UDC 528.9

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https://doi.org/10.23939/istcgcap2023.97.032

GIS TECHNOLOGIES APPLICATION FOR ANALYSIS OF THE TOPOGRAPHIC MAP SCALE EFFECT ON HYDROLOGICAL CHARACTERISTICS OF THE SIVERSKYI DONETS RIVER NETWORK

Nowadays, GIS Technologies are used in many areas of human life, both in everyday life and scientific research. The purpose of the presented study is to identify the relationship between the scale of topographic maps and the main hydrographic characteristics of the river based on the data of observations in the Siverskyi Donets basin. The study is based on the results of the identification of the hydrographic network, which was performed based on the Open Street Map in the GIS environment of the QGIS program using the method of A. N. Straller and I. N. Hartzman. The process of identifying, describing, and analyzing subcontracted connections consists in assigning its identification order to each element of the river network, which makes it possible to compare and standardize streams. Operating with a hierarchical "tree" of the channel network, the main characteristic of which is the number of elementary, unbranched streams, it is possible to identify and analytically describe the dependencies between the detailing of the map and the main characteristics of the river network structures, such as water discharges, network density, drainage basin area, and river length. The basis for describing these relationships was the method of B.V. Kindiuk, who introduced the concept of the coefficient of the river network structure or the fractional order of the stream as a basis for approximating the above-mentioned dependencies, which allows mathematically describing the obtained functions and obtaining numerical values of empirical parameters. Using QGIS made it possible to create maps of the Siverskyi Donets hydrographic network within Ukraine based on maps of scales 1:50 000 and 1:200 000. With their help, as well as data from a 1:100 000 map, the number of elementary unbranched watercourses was calculated, and each element of the system was identified, where the order of the main river changes depending on the map scale. The change in these indicators shows a tendency to increase the density and complexity of the river network with increasing map detail, and, as a result, potential changes in indicators of the catchment area, water runoff, and river length. The identified dependencies were expressed mathematically in the form of functions, and are also characterized by high values of the approximation reliability coefficient, which made it possible to construct a general transitional graph from the order of the water flow to the scale of the map with the corresponding values of the calculation parameters. The novelty and practical significance lie in the fact that the use of modern GIS technologies in hydrological science significantly increases the quality of cartographic data and concerning the studied object – the Siverskyi Donets River creates a database in the form of digital maps for further use in hydrographic studies. This sub-basin has not been previously studied using the methodology proposed by B. V. Kindiuk about the influence of map scales on the characteristics of the river network structure. Such study from a practical point of view, can significantly help the work of engineers, researchers, and designers with cartographic data. This study is designed to explain the peculiarities in the scaling of river networks and propose a mechanism for a scientifically based transition from the existing map scale to the desired one within the Siverskyi Donets sub-basin.

Key words: QGIS; hydrographic network; stream order; hydrological characteristics; map scale.

Introduction

The Siverskyi Donets sub-basin within the state border is the main waterway in the eastern region of Ukraine with more than a century of hydrological observation. A large amount of data has been accumulated, including paper cartographic data, which may be less comfortable for practical use. Therefore, GIS Technologies and their applications represent a modern cartographic tool designed to update hydrological data for the needs of designers and researchers. The electronic maps also can have different scales that reflect real objects on the ground, including hydrographic ones, in different detail. According to the current regulatory requirements of Ukraine [Regulations, 1999], state topographic maps at 1:50 000, 1:100 000, and 1:200 000 scales usually only show rivers with a length of 1 cm or more at the map scale, while watercourses of shorter lengths are not shown. Thus, 1:50 000 scale maps typically show all more or less distinct watercourses longer than 0.5 km, 1:100 000 scale maps show watercourses longer than 1 km, and 1:200 000 scale maps show watercourses longer than 2 km. The less detailed map simplifies the structure of the river network, and therefore in the practical use of such map scales some difficulties may arise due to the discrepancy between the real characteristics of the river and their calculated value. This problem was identified by Professor, Doctor of Geographical Sciences B.V. Kindiuk in his studies of mountain rivers in western Ukraine, studying the impact of map scale on the characteristics of the hydrographic network of the Rika River [Kindiuk, 2003b). The study of the rivers of the Siverskyi Donets sub-basin was conducted by O. Biriukov, who focused on the rivers of the Kharkiv region [Biriukov, 2012, 2016].

Analysis of recent research and publications. A retrospective analysis of studies of certain morphometric characteristics of the river network and the number of rivers in Ukraine (including depending on the scale of topographic maps) and the application of the EU Water Framework Directive river typology at the present stage is devoted to the work of scientists V.V. Grebin and V.V. Khilchevskyi [Grebin, Khilchevskyi, 2016]. Issues related to the use of remote sensing and GIS data instead of outdated topographic maps at 1:100 000 and 1:50 000 scales, etc. in studies of the state of small rivers in southern Ukraine have been repeatedly considered in publications by scientists of Odesa State Environmental University [Hryb et al. 2019; Loboda et al. 2020; Hryb et al. 2021]. An analytical review of current research by foreign scientists has shown that this topic is relevant in the world. For example, Canadian scientists [Lindsay et al., 2019], as a result of a study of the river system in the Lake Ontario and Lake Erie region, proposed a new vector method for analyzing the hydrographic network to organize watercourses, designate basins, and identify the main watercourses and their tributaries. Using the example of Kosovo's rivers, the authors of [Hazir S. Çadraku, 2022] showed that the use of GIS methods, digital elevation models (DEMs), raster geoprocessing tools, and software such as ArcMap is a quick and simultaneous solution for assessing, measuring, and analyzing the morphometric parameters of river basins. Romanian scientists [Răducă et al., 2021] at one stage of their study of the evolution of the Blahnica River in the context of anthropogenic interventions, such as the construction of an irrigation system, ponds, earthen dams, and channelization, used digital data obtained from the analysis of cartographic documents. This significantly contributed to the identification of the hydrographic network for the period under consideration (1978-2020). The importance of determining the order of watercourses for topographic modeling of the Indonesian surface is shown in the work of Indonesian scientists "Stream order selection for model generalization of the topographic map of Indonesia" [Fahrul Hidayat et al., 2020]. The authors of this study compared the methods of river network identification proposed by Strahler [Strahler, 1957], Shreve [Shreve, 1966], Scheidegger [Scheidegger, 1966] and Drwal [Drwal, 1982] and gave preference to the Scheidecker's method.

The purpose of this study is to provide and improve the scientific and methodological basis for project engineers working with the hydrographic network, using the example of the Siverskyi Donets, who do not always have the technical capabilities to study each watercourse of this system to make practical decisions. **The objective of the study** is to analyze the influence of the map scale on the quantitative characteristics of the river network structure of the Siverskyi Donets using data from field hydrological observations and identification from the geoinformation system QGIS.

Research Methodology

The identification of the river network is based on the method proposed by A.N. Straller and I.N. Gartsman, the essence of which is that an elementary unbranched watercourse receives the order P1, merging single-order elements increase the order of the resulting watercourse by one step. However, if a stream of a higher order merges with a stream of a lower water flow order, then the order value does not increase and remains unchanged until the single-order element falls. With this method of identification, the most powerful river will have the highest order value, and the system as a whole is subject to standardization and comparison of elements among themselves. In this study, bonneting is performed using maps of different scales, namely, it is 1:50 000, 1:100 000, and 1:200 000. The process involves creating a map of the hydrographic network in a hierarchical "tree" format, with all the mapped watercourses of the system, considering subcontracting relationships. This study also provides for mapping hydrological stations to operate individual elements of the overall catchment.

To introduce GIS Technologies into hydrological science, the above mapping schemes were created using digitization tools in the QGIS program, and tools for working with GPS coordinates were used to map the location of hydrological stations [Chaskovskyi et al., 2021].

Identification of the hydrographic network involves not only ranking the system elements in order but also counting the number of watercourses within each water intake area bounded by a hydrological station.

However, the chosen method of identification has a drawback, which is that the orders of watercourses are integers, which complicates their application and analytical description because in this case, rivers that differ in many characteristics and cannot be objectively compared fall into one category of watercourses. Therefore, following the amendments made by R.L. Shreve and I.N. Gartzman, to avoid a large share of generalization in the comparison of watercourses, and, as a result, to increase objectification, a metric step in the form of the number of elementary watercourses S_i was introduced since this characteristic most eloquently describes the complexity of the system.

Using this parameter, it is possible to calculate the coefficient of river network structure or the fractional order of watercourse proposed by B.V. Kindiuk. This makes it possible to expand the hierarchy of orders to improve the comparison process [Kindiuk, 2003].

The analytical expression of the dependence of the number of elementary streams on the map detail is represented by the expression:

$$K_i = 1 + \mathrm{lb} S_i , \tag{1}$$

where K_i is a fractional order exponent; lb – binary logarithm (with base $e = 2$); S_i – number of elementary watercourses.

Using the fractional order of the watercourse K_i as an argument and the river network structure characteristic as a function, we can build relationships that allow us to analyze the impact of scale granularity on each characteristic. In this study, four main river network parameters are used: water discharge, river network density, catchment area, and river length.

The basic relationship of the watercourse order to scale is a family of reducing curves, where a single element belongs to a single catchment area. To geographically relate these curves to the total catchment area, the maximum and minimum values of the fractional order of the water flow from the entire field of calculated values are used, forming two corresponding curves on the graph and thus outlining the limits of this parameter for the entire catchment.

The analysis of the above dependencies makes it possible to substantiate the specificity of the chosen scale in any hydro-technical work using maps, as well as to propose a methodology for calculating numerical indicators of hydrographic characteristics for different degrees of terrain detail without being limited by the scale of the available map.

Results of hydrographic network identification

Identification of the hydrographic network of the Siverskyi Donets sub-basin within the state border of Ukraine was performed using three scales – 1:50 000, 1:100 000, and 1:200,000. It should be noted that only two scales – 1:50 000, and 1:200 000 – were processed in the QGIS Desktop 3.28.2 geographic information system.

To demonstrate the advantages of an electronic map over a paper map, data on the 1:100 000 scale were taken from a previous study and presented as a final result without a detailed description of the identification process [Selehieiev, 2019]. To organize the structure of the river network of the Siverskyi Donets into a common hierarchical system, we used a free Open Street Map with the coordinate system EPSG:3857-WGS84 / Pseudo-Mercator, based on which we digitized two map schemes (Figs. 1, 2) of the hydrographic network for two different scales.

Downstream from the villages of Ohirtseve and Ratyshche, its first left-bank tributary, the Vovcha River, flows into the Siverskyi Donets, changing its order from P2 to P3 depending on the scale used – 1:200 000 and 1:50 000, respectively. Similarly, the order of the Pilna River (P1→P2), the Khotomlya River (P2→P3), which flows near the village of Pershotravneve, and the Hnylytsia River (P1→P3), which feeds the main river near the village of Artemivka, changes.

Moving downstream, its left-bank tributaries, the Sukhyi Burluk River (P1→P2) and the Velykyi Burluk River (P1→P3), flow into the Siverskyi Donets, and it should be noted that there is a significant jump in the number of watercourses and their orders depending on the scale.

For example, moving to the right bank of the Siverskyi Donets, the Velyka Babka, Tetlezhka, and Chuhovka rivers flow into it alternately, the order of which at a scale of 1:200 000 is P1, and the Chuhovka river is not displayed at all.

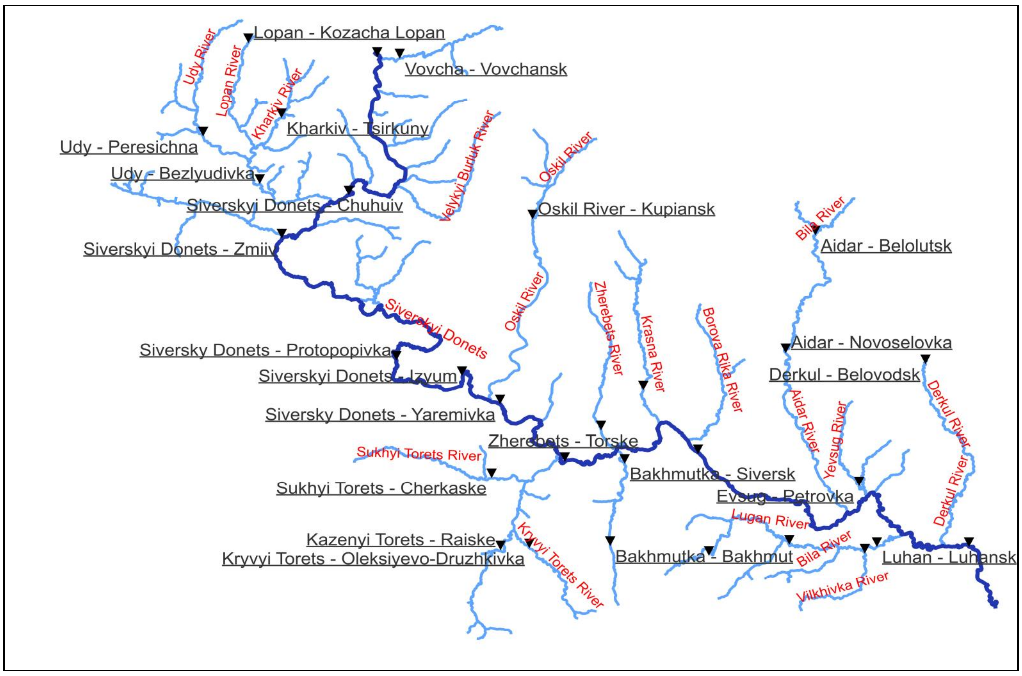


Fig. 1. Map of the hydrographic network of the Siverskyi Donets obtained using a map at a scale of 1:200 000

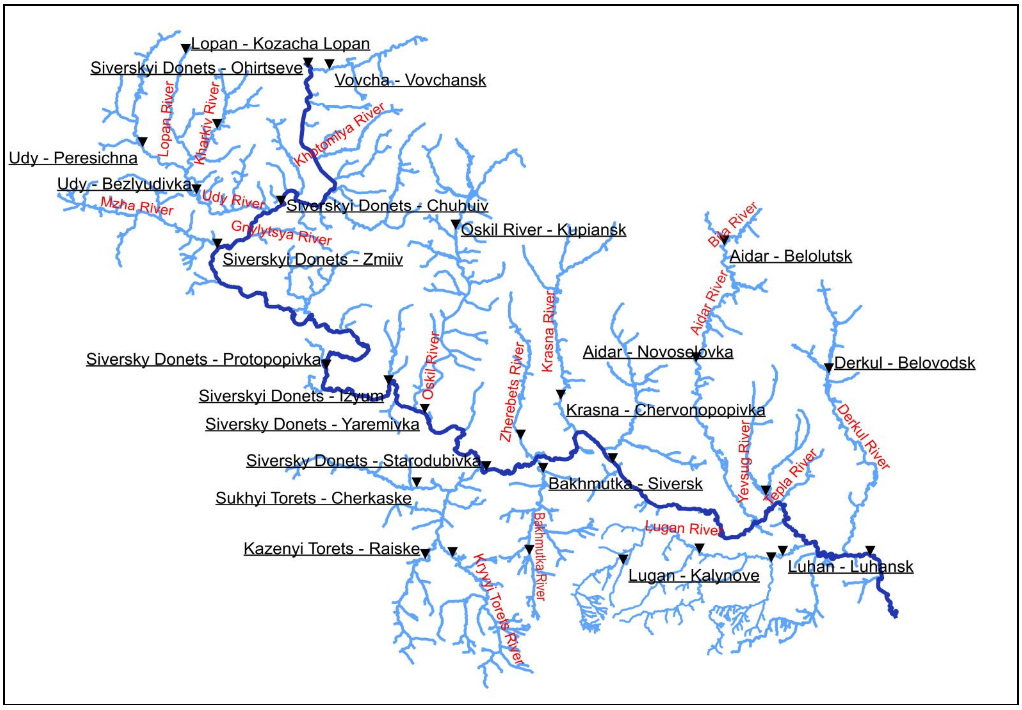


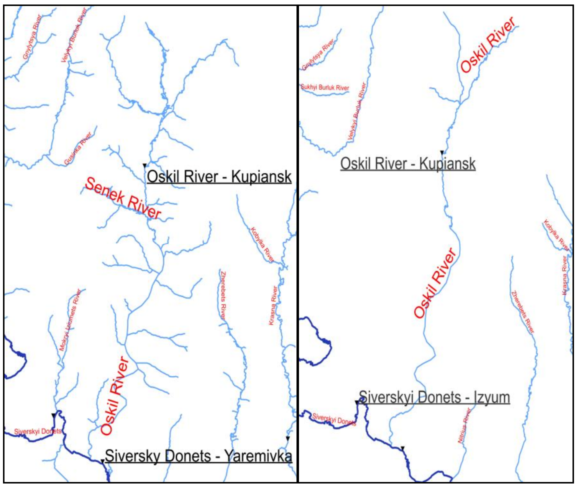
Fig. 2. Map of the hydrographic network of the Siverskyi Donets obtained using a map at a scale of 1:50 000

However, at a scale of 1:50 000, the order of the Velyka Babka river increases to P3, and the Chuhovka river "manifests" and receives P1. The tendency to increase the number of watercourses and their orders depending on the map scale is observed almost throughout the entire area of the studied hydrographic network.

Thus, we have come to one of the most extensive tributaries of the Siverskyi Donets, the Uda River, which receives the waters of the major rivers Kharkiv and Lopan. Considering the identified tendency of the map scale to influence the number and order of watercourses, it turned out that in this river system, it manifests itself only in changing the number of watercourses, but does not affect the order of the main rivers. Thus, the Kharkiv River at both scales has an order of P3, the Lopan River has an order of P2, and the Udy River itself, as the leading watercourse of the region, is a system with an order of P4, which is the highest value in this section of the hydrographic network, so the Siverskyi Donets appropriates it and leaves it unchanged until the confluence of the Oskil River. It should be noted that in this section at a scale of 1:200 000, the order of the Siverskyi Donets will remain unchanged until the final identification reach and will be P4, so further descriptions of the order increase will refer exclusively to the 1:50 000 scale.

Later, the rather small Hnylytsia River flows in from the left bank, which has the same order regardless of the scale P2=P2, and the Mzha River flows in from the right bank, whose order also does not change due to the change in map scale (P3=P3). However, it should be noted that, as in the vast majority of watercourses, the total number of watercourses in the Mzh River varies significantly depending on the map scale used, i.e., at 1:200 000 it is 9, and at 1:50 000 it is 34. This implies two aspects of the identified tendency of the map scale to influence the number and order of watercourses, namely: first, a more detailed map scale almost always (except for very small unbranched watercourses that are directly adjacent to the Siverskyi Donets) increases the number of watercourses that are part of a particular hydrographic network, and second, unlike the number of tributaries, their order is more constant.

Near the town of Balakleya, the left-bank tributary of the Balakleyka River (P1→P3) flows into the Siverskyi Donets with a significant fluctuation in the order of the main river. And then, interestingly, when moving from a scale of 1:200 000 to 1:50 000, several watercourses that directly flow into the Siverskyi Donets and have a fairly extensive channel network "appear" in the area between the Balakleyka River and the Oskil River. Thus, the left-bank Mokryi Iziumets, which flows near the city of Izium, has the highest order (P3), and somewhat smaller watercourses upstream – the Teplyanka River (P1), Savynka River (P1), and the right-bank tributaries of the Berechka River (P2) and Chepil River (P1). Moving further from Izyum, the waters of one of its largest tributaries, the Oskil River (P2→P4), flow into the Siverskyi Donets, which clearly demonstrates the impact of the map scale on the number and order of watercourses. Thus, Figs. 3 and 4 show that when using a scale of 1:200 000, it has only 3 tributaries, which merge to form a fairly elementary watercourse of the P2 order, but when moving to a more detailed scale of 1:50 000, the number of elementary watercourses increases many times to 121, and the order of the main river increases by two steps, i.e., to P4.



Figs. 3, 4. The influence of scale on the detail of the hydrographic network (for example, the Oskil River)

After the Oskil River, the Siverskyi Donets alternately receives the waters of a minor left-bank tributary of the Nitrius River (P1=P1) and the right-bank, more extensive Kazenyi Torets River (P3→P4), which in turn is adjacent to the Dry Torets (P2→P3) and Kryvyi Torets (P2→P4). This local hydrographic network shows both aspects of the trend of changing the number of watercourses and their order. Thus, on a scale of 1:200 000, the number of elementary watercourses is 13 for the entire system, and the order of the main river Kazennyi Torets is P3, but if we detail this section, we get a much larger number of elementary tributaries (110), the most branched river of the system is Kryvy Torets (P4), after which the Kazennyi Torets takes over this order.

By that time, lower-graded tributaries flow into the Siverskyi Donets: the Bakhmutka River (P2→P3), the Zherebets River (P1→P3), the Krasna River (P2→P3), and the Borova River. Borova, which is transformed from a rather elementary P2 stream at a scale of 1:200 000 to an extensive system of watercourses at a scale of 1:50 000 with the order of P4, which only confirms the previously identified tendency of the map scale to influence the number and order of watercourses in the hydrographic network. Later, when boning the Siverskyi Donets, two small right-bank tributaries were identified using a scale of 1:50 000 – the Bilenka River (P2) and the Bilenka River (P2), which are not visible at larger scales and clearly demonstrate the benefits of a detailed scale in the study of the channel network.

Moving south from the village of Stary Aidar, the left-bank tributary of the Siverskyi Donets, the Aidar River (P2→P4), flows into the main river, visually changing depending on the map scale used to study it. Thus, as the map's detail increases, the number of elementary watercourses increases from 2 to 45, and the order of the main watercourse in such circumstances rises to P4, but it does not affect the order of the Siverskyi Donets, because in this section it is already P5. Similar metamorphoses are characteristic of the left-bank tributaries downstream – the Kovsug River (P2→P3) and the Tepla River (P1→P3).

However, the most significant changes are demonstrated by the right-bank tributary of the Siverskyi Donets, the Luhan River, whose identification scheme is shown in Fig. 5.

Thus, using a smaller scale of 1:200 000, there are only 7 elementary watercourses within this hydrographic system with the order of the main river P3, which is not an indicator of anything extraordinary.

But when we scale up this section, we see that the Lugan River increases its channel branching many times over, forming a complex tree-like system of watercourses, of which there are already 124, and the order of the main river is P5, which is the highest for all tributaries of the Siverskyi Donets. Thus, from this point on, the order of the main river rises to P6, which is an important scientific result of this study.

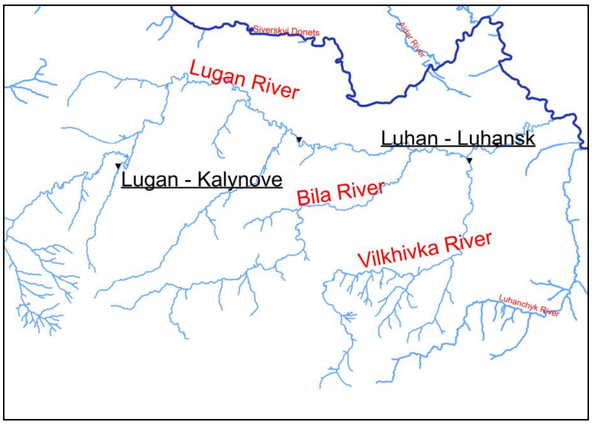


Fig. 5. Detailing the channel system of the Lugan River

The final section of the closure stem near the village of Popivka, Donetsk Area. The Siverskyi Donets receives water from quite significant tributaries, such as the right-bank Luhanchyk River, which is shown only at a scale of 1:5 000 and has a P4 order, and the left-bank Derkul River (P1→P3), which is also significantly affected by the map scale. In addition to the named watercourses, the 1:50 000 scale map shows that 35 elementary watercourses flow into the Siverskyi Donets, which do not have their own names, but they account for about 4% of the total number of elementary watercourses in the system.

Table 1 provides comparative data on the number of watercourses of different orders depending on the map scale used.

Table 1

The number of watercourses of different orders for the rivers of the Siverskyi Donets sub-basin

Water flow order	Scale		
	1:50 000	1:100 000	1:200 000
I	838	273	80
II	198	91	23
III	41	22	5
IV	8	6	1
V	2	1	-
VI	1	-	-

River network structure coefficient. The study area of the Siverskyi Donets sub-basin includes 30 hydrological stations, which are scattered throughout the hydrographic system. For each water intake area bounded by a gauging station, the river network structure coefficients were calculated based on the number of elementary unbranched watercourses S_i.

The analysis of such characteristics of the Siverskyi Donets river system as river length, catchment area, average long-term water flows, and network density was based on data from 28 hydrological stations in its catchment area [Vyshnevskyi and Kosovets, 2003]. It should be noted that the data from the gauging stations of the Siverskyi Donets River – Ogirtseve village and the Oskil River – Kupiansk town were not used. Kupiansk were not used due to the significant "trimming" of their water intake areas by the state border, which does not allow for an objective assessment of the announced dependencies due to the fictitious value of the water flow order that does not correspond to the physical reference.

For example, the drainage basins range from 189 km² (Lopan River – Kozacha Lopan village) to 73,200 km² (Siverskyi Donets River – Kruzhylivka village), river lengths range from 23 km (Bakhmutka River – Bakhmut city) to 790 km (Siverskyi Donets River – Kruzhylivka village); water discharges are represented by the average long-term values of maximum water content on the rivers of this region [SWC, 2017].

Using the number of elementary watercourses, the fractional order of watercourses K_i was calculated for each catchment area, the values of which are presented in Table 2. According to the calculations, this characteristic varies with scale as follows: at a scale of 1:50 000 K_i varies from 1 to 10.7; at a scale of 1:100 000 – from 1 to 9.1; at a scale of 1:200 000 – from 1 to 7.3.

Once the K_i values for each site were calculated, it became possible to build four empirical relationships using alternately the catchment area F, river length L, average long-term maximum flows $\overline{Q}_{\max}$, and the sum of elementary watercourses within the catchment S_i as a function of K_i, i.e., the fractional order of the watercourse. The graphs are plotted for all three scales used in the identification.

To build a logical chain of reasoning, it is necessary to start with the basics, namely the density of the river network, on which further conclusions about the impact of the map scale on river characteristics will be based.

Approximation of the first dependence of the number of elementary watercourses S_i on the fractional order of the watercourse Ki allowed us to obtain an analytical expression of this function.

$$S_i = a_1 e^{b_1 K_i}, \quad (2)$$

where e is the base of the natural logarithm; a_1 and b_1 are empirical coefficients that depend on the map scale.

Table 2

Basic hydrographic data and topographic parameters of the rivers of the Siverskyi Donets sub-basin

Sl. no.	River – Point	Drainage basin area F, km^2	River length L, km	Discharge $\overline{Q}_{\max}$, м^3/s	The total number of watercourses, S_i			The coefficient of river network structure, K_i		
					1:50 000	1:100 000	1:200 000	1:50 000	1:100 000	1:200 000
1	2	3	4	5	6	7	8	9	10	11
1	Siverskyi Donets – Chuhuiv	10.300	216	190.4	105	33	11	7.7	6.0	4.5
2	Siverskyi Donets – Zmiiv	16.600	260	310.8	208	84	40	8.7	7.4	6.3
3	Siversky Donets – Protopopivka	19.400	389	211.5	223	111	44	8.8	7.8	6.5
4	Siverskyi Donets – Izyum	22.600	451	271.4	226	122	44	8.8	7.9	6.5
5	Siversky Donets – Yaremivka	38.300	480	485.1	356	159	47	9.5	8.3	6.6
6	Siversky Donets – Starodubivka	44.400	543	508	440	194	59	9.8	8.6	6.9

Continuation of Table 2

1	2	3	4	5	6	7	8	9	10	11
6	Siversky Donets – Starodubivka	44.400	543	508	440	194	59	9.8	8.6	6.9
7	Siversky Donets – Lysychansk	52.400	623	474	556	222	67	10.1	8.8	7.1
8	Siversky Donets – Kruzhylivka	73.200	790	578.4	838	273	80	10.7	9.1	7.3
9	Vovcha – Vovchansk	1.330	84.1	65.6	8	6	2	4.0	3.6	2.0
10	Udy – Peresichna	905	107	30.2	23	14	5	5.5	4.8	3.3
11	Udy – Bezlyudivka	3.300	122	111.1	54	53	14	6.8	6.7	4.8
12	Lopan – Kozacha Lopan	189	31	11.4	1	1	1	1.0	1.0	1.0
13	Kharkiv – Tsirkuny	890	56	39.4	16	15	4	5.0	4.9	3.0
14	Kazenyi Torets – Raiske	936	56	26	15	8	5	4.9	4.0	3.3
15	Kryvyi Torets – Oleksiyevo-Druzhkivka	1.530	75	28.1	42	16	2	6.4	5.0	2.0
16	Sukhyi Torets – Cherkaske	1.310	76	46.8	7	6	2	3.8	3.6	2.0
17	Bakhmutka – Bakhmut	433	23	9	16	6	1	5.0	3.6	1.0
18	Bakhmutka – Siversk	1.560	77	44.9	43	14	2	6.4	4.8	2.0
19	Zherebets – Torske	857	72	28.8	18	4	1	5.2	3.0	1.0
20	Krasna – Chervonopopivka	2.540	131	77.2	20	5	3	5.3	3.3	2.6
21	Aidar – Belolutsk	2.250	73	113.3	8	7	2	4.0	3.8	2.0
22	Aidar – Novoselovka	6.370	149	198.5	31	15	2	6.0	4.9	2.0
23	Evsug – Petrovka	784	72	28.1	11	2	1	4.5	2.0	1.0
24	Lugan – Kalynove	751	68	15.8	2	1	1	2.0	1.0	1.0
25	Luhan – Zymohirya	1.820	132	32.5	68	12	4	7.1	4.6	3.0
26	Luhan – Luhansk	3.510	176	50.7	125	18	7	8.0	5.2	3.8
27	Vilkhivka – Luhansk	814	82.1	17.2	42	3	1	6.4	2.6	1.0
28	Derkul – Belovodsk	1.380	33	41.5	29	8	1	5.9	4.0	1.0

Also, the obtained empirical dependencies (2)-(5) include the parameters a_i and b_i, the values of which are taken from the graph of the relationship between the hydrographic characteristic and the river network structure coefficient.

According to mathematical statistics, the closeness of the relationship between a function and an argument is estimated by the value of the correlation coefficient r for linear relationships, and the approximation reliability coefficient R for non-linear ones (Table 3).

Analyzing the dependence obtained (Fig. 6) for the three map scales, it should be noted that the closest relationship is observed at the scale of 1:50 000 (R=0.99) and decreases in a downward trend at the scale of 1:200 000 (R=0.85). This change can be explained by the fact that with a decrease in the scale value, i.e., in the case of increasing terrain detail, the number of elementary unbranched watercourses increases significantly, and the river network is transformed into a more complex subcontracting system, and, as a result, through hierarchical connections, stimulates the growth of the order of the watercourses that are formed. That is, the larger the scale, the smaller and more stable the watercourse order (indirectly influenced by the complexity of the identification process), because it is the density of the river network that affects its increase.

Table 3

Reliability coefficients of approximation of hydrographic characteristics of watercourses from K_i for the rivers of the Siverskyi Donets sub-basin

Characteristic	Scale / R		
	1:50 000	1:100 000	1:200 000
$F = f(K_i)$	0.89	0.92	0.91
$L = f(K_i)$	0.85	0.86	0.91
$\overline{Q}_{max} = f(K_i)$	0.79	0.88	0.87
$S_i = f(K_i)$	0.99	0.92	0.85

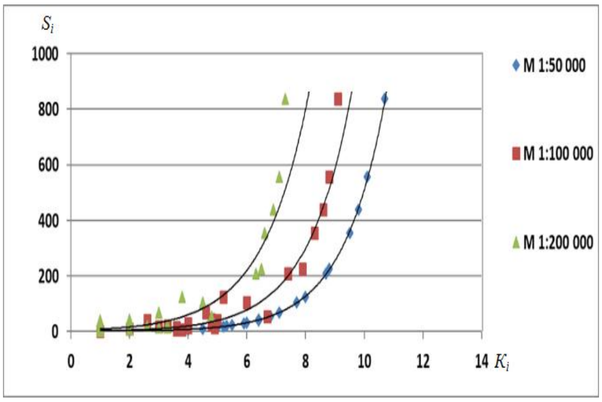


Fig. 6. Graph of the dependence of the number of elementary watercourses S_i on the fractional order of the watercourse K_i (the rivers of the Siverskyi Donets sub-basin)

Approximation of the second relationship between the length of the river L and the value of K_i allowed us to obtain an analytical expression of the function, which has the following form:

$$L = a_2 e^{b_2 K_i}, \quad (3)$$

where e is the base of the natural logarithm; a_2 and b_2 are empirical coefficients that depend on the map scale.

Using the approximation reliability coefficient R, we can see that the downward trend, which demonstrates a decrease in the closeness of the relationship with a decrease in the scale value, is also evident in the graph of the dependence of river length on the order of water flow (Fig. 7). This means that the correlation coefficient R at a scale of 1:50 000 is 0.85, and for 1:200 000 it is 0.91.

Earlier, we found out that mapping in greater detail leads to a more complex river system, increases the number of available watercourses, and increases the order of the latter. If the network develops in the form of an increase in subcontractor connections between watercourses (the density of the system increases), then a logical consequence of this process is an increase in the length of watercourses. This is because the place that is taken as the source of a river at a given scale can change its location depending on the scale (and as we know, the length of a river is measured from the source to the mouth). After all, the detail allows us to trace the exact moment of formation of a new watercourse or its existence as such (and, accordingly, changes in length). The above analysis suggests that the change in the length of the watercourse is to some extent influenced by the scale detail, and the closer relationship of length to decreasing watercourse order is due to the greater relative location of the point that is taken as a branch.

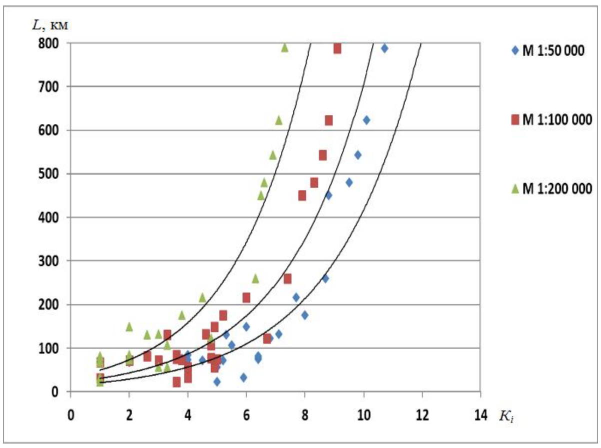


Fig. 7. Graph of the dependence of the hydrographic length of rivers L on the fractional order of water flow K_i (the rivers of the Siverskyi Donets sub-basin)

Approximation of the second relationship between the length of the river L and the value of Ki allowed us to obtain an analytical expression of the function:

$$F = a_3 e^{b_3 K_i}\,, \tag{4}$$

where e is the base of the natural logarithm; a_3 and b_3 are empirical coefficients that depend on the map scale.

As in expressions (2) and (3), the size of the catchment area has a fairly close relationship with the order of the watercourse (Fig. 8).

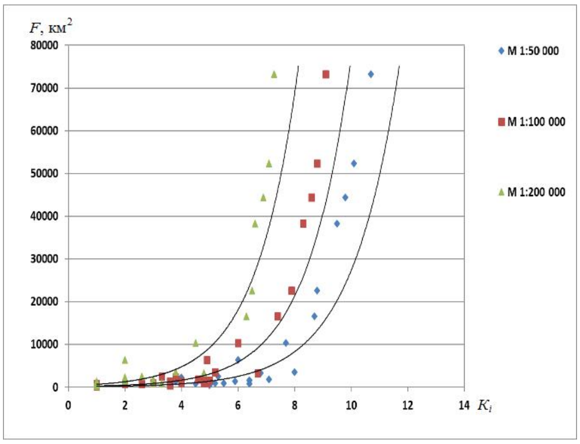


Fig. 8. Graph of the dependence of the catchment area F on the fractional order of the water flow K_i (the rivers of the Siverskyi Donets sub-basin)

Thus, the conclusions drawn in the previous analyses can be used to generalize and develop them throughout the entire watershed. Thus, as the map scale decreases, the density of the river network increases, the order increases, and the length also undergoes quantitative changes due to the "manifestation" of new subordinate elements of the river that can be used as a branch. Then the catchment, as a characteristic that combines all the processes that occur with the river network under the influence of physical and geographical factors, as well as the cartographic image, takes over the previously made conclusions. That is, an increase in the scale value creates a more static river system, as the detail of the terrain is reduced and elevation points are generalized. Thus, the catchment area gets an average outline rather than the exact perimeter of the watershed line. If we take into account a more detailed scale, then, firstly, the factor of a larger number of elevation points increases, and secondly, as the river system gradually branches out, it captures new territories from which it receives nutrition. That is, as the order of water flow decreases, the catchment area, like the river system, becomes simpler and more generalized.

Approximation of the fourth relationship between the average long-term values of maximum discharge water $\overline{Q}_{\max}$ and K_i allowed us to obtain an analytical expression of the function, which has the following form:

$$\overline{Q}_{\max} = a_4 e^{b_4 K_i}\,, \tag{5}$$

where e is the base of the natural logarithm; a_4 and b_4 are empirical coefficients that depend on the map scale.

Considering the conclusions drawn from the analysis of the previous dependencies of the type (2), (3) and (4), we can analyze the relationship between water flows and the order of watercourses, as shown in the graph (Fig. 9).

Thus, during the disaggregation, the river network undergoes quantitative changes in the system density, which in turn causes changes in the catchment area and river length.

In addition to quantitative changes, the river system also changes qualitatively in terms of water flow, however, this characteristic within the scales used is least dependent on the order of the watercourse, and for the scale of 1:50 000 (R=0.79) is on the verge of significant influence. This circumstance is explained by the fact that water discharge, unlike the number of watercourses, river length, and catchment area, is a characteristic that is quite variable and almost entirely depends on the physical and geographical conditions of the territory rather than on the scale detail.

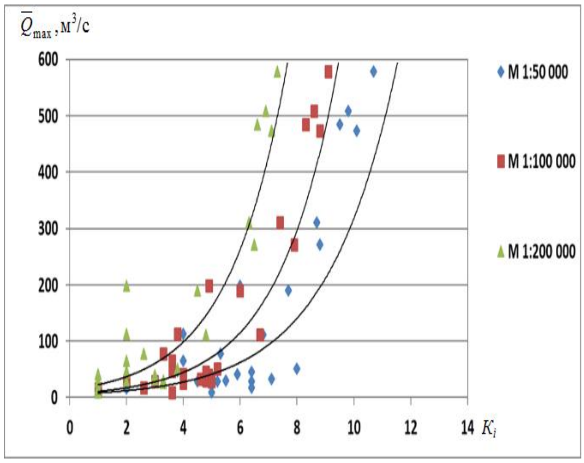


Fig. 9. Graph of dependence of discharge $\overline{Q}_{\max}$ on the fractional order of the water flow K_i (the rivers of the Siverskyi Donets sub-basin)

However, the river network is a system of interconnected characteristics, so a change in the catchment area F (as a unifying characteristic for the territory) depending on the map scale will indirectly affect water flows. Here, the identified tendency remains, where, as the map scale increases, the hydrographic characteristic has a closer connection with the water flow order, because as the complexity of the system decreases, the number of points at which differences can be observed also decreases, which will significantly affect the water content of the river.

Parameters of calculated dependencies

Analyzing the values of the parameters a_i and b_i (Table 4), which appear in the calculation formulas of the form (2)-(5), we can assert the existence of some regularities. Thus, the parameters a_1, a_2, a_3, a_4 in all dependencies increase with an increase in the scale (or with a decrease in detail), however, their numerical values significantly exceed the results of a similar study on small rivers of the Rika River basin, which was carried out by B. V. Kindiuk. This difference can be explained by the novelty of this study, which consists in changing the type of the studied network from mountainous to plain and, as a result, a significant increase in such characteristics as L, F, $\overline{Q}_{\max}$ and S_i. The parameters b_1, b_2, b_3, b_4 also increase, but the change in their values is relatively small depending on the map detail. From a physical point of view, the above dependency trends can be explained by employing relationship graphs (see Figures 6-9), where the lines describing the functions are almost exactly equal to each other and analytically describe the same hierarchical structure with different degrees of detail.

It should be noted that the discrepancy in the values of the approximation reliability R is quite acceptable and ranges from 0.79 to 0.99, which corresponds to the significance of this indicator and justifies the analyzes performed.

In the process of identifying the river network at three decreasing scales, the resulting values of the watercourse orders are naturally also gradually reduced. For example, the fractional order of the main river of the Siverskyi Donets network near the village of Kruzhylivka at a scale of 1:50 000 is 10.7, at a scale of 1:100 000 – 9.7, at a scale of 1:200 000 – 7.3.

Similar patterns of decreasing watercourse order with increasing map scale are observed in all 28 sections of the watershed. This makes it possible to construct a joint graph of dependencies (Fig. 10) of the form $M = f(K_i)$, where the map scale M is the function and the argument is the river network structure coefficient K_i (or fractional water flow order). For these dependencies to apply to the entire catchment area, the minimum and maximum values of K_i (see Table 2) are plotted on the graph following the scale.

The novelty of the study

The use of GIS technologies (for example, the QGIS program) allowed us to reach a qualitatively new level of river network identification due to the expanded possibilities of map manipulation. The creation of a paper map is quite difficult, and therefore the results of previous studies using a paper map can provide relative examples of the complexity of the river network. The QGIS toolkit has improved the identification methodology, which has significantly increased its information content and accuracy.

The main studies related to the identification of the hydrographic network of the Siverskyi Donets belonged to the works of O.V. Biriukov, however, they did not operate with the amount of data that was provided by the use of three different scales. It would be more appropriate to transpose this feature to the study of rivers in Western Ukraine by B.V. Kindiuk, but he also did not use the power of geographic information systems in his work. Therefore, this study combines the methodology of B.V. Kindiuk and the specifics of the region of O.V. Biriukov with the latest technological capabilities.

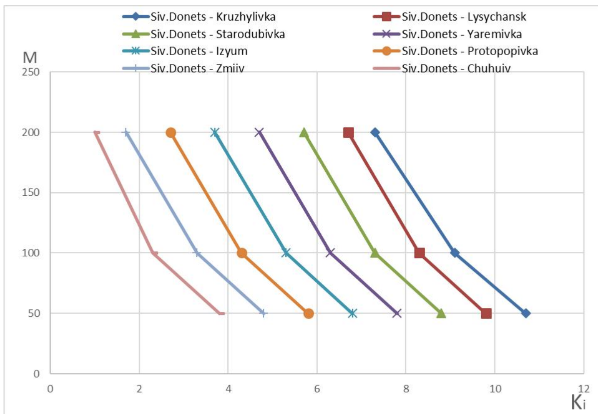


Fig. 10. General dependence of the watercourses order K_i on the map scale M (the rivers of the Siverskyi Donets sub-basin)

Table 4

Values of the parameters of the calculated dependencies a_i and b_i for the rivers of the Siverskyi Donets sub-basin

Characteristic	Parameter	Map scale					
		1:50 000		1:100 000		1:200 000	
		Numerical values of parameters	R	Numerical values of parameters	R	Numerical values of parameters	R
1	2	3	4	5	6	7	8
Number of watercourses S_i	a_1	0.50	0.99	1.40	0.92	4.61	0.85
	b_1	0.69		0.67		0.65	
River length L, km	a_2	14.85	0.85	21.43	0.86	33.76	0.91
	b_2	0.33		0.35		0.39	
Drainage basin area F, km^2	a_3	69.87	0.89	122.12	0.92	328.03	0.91
	b_3	0.59		0.65		0.67	
Average long-term values of maximum discharge water $\overline{Q}_{max}$, м^3/s	a_4	5.39	0.79	6.71	0.88	13.90	0.87
	b_4	0.41		0.47		0.49	

Practical significance

An important result of the work was the demonstration of the actual use of GIS technologies in research related to the cartographic component of hydrological science. The popularization of this method improves the quality, information content, and speed of processing hydrological data in a long-term perspective. Regarding the specific example given in the article, the practical result of the work was the mapping of the hydrographic network of the Siverskyi Donets, which will be used in the further development of this topic or can be used for the needs of other scientists or future research.

The application of the presented methodology for studying the influence of map scale on the characteristics of the river network structure allowed us to identify, mathematically describe and scientifically substantiate the dependencies that will allow engineers or researchers to calculate the hydrographic characteristics of the Siverskyi Donets necessary for the implementation of practical tasks using only the value of the water flow order. This means that having a map of a certain scale that does not meet the needs of a project or study, the user can simply use the graph of the dependence of the watercourse order K_i on the map scale M (see Fig. 10), remove the fractional watercourse order K_i (according to the desired scale), and select the appropriate values of the parameters a_i and b_i. Having received all the necessary numerical data on the terms of the calculated dependencies, it is possible to calculate the value of any hydrographic characteristic of the Siverskyi Donets from equations (2), (3), (4) or (5) and apply it in your calculations.

Conclusions

The Siverskyi Donets basin is currently almost entirely within the territory of military operations, so the study of its hydrographic network using GIS-technologies is practically the only possible tool under martial law;

One of the most important tasks in the post-war reconstruction of the country will be the restoration of destroyed hydraulic structures, dams, bridge crossings, and bridges. To solve these problems, detailed and up-to-date information about the hydrographic network of the territory is needed;

This study shows that the use of GIS technologies allows for obtaining high-quality hydrographic network maps that can be used in hydrological and hydraulic engineering studies;

The analysis of the impact of scaling on the characteristics of the structure of the river network of the Siverskyi Donets showed its importance for practical use and proves the value of the methodology used, which was once proposed by B. V. Kindiuk.

Further prospects for the development of the study are to use the characteristics of the hydrographic network obtained using GIS technologies as an indicator of climate change and its impact on water resources in eastern Ukraine. For example, a comparison of topographic maps of different years of publication will allow us to trace the dynamics of the disappearance of small watercourses and the emergence of new anthropogenically altered ones.

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ЗАСТОСУВАННЯ ГІС-ТЕХНОЛОГІЙ ДЛЯ АНАЛІЗУ ВПЛИВУ МАСШТАБУ ТОПОГРАФІЧНОЇ КАРТИ НА ГІДРОЛОГІЧНІ ХАРАКТЕРИСТИКИ РІЧКОВОЇ МЕРЕЖІ СІВЕРСЬКОГО ДОНЦЯ

Геоінформаційні технології сьогодні використовуються у багатьох сферах життєдіяльності людини, як у повсякденному житті, так й у наукових дослідженнях. Представлене дослідження присвячено виявленню зв'язку між масштабом топографічних карт та основними гідрографічними характеристиками річки на основі даних спостережень в басейні Сіверського Донця. Дослідження базується на результатах ідентифікації гідрографічної мережі, яка була виконана на основі відкритої карти світу Open Street Map в геоінформаційному середовищі програми QGIS з використанням методу А. Н. Штраллера та І. Н. Гарцмана. Процес виявлення, опису та аналізу субпідрядних зв'язків полягає в присвоєнні кожному елементу річкової мережі свого ідентифікаційного порядку, за допомогою якого з'являється можливість порівняння та стандартизації водотоків. Оперуючи ієрархічним «деревом» руслової мережі, головною характеристикою в котрій є кількість елементарних нерозгалужених водотоків, можливо виявити та аналітично описати залежності між деталізацією карти та основними характеристиками будови річкової мережі – витратами води, щільністю мережі, площею водозбору та довжиною річки. За основу для опису даних зв'язків була взята методика Б. В. Кіндюка, який ввів поняття коефіцієнта структури річкової мережі або ж дробового порядку водотоку, як базис в апроксимації вищезазначених залежностей, котрий дозволяє математично описати отримані функції й отримати числові значення емпіричних параметрів. Використання QGIS дозволило створити картосхеми гідрографічної мережі Сіверського Донця в межах України на основі карт масштабів 1:50 000 та 1:200 000. За їх допомогою, а також за даними з карти масштабу 1:100 000, підрахована кількість елементарних нерозгалужених водотоків, а також ідентифікований кожен елемент системи, де порядок головної річки зазнає змін залежно від масштабу карти. Зміна цих показників демонструє тенденцію до збільшення щільності та складності річкової мережі зі збільшенням деталізації карти, і, як наслідок, потенційної зміни показників площі водозбору, витрати води й довжини річки. Виявлені залежності отримали математичне вираження у вигляді функцій, а також характеризуються високими значеннями коефіцієнта достовірності апроксимації, що дозволило побудувати загальний перехідний графік від порядку водотоку до масштабу карти із відповідними значеннями розрахункових параметрів. Новизна та практична значущість полягає в тому, що використання сучасних геоінформаційних технологій в гідрологічній науці значно підвищує якість картографічних даних, а щодо досліджуваного об'єкта – річки Сіверський Донець, створює базу у вигляді цифрових карт для подальшого використання в гідрографо-геодезічних дослідженнях. Даний суббасейн раніше не досліджувався з використанням запропонованої Б. В. Кіндюком методики стосовно впливу масштабів карт на характеристики будови річкової мережі, що в практичному плані значно ускладнює роботу інженерів, дослідників і проєктантів з картографічними даними. Дане дослідження покликано пояснити особливості в масштабуванні річкових мереж, а також запропонувати механізм науково обґрунтованого переходу від наявного масштабу карти до бажаного в межах суббасейну Сіверського Донця.

Ключові слова: QGIS; гідрографічна мережа; порядок водотоку; гідрологічні характеристики; масштаб карти.

Received 26.04.2023