Methods of hydrological and hydraulic modelling of the first flush of stormwater from urban runoff catchments: the experience of Austria and Ukraine

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Abstract

New detailed analysis of actual data on the problem of flooding of urbanized areas in Europe is performed. The analysis of methods of hydrological and hydraulic modelling, as well as modelling of the qualitative composition of the first flush of stormwater from urban runoff basins is presented with special emphasis on the approaches used in Austria and Ukraine. Using a rational method, as well as the results of large-scale interdisciplinary surveys and studies of the Baltic Sea catchment within the city of Lviv, the estimated maximum daily stormwater runoff flow rates at the inlet of Lviv WWTP were obtained as a function of return period and should be recommended for use in the implementation of the feasibility study of the reconstruction and modernization of Lviv WWTP.

***Keywords**:* first flush, pluviograph, rainfall intensity, runoff hydrograph, stormwater runoff, time of concentration

1. Introduction

The problem of flooding of urban areas and first flush discharge of highly polluted surface wastewater into natural reservoirs has become more acute in recent decades. Therefore, it is important today to develop and implement advanced methods of modelling stormwater, taking into account the specifics of urban basins, using modern technical capabilities for monitoring, collection and analysis of diverse interconnected data sets and using the latest software.

Scientifically based modelling and forecasting of stormwater runoff parameters is important from both economic and social and environmental points of view.

In recent decades, most countries around the world have seen a sharp increase in the frequency of heavy rainfall, which, together with intensive urbanization, leads to increasing flooding of human settlements, causing significant economic damage and social problems.

The results of the long-term analysis presented in [6] indicate that the last three decades are one of the four periods with the largest floods in Europe in the last 500 years, and the current period differs from other similar periods in the past, such as 1560 −1580 in Western and Central Europe, 1760−1800 – in most of Europe, 1840−1870 – in Western and Southern Europe. All previous periods of large-scale flooding took place against the background of temporary periods of cooling, during which the average air temperature was about 0.3 °C lower than the temperature in the inter-flood periods [6], while the current flood wave, which began around 1990 and continues to this day, accompanied by large-scale warming, which is currently continuing to increase. Official data from the World Meteorological Organization indicate, for example, that 2020 was among the three warmest in the history of meteorological observations, 2015–2020 was the warmest six-year period for the entire observation period, and the average surface temperature in 2020 exceeded preindustrial by more than 1 °C level [31].

2. Flooding in Europe: Trends and New Cases

Analysis of the results of large-scale long-term observations at about one hundred meteorological stations in Europe in 1946–1999 showed an overall increase in the average annual precipitation height of 0.76 mm/year and an increase in the number of days with precipitation of 0.04 year^{-1} [25].

In 2018, a team of experts from the Joint Research Center, the EU and the world's leading scientists, using a multifactor modelling system, assessed potential human casualties, direct economic losses and subsequent indirect losses (so-called decline in welfare) caused by river floods, increasing global average temperature on the planet at 1.5 °C. It is established that in the absence of measures to adapt to climate change, depending on the socio-economic scenario, human losses from floods can increase by 70–83% of current, direct losses – by 160–240%, and relative decline in welfare – by 0, 23–0.29% [11].

Large-scale flooding in Western and Central Europe in 2021

The most recent events of the summer of 2021 in Central Europe confirm the concept of increasing the intensity of the most powerful showers. In July 2021, a series of floods caused by Cyclone Bernd were observed in seven Central European countries (Austria, Belgium, Great Britain, Italy, the Netherlands, Germany, France and the Czech Republic). Thus, in Germany, on July 12–15, 2021, the monthly norm (about 150 mm) fell, and in some cases even more than the monthly precipitation norm (over 200 mm). For some regions, this level of precipitation has become the highest in the last 1,000 years, and the floods themselves have been called the greatest natural disaster of the last century. After a series of heavy rains in late June 2021, heavy rains in the first half of July caused small flowing lakes and sudden local floods to overflow, followed by medium and large rivers in western Germany, leading to massive flooding from the Eiffel National Park. the federal state of Rhineland-Palatinate up to South Westphalia (Germany) and further to south.

On July 12, 2021, the centre of the low-pressure area moved from south-western Europe to Germany, causing precipitation of 20 mm per day in the federal states of Hesse and Saarland to more than 50 mm per day in the federal state of Baden-Württemberg (Fig. 1). On July 13, the peak of precipitation fell in central Germany. In the Marienberg and Upper Franconia districts, precipitation levels of 43 mm were observed in 30 minutes, up to 88 mm in 120 minutes The cities of Solingen, Hagen and Wuppertal (North Rhine-Westphalia in western Germany) suffered the most. More than 241 mm of rain was recorded at the station of the State Administration for Nature, Ecology and Consumer Protection of North Rhine-Westphalia (LANUV) in Hagen in 22 hours [13]. On July 14 and the morning of July 15, the centre of activity of Cyclone Bernd fell in the territory of western Germany from Dortmund through Cologne to Trier. Continuous rains were intensified by squalls, more than 150 mm of precipitation per day were recorded.

Excessive rainfall, significant soil moisture and geographical location have led to significant human losses and destruction. In the valley of the river Ahr, the element destroyed numerous residential buildings and infrastructure: roads and part of the railways were blurred, many bridges were completely destroyed (Fig. 2) [14].

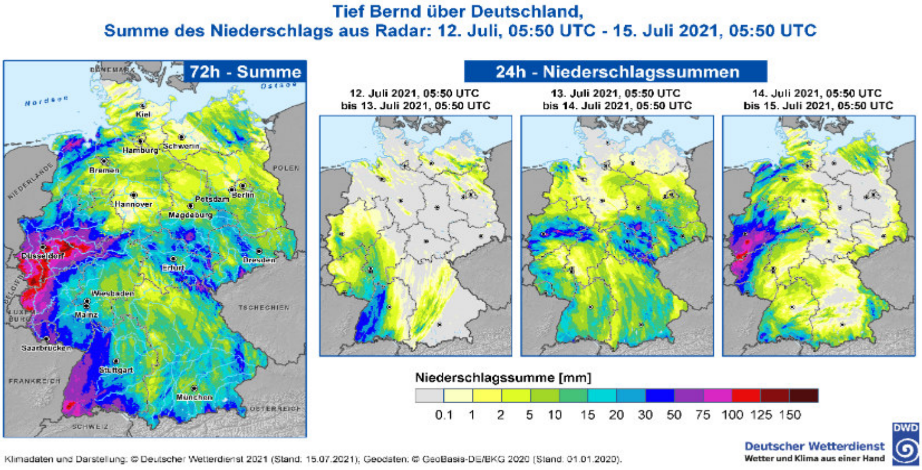

Fig. 1. Cyclone Bernd in Germany July 12-15, 2021 (© Deutscher Wetterdienst)

Fig. 2. The valley of the river Ahr before and after the flood in July 2021 [14]

The SWR website (Regional Public Broadcasting Corporation serving south-western Germany, including the federal states of Baden-Württemberg and Rhineland-Palatinate) has created a map of all local communities affected by this natural disaster (Fig. 3–4) [15].

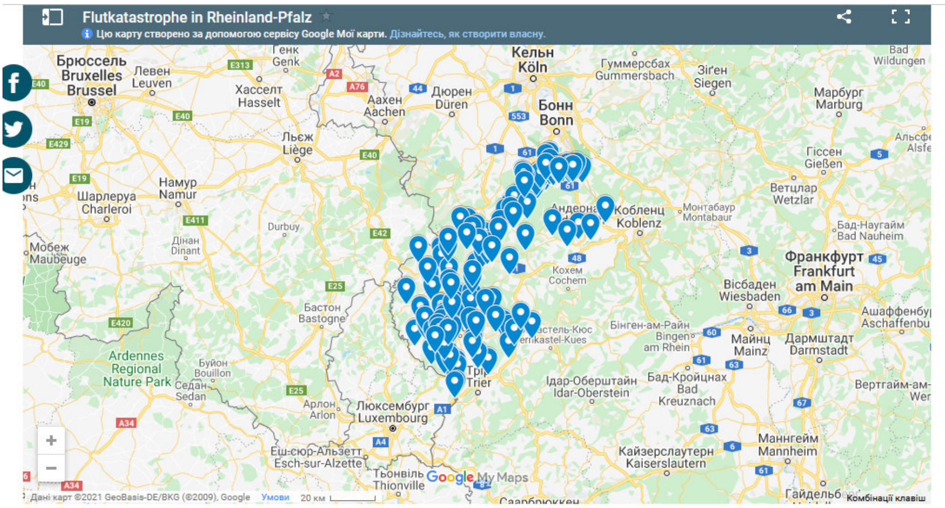

Fig. 3. Map of affected communities in southwestern Germany in July 2021
(© SWR.de [15])

Fig. 4. Flooded streets of Rayland Palatinate (Germany),
July 2021 [15]

In Austria in July 2021, significant flooding was observed in Vienna, Salzburg, Graz and the city of Galline. In Vienna on July 17-18, a large part of basements, underground parking lots and passages were flooded. Due to heavy rains, there was an emergency power outage. To overcome the consequences, fire brigades were involved, 1,200 rescue operations were carried out [16].

The town of Galline, located near the German border, suffered the most in Austria. Due to the flooding of its city centre, as well as the threat of landslides, civil defence alerts were used and residents were evacuated for fear of casualties among the population [17]. The amount of precipitation in this region for one and a half days (July 17–18, 2021) reached 135 mm, the situation was aggravated by floods in the neighboring region of Germany [18].

In Graz (Austria) on July 30, 2021 about 160 mm of precipitation fell. This caused flooding of many streets. However, the Graz Security Service noted that numerous stormwater storage tanks (SWST) saved the city from the devastating effects of bad weather [19].

Cyclone Bernd also passed over the Benelux countries, Great Britain, France, Switzerland, Poland and weakened to the Balkans (Fig. 5). In the United Kingdom, particularly in London, isolated torrential rains with a precipitation height of more than 24 mm/day were recorded, and central streets and roads of regional importance were flooded.

In the Netherlands, the Limburg region was hit by floods, a motorway was partially flooded, and an army was used to evacuate the victims. The east of Belgium has been hit by heavy rains, rail services have been suspended, flooding of up to 2 meters has been recorded on some streets in the provinces of Namur and Luti, and 2,000 residents have been evacuated. In Luxembourg, the height of the precipitation layer exceeded 79 mm in 24 hours, which is much higher than the July average.

France was also covered by rains, which were equal in intensity to the amount of precipitation for 2 months. During July 12–15, an average rainfall of 100 mm was recorded in the east, sometimes up to 150 mm [20].

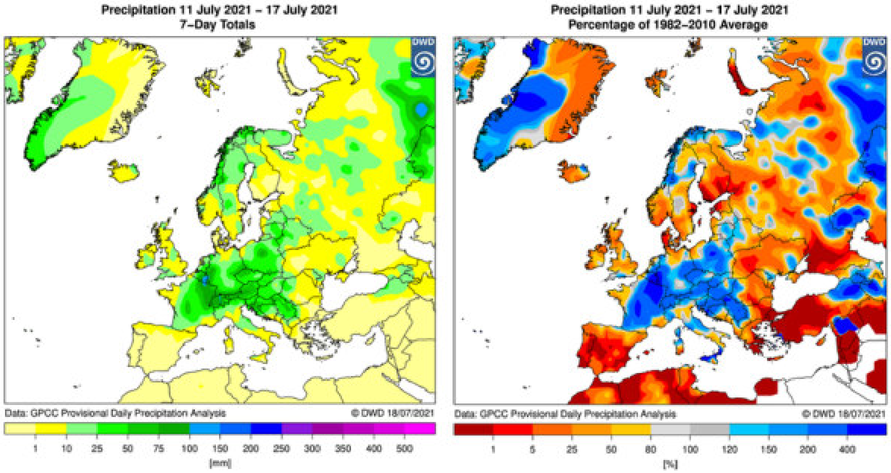

Fig. 5. The amount of precipitation during 11−17.07.2021 in Europe is absolute (left) and as a percentage of the average value for 1982−2010 (right), © DWD [18]

In Switzerland, with an average rainfall of 112 mm per month in July, only 10 minutes. on the night of July 12–13, 2021, 27 mm of precipitation was recorded. Gusts of wind and torrential rains led to falling trees, damage to cars and houses, massive landslides. In the first 14 days of July, 300 mm of precipitation was recorded at Sedrun station, which is twice the maximum for the last 60 years [21].

By July 13, 2021, Cyclone Bernd reached northern Italy, where it caused severe thunderstorms with hail precipitation of up to 7 cm and heavy rainfall of about 83 mm in 30 minutes. Many houses and plantations were affected [22].

Flooding of urban areas in Ukraine

The results of meteorological observations show that the climate in Ukraine has been actively changing in recent decades. There is a sharp temporal and spatial variability of precipitation distribution in Ukraine in the period from 2002 to 2011 [40]. A large-scale analysis of changes in rainfall parameters in Ukraine in 1991–2013, presented in [42], showed that 36 of the 40 hydrometeorological stations studied during this period exceeded the long-term maximum monthly altitudes of the precipitation layer. There is a high probability of continuing the trends of recent decades, namely - an increase in the amount of rain, especially high intensity, as well as increasing the unevenness of precipitation during the year.

The last three decades have seen a sharp rise in average air temperatures throughout Ukraine. For example, in Kyiv during this period the temperature of the surface air layer increased by almost 2 °C, and climate modelling predicts the continuation of such rapid growth in the current century [41] (Fig. 6).

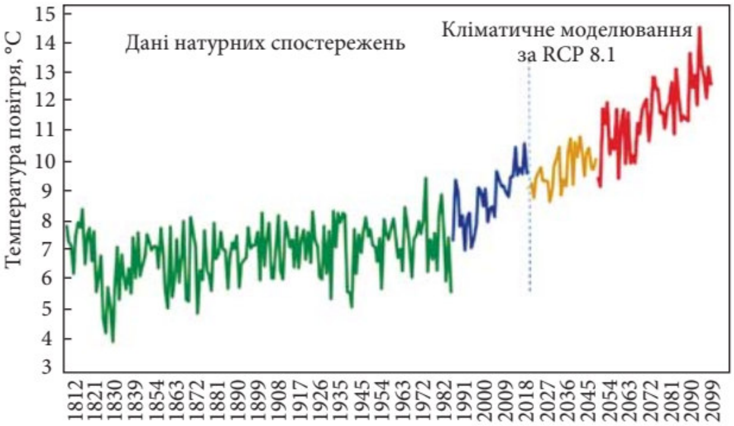

Fig. 6. Actual and projected long-term changes in the surface air temperature in Kyiv (according to [41])

Similar trends in temperature rise are typical of all major cities in Ukraine. For example, according to the Ukrainian Hydrometeorological Center, the average annual air temperature in Lviv has been growing at a rate of about 0.016 °C/year in recent decades (Fig. 7), which corresponds to a century above the first critical indicative value of 1.5 °C. Despite the same trend throughout Ukraine to increase the average air temperature, trends in precipitation in different cities differ slightly. For example, in Kyiv there is a decrease in the average annual height of the precipitation layer, while in Lviv – on the contrary, an increase.

This confirms the general global trend regarding the diversity of changes in average precipitation parameters, even within one geographical region [31]. On the other hand, as in the countries of Western and Central Europe, the frequency and capacity of the most intense rains in the cities of Ukraine is increasing, which leads to an increase in the frequency and scale of flooding of urban areas. Similar consequences with the flooding of urban areas after heavy rains occur every year in most regional centres of Ukraine.

Given the above, improving the methods of hydrological modelling of water runoff in climate change is today one of the priority areas of research in water management in Ukraine [41], and integrated stormwater runoff management in urban areas - an important element of practical adaptation to global climate change.

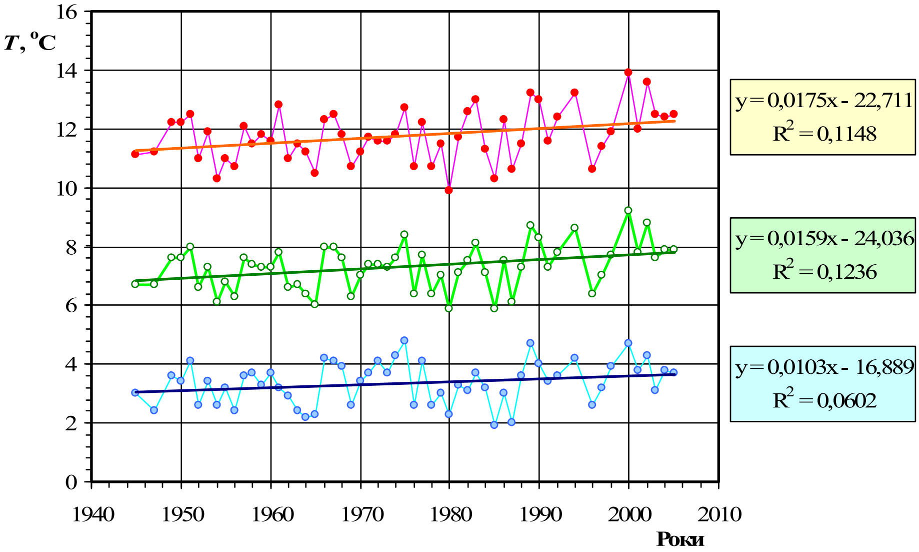

Fig. 7. Average annual maximum, average and minimum air temperatures in Lviv (data of Ukrhydrometeocenter)

3. *Features of the first flush discharge of surface runoff from urban areas*

Today, progressive urbanization is becoming one of the key factors of negative impact on the environment. It causes a number of problems, including in terms of stormwater management. These problems are complicated by the lack of an integrated approach to the design of municipal infrastructure, including sewerage systems.

The first flush discharge of surface stormwater from urban areas poses a special threat to the normal operation of both the sewerage network and sewage treatment plants. During this phase of the runoff hydrograph, the most concentrated part of the surface runoff from the territories characterized by a high proportion of impervious surfaces enters the drainage network. Simultaneously with high concentrations of pollutants, the first flush discharge is characterized by a sharp increase in volumetric flow, which causes a complex peak load on the drainage system, both in terms of quantitative parameters of surface runoff (maximum volumetric costs) and in terms of maximum concentrations and mass consumption of pollutants. The first discharge can indeed be considered a flush if at least 70–80% of the total mass of pollutants is transported in the initial 25–30% of the volume of stormwater runoff [5].

Identifying the nature and characteristics of the phenomenon of the first flush discharge is especially important for the sound implementation of stormwater quality management practices. An alternative methodology for detecting the first flush discharge is the mass factor of the first flush. A number of researchers have established in practice that the first flush release is present only for part of the analyzed rains. Thus, less than half of the rains in the study [5] showed more than 40% of the total mass of pollutants in the first 20% of the total volume of runoff.

Another disadvantage of the traditional approach to determining the first flush discharge is the immensity of the key parameters, which does not allow to take into account the influence of the absolute value of the surface runoff. The total amount of runoff due to light rain may be equal to the volume of the first 20% of heavy rain, and therefore may be completely within its first flush discharge. Two types of pollutant sources have been identified in urban runoff basins:

- short-term pollution accumulated during the period of dry weather, which is completely washed away from the surface of the runoff basin, if the rain is sufficiently intense and prolonged;

- long-term pollution that corresponds to the background level of pollution for a given runoff basin and that cannot be completely washed away by rain of arbitrary duration and intensity.

If a short-term source of contaminants is not exhausted as a result of rainfall with a low layer height, the concentration of the pollutant will be consistently high. This explains the results of studies in which the effect of the first flush was much weaker and less frequent for rains with a low height of the precipitation layer.

Lee at al. [26] presented an improved technique was presented, which relates the first discharge to the absolute volume of runoff and allows you to simulate changes in the mass of contaminants over several rains over a sufficiently long period of time, presented. Continuing this direction, Bach et al. [1] presented a new approach to the definition of the first flush discharge, which corrects a number of shortcomings of the traditional approach, including the use of actual values of runoff compared to dimensionless fractions of the total volume, more accurate definition of the first flush, as a function of the characteristics of the catchment, rather than a separate estimated rain.

4. *Maximum daily flow rates of the stormwater runoff at the inlet of Lviv WWTP*

Scientifically based modelling of stormwater drainage systems should be based on the fullest possible consideration of climatic, topographic, hydrological, hydrogeological, hydraulic and urban planning characteristics of the object [23]. Stormwater modelling involves solving a set of stochastically determined non-stationary hydrodynamic and mass transfer equations, and the quality of the model depends on the completeness and relevance of the original data, which can be obtained only with multidisciplinary approaches and the widespread introduction of specialized computer programs [38]. The following is an example of a multidisciplinary study performed to determine the maximum daily surface runoff costs at the entrance to Lviv sewage treatment plants.

The peculiarity of the geographical location of Lviv is that the territory of the city is almost equally divided by the line of the Main European watershed into the basins of the Baltic and Black Seas (Fig. 8). The Poltva River, which originates in the city, is the main sewer collector of the general-alloy sewerage system, which collects domestic and industrial wastewater from the whole city, as well as surface wastewater from the Baltic Sea runoff basin and underground river runoff Poltva and delivers wastewater to Lviv WWTP. From the territory of the Black Sea runoff basin, only heavily polluted part of rain and melt runoff, which enters the all-alloy network through separation chambers, and insignificant part of runoff, which enters the network due to leaks of sewage system elements, enters Lviv WWTP. The area of the Baltic runoff basin within the official boundaries of Lviv is 59.5 km^2, and the area of the Black Sea runoff basin is 62.1 km^2.

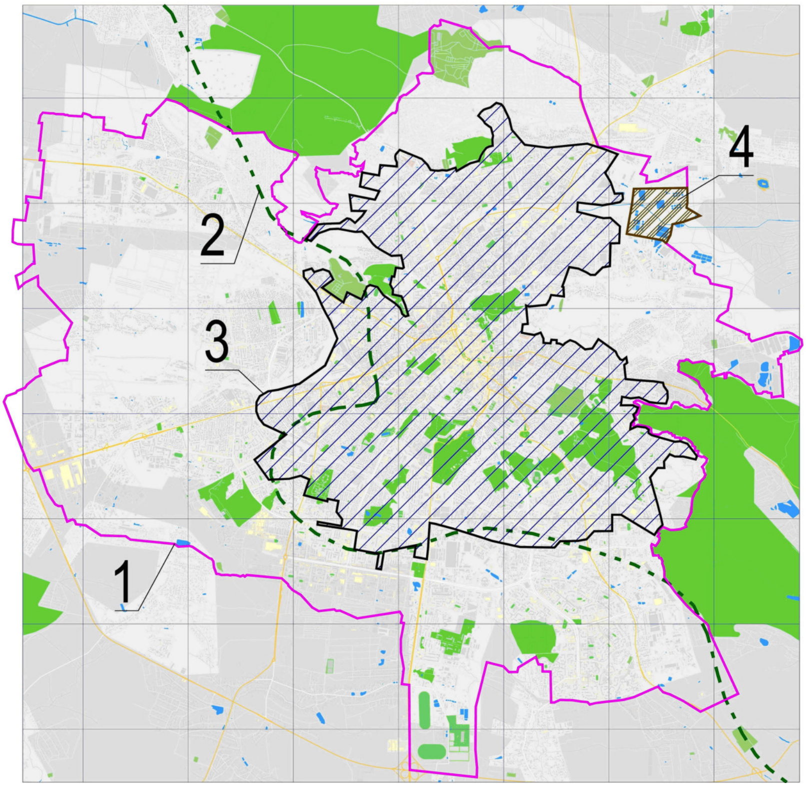

Fig. 8. Plan-scheme of Lviv city: 1 – official city boundaries; 2 – the main European watershed (geographical watershed); 3 – technical watershed of the Baltic Sea catchment, 4 – territory of Lviv WWTP

As of 2021, Lviv WWTP are in a rather problematic technical condition and need large-scale reconstruction and modernization.

Estimated maximum daily volumes of surface runoff of different recurrence, which enter the all-alloy system of Lviv city sewerage and enter the Lviv WWTP, determined using a rational method, which is most often used to solve similar problems both in Ukraine and abroad:

$$W_{d.max,P} = (\Sigma\ \psi_{i,P}\ F_i\ )\ h_{d.max.P} / 1000, \qquad (1)$$

$\psi_{i,P}$ – calculated values of runoff coefficients for pervious and impervious surfaces in Lviv, as a function of the return period P; $h_{d.max.P}$ – maximum daily height of the precipitation layer in Lviv, as a function of the return period P; F_i is the area of different types of coverage of the Baltic Basin of Lviv.

The total area of the Baltic Sewage Basin within the technical watershed was determined by processing and analyzing a map of the main sewers of Lviv, made at a scale of 1:2000, as well as satellite photographs of the city with the current state of development. The total area of the Baltic runoff basin was determined by an analytical method: $F = 40.79$ km^2.

To determine the share of waterproof surfaces, a statistical sample analysis of 20,000 elementary cells of the satellite photographic image of the Baltic runoff basin within the city of Lviv of high resolution was performed. An example of identification of cover types is shown in the fragment shown in Fig. 9.

Fig. 9. Fragment of a satellite image of the city of Lviv with examples of determining the types of coverage: blue cells - improved waterproof surfaces; yellow cells - water-permeable surfaces

Among the 20,000 analyzed cells measuring 2×2 m, each number of cells with waterproof coatings amounted to 10,157 units. Thus, the use of the method of simple statistical sampling for the Baltic basin of the city of Lviv, allowed to determine the share of total watertight surfaces at 50.8% ($p_{tot} = 0.508$). The relative error of this value is ± 0.9% with a confidence interval of 99% or ± 0.7% with a confidence interval of 95%.

To establish the relationship between the share of total waterproof coverings and the share of effective waterproof coverings within the Baltic Basin of Lviv runoff, the results of sample field studies of the degree of improvement of 75 quarters in six administrative districts of Lviv with a total area of over 1000 hectares were analyzed. Table 1 shows a summary of the areas of all 75 studied sub-basins of the Baltic runoff basin within the city of Lviv.

Table 1 - Summary of the surveyed areas of 75 neighborhoods within the Baltic Basin of Lviv

#	Type of surface cover	Area		p, %
		m^2	ha	
1	Directly connected impervious areas	5518094	551.81	55.12
2	Non-connected impervious areas	666536	66.65	6.66
3	Pervious areas	3808196	380.82	38.04
4	Water bodies	17723	1.77	0.18
5	Impervious	6184630	618.46	61.78
	Total:	10010549	1001.05	100.00

Mathematical processing of field sample data revealed a statistically significant relationship between the share of total waterproof coatings and the share of effective imperviousness in the Lviv Baltic Sea catchment (Fig. 10):

$$p_{ef} = p_{tot}^{1.318} \qquad (2)$$

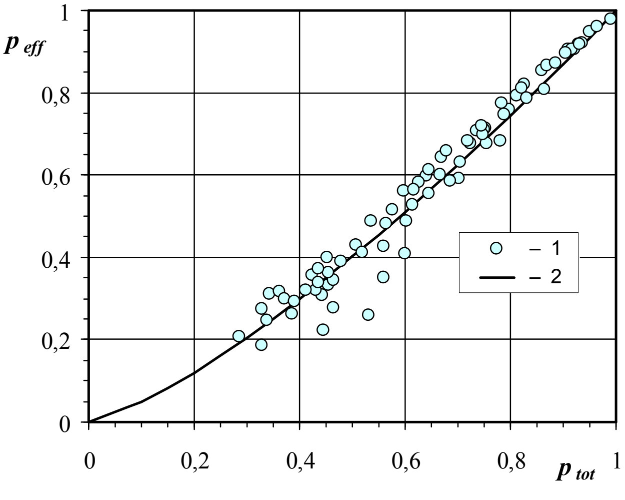

Fig. 10. Relationship between the shares of effective and total impervious covers in the Baltic Sea catchment of the Lviv city: 1 – survey results of 75 quarters; 2 – power-law function (2)

Applying the dependence (2) for the entire Baltic basin runoff at p_{tot}=0.508 gives the calculated value of the share of effective waterproof covers p_{ef}=0.410, surface runoff from which directly enters the sewer system through a network of drains, trays, stormwater catchments, etc. The maximum relative error in converting the share of total to the share of effective waterproof coatings for the Baltic runoff basin as a whole is ±1.32%.

Ranking and statistical processing of the highest rainfall in Lviv for the period from 1984 to 2019 revealed the dependence of the maximum daily height of the rainfall on the return period P in the form of Weibull function:

$$h_{d.\max} = 72.1 - 67.5e^{-0.765 \cdot P^{0.667}} \tag{3}$$

Estimation of runoff values for different types of surfaces in Lviv (Table 2) was determined by the method of ordinal curves, which is most often used today in US engineering practice [32], and is widely around the world.

Table 2 – Estimated values of runoff coefficients ψ by the method of the order curve [32] for the city of Lviv

Return period *P*, years	Rainfall depth $h_{d.max}$, mm	Runoff coefficient ψ	
		impervious surfaces	pervious surfaces
0.1	14.85	0.677	0.040
0.25	22.27	0.767	0.0001
0.5	30.41	0.821	0.016
1	42.24	0.867	0.067
2	56.23	0.897	0.135
3	63.46	0.908	0.168
4	67.43	0.913	0.186
5	69.69	0.916	0.196

The maximum daily flow rates of surface runoff of different return periods, determined by the rational method, are given in Table 3.

Table 3 – Estimated maximum daily volumes of surface runoff at the inlet of Lviv KOS and relative errors of their determination

Return period *P*, years	Rainfall depth $h_{d.max}$, mm	Maximum daily flow rates $W_{d.max}$, th. m^3/day	Errors	
			+ δW_{max}, %	− δW_{max}, %
0.1	14.85	182.42	2.34	2.31
0.25	22.27	285.55	2.50	2.47
0.5	30.41	428.96	2.45	2.42
1	42.24	680.06	2.30	2.27
2	56.23	1026.0	2.13	2.11
3	63.46	1220.8	2.06	2.04
4	67.43	1331.8	2.03	2.01
5	69.69	1396.1	2.01	1.99

5. Summary and Conclusions

New detailed factual data on the problem of flooding of urban areas in Europe.

The analysis of methods of hydrological and hydraulic modelling, as well as modelling of the qualitative composition of the first flush discharge of stormwater from urban runoff basins with special emphasis on the approaches used in Austria and Ukraine.

Using a rational method, as well as the results of large-scale interdisciplinary surveys and studies of the Baltic Sea catchment within the city of Lviv, the estimated maximum daily stormwater runoff flow rates at the inlet of Lviv WWTP were obtained as a function of return period and should be recommended for use in the implementation of the feasibility study of the reconstruction and modernization of Lviv WWTP.

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