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Spatial distribution of average annual water runoff in the Pripyat basin rivers (Ukraine)

Abstract: The article presents the results of a study on spatial distribution of water runoff in the Pripyat basin rivers in Ukraine. The authors analysed long-term observational data from 28 hydrological stations in the territory of Ukraine and 30 stations outside its borders. The data obtained from these stations comprised a period from the beginning of their operation up to and including 2017. The authors employed GIS technology to automate the process, and made use of different types of interpolation to ensure more accurate calculations. The study resulted in the creation of an updated modern map of water runoff for the territory of the Pripyat basin rivers in Ukraine, with isolines every 0.2 $l \cdot s^{-1} \cdot km^{-2}$. This can be used to determine the values of specific water runoff rates for rivers not subject to constant observations, in particular with regard to rivers featuring small water catchment for more convenient and faster use.

Keywords: specific water runoff rate, runoff map, river basin, Pripyat basin rivers, Ukrainian part of the Pripyat basin, spatial analysis of water resources.

1. Introduction

Scientists have always paid attention to the assessment of water resources and the study of spatial patterns in surface runoff of rivers. Spatial and temporal variability of runoff is crucial to understanding past, present and future environmental conditions (Konovalov, 2011). For this purpose, scholars tend to analyse data pertaining to the average annual water runoff, as it is the main characteristic of river runoff. It is known that fluctuations in river water runoff display cyclical patterns. Therefore, having more observational data at disposal offers an opportunity to update or revise the results of previous studies.

The first generalization of the average annual river runoff for the European part of the Soviet Union was performed by Kocherin in 1927 (Kocherin, 1932). Subsequently, many scientists discussed to the issue of the spatial distribution of water runoff norms. Some of the earliest fundamental generalizations of runoff norms include the works of Kocherin (1932), Zaykov and Belynkov (1937), Zaykov (1946), Voskresenskiy (1962) and Onufrienko (1966). In 1962, a book entitled *Hydrological calculations for rivers of Ukraine* was published under the editorship of G. Shvets, and included a chapter named "Calculation of annual runoff and its distribution in a year" (Shvets et al., 1962). In the years 1966–1971, several issues of *Surface Water Resources of the USSR* were published, which provided detailed characteristics of the average annual runoff of the Ukrainian rivers, with particular focus on the territory of the Pripyat basin (Kupriyanov, 1966). In order to create the USSR Building Codes and Regulations, the scientists developed a comprehensive map of water runoff for the rivers in the USSR (Shmydt, 1984).

The maps were compiled for the European part of the USSR territory and for the entire country. Their scales were, respectively, 1:20 000 000, 1:15 000 000, 1:10 000 000 and 1:5 000 000. Their scope is approximately 8.5 and 37 times larger than the modern territory of Ukraine, and even more so when compared to the area of the Pripyat basin. The maps in question have a schematic form, and thus pose certain difficulties in determining the values of specific water runoff rate, for example in the Pripyat basin, allowing for generalized results only. Quantitative values therein range from 2 to 4 $l·s^{-1}·km^{-2}$, and isolines at 4 $l·s^{-1}·km^{-2}$ are typical of most of the Ukrainian part of the Pripyat basin.

A map of the average long-term runoff was prepared for the *National Atlas of Ukraine*, which covers the observation period from 1950 to 2000 (Rudenko, 2007). In 2003, a monograph was published under the title: *Monitoring, use and management of water resources of Pripyat River* (Kalinin and Obodovskyi, 2003), which includes a map of water runoff for the Pripyat basin (within Ukraine and the Republic of Belarus) based on the observations for the period up to 2000. In 2017, the work of Belarusian scientists was published (Volchak and Bulskaya, 2017), which presents a modern map of water runoff in the Pripyat basin within the territory of the Republic of Belarus. The map was based on observational data from the period of 1956-2015, with an isoline every 0.5 $l·s^{-1}·km^{-2}$. Recently, the application of geographic information systems has become relevant, allowing for the inclusion of different types of interpolation for the preparation of runoff maps. The practical application of GIS technologies is discussed in the works of foreign scientists (Cederstrand and Rea, 1995; Masoner and Ferrella, 2006; Denisova and Perevoschikov, 2009; Doganovskiy and Orlov, 2011; DEM Processing for Watershed Delineation using QSWAT, 2015).

Using GIS technologies, the Ukrainian researchers prepared runoff maps for the entire territory of Ukraine as a whole, and for selected river basins individually (Gorbachova, 2010; Obodovskyi et al., 2016, 2017). While the rivers of the above-mentioned basin may have been discussed on numerous occasions, the authors of this paper set out to apply new methods pertaining to the preparation of runoff maps, which allow for increased accuracy of obtained values, and thus, improved spatial assessment.

The main aim of the work is to create a detailed modern map of the average annual runoff in the rivers of the Pripyat basin in Ukraine. To this end, we set goals to review existing methodological approaches to mapping river water runoff, especially with the involvement of GIS technologies, presenting the spatial distribution of average annual water runoff of the Pripyat basin rivers in Ukraine in the form of a map with the most informative distribution of isolines for detailed coverage (even for unexplored rivers in hydrological terms), and to evaluate the accuracy of the constructed water runoff map.

2. Methodical approaches to the preparation of runoff maps.

Spatial changes in the average annual river water runoff rivers are subject to certain patterns, in particular, geographical zoning (Khilchevskyi and Obodovskyi, 2008).

Bearing that in mind, a runoff map can be prepared directly based on the observations of river water runoff in the studied area. In this case, the average annual runoff is defined as:

$$\bar{Q}_n = \frac{Q_1 + Q_2 + \dots + Q_n}{n} = n^{-1} \sum_1^n Q_i \qquad (1.1)$$

where, … – annual runoff values; *n* – the number of observation years

However, in different series of observations (*n)* the value is unstable, because the considered period of time may coincide with the periods of only high or low water phase. Therefore, in order to obtain a stable value , it is necessary to have a series of a certain length (*N*), which includes periods of high and low water phase. In this case, is the norm of runoff. Since in most cases the lengths of the actual series of observations of the annual runoff are short, the value of the runoff norm obtained with formula (1.1) differs from its actual value observed at N → ∞ by the value :

$$\tilde{Q}_N = \bar{Q}_n \pm \sigma_{Qn} \qquad (1.2)$$

where – average annual runoff for a limited n-summer period; – standard deviation of the mean value for the same period of time (Rozhdestvenskiy et al., 1990).

To compare the accuracy at which water runoff rate is determined for different rivers, the concept of a relative value of the standard deviation is introduced, which is expressed as a percentage:

$$\sigma_n = \pm \frac{100\, C_v}{\sqrt{n}}, \quad (1.3)$$

where – variation coefficient of a number of annual runoff values for *n* years (Rozhdestvenskiy et al., 1990)

To prepare maps of the spatial distribution of water runoff in a given area, it is necessary to exclude the influence of the river catchment area. Therefore, the rates of water runoff in rivers are applied, which are given in the form of water runoff layers (Y, mm) (1.4) or specific water runoff rate (q, $l \cdot s^{-1} \cdot km^{-2}$) (1.5):

$$Y = Q \cdot T \cdot F^{-1} \cdot 10^{-3}, \quad (1.4)$$

$$q = Q \cdot 10^{-3} \cdot F^{-1}, \quad (1.5)$$

where *Q*– water flow (m^3/s), which is directly measured at hydrological stations, *T* – the number of seconds in the interval being calculated time interval (in our case, this is the number of seconds per year) (Khilchevskyi and Obodovskyi, 2008)

By examining river runoff we can surmise the conditions of its formation against the background of the entire basin. Therefore, mapping of hydrological characteristics is unique in that the values shown on the map are not related to any given measurement point (as is the case in mapping of climatic characteristics), but rather to the entire catchment as a whole. This is due to the fact that the flow of water, which is measured at the hydrological station, constitutes an average runoff from the entire river basin.

When preparing the map, data on small basins are not plotted, as their average annual runoff is largely determined by local factors and primarily depends on the size of catchment areas. Observation data for large rivers, which usually flow over several geographical areas, are also not taken into account when preparing maps. The runoff rates for both small and large river basins serve only to control the reliability of the map (Khilchevskyi and Obodovskyi, 2008).

Methods of using GIS technologies to prepare water runoff maps include information collection (creation of the initial data bank), preparation and processing of data (geospatial analysis) and visualization of the results (preparation of the multilayer maps). This requires digital maps, spatial and attributive data obtained from hydrological stations, morphometric characteristics of the rivers, relief, climatic characteristics, etc. (Obodovskyi et al., 2019).

3. Initial data and assessment of the accuracy in determining the flow rate (long-term values)

To study the spatial changes, as well as distribute and generalize the average annual water runoff in the Pripyat basin rivers in Ukraine, the authors applied data on average annual water flow from 28 hydrological stations in Ukraine and 30 hydrological stations of neighbouring basins outside the Pripyat basin within the boundaries of the country (Fig. 1). This served as a basis for calculating the average long-term specific water runoff rate.

Periods of observations at these stations span over more than 30 years (from the beginning of continuous observations up until and including 2017). The observation period of ≥ 70 years is typical for about 26.9% of hydrological stations within the Ukrainian part of Pripyat basin, 34.6% have 60 ÷ 69 years, 30.8% – 50 ÷ 59 years, and only 7.7% feature an observation period ≤ 50 years. In general, 92% of the hydrological stations involved in the preparation of the map have observation periods from 50 to 79 years (river Vyzhivka, Stara Vyzhivka station – 75; river Styr, Lutsk station – 71).

Analysing the obtained results of calculations, the average long-term runoff module for the study area is 3.89 $l \cdot s^{-1} \cdot km^{-2}$, its largest value is 5.85 $l \cdot s^{-1} \cdot km^{-2}$ (river Radostavka – station Triitsia), the lowest value is 2.07 $l \cdot s^{-1} \cdot km^{-2}$ (river Prypiat – station Liubiaz), and the range of values on the territory amounts to 4 $l \cdot s^{-1} \cdot km^{-2}$.

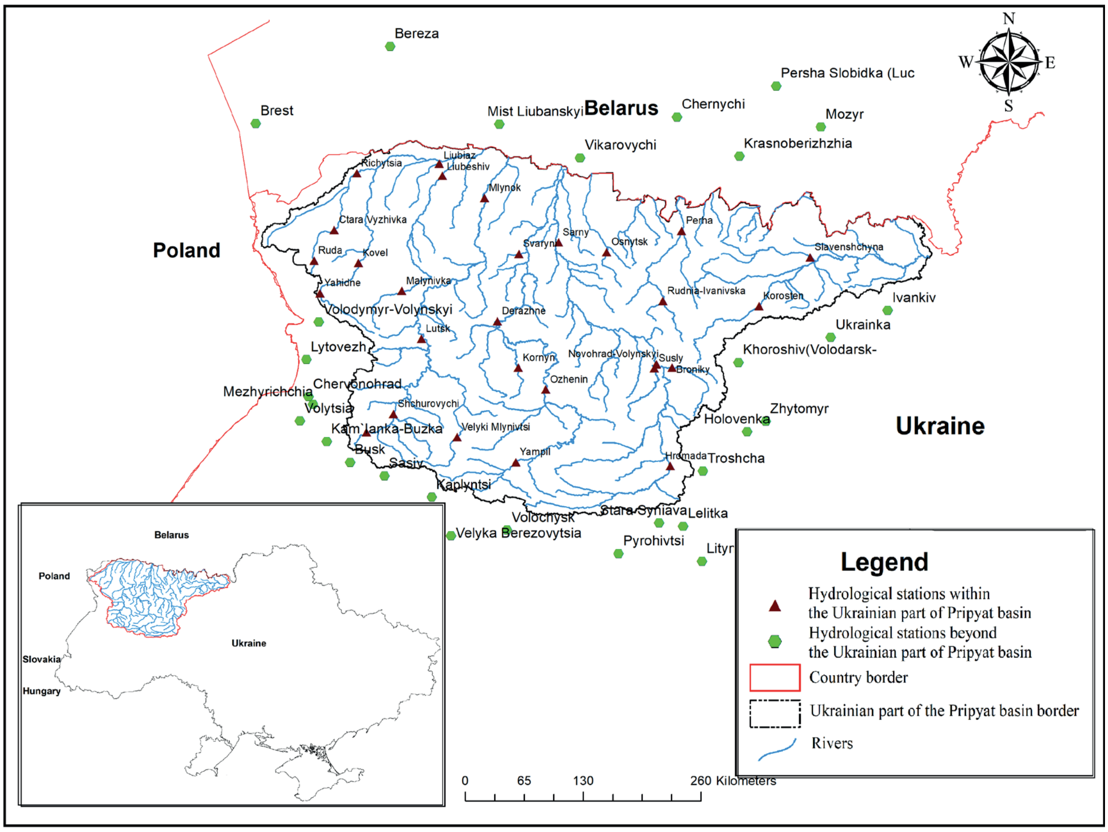


Figure 1. Hydrological stations within the Ukrainian part of the Pripyat basin and the adjacent basins, from which observational data were obtained for the work (the Authors' own study prepared by QGIS)

As with any research, it is important to account for the calculation error to ensure reliability of the received results, therefore we calculated the root-mean-square errors with regard to the average annual runoff for the territory of the Pripyat basin in Ukraine. Analysis of the relative errors in the calculation of water runoff rates demonstrated variability in the range from ± 2.63 to ± 8.93%, with the average value in the basin being ± 5.22%, which corresponds to the average deviation of the specific water runoff rate – ± 0.21 $l \cdot s^{-1} \cdot km^{-2}$.

Since the root-mean-square errors are <10%, the series were considered representative and the calculation results were deemed acceptable.

4. Results and Discussion

Drawing up run off maps using the analytical functions of GIS calls for detailed analysis of the existing hydrological and mapping information, with particular emphasis on the density and uniformity of points distribution and proper preparation of the data used in the creation of a digital map. GIS offers high accuracy of the results and efficiency in solving a number of hydrological problems. For the purpose of this study we elected to use The Quantum GIS software (QGIS), which is one of the most commonly used open source software of this kind in the world.

An algorithm consisting of several stages (automatic separation of watershed lines, automatic interpolation of isolines, determination of the runoff module for catchment centres) was applied to prepare a map of river runoff in the Pripyat basin in Ukraine (Obodovskyi et al., 2016, 2017, 2019).

The interval of specific water runoff rate values between isolines is chosen depending on the range of the obtained values and their visual spatial distribution. Most of the existing water runoff maps for plain rivers, including the Pripyat basin, are presented with an interval of 0.5 $l \cdot s^{-1} \cdot km^{-2}$

(Kalinin and Obodovskyi, 2003; Obodovskyi et al., 2017; Volchak and Bulskaya, 2017).

In our opinion, such an approach may not accurately reflect the spatial distribution of runoff and its fluctuation. Therefore, we proposed several variations of maps with distribution of isolines every 0.5 l·s^{-1}·km^{-2}, 0.2 l·s^{-1}·km^{-2} and 0.1 l·s^{-1}·km^{-2}.

If one prepares the cartographic presentation with isolines at intervals of 0.5 l·s^{-1}·km^{-2} (Fig. 2), about 46% (12 values) of the calculated values of specific water runoff rate of the Pripyat basin rivers in Ukraine will be in the range of 3 to 4 l·s^{-1}·km^{-2} (Fig. 3 a, b). Furthermore, were we to take into account the distribution of hydrological stations in the study area, where 1 hydrological station accounts for 4.6 thousand km^2 of the basin, a significant part of the basin (about 55 thousand km^2) would be covered by only several isolines, which is deemed insufficiently informative for a territory of this size.

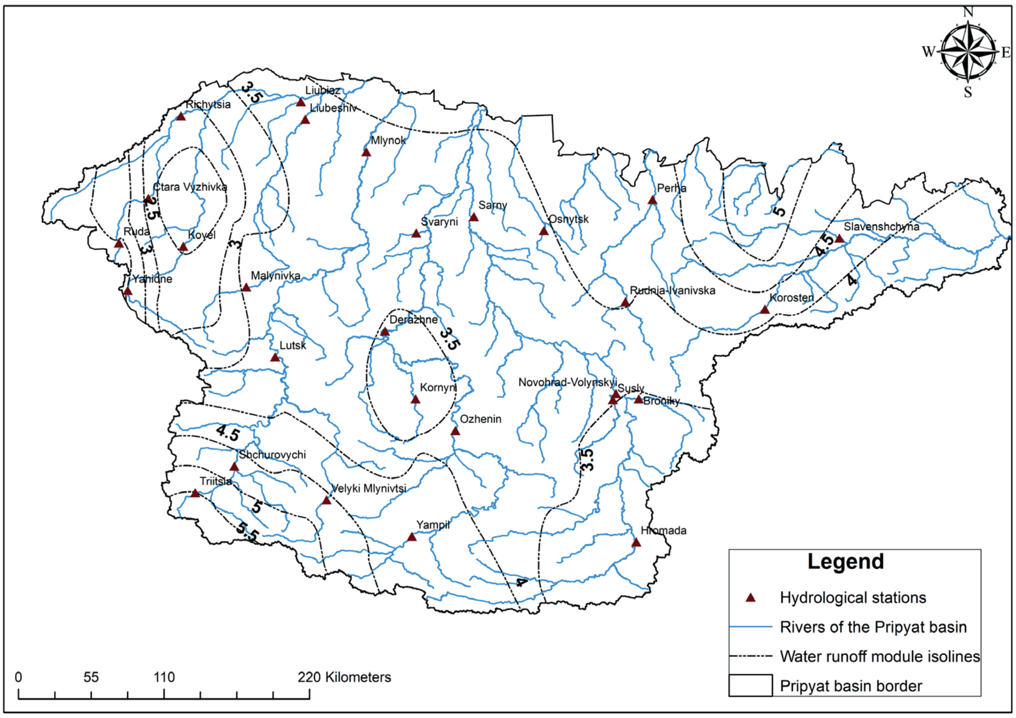
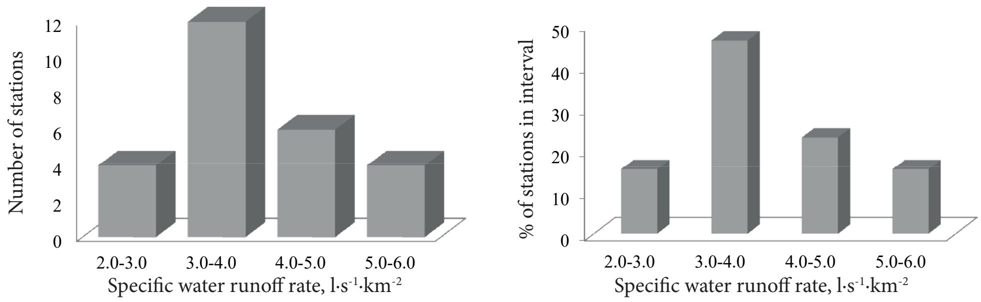


Figure 2. Map of the average long-term module of water runoff in the Pripyat basin rivers in Ukraine, with isolines every 0.5 l·s^{-1}·km^{-2} (the Authors' own study prepared by QGIS)



a b

Figure 3. Distribution of specific water runoff rates in interval terms (prepared based on the Authors' own study)

Variation of the map with isolines every 0.1 l·s^{-1}·km^{-2} (Fig. 4) creates an increased concentration of the isolines in individual cells. However, such a detailed distribution requires data from a larger number of hydrological stations, since such detailing applies mostly to small catchments, which are significantly influenced by the regional runoff factors. This can result in a possible change in the directions of isolines distribution in the selected interpolation method.

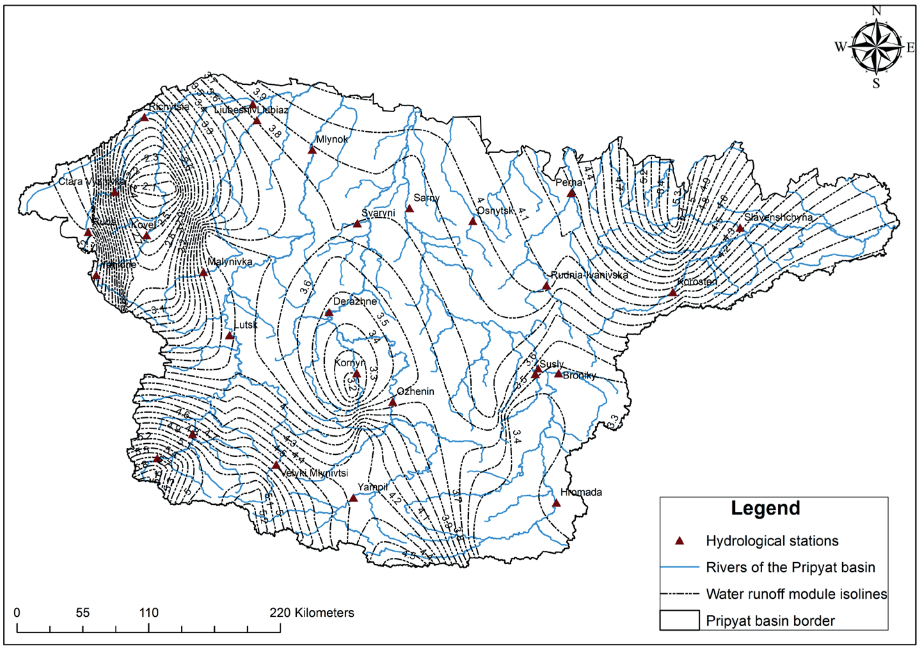


Figure 4. Map of the average long-term module of water runoff in Pripyat basin rivers in Ukraine, with isolines every 0.1 l·s^{-1}·km^{-2} (prepared based on the Author's own study)

With that in mind, the authors believe the most optimal variation of the map presenting the distribution of specific water runoff rate in the Pripyat basin rivers (in Ukraine) involves isoline distribution every 0.2 l·s^{-1}·km^{-2} (Fig. 5). In this case, the map with a greater number of isolines contributes to a more detailed perception and determination of the runoff characteristics for rivers that do not feature long periods of observation *in situ*.

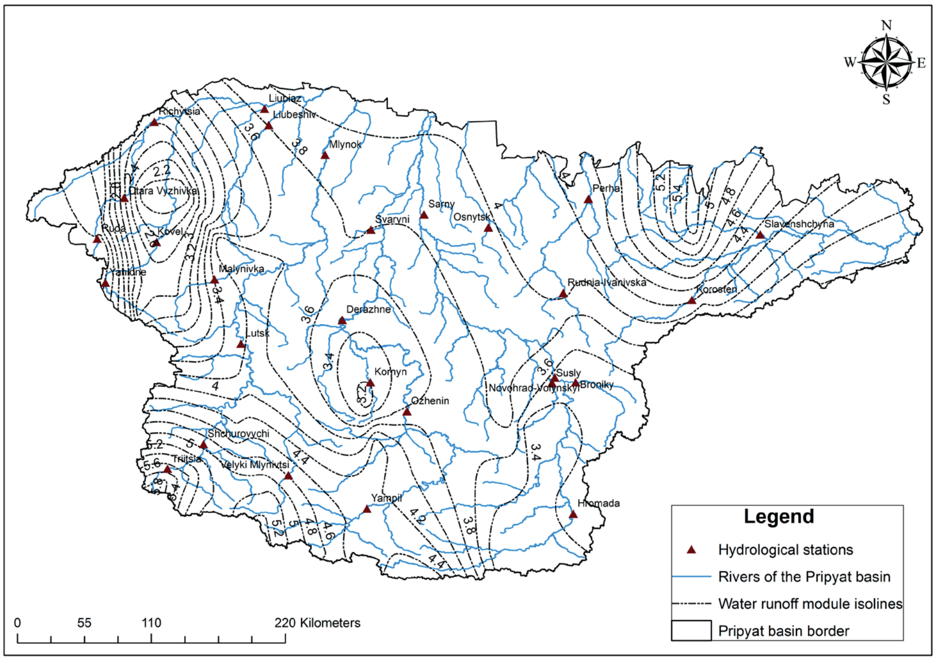
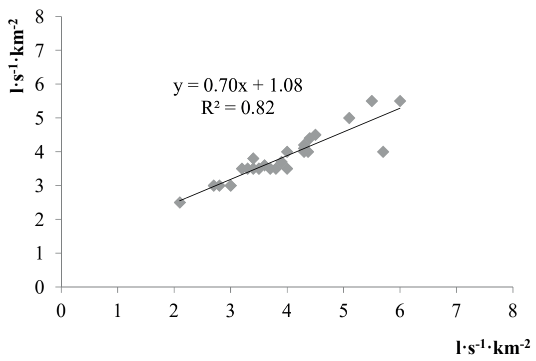


Figure 5. Map of the distribution of the average long-term module of water runoff in the Pripyat basin rivers in Ukraine, with isolines every 0.2 l·s^{-1}·km^{-2} (prepared based on the Author's own study)

To substantiate the selected map variation, we compared the values taken from the maps with isolines every 0.5 and 0.2 l·s^{-1}·km^{-2} with the actual calculated values in order to indicate discrepancies in curvilinear relationships (Table 1, Fig. 6).



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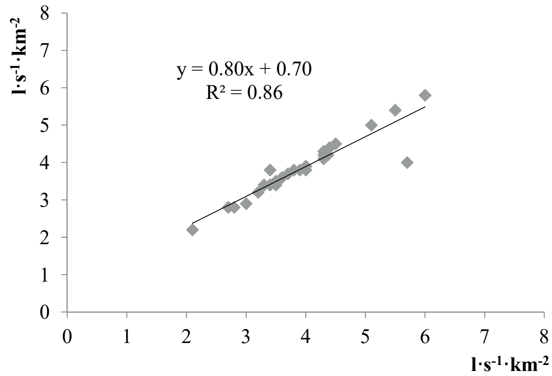

b

Figure 6. Dependencies between the calculated values of specific water runoff rate (actual) and those taken (manually) by means of maps with isolines every 0.5 $l \cdot s^{-1} \cdot km^{-2}$ (a) and 0.2 $l \cdot s^{-1} \cdot km^{-2}$ (b) (prepared based on the Authors' own study)

Table 1. Comparative assessment concerning the values of specific water runoff rate in the Pripyat basin rivers (in Ukraine) between those calculated from observational data and those obtained using the prepared runoff maps with isolines every 0.5 and 0.2 $l \cdot s^{-1} \cdot km^{-2}$, respectively (based on the Authors' own study)

River	Station	M calc.	M (0.5)	M (0.2)
Prypiat	Richytsia	3.70	3.50	3.70
Prypiat	Liubiaz	2.10	2.50	2.20
Vyzhivka	Ruda	4.30	4.00	4.30
Vyzhivka	Stara Vyzhivka	3.60	3.60	3.60
Turiia	Yahidne	2.80	3.00	2.80
Turiia	Kovel	2.70	3.00	2.80
Stokhid	Malynivka	3.00	3.00	2.90
Stokhid	Liubeshiv	3.80	3.50	3.80
Styr	Shchurovychi	5.50	5.50	5.40
Styr	Lutsk	4.40	4.40	4.40
Styr	Mlynok	4.00	4.00	3.90
Ikva	Triitsia	6.00	5.50	5.80
Ikva	Velyki Mlynivtsi	5.10	5.00	5.00
Horyn	Yampil	4.50	4.50	4.50
Horyn	Ozhenin	4.30	4.10	4.20
Horyn	Derazhne	4.37	4.00	4.20
Vyrka	Svaryni	3.90	3.70	3.80
Sluch	Hromada	3.40	3.50	3.40
Sluch	Novohrad-Volynskyi	3.50	3.50	3.40
Sluch	Sarny	4.00	3.50	3.80
Tnia	Broniky	3.50	3.50	3.50
Tnia	Broniky	3.30	3.50	3.40
Lva	Osnytsk	5.70	4.00	4.00
Ubort	Rudnia-Ivanivska	3.40	3.80	3.80
Ubort	Perha	4.30	4.20	4.10
Ustia	Kornyn	3.20	3.50	3.20

M calc. – specific water runoff rate calculated based on the observations; M (0.5) – specific water runoff rate received by means of the prepared runoff map with isolines every 0.5 $l \cdot s^{-1} \cdot km^{-2}$; M (0.2) – specific water runoff rate received by means of the prepared runoff map with isolines every 0.2 $l \cdot s^{-1} \cdot km^{-2}$.

Figure 6 shows that both dependencies have a fairly good relationship, as evidenced by the determination coefficients $R^2 = 0.82$ (a) and $R^2 = 0.86$ (b), and the corresponding correlation coefficients r = 0.90 and r = 0.93. However, the relationship between the calculated values of specific water runoff rate (actual) and the values of specific water runoff rate taken from the map with isolines every 0.2 $l \cdot s^{-1} \cdot km^{-2}$ is closer ($r \to 1$).

This indicates that the map with isolines every 0.2 $l \cdot s^{-1} \cdot km^{-2}$ may serve as a practical confirmation of a more detailed and accurate definition of the characteristics of river runoff in the Pripyat basin in Ukraine. It should be used in the spatial assessment of these characteristics for rivers with no constant observations, in particular for rivers with small catchments, especially in view of current climate changes.

Based on the results of the analysis of the prepared map depicting the average annual specific water runoff rate, its reliability was assessed. The comparison was made between the values of specific water runoff rate at the points of hydrological stations brought to the catchment centres (Fig. 5), which were calculated for a multi-year period (actual) and taken from the raster surface obtained in the creation of the map.

According to Figure 7, a fairly close relationship was obtained, with the determination coefficient of $R^2 = 0.88$. In 96% of cases, the deviations of the calculated and mapped values of the average annual specific water runoff rate are within the relative errors (for the calculation of runoff rates). The points with values of 2.0–4.5 $l \cdot s^{-1} \cdot km^{-2}$ are closest to the relationship line, which corresponds to most values of specific water runoff rate within the studied region.

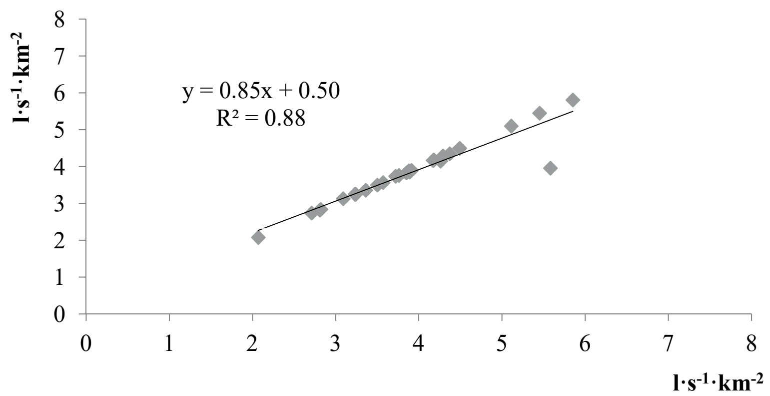

Figure 7. - Dependence between the values calculated and obtained from the map of average annual specific water runoff rate with isolines every 0.2 $l \cdot s^{-1} \cdot km^{-2}$ (prepared based on the Authors' own study)

A significant deviation of the values between the calculated and cartographic specific water runoff rate is observed for river Lva – station Osnytsk. This is caused by the fact that the reservoirs, which are located 40 m and 11 km upstream of the hydrological station, have a significant impact on the hydrological regime of this river, and as a result the calculated specific water runoff rate has been subject water management interference. However, other values of specific water runoff rate (Fig. 5) are close to the line of equal values.

5. Conclusions

The prepared map of spatial distribution of water runoff in the Pripyat basin rivers in Ukraine is based on long-term data obtained from hydrological stations conduction observation since the beginning of their operation up to and including 2017. It is updated and detailed with isolines every 0.2 $l \cdot s^{-1} \cdot km^{-2}$.

Distortions in the distribution of isolines outside the studied region due to the limited data on one basin (28 stations) were mitigated by the inclusion of data from 30 hydrological stations (with similar observation periods) in neighbouring basins outside the studied region.

According to the spatial distribution of water runoff in the Pripyat basin rivers in Ukraine, the average annual specific water runoff rates are in the range of 2.2–5.8 $l \cdot s^{-1} \cdot km^{-2}$. In a large area, including the basins of the Vyzhivka, Turiia, and Stokhid rivers, the middle and lower reaches of the rivers Styr, Horyn, Sluch (central part of the basin), the average annual runoff module is in the range of 3.2 to 4 $l \cdot s^{-1} \cdot km^{-2}$. The source of the largest average annual module of water runoff in the Pripyat basin is observed in the upper basins of the Styr and Horyn rivers: 5–5.8 $l \cdot s^{-1} \cdot km^{-2}$. The second source of increased runoff is the head of tributaries of the rivers Ubort, Noryn, Zherev: 4.2–5.4 $l \cdot s^{-1} \cdot km^{-2}$. The lowest values of the average annual runoff module in the basin of the Ukrainian part of the Pripyat are observed within the middle and lower reaches of the Turiia River, and its values are in the range of 2.2–3.0 $l \cdot s^{-1} \cdot km^{-2}$.

The developed map of spatial distribution of specific water runoff rate in the Pripyat basin in Ukraine can serve as a convenient instrument to quickly determine the values of specific water runoff rate for rivers not subject to constant observation, including rivers with small catchments.

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