% rate) for the Służewiecki Stream Catchment (Figures A3 and A4), and photo evidence showing various installations that are referenced in the study (Figures A5–A16).

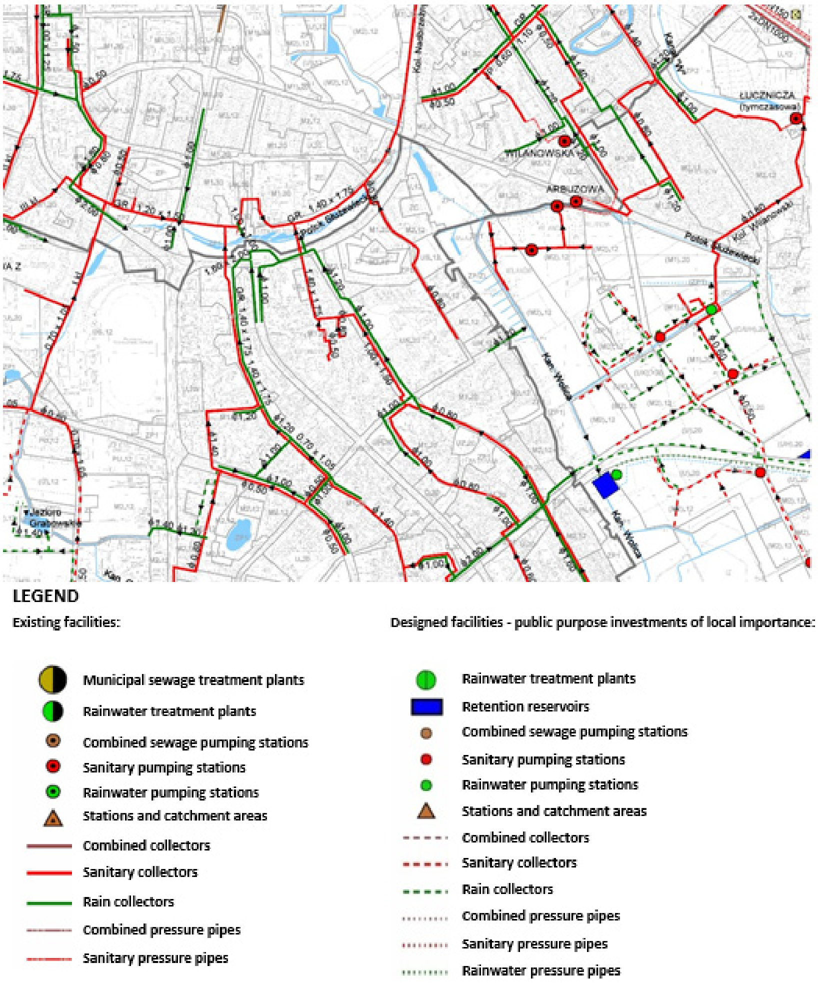

Figure A1. Sanitary, storm and combined sewer system for the catchment area of the Służewiecki Stream and the Wolica Canal (the part covering the districts of Mokotów and Wilanów).

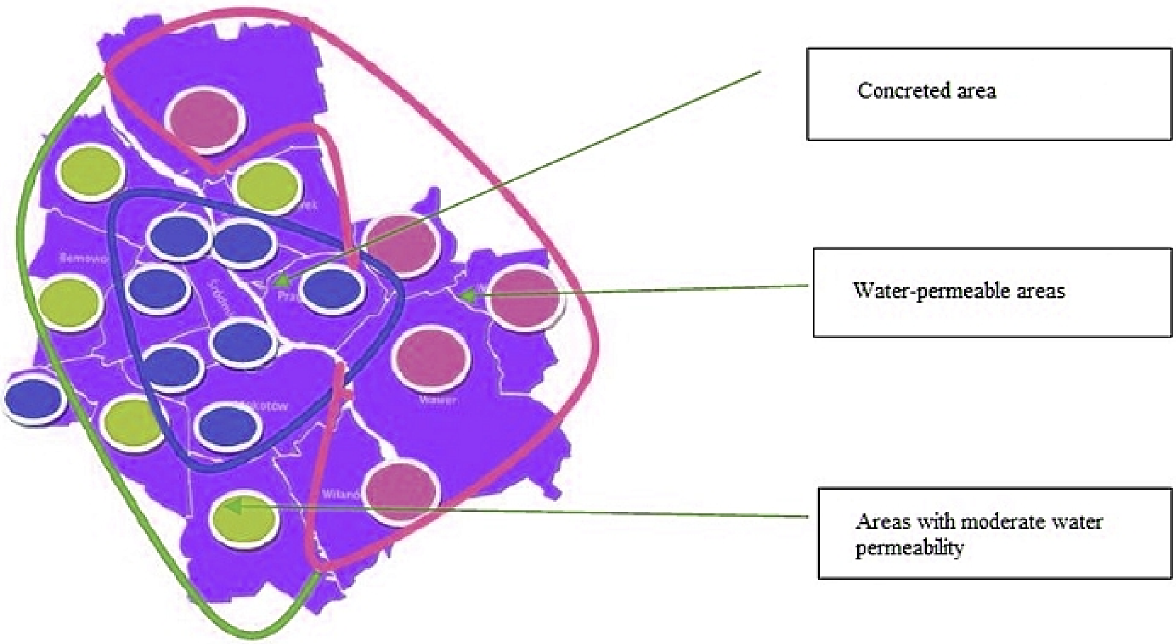

Figure A2. The structure of densification and urbanisation of individual districts, which means that individual areas have different soil permeabilities and runoff rates.

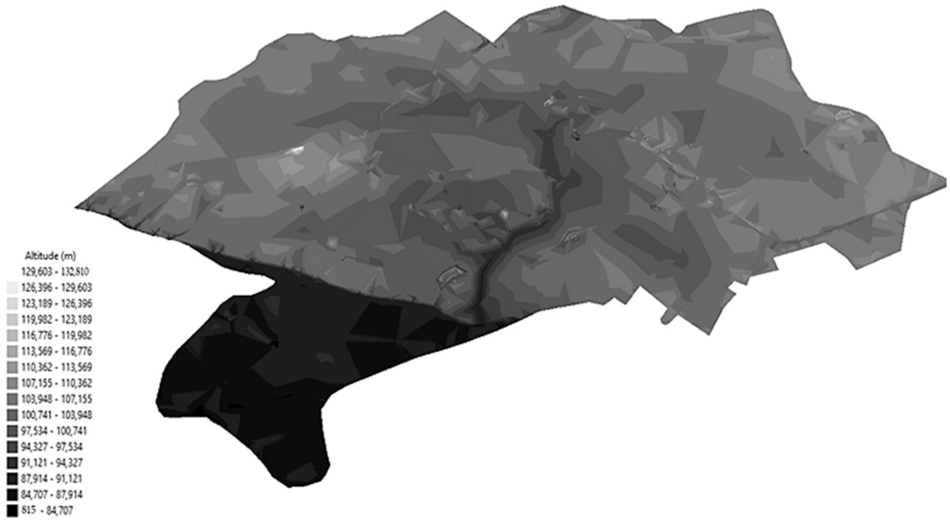

Figure A3. Digital Elevation Model (DEM) for the Służewiecki Stream Catchment area.

Figure A4. Slope (% rate)—Służewiecki Stream Catchment.

Figure A5. Discharge of water from the banks of the stream (onto the left bank) along Przy Grobli St. (towards the junction with the Wolica Canal) (K. Banasik).

Figure A6. Stone waterfall in Wilanów Park (source: own).

Figure A7. A view of the outflow from Ursynów rain collector measuring 4 metres in diameter, with a flow of 8 m^3s^{-1} (source: own).

Figure A8. Wąsal Pond reservoir at Katarynki Street (source: own).

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

Figure A9. Priest's Pond (**a**) historical (left) and (**b**) and contemporary (right) view.

Figure A10. Dried-up Zgorzała Lake and site plan of the restoration project at Zgorzała Lake (source: own).

Figure A11. Fort Bema in the Bemowo district of Warsaw (source: own).

Figure A12. Above the Fort Bema ditch in midsummer—path across the moat (source: own).

Figure A13. Służewiecki pond—flow-through basin at the intersection of Puławska and Rzymowskiego streets (source: own).

Figure A14. Elevated water level of the Służewiecki Brook at Wyścigowa Street (source: own).

Figure A15. Wolica Canal draining rainwater from Ursynów with an intensity of 8 m^3s^{-1} at the confluence with the Służewiecki Stream (source: own).

Figure A16. A part of the Służewiecka Valley with possible retention of stormwater (source: own).

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