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Estimation the Subterranean Sources of Lakes Water Supply Based on Bathymetric Survey

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***Abstract* – Modern technologies give an opportunity to create a large number of bathymetric maps, but less of them have been focused on processing the water depth data in order to study and estimate the subterranean sources of water object supply. This study aims to create a mechanism for estimating the productivity of subterranean sources of lakes water supply, based on bathymetric survey data. Lake Svitiaz was chosen as the study site as the deepest closed lake of natural origin in Ukraine with an area of 2500 ha and a maximum depth of 58.4 m. To get depth data, ground-based measurements were conducted using an echo-sounder *Lowrance LMS-527cDF*. The Lake morphometric changes were investigated, using bathymetric data and Sentinel A, and B data in the digital elevation model (15×15 m). Bathygrahic analysis was performed, allowing selecting areas for further echo- sounding, taking into account complex relief and specific basin forms of the Lake. To develop an appropriate technique for estimating the productivity of subterranean water supply sources, GIS and image (echogram) processing techniques were applied. The research tasks are completed as a technique for detecting 'tracks' and a mechanism that is quite effective, particularly for early evaluation of subterranean sources of water supply productivity that can be repeated on any similar water objects.**

***Keywords* – Bathymetric survey; echogram; lake; 'track'; sinkhole; subterranean sources**

Nomenclature		
BR	Biosphere Reserve	–
GIS	Geographic information system	–
'track'	Trace that remains in the environment (water) through moving still particles and air bubbles	–

1. INTRODUCTION

Bathymetry is a data collection on water objects depth [1]–[3], received by bathymetric survey using special technical facilities. This georeferenced data contain information about depth'spatial distribution within a certain location [3]–[6]. Today, bathymetric maps are widely used for studying underwater topography and physical-geographical characteristics of water objects bottom. They allow to receive detailed depth contours of water objects, define the size, form, and distribution of underwater objects [3], [7]–[9]. It should be noted, that water level fluctuations depend on atmospheric circulation, solar activity and processes related to it; rainfalls as well as subterranean sources of water supply if such exists [10].

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The role of water resources in the problem of providing socio-economic progress all over the world is vitally important [11]. The state of these resources is one of the integrated ecological indicators of countries' sustainable development [12]. The dissatisfactory state of groundwater and surface waters is a pressing problem for most countries. The reason is not only their quantity but also their quality deterioration caused by regular and long-term anthropogenic load [13], [14].

Lakes are an important and the most sensitive to environmental changes part of ecosystems [15]. The bathymetric survey, except depths data, allows the calculation of the morphometric characteristics of water objects. The last, in turn, show the specificity of lakes basins giving information about lake genesis and the history of the most hydrological processes [16], [17].

During the last years, on the national level, considerable attention was given to the problem of water level decreasing within the 'Shatskyi' BR, which is a Ukrainian part of Trilateral Biosphere Reserve 'West Polesie'. Its area is 75 000 ha and is sufficiently aquatic, rich in landscape and biological diversity. It plays an important climate formation role for most of Europe [18], [19]. The overall length of rivers and streams with a permanent watercourse is more than 114 km. Melioration channels network with an overall length of more than 1115 km is very powerful. A cascade of lakes consists of 31 lakes, mainly of karstic origin with an overall area of about 5928 ha.

The presented study was initiated in 2019 and was related to the most burning issue that has arisen for the Svitiaz Lake that is located in the west of Ukraine within the Bioreserve. This deepest lake of Ukraine is of great importance as a freshwater source.

The necessity of detailed bathymetric surveys of Svitiaz Lake was conditioned by a significant fluctuation of its hydrological regime. In addition to analysis of climate changes and anthropogenic factors' influence on water level, the aim was to estimate the state and probable siltation of the Lake within its deepest sinkholes, the main subterranean sources of its water supply. Therefore, additional bathymetric surveys within these areas were initiated.

General aspects of West Polesie Lakeland analysis, including some morphometric peculiarities and bathymetric surveys of different scientists, are considered in [20]–[25]. In particular, a bathymetric survey of Svitiaz Lake area was performed by the authors of this paper in 2013. According to echo-sounding results a bathymetric database [26], digital relief model and depths map [27] were created. However, during the above-mentioned survey, it was not found the clear locations of subterranean sources of the Lake water supply and how it exactly happens. But, in 2019, based on results of dual-frequency on 200 and 50 kHz echo-sounding we have detected some features of subterranean water flows within the deepest Lake sinkholes. These flows include moving silt particles and air bubbles, which circulation forms appropriated 'tracks' on echograms. Their number and form differ on the above frequencies and give information about the moving parameters of these particles [28].

The aim of this study lies in the development and validation of techniques to estimate the productivity of subterranean sources of lakes water supply using a complex approach based on information-analytical methods and technology of bathymetric survey.

The following tasks have been set:

- to analyze the hydrogeological conditions of the territory of research;
- to calculate main morphometric characteristics of study water object;
- to develop the mechanism for estimating the productivity of subterranean sources of water supply based on bathymetric surveys and to test it on Svitiaz Lake;
- to summarize the results and highlight risks and ways of improving the proposed mechanism.

2. MATERIALS

2.1. Hydrological Conditions of Biosphere Reserve

Biosphere Reserve is a small part of Volyno-Podylskyi artesian basin according to hydrogeological zoning. Fissured rocks monoclinal occurrence and their massive overlapping by marine Upper Cretaceous deposits, condition the distribution regularity and moving of subterranean waters [29].

Plain, predominance of sandy deposits, relatively high amount of precipitations – up to 680 mm per year – contribute to the formation of subterranean waters of different genesis within the quaternary deposits.

The water-saturated layer begins right after a silting zone and is up to 70 m in depth. In this interval, the cracking of Cretaceous-marl sediments increases from top to bottom with a maximum of 30–60 m of depth. Below this depth fracture gradually decreases and the cracks themselves become much smaller. Already at a depth of about 80 m the mentioned layer becomes almost waterproof [29].

Concerning Svitiaz Lake genesis the information is received from the aquifer features of the Cretaceous-marl stratum of the Upper Cretaceous. Water migration occurs in a cracked layer of chalk**,** which is 50–70 m. A slight slope of writing chalk sea sediments in the western direction determines the active zone of the water flow, which does not exceed 100 m depth in Svitiaz Lake area. Therefore, below the 100 m depth, active water exchange and water flows, in general, are absent [23].

It was defined that cracking in the Cretaceous massif of Western Polesie can be observed at the depths of the chalk upper layer at 20–80 m depth. Actually, within this depths interval, a karst process occurred in the Neogene period, and it lasts to the present day. Waters of fractured chalk being in the discharge zone acquired a pressure character. The water level mirror is 0.8 m higher than the daylight area and Svitiaz Lake surface, respectively, and it provides a continuous supply of water object by pressure waters. Results of Svitiaz Lake water chemical analysis and the Upper Cretaceous aquifer coincide [23].

2.2. Svitiaz Lake Morphometric Characteristics

Analysis of morphometric characteristics of Svitiaz Lake was performed by parameters, shown in Table 1. These characteristics were calculated using the Earth Remote Sensing data from Sentinel 2-A, B per 2013, 2019 and 2021 (Tables 1 and Table 2). Data on Svitiaz Lake bathymetric survey, performed by authors, were also used [28].

According to water surface area F_0, as provided by Ilyin [30], [31], Svitiaz Lake is referred to very large with a lengthened form of a basin, according to K_{length} [32]. Pursuant to the shoreline sinuosity coefficient, Svitiaz Lake shoreline refers to weakly sinuous (Table 1).

The coefficient of openness indicates the water masses mixing degree and opportunities of stratigraphy appearance. The average value of this coefficient for Svitiaz Lake is 3.62, which allows one to refer this water object to sufficiently opened, according to the appropriate classification [30], [31]. However, despite the openness, large water masses, and the depth of the Lake, we can observe the water stratification and thermocline formation in the Lake.

TABLE 1. LAKE SVITIAZ MORPHOMETRIC MEASURES

Name	Area of the lake, sq.km	Length of the lake, km	Width of the lake, km	Width of the lake, km	Coefficient of lengthening	Coefficient of shoreline sinuosity
	F_0	L	B_{max}	B_{avr}	$K_{length} = \frac{L}{B_{avr}}$	$K_{sinuous} = \frac{L}{2\sqrt{F \cdot \pi}}$
Svitiaz	24.77	7.76	4.29	3.19	2.43	0.44

Note: averaged per 2013, 2019, and 2020, calculated data

TABLE 2. LAKE SVITIAZ DEPTH VALUES

Name	Maximum depth, m	Mean depth, m	Classification according to depth	
			Mean depth, m	Maximum depth, m
Svitiaz	–58.4	6.8	Medium	Very large

Note: calculated data

The form of the basin is the most important morphometric characteristic that defines dynamic processes in water objects, such as heating and mixing. The coefficient of water object basin size (C) is calculated as the ratio between mean and maximum depths. Svityaz Lake basin has a specific form – concave cone ($C < 0.33$) [33].

GIS modeling shows that the bottom relief of Svitiaz Lake differs from most Shatsk Lakeland water objects (Fig. 1).

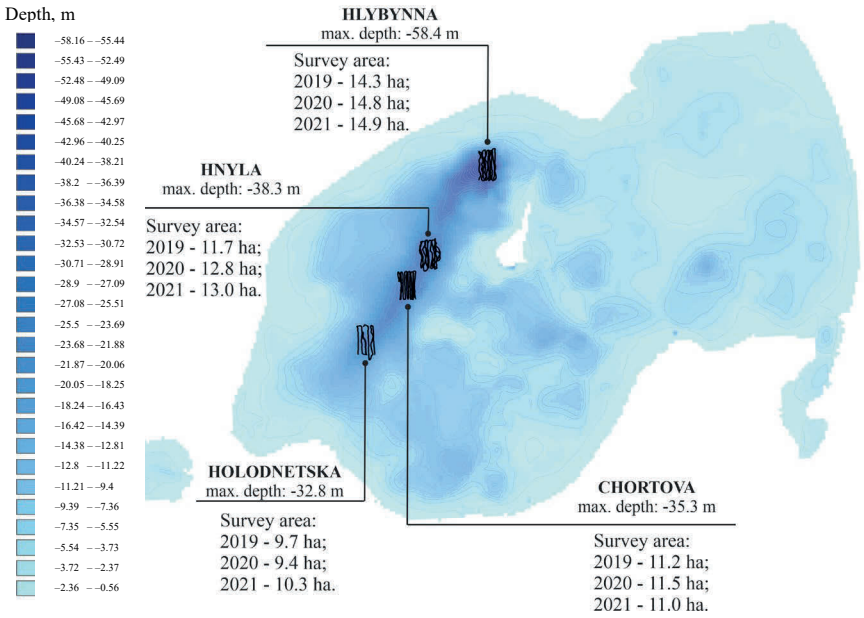


Fig. 1. Areas of bathymetric surveys within the deepest sinkholes of Svitiaz Lake.

Determination of water volumes was performed using previously created isobaths maps [27], based on the 'prism technique'. If areas restricted by isobaths are f_1, f_2, f_3,…, f_n, and vertical distances between isobaths planes are h_1, h_2, h_3…, so lake volume (W) will be calculated according to:

$$W = \frac{h_1(f_1 + f_2)}{2} + \frac{h_2(f_2 + f_3)}{2} + ... + \frac{h_{n-2}(f_{n-2} + f_{n-1})}{2} + \frac{h_{n-1}(f_{n-1} + f_n)}{2}. \quad (1)$$

In the case of water mass volume calculation, the water object area is the most important parameter. A comparison analysis of Svitiaz Lake shorelines using Landsat and Aster satellite data from 1988 to 2003 revealed that the lake area of 26.2 km^2, which corresponds to a water mass volume of 180.8 million m^3, has hardly changed during the last 15 years [34]. Such data may be found in any open Web source [35], [36].

However, during the last decades, except for seasonal fluctuations some changes both in lake area and water mass volume caused by the intensification of different natural and anthropogenic factors influence can be observed (Table 3).

TABLE 3. WATER MASS VOLUME

Water mass volume, mln. m^3	2013	2019	2021	Data from Web sources
Svitiaz	170.08	169.01	169.67	180.8

Note: calculated data

For most lakes with cone-shaped and parabolic forms of basins, a similar tendency can be seen: with depth increase, the value of water masses volume decreases. But the specific form of Svitiaz Lake basin allows trending this tendency only up to a certain depth equal to 42 m.

Fig. 2 shows that a maximum isobaths area is fixed on 2 m and equal to 19 985 800.41 sq. m (2013 – 79 %, 2019 – 82 %, 2021 – 80 %). The smallest belongs to the isobaths area that is fixed on 58 m and equals 201.67 sq. m.

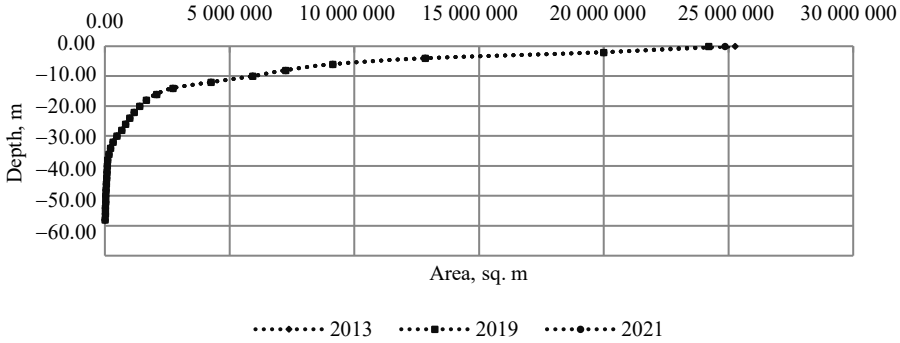


Fig. 2. Bathygraphic curve of Svitiaz Lake (dependence between area and depth).

Beginning from the isobaths area, which is fixed by 42 m and equals 71 500.41 sq. m. (2013 – 0.28 %, 2019 – 0.29 %, 2021 – 0.28 %), the further change of areas is insignificant taking into consideration that Svitiaz Lake has a specific form of the basin (Fig. 3).

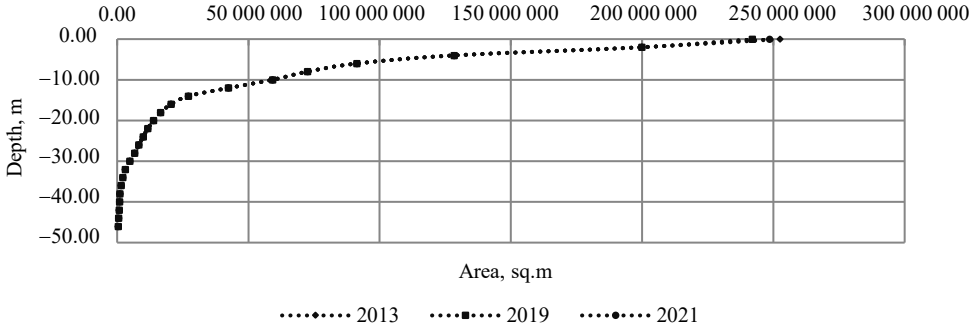


Fig. 3. Bathygraphic curve of Svitiaz Lake up to 45 m depth (dependence between area and depth).

Analysis of volume curves (Fig. 4) shows that increasing the water masses volume is observed for depths of 10 m and 18 m that corresponds to sinkholes (Fig. 1), located within the plane part of the Lake.

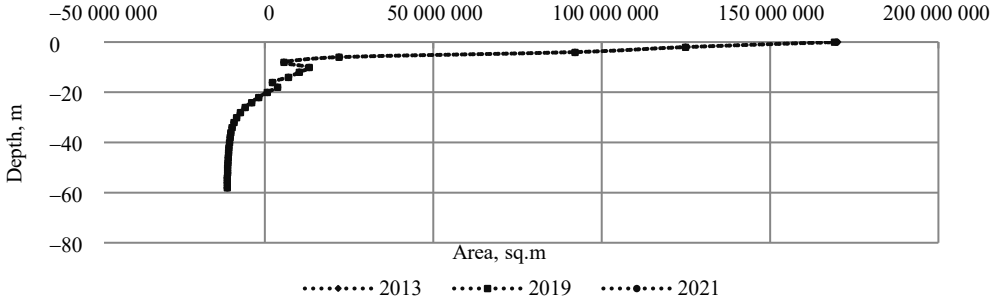


Fig. 4. Volume curve of Svitiaz Lake (dependence between water volume and its depth).

The above-stated morphometric analysis allows us to select areas for further hydro-acoustic sounding, taking into account complex relief and specific basin forms of the Lake.

3. Methodology

3.1. Bathymetric Survey Technique

The bathymetric survey technique included three stages.

1. A preparatory stage was based on studying the materials of previous bathymetric surveys and Earth Remote sensing data. The network of measurement points and tracks was defined using GIS of the BR 'Shatskyi' [26], [37]. Distance between longitudinal and latitudinal tracks was determined according to the stetted task: track length by latitude is equal to 300 m and discreteness by longitude was ≈ 20 m. The chosen spatial discreteness took into account relatively low sonar speed, namely: to record sonar and GPS receiver data with a resolution of 1 m, the speed should not exceed 3.6 km/h. This is especially important in the study of complex relief areas of Svitiaz Lake bottom.

Areas of bathymetric survey (Fig. 1) within each sinkhole were calculated basin on sonar technical characteristics is shown on Fig. 5.

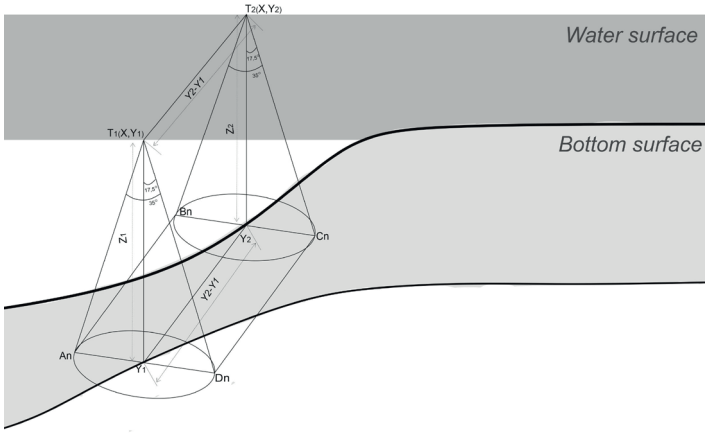


Fig. 5. Scheme of calculations of the bottom area covered by the sonar sensor.

According to the above scheme:

- Points T_1, T_2 – the first and the second position of the sonar sensor, accordingly, with X (longitude) and Y (latitude) coordinates. Longitude along one gals is stable, and latitude changes;
- Points Y_1, Y_2 – latitude value that matches the first and the second position of the sonar sensor;
- Points T_1Y_1, T_2Y_2 (Z_1, Z_2 accordingly) – depth that matches the first and the second position of the sonar sensor, m;
- A_nD_n, B_nC_n – segments on the projection parallel to Earth's surface (meaning the planet, or the parallel surface of the geoid), which are the basis for isosceles triangles $\Delta A_nT_1D_n$ and $\Delta B_nT_2C_n$ accordingly;
- They are formed by the echo-sounder beam cone in measuring points T_1 and T_2 accordingly, and by trapezoid basis $A_nB_nC_nD_n$ or opposite sides of the rectangle $A_nB_nC_nD_n$ (if $T_1Y_1 = T_2Y_2$, because then $A_nD_n = B_nC_n$)), m;
- 35˚ – angle/corner of echo-sounder beam cone at 200 kHz, degrees;
- $A_nB_nC_nD_n$ – trapezoid or rectangle (if $T_1Y_1 = T_2Y_2$, because then $A_nD_n = B_nC_n$) on the projection that is parallel to Earth's surface, area of this shape corresponds to area covered by echo-sounder beam between measuring points T_1 and T_2;
- $Y_2–Y_1$ – the distance passed between measuring points T_1 and T_2, m.

The second stage includes ground-based measurements within water object using the following equipment: a) echo-sounder *Lowrance LMS-527cDF*, incorporated with *GPS*. Operating frequency – 50 or 200 kHz; the angle of the ultrasonic transducers diagram is 35° (50 kHz) or 12° (200 kHz); maximum sounding depth – 760 m; maximum speed during measurements – 130 km per hour, b) *Garmin GPSMAP 76CSx* for additional navigation control;

The third desktop stage includes the final processing of measurements, creation of digital maps and illustrations, examination of the echograms, and development the techniques of their processing.

Then, echo-sounder profile data were converted for their further visualization and processing for obtaining a bathymetric scheme. *Lowrance Sonar Viewer Software* was used to eliminate interference to secondary reflection of the signal from the water surface, other extraneous noise, fixing inhomogeneities in the water column. The next step included the

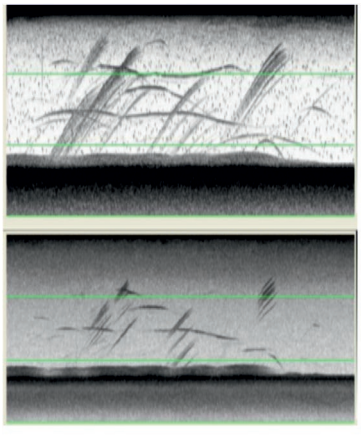
application of the developed technique for 'tracks' automatic detection on echograms. According to detection results, time-spatial calculations of 'tracks' density were performed by Eq. (1).

3.2. Subterranean Sources of Water Supply Estimation

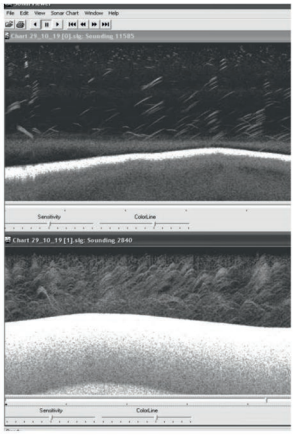
Dual-frequency sounding was performed within the selected four sinkholes (Fig. 1) of Svitiaz Lake: 'HLYBYNNA', 'HNYLA', 'CHORTOVA', 'HOLODNETSKA' (Fig. 1). Such a decision was grounded by the results of previous studies [28]. According to the last, the most interested are sinkholes, located within the Lake rift with the highest intensity of 'tracks'. 'Track' is a trace that remains in the environment (water) through moving silt particles and air bubbles.

The meaning of 'productivity' is used in many spheres of life, in ecological systems, in most cases, related to the estimation of the speed of substances and energy flows. In this study, the term 'tracks' density for description the 'productivity' of water supply subterranean sources is used

The analysis of recent scientific literature showed that the only similar to our studies relate to estimation of methane bubbles flow, based on bathymetric surveys of different water objects [38]–[40]. Visually this methane bubbles flow looks like tilted tracks, similar to ones, observed by authors as a result of Svitiaz Lake bathymetric surveys (Fig. 6).



Fragments of rising methane bubbles in the reservoir by results of echo-sounding on 200kHz (upper echogram) and 83kHz (lower echogram) [19]



Fragments with rising "tracks", formed by moving particles of silt and gas bubbles within the "Hnyla" sinkhole (Svitiaz Lake) by results of echo-sounding on 200kHz (upper echogram) and 50kHz (lower echogram)

Fig. 6. Comparative fragments of echograms.

Among instrumental and remote techniques for estimation the methane bubbles flow the most widespread are images processing (photo or video surveying, echograms) [39]. As opposed to echograms, photo resolution allows counting the number of methane bubbles per unit of volume, defining their distribution by size, and calculating the flow speed.

However, echograms resolution allows one to detect moving silt particles and air bubbles in the form of tracks.

Software for automatic 'tracks' detection was developed by authors and realized on C++ of C++17(C++1z) standard. *Cross-Platform Application Framework Qt GUI* module was

used as well as *OpenCV Library* and quick calculations frameworks, such as *Eigen*, *MKL*, *OpenBLAS*.

'Tracks' density on echograms within each sinkhole was calculated according to Eq. (2):

$$D_T = \frac{\sum_{i=1}^{n} T_i}{S_{WB}}, \tag{2}$$

where

D_T 'Tracks' density;
T_i 'Track' area in pixels;
S_{WB} Water body area in pixels.

The image is classified into layers: water body, bottom, and the near-surface layer of noises for S_{WB} calculation. 'Tracks' detection and areas calculations are performed only within the water body layer (Fig. 7).

Detection of bottom layer includes the following steps: image binarization using Otsu method; morphological operation 'Breaking' that includes erosion with the structural element 'Cross' and 21 × 21 pixels mask, and dilation with structural element 'Ellipse' and 55 × 55 pixels mask; searching for contours; searching the largest contour the highest border of which will separate the bottom from the water body and a near-surface layer of noises; formation of the bottom layer class mask from the highest border of received contour to image bottom.

Detection of near-surface layer of noises includes: adaptive binarization with 33 pixels window; contours detection; segmenting of the upper image part on horizontal segments and defining the dispersion within these segments; searching for two segments, the dispersion ratio between which will be the largest, and that will form a line which separates near-surface layer from water body; formation of near-surface layer class mask.

Detection of 'tracks' density includes cutting off the contours to water body class; calculation of their sum and D_T.

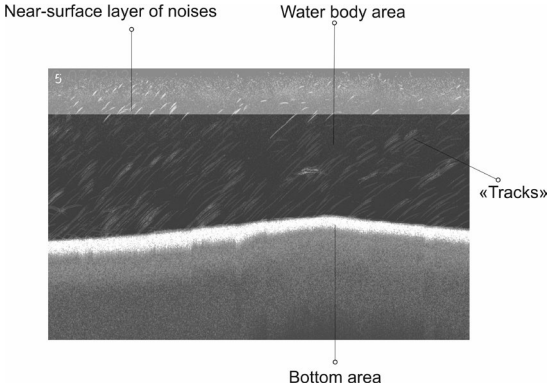


Fig. 7. Areas for 'tracks' detection.

The analysis and calculations of 'tracks' density were performed for the 2019–2021 period within each sinkhole of Svitiaz Lake using echo-sounding data on 200 kHz.

4. RESULTS AND DISCUSSION

Stratification of water columns is characteristic for lakes of such size and depth as Svitiaz Lake. Therefore, a thermocline is one more feature that can be observed on most studied echograms. As the rule water layers below a thermocline contain not much oxygen, and much more sulphureted hydrogen, CO_2, and other gases, which are formed due to the decomposition of natural organic and are toxic for fish. Therefore, the above-mentioned is an additional argument in favor of the separation of water flows from fish on echograms within the deepest sinkholes.

The highest productivity of subterranean sources of water supply, according to calculated 'tracks' density from 0.0288 up to 0.0765 units, were observed in 2019 for 'HNYLA', 'CHORTOVA' and 'HOLODNETSKA' sinkholes (Fig. 8).

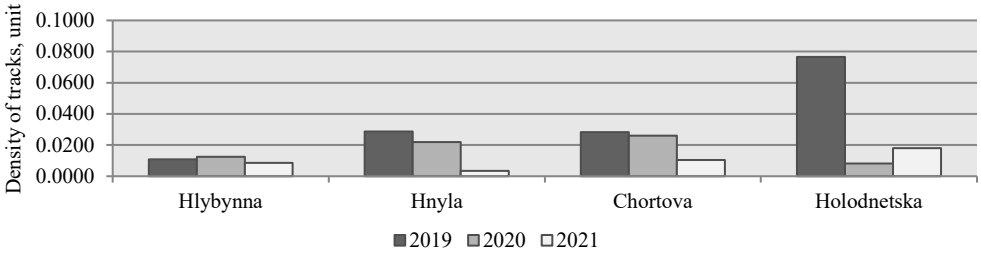


Fig. 8. 'Tracks' density within Svitiaz Lake sinkholes.

Differences between seasonal and annual fluctuations of meteorological parameters during 2019–2020 are shown in Fig. 9. The average air temperature and the rainfall in 2019 were +10.4 °C and 504.1 mm, accordingly. In 2020 these parameters were +10.1 °C and 732.7 mm. The increased values of air temperature and sufficiently low precipitations in spring and summer of 2019 led to a high evaporation rate from the water surface and a decrease in the Lake water level.

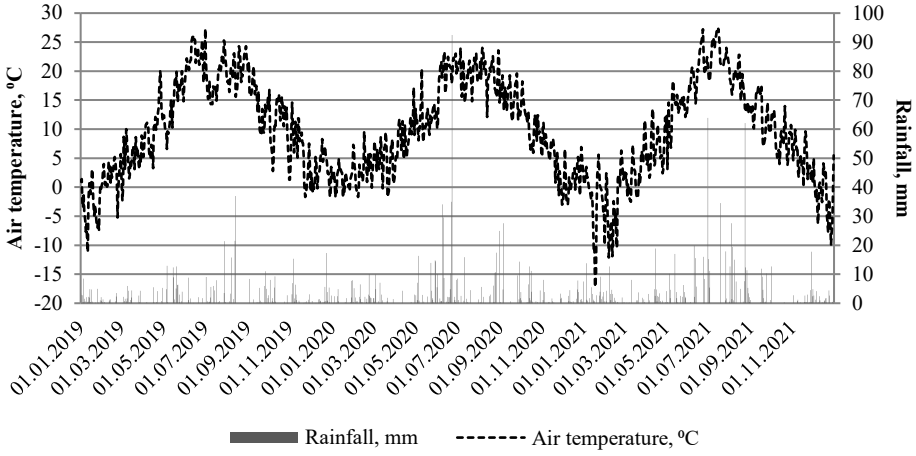


Fig. 9. Dynamics of monthly average air temperature and rainfall within BR 'Shatskyi'.

The higher precipitations in winter 2019–2020 and at the beginning of summer 2020 together with lower monthly average air temperature contributed to a gradual increase of Svitiaz Lake water level. Moreover, the latter led to a productivity decrease of subterranean sources of water supply in Svitiaz Lake during 2020–2021 (Fig. 8).

Small changes in 'tracks' density during the studied period can be observed for the deepest 'HLYBYNNA' sinkhole (Fig. 8). This can be explained by sharp changes in-depth, up to –58.4 m, and topography features of this sinkhole (Fig. 10).

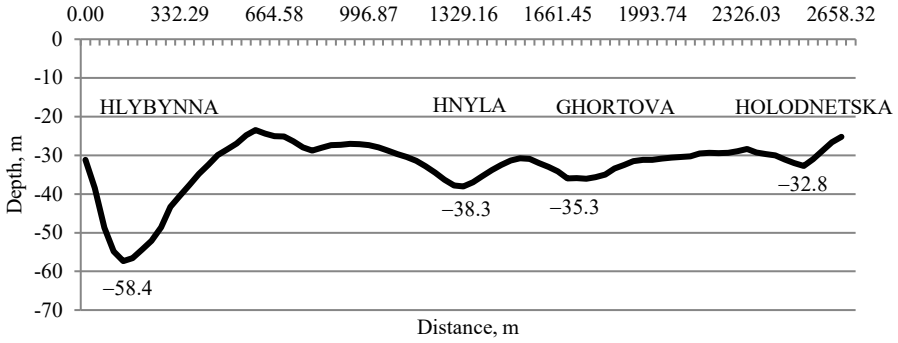


Fig. 10. Depth profile within the rift of Svitiaz Lake.

All results of this study prove a hydrogeological thesis that the increased flow of pressured waters within the Svitiaz Lake can be observed during periods with a small number of precipitations. The decreased flow can be observed during high-water a period that confirms the fact of a close relationship with a pressured aquifer.

The proposed technique of 'tracks' detection and mechanism of preliminary estimation of productivity of subterranean sources of lakes' water supply, on the example of Svitiaz Lake, make a very important basis for establishing regularities and directions of transformation hydro-ecological processes under the influence of natural and anthropogenic factors.

5. CONCLUSIONS

The proposed and described mechanism proved to be quite effective especially for preliminary estimation of subterranean sources of water supply productivity based on bathymetric survey images processing. The received results allowed one, for the first time, to quantify the power of subterranean sources of Svitiaz Lake water supply. Moreover, they confirmed a theory forwarded by the authors in previous studies [28]. Received by calculation data on Svitiaz Lake water sources supply productivity, received within our studies, is proved by hydrogeological features of territory [29] as well as by results of hydrological measurements of Svitiaz Lake over the research period.

The proposed technique can be used for other water objects with subterranean sources of water supply. However, it should be mentioned that long-term hydrological forecasting needs to solve the additional tasks: increasing of sonar measurements statistics and image processing techniques that will allow moving from standard units for estimation the productivity of subterranean sources of water supply to quantitative values such as cubic meters or cubic meters per minute.

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