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Groundwater for urban water supply in Ukraine: a case study of Mykolaiv (Military challenges and lessons for the future)

Le acque sotterranee per l'approvvigionamento idrico urbano in Ucraina: il caso studio di Mykolaiv (sfide militari e lezioni per il futuro)

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Parole chiave: acque sotterranee di Mykolaiv, acquifero Upper Sarmatian, modellazione matematica, periodo di emergenza, operazioni militari.

Riassunto

L'articolo discute la possibilità di utilizzare le acque sotterranee come fonte di approvvigionamento idrico per Mykolaiv durante le emergenze o le operazioni militari. È stato sviluppato un modello idrogeologico delle acque sotterranee di Mykolaiv per studiare il flusso idrico sotterraneo e le sorgenti di acque sotterranee nell'acquifero Upper Sarmatian, che è un'importante riserva di acqua potabile nell'area di Mykolaiv. È stata valutata l'influenza di diversi fattori sul moto dell'acqua attraverso i sedimenti dell'acquifero, inclusa la vulnerabilità delle acque sotterranee all'intrusione di acqua salmastra dall'estuario Bug. Lo studio valuta anche la possibilità di utilizzare le risorse dell'acquifero in condizioni di emergenza o nel corso di operazioni militari.

Abstract

The paper discusses the possibility of using groundwater as a source of water supply for Mykolaiv during emergencies or military operations. A hydrogeological model of the Mykolaiv groundwater field was developed to investigate the water exchange pattern and sources of operational groundwater reserves in the Upper Sarmatian aquifer, which is a primary source of drinking groundwater in the Mykolaiv area. The influence of various factors on water-bearing capacity of the Upper Sarmatian sediments was assessed, including the vulnerability of the fresh groundwater to the intrusion of brackish water from the Bug Estuary. The study also examined the feasibility of operating the aquifer under forced conditions, depending on the duration of emergency periods or military operations.

Introduction

Since the beginning of the Russian military invasion of Ukraine, the issue of drinking water supply has become critical due to the destruction of a stable centralized water supply system in many cities. A reliable supply of drinking water is one of the most important life-sustaining factors for the population, especially given the high potential risk of massive fire damage in urban centres. The ongoing hostilities have already destroyed water intake structures in urban areas, leading to a humanitarian water crisis in cities such as Mariupol and Mykolaiv. This underscores the need to establish reliable and disaster resilient water supply systems, including for military operations. These systems should include reserve water sources and methods for delivering water to the distribution network (Sanina and Lyuta, 2021; Shestopalov, 2022; Shevchenko et al., 2022).

For Mykolaiv city with population of 476 thousand people (in 2021), the supply of drinking water to households in peacetime should be 105 thousand m^3/day, without taking into account the consumers of industrial enterprises.

Prior to hostilities breaking out in 2022, Mykolaiv was supplied by surface water from the Dnipro River. However, due to a damaged pipeline, the city faced a humanitarian crisis. Wells were urgently drilled and equipped to tap into the Upper Sarmatian aquifer.

It should be noted that Mykolaiv is located close to the Bug Estuary, which puts the use of groundwater for the drinking water supply of the city at risk, due to the intrusion of brackish water from the Estuary into the water intakes. According to the classification of cities given in La Vigna (2022), the area under consideration belongs to the category of coastal cities, lagoon cities and delta cities with groundwater (CGC - LDGC).

The intrusion of saline seawater into freshwater aquifers is causing a decline in groundwater quality in coastal areas around the world, so much research has been focused on understanding this process and developing methods to minimise the effects of such phenomenon under a wide variety of climatic, geological, tectonic and hydrogeological conditions (e.g., Michael et al., 2013; Hussain et al., 2019; Prusty & Farooq, 2020). Key drivers of seawater intrusion and approaches to minimise the impact of this process on fresh groundwater quality have been identified, including geological factors (e.g., lithology, geological history of the water-bearing formations, hydraulic gradient, etc.), human activities (especially the rate and volume of water extraction), tidal activity, climate change, sea level rise, and others (Prusty and Farooq, 2020).

Methods to minimise the negative impact of saline seawater intrusion into coastal freshwaters on water quality depend on the factors controlling this process and are individual to each study area (Prusty and Farooq, 2020). The most effective and widely used approach is the regulation of water extraction from wells (Manivannan and Elango, 2018; Hussain et al., 2019; Prusty and Farooq, 2020), optimising the well siting pattern (i.e., moving pumping wells towards inland areas; Manivannan and Elango, 2018; Hussain et al, 2019; Prusty and Farooq, 2020), artificial recharge and rainwater harvesting (Prusty and Farooq, 2020), construction of wells close to the sea to inject large volumes of freshwater under high pressure (Manivannan and Elango, 2018) or wells to pump saltwater (Hussain et al., 2019), creating subsurface barriers (Hussain et al., 2019; Dey and Prakash, 2020), and combined methods (Hussain et al., 2019).

The aim of this research was to develop the hydrogeological model and investigate the possibility of using a network of existing and forecast operational wells to provide an alternative source of drinking water supply to the residents of Mykolaiv. This paper also describes modelling scenarios to protect the operated freshwater aquifers from salt water intrusion by creating a linear series of barrier wells. The potential use of groundwater as a reserve source of drinking water supply for the city of Mykolaiv in case of emergency or military operations is analysed and discussed.

Material and Methods

Hydrogeological setting of the study area

The research area covers the territory of Mykolaiv and its suburban outskirts - Zhovtneve settlement, Balabanivka and Sviatotroitske villages in the Mykolaiv region of Ukraine (Fig. 1).

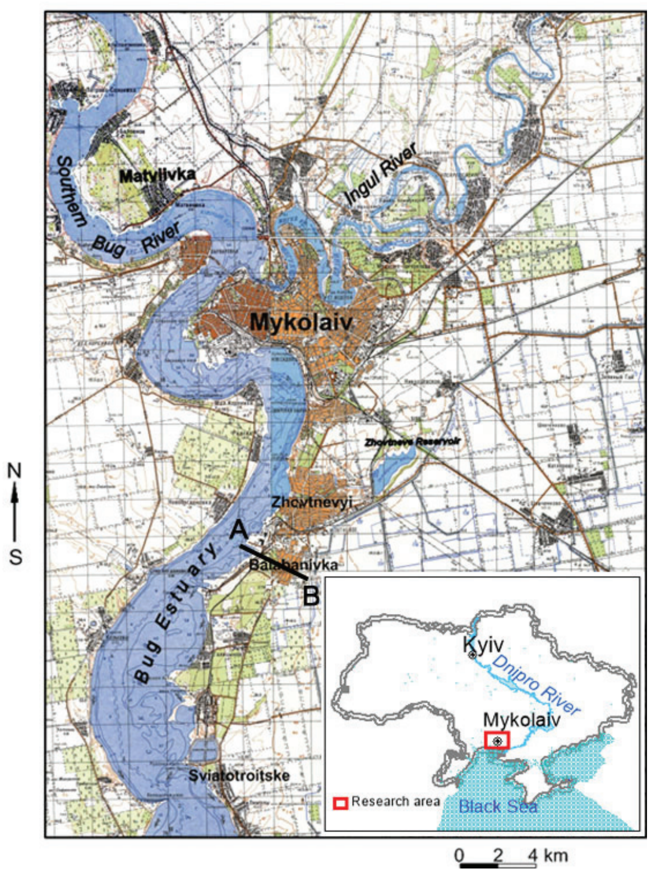

Fig. 1 - General overview map of the study area showing the line of geological section A-B.

Fig. 1 - Carta generale dell'area di studio e traccia della sezione geologica A-B.

Climate in the Mykolaiv region is temperate continental with hot, dry summers and mild winters with frequent thaws. According to the amount of atmospheric precipitation and evaporation conditions, the study area belongs to the arid zone. The norm of atmospheric precipitation for a multi-year period is 410 mm. The minimum annual precipitation for the whole period of observations is 199 mm, and the maximum 691 mm. The infiltration of atmospheric precipitation into the soil in the research area usually occurs in autumn and spring.

The primary waterways in the research area are the Bug Estuary, which flows to the Black Sea, the mouth of the Southern Bug River and its tributary, the Ingul River.

The geological structure of the research area is characterised by a rather thick (1000-1200 m) sequence of the sedimentary deposits, slightly inclined to the south towards the axial part of the Black Sea Basin, which lies on the Precambrian crystalline basement. The sedimentary cover is represented by Cretaceous, Paleogene, Neogene and Quaternary deposits (Chekhanskaya and Rodnyak, 1974). Figure 2 shows the geological section of the upper part of the sedimentary cover containing fresh groundwater.

According to the hydrogeological zoning, the research area is located within the northern wing of the Black Sea artesian basin with a characteristic interlayering of water-bearing and relatively impermeable rock layers. Aquifers occur within all stratigraphic complexes in the area.

The study area refers to sheet E 5 (Bucharest) of the International Hydrogeological Map of Europe IHME1500. According to the hydrogeological settings of the map, it belongs to the low and moderately productive pore aquifers (International Hydrogeological Map of Europe, https://www.bgr.bund.de/EN/Themen/Wasser/Projekte/laufend/Beratung/Ihme1500/ihme1500_projektbeschr_en.html).

The primary source of groundwater for the population of Mykolaiv is the Upper Sarmatian aquifer on the left bank of the Bug Estuary, south of the Ingul River. This aquifer is composed of fractured limestones, heavily karstified and cavernous in some areas along the coastal part of the Bug Estuary. Less frequently, this aquifer is composed of marls and quartz sandstones with interbeds of dense clays.

The aquifer thickness ranges from 18.0-40.0 m, with a depth of occurrence of 1.0-22.0 m on the left bank of the Bug Estuary and 30.0-60.0 m in the watershed areas.

The Upper Sarmatian aquifer is overlain by a layer of Meotian clays eroded in riverine areas. This clay layer, where present, separates the aquifer from the overlying, less prospective, multi-age aquifers. According to the hydrogeodynamic regime, the Upper Sarmatian aquifer is classified as a confined-unconfined aquifer (Nasad and Nasad, 1976).

A dense layer of Upper and Middle Sarmatian clays underlies the Upper Sarmatian aquifer. Over a large part of the research area, especially in its southern part, this clay layer is thin and may contain ‘hydrogeological windows’.

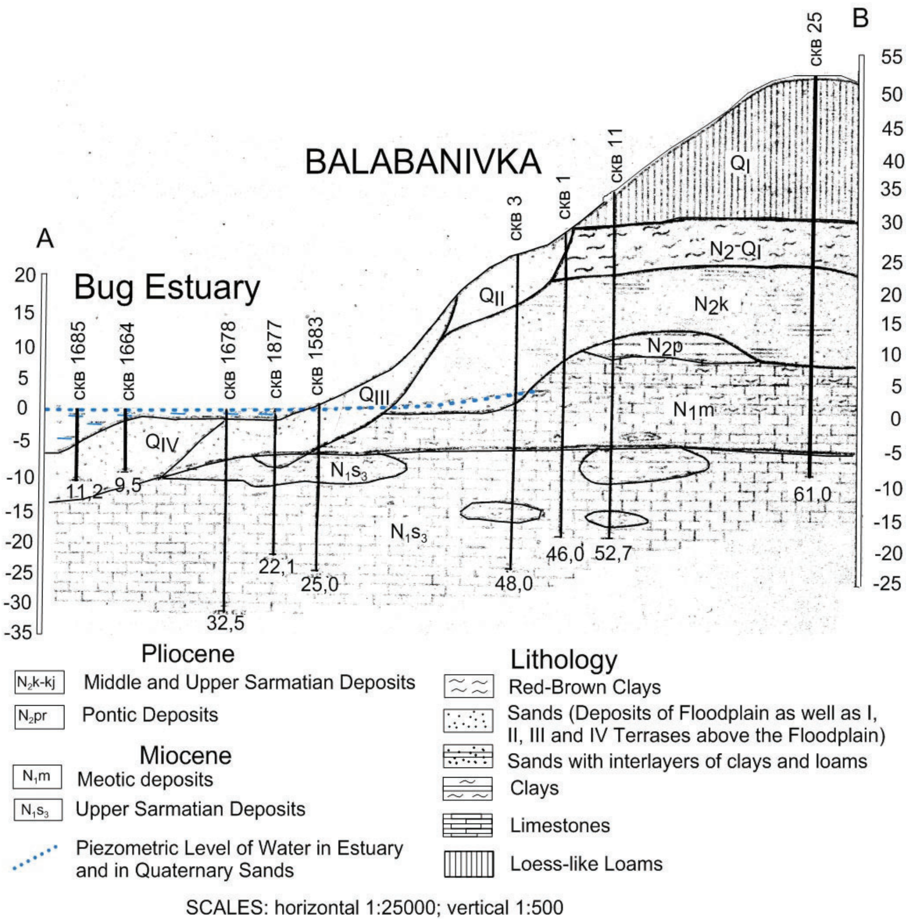

Fig. 2 - Geological section A-B of the upper part of the sedimentary cover through the Bug Estuary and its left bank near the village of Balabanivka (modified from Kuzmenko, 1949). Heigths in the vertical axis are expressed in m with respect to mean sea level.

Fig. 2 - Sezione geologica A-B della parte superiore della copertura sedimentaria attraverso l’estuario del Bug e la sua sponda sinistra vicino al villaggio di Balabanivka (modificata da Kuzmenko, 1949). Le quote sull’asse verticale sono espresse in m rispetto al livello del mare.

The hydraulic connection between the Upper Sarmatian aquifer and the Bug Estuary is strong, as shown by the values of the absolute water levels. It has been observed that groundwater salinity increases with increasing groundwater extraction rates (Inzhevatov, 1969).

The Upper Sarmatian aquifer is replenished by vertical water inflow from the overlying and underlying aquifers in the Cimmerian-Kuyalnik, Meotian, Quaternary and Middle Sarmatian deposits. It is also recharged by infiltration of atmospheric precipitation in areas with a thin layer of Quaternary sediments covering the Upper Sarmatian limestones, and by infiltration from the riverbed of the Ingul River near Mykolaiv. The Upper Sarmatian aquifer discharges into the Bug and Dnipro estuaries.

The water-bearing capacity and filtration properties of the Upper Sarmatian deposits depend on their lithological composition, thickness and degree of karstification. Thus, aquifer transmissivity in highly karstified Upper Sarmatian limestones near Balabanivka village is estimated at 450 m^2/day or more, and decreases to 25-30 m^2/day in areas of non-karstified limestones and marls (Inzhevatov, 1969).

Water supply for Mykolaiv

Before the start of the military operations, the primary source of water supply for Mykolaiv was the Dnipro River. Groundwater has also been used for a long time to supply the city and surrounding areas.

In 1950-1952 small groundwater intakes were put into operation in the suburban settlements of Zhovtneve and Balabanivka. These intakes exploited the Upper Sarmatian aquifer and were used for centralised drinking water supply in Mykolaiv.

In the mid-1960s, a groundwater intake structure was constructed in the central part of Zhovtneve village. The structure consisted of 7 operational wells and underground gallery and its purpose was to provide centralized water supply to Mykolaiv. Between 1965 and 1969, the total flow rate of this water intake ranged from 3.5 to 13.5 thousand m^3/day, with an average of 9.6 thousand m^3/day (Inzhevatov, 1969). The well water from the Zhovtneve intake had a salinity level exceeding the standard value of 1.5 g/dm^3. To bring it within acceptable limits, it was mixed with surface water from the Zhovtneve reservoir before being delivered to Mykolaiv. Due to the high degree of hydraulic connection between the Upper Sarmatian aquifer and the surface water of the Bug Estuary, the increase in the flow rate of the Zhovtneve water intake structure resulted in a sudden increase in total salinity and chloride content. This rise made it difficult to improve the productivity of the intake.

From 1966 to 1968, the water intake structure in the northern part of Balabanivka village, just south of Zhovtneve water intake, extracted 1850-5420 m^3/day, with an average of 3910 m^3/day at a groundwater salinity of 0.5 g/dm^3 (Inzhevatov, 1969). However, increased groundwater extraction from the Upper Sarmatian aquifer has led to an increase in salinity due to the intrusion of highly saline water from the Bug Estuary.

By the end of 1968, Mykolaiv industrial enterprises extracted 7210 m^3/day of groundwater from the Upper Sarmatian aquifer.

Thus, the peak of water extraction within the Mykolaiv groundwater field occurred in 1968-1969, with a total of 26750 m^3/day from all the above-mentioned water intake sites.

However, this resulted in a rapid increase in the salinity of the groundwater being extracted. Three approaches were taken to address this problem. Firstly, water extraction from existing groundwater intake structures was continuously reduced. Secondly, groundwater prospecting and exploration was carried out at the alternative sites. Finally, various scenarios for supplying water from surface sources (such as the Zhovtneve reservoir and the Dnipro-Mykolaiv water supply pipeline) were considered.

In 1968, a groundwater intake structure was designed with 15 wells arranged in a linear series. The wells were drilled between the villages of Balabanivka and Sviatotroitske. However, calculations showed that the explored groundwater reserves for this designed intake were limited due to the potential negative impacts from the water of the Bug Estuary. As a result, no intake structure was commissioned at this site. Additionally, a scenario was modelled for possible barrier effects caused by a series of operational wells located between the Bug Estuary and the wells of previously designed water intake at the Balabanivka-Sviatotroitske site. However, the analysis of Shestopalov et al. (2019a) suggested that it was not effective.

At present, the water intake structures of industrial enterprises in Mykolaiv extract groundwater from the Upper Sarmatian aquifer mainly for technical purposes (i.e., technological processes of industry, cooling of machinery, domestic needs of personnel, etc.) due to the high salinity. As of the end of 2020, the State Municipal Enterprise 'Mykolaivvodokanal' supplied only 0.88 thousand m^3/day of drinking groundwater to the population, while 37 wells of various urban enterprises extracted a total of 0.591 thousand m^3/day of groundwater from the Upper Sarmatian aquifer for technical purposes.

Hydrogeological model of the study area

The numerical model used in this study is based on systems of differential equations with distributed parameters (Chiang and Kinzelbach, 2001). The hydrogeological model of the study area comprises systems of two equations. The first equation describes the process of groundwater flow in the Upper Sarmatian aquifer, while the second equation simulates the transport of dissolved salts in this aquifer as a result of brackish water intrusion from the Bug Estuary into the operational wells of water intake structures. The influence of the density of the saline water on the rate of its intrusion into the aquifers has not been considered in this study, as the difference between the density of the fresh groundwater (1.00 g/dm^3) and the density of saline water in the Bug Estuary (1.05 g/dm^3) is not significant.

The hydrogeological model includes two aquifer layers (i.e., Quaternary and Upper Sarmatian) separated by a relatively impermeable layer (aquitard). The total depth of the model domain was 35 m, which corresponds to the depth of occurrence of fresh groundwater.

The hydrographic network in the research area (excluding the Southern Bug River and the Bug Estuary) was specified in the model using the 3rd type boundary condition (BC) ($q = f(\Delta H)$, where q characterises the intensity of water exchange between the river and the underlying aquifer; $f(\Delta H)$ is a given function of the difference between the water levels in the river and the underlying aquifer.

The water levels and salinity of the Southern Bug River and the Bug Estuary were specified using the 1st type BC (H = constant; ΔM = constant, where H is the water level in the Estuary; ΔM is the difference between the salinity in the Estuary and the salinity of the fresh groundwater prior to the start of the saltwater intrusion process, g/dm^3). The 1st type boundary conditions for these surface water bodies have been set on the assumption that the water volume they contain make it possible to maintain a constant head and salinity, regardless of any changes in the hydrodynamic conditions.

The flow rates of operational wells were specified using the 2nd type BC (Q = constant, where Q is the well flow rate). At the contour of the modelling domain, the 2nd type BC ($Q = 0$) was specified. The model area was chosen so that the influence of the modelled water intake on the outer boundary was negligible.

In this study, the system of differential equations for groundwater flow and contaminant transport was solved in the finite-difference form using the MODFLOW and MT3D codes from the PMWIN package (Chiang and Kinzelbach, 2001). For this purpose, the modelled area was covered by a non-uniform rectangular numerical grid made of computational blocks ranging in size from 500x500 m at the periphery of the modelling area to 250x250 m in the centre of the model. The total modelled area was 1300 km^2, which was subdivided into 13680 cells.

Data for the initial model parameters (layer transmissivity and storativity) were based on previous studies in the region (Yevsyukov, 2009; Fedosova and Goloshchak, 1984; Inzhevatov, 1969; Ivanitsky, 1987; Pereyaslavskaya et al., 1971; Semenov, 1966) and other published sources (Klimentov and Bogdanov, 1977; Maksimov, 1967).

In solving the inverse problems, the initial model parameters and their spatial distribution were adjusted or fitted (recharge rate and active porosity of aquifer layers) using data on groundwater levels in the monitoring well network and on the salinisation history in local water intake wells. Some model parameters were also estimated based on analogies or calculated analytically (e.g., active porosity of fractured rocks of the Upper Sarmatian aquifer). The model was calibrated by trial and error using monitoring data from 12 wells based on observations carried out in 1968.

According to pumping tests, the transmissivity of the Upper Sarmatian aquifer within the study area is quite variable (25-450 m^2/day) due to the different degree of karstification in certain parts of the aquifer on the left bank of the Bug Estuary. After schematising the natural conditions, 3 zones of transmissivity were identified in the model. In zone 1 (area of the Balabanivka water intake) and zone 2 (area of the Mykolaiv water intake) the transmissivity was 250 m^2/day. In the remaining area of the model (zone 3) the transmissivity was 60 m^2/day. The storativity for the Upper Sarmatian aquifer was set to $\mu 2 = 0.002$, based on the average piezoconductivity and transmissivity data. At the sites near the Bug Estuary, where the fractured Upper Sarmatian aquifer occurs close to the surface and is significantly karstified, the specific yield was set to $\mu 2 = 0.1$.

To fit the model recharge rate of the Upper Sarmatian aquifer during the operation of the Mykolaiv, Zhovtneve and Balabanivka water intakes with the maximum recorded flow rate (26750 m^3/day), the hydroisopiestic contour map of this aquifer at the end of 1968 was used for model calibration (Fig. 3), which was the period of maximum groundwater extraction, with the most developed monitoring network, and therefore the most complete information available for model calibration. Groundwater flow was modelled in steady-state conditions, while solute transport was modelled in transient conditions.

The fitted average value of recharge rate for the Upper Sarmatian aquifer is 7 mm/year (1.9×10^{-5} m/day). The map of groundwater recharge in the Black Sea basin (Shestopalov, 1989) shows that infiltration recharge in the area of the Bug Estuary generally does not exceed 5 mm/year, which is close to the fitted value above.

Modelling the brackish water intrusion from the Bug Estuary into the operational wells of the Mykolaiv groundwater intakes using mass transfer equations required information on the salinity of the water in the Bug Estuary and the Upper Sarmatian aquifer under natural conditions, and on active (dynamic) porosity (n).

According to reference data, the salinity of the water in the Bug Estuary, depending on the distance from the mouth of the Southern Bug to the Black Sea, is in the range of 1-17 g/dm^3, with the lower value referring to the mouth of the Southern Bug and the higher value referring to the southern part of the Bug Estuary. Specifically, in the area of the modelled water intake, water salinity in the Bug Estuary varies from 4 g/dm^3 near Balabanivka village to 12 g/dm^3 near Sviatotroitske village.

The active porosity of the Upper Sarmatian limestones was estimated by fitting and analogy for different study sites. For example, at the Mykolaiv, Zhovtneve, Balabanivka and Sviatotroitske sites, the active porosity of the aquifers was fitted to the model in the range of 0.1-0.05 based on actual data on the history of salinisation of local groundwater intakes.

Within the previously designed Balabanivka-Sviatotroitske water intake, this parameter was calculated to be 0.01 using the Bindemann formula (Inzhevatov, 1969). A detailed analysis of the validity of these parameters was performed by Shestopalov et al. (2019b).

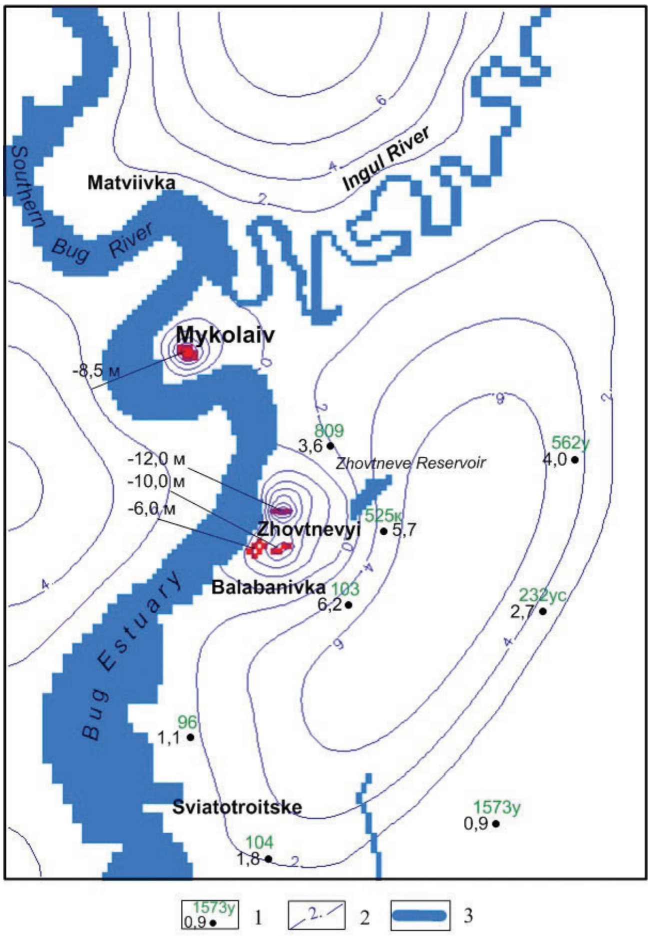

Fig. 3 - Schematic map of the hydroisopiestic lines for the Upper Sarmatian aquifer at the end of 1968: 1 – well, from the top - its number (shown in green), on the side – absolute hydroisopiestic level, in m with respect to the mean sea level (shown in black); 2 – hydroisopiestic line, values in m with respect to the mean sea level; 3 - hydrographic network.

Fig. 3 - Carta schematica delle isopieze dell'acquifero Upper Sarmatian alla fine del 1968: 1 – pozzo, in alto – l'ID del pozzo (in verde), al lato – livello piezometrico, in m rispetto al livello medio del mare (in nero); 2 – isopieza, valori in m rispetto al livello medio del mare; 3 – reticolo idrografico.

Processes of hydrodynamic dispersion and molecular diffusion of dissolved salts in aquifers were not considered in the solute transport model, due to their assumed relatively small influence on the rate of contaminant transport. This assumption is based on modelling analyses for the Balabanivka-Sviatotroitske reserve water intake, operating at flow rates of 7800 and 2866 m^3/day using the longitudinal dispersivity of 20 m, which was analytically calculated for a fractured medium with volume-isotropic structural heterogeneity (Stetsenko, 2017). Therefore, the modelling of migration processes presented below has accounted only for advection of the dissolved salts. Taking into account uncertainty in longitudinal dispersivity parameter, the influence of hydrodynamic dispersion on salt transport process deserves attention in future studies.

Results and Discussion

Forecast modelling

The military actions of the Russian aggressor have caused significant disruptions to the centralised water supply of the city of Mykolaiv. Moreover, possible negative effects of natural or man-made factors should be taken into account. Therefore, in this research, the hydrogeological model was developed to investigate the possibility of using a network of existing and forecast operational wells to provide an alternative source of drinking water supply to the residents of Mykolaiv. In this study, 15 wells of the previously designed but not yet commissioned water intake along the left bank of the Bug Estuary, between the villages of Balabanivka and Sviatotroitske, and additional operational wells in new prospective areas are considered as forecast water supply wells.

The hydrogeological model was used to simulate the extraction of approved groundwater reserves at the previously designed (reserve) water intake structure.

Forecast of the operation of the reserve Balabanivka -- Sviatotroitske water intake

The modelling results shown in Figure 4, indicate that after 5.5 years of intensive operation of the water intake at a flow rate of 7800 m^3/day (15 wells) acceptable groundwater quality may begin to deteriorate (in the central part of the linear series of water intake wells, salinity reaches 1.5-1.6 g/dm^3). The flow rate of 7800 m^3/day used in the calculations corresponds to the amount of operational groundwater reserves previously approved by the State Commission of Ukraine on Mineral Reserves.

The model was run in transient mode. When solving the groundwater flow problem, 10 stress periods of 1000 days duration were assigned (the service life of the water intake according to Ukrainian legislation is 10000 days). When solving the transport problem, additional stress periods of shorter duration were specified in order to control the time of occurrence of increased salinity at the water intake.

Further, the dependence of the maximum possible operational life of the forecast water intake was determined, provided that the groundwater salinity in the operation wells shall not exceed 1.5 g/dm^3 and the maximum permissible drawdown in the wells is 20 m at different flow rates.

The results of this study are summarised in Figure 5. It can be seen that with a total flow rate of 4,000 m^3/day, the water intakes can operate for 6,000 days (16.4 years) before becoming contaminated by brackish water from the Bug Estuary (i.e., salinity will exceed the level of 1.5 g/dm^3). This flow rate scenario is associated with a 10 m drawdown in the centre of the intake. At a flow rate of 8,000 m^3/day (as mentioned above), the water intakes can operate for almost 2100 days (5.75 years) before brackish water intrusion begins, with a groundwater drawdown of 19 m at the centre of the intake structure. At a total flow rate of over 8,400 m^3/day, the drawdown at the centre of the intakes will exceed 20 m.

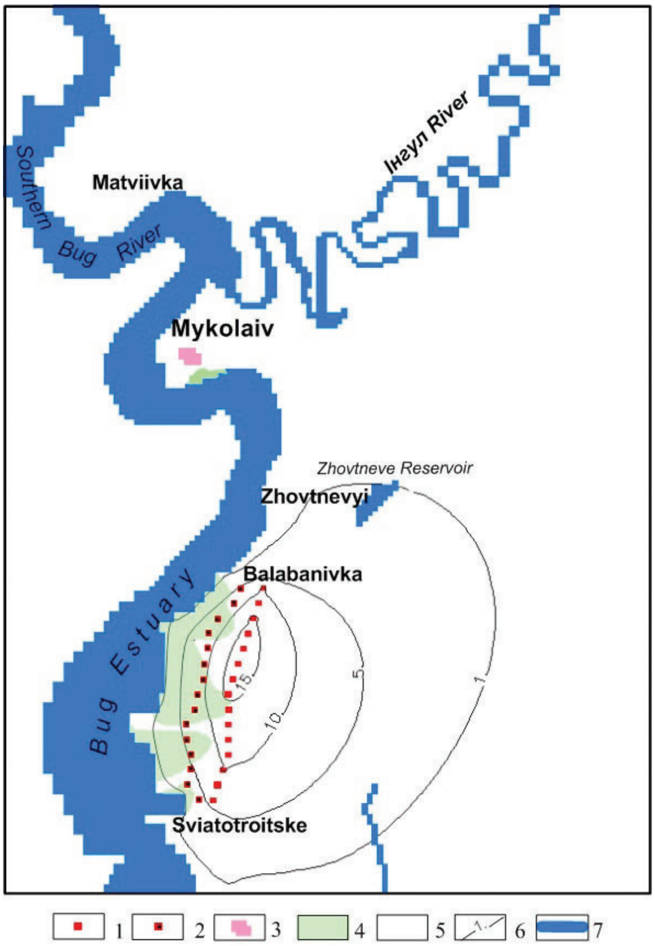

Fig. 4 - Scheme of groundwater salinity and water levels drawdown in the Upper Sarmatian aquifer after 5.5 years of operation of the reserve groundwater intake at a flow rate of 7800 m^3/day: 1 – previously designed water intake wells; 2 – barrier wells; 3 - operating groundwater intake in Mykolaiv; 4 - groundwater salinity above 1.5 g/dm^3; 5 - groundwater salinity below 1.5 g/dm^3; 6 - groundwater drawdown contour (values in m); 7 - hydrographic network.

Fig. 4 - Salinità dell'acquifero e abbassamenti dopo 5.5 anni di operatività del sistema di emungimento alla portata di 7800 m^3/giorno: 1 – pozzi precedentemente progettati; 2 – pozzi barriera; 3 – campo pozzi di Mykolaiv; 4 – salinità dell'acquifero superiore a 1.5 g/dm^3; 5 - salinità dell'acquifero inferiore a 1.5 g/dm^3; 6 – curve di abbassamento del livello piezometrico (valori in m); 7 - reticolo idrografico.

Forecast of forced operation of existing water intakes (Mykolaiv, Zhovtneve , Balabanivka)

Scenarios were also modelled for forced water supply to the city lasting at least one week by operating the Balabanivka-Sviatotroitske intake site (Fig. 6a), as well as by operating the Mykolaiv, Zhovtneve , Balabanivka and previously designed water intakes with distribution of water flow rate among them in the ratio of 1.5:4:2.2:2.2, respectively, according to the previously achieved maximum flow rates and proven operational reserves (Fig. 6b).

As it can be seen from the graphs above, the maximum possible one-week water supply to the city's inhabitants under conditions of concentrated groundwater extraction at the Balabanivka-Sviatotroitske intake is 45 thousand m^3/day (0.090 m^3/day per 1 inhabitant). The same amount of

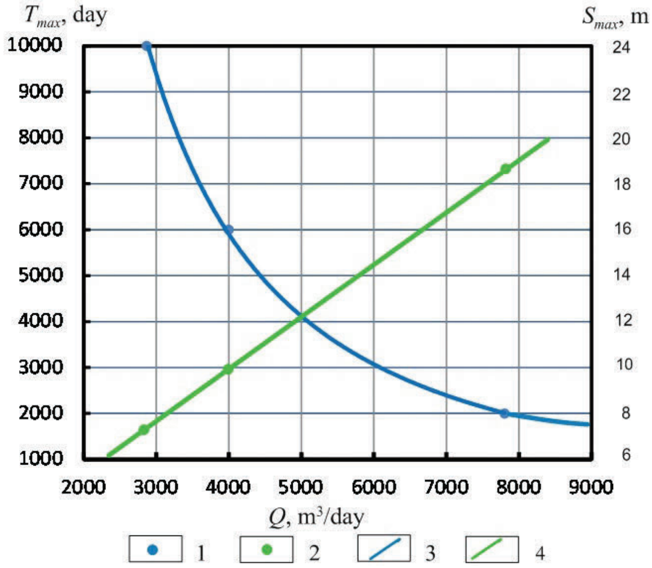

Fig. 5 - Dependence of the maximum operational life (T_{max}) and of the maximum drawdown (S_{max}) in the operational wells on the total flow rate (Q) for the reserve water intake: 1 - T_{max} value according to modelling data, day; 2 - S_{max} value according to modelling data, m; 3 - the graph $T_{max} = f(Q)$; 4 - the graph $S_{max} = f(Q)$.

Fig. 5 - Correlazione tra il massimo tempo di operatività (T_{max}) e l'abbassamento massimo (S_{max}) rispetto alla portata di emungimento totale (Q): 1 – valore di T_{max} in base ai dati modellati, in giorni; 2 – valore di S_{max} in base ai dati modellati, in m; 3 - curva T_{max} = f(Q); 4 - curva S_{max} = f(Q).

water can be supplied to the population for 600 days using operational wells distributed over four sites (point 1 on the graph in Figure 6b). Even 0.220 m^3/day (the Ukrainian standard for a city with centralized hot water supply) can be supplied for almost 2 months (point 2 on the graph in Figure 6b). In this case, the established standard of 1.5 g/dm^3 for salinity is not exceeded.

Forecast of preventive measures to protect groundwater against salinisation

Further, the forecast scenarios for protecting the previously designed water intake from groundwater salinisation were modelled assuming an additional series of operational wells drilled at different spacing between the previously designed water intake and the Bug Estuary. (Fig. 4). The reserve wells within the Balabanivka-Sviatotroitske water intake site were located at a distance of 3750-3850 metres from the Bug Estuary, and the barrier wells were located at a distance of about 1900 metres from the Estuary. Thus, the total groundwater extraction rate of these barrier wells and the previously designed water intake was equal to the approved reserves - 7800 m^3/day, under the condition of not exceeding the permissible drawdown of the groundwater levels (20 m). Specifically, the flow rate for the previously designed water intake was assigned the value equal to the proven balance reserves of 2,866 m^3/day, and the barrier well series was assigned a flow rate equal to the previously explored reserves of 4,934 m^3/day.

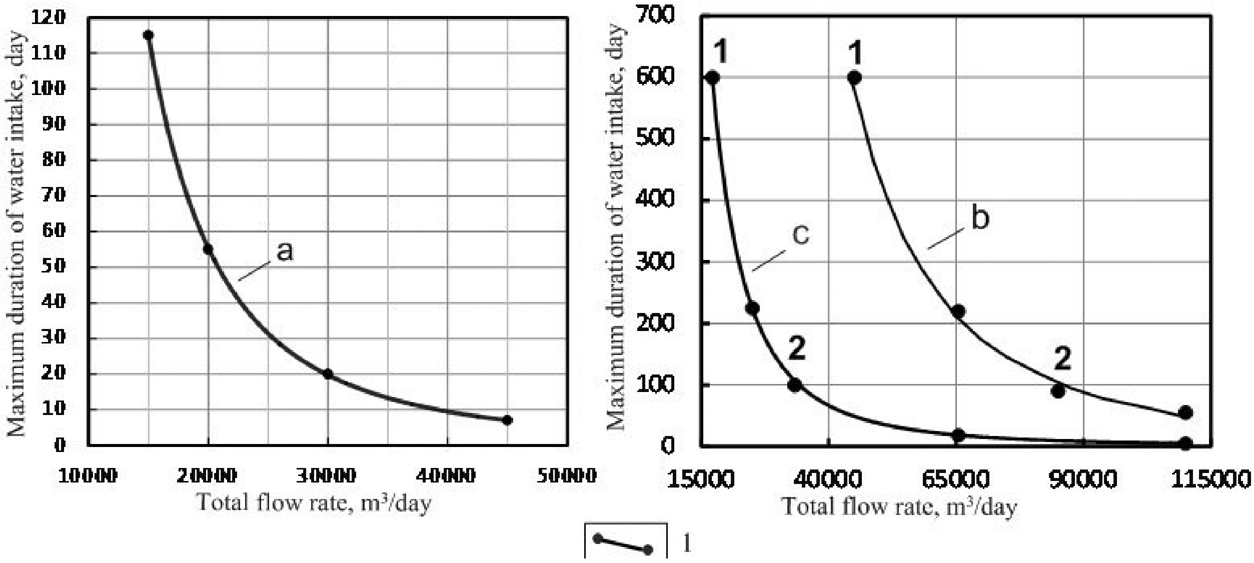

Fig. 6 - Dependence of the water intake operational life (up to the maximum permissible drawdown of 20 m) on the total flow rate for different operation scenarios, namely: operation of the previously designed water intake wells at the Balabanivka-Sviatotroitske site (a), operation of four water intakes in Mykolaiv (b), operation of the previously designed Balabanivka-Sviatotroitske water intake extended to the Ingul River (c). 1 – points of model estimation and interpolation curve.

Fig. 6 - Dipendenza dell'operatività dei pozzi (fino al massimo abbassamento di 20 m) rispetto alla portata di emungimento totale per diversi scenari, ovvero: attivazione dei pozzi precedentemente progettati nel sito di Balabanivka-Sviatotroitske (a), attivazione dei quattro pozzi di Mykolaiv (b), attivazione dei pozzi precedentemente progettati nel sito di Balabanivka.

The operational life of such a water intake was 25 years until the salinity reached 1.5 g/dm^3 in some of the operational wells. This corresponds to the period of operation of a water intake with a flow rate of 2866 m^3/day without barrier wells.

In addition, scenarios were modelled for a gradual increase in the flow rate of the water intake wells and a decrease in the flow rate of the barrier wells, with maintaining the sum of the flow rates at 7800 m^3/day unchanged, namely 3000 m^3/day for the barrier wells and 4800 m^3/day for the water intake wells, or 2000 m^3/day for the barrier wells and 5800 m^3/day for the water intake wells. The modelling results showed that with a relative increase in the flow rate of the water intake, the operational life (before groundwater salination starts in the operational wells) is less than 25 years, meaning that such barrier wells are inefficient to protect the water intake wells.

The scenario of operation of the previously designed Balabanivka-Sviatotroitske water intake was also modelled with a total flow rate which equals to all the approved reserves (7,800 m^3/day), provided that the series of barrier wells is created to operate with a total flow rate of about 5.0 thousand m^3/day. With this scenario, after 400 days of operation, the maximum permissible drawdown (20 m) was achieved in the water intake wells, although the groundwater salinity remained constant. This water intake protection scenario was therefore not quite efficient.

In addition, a modelling scenario was considered where the previously designed water intake structure is moved 2.5 km further inland. Under this scenario (assuming exploration of the new site and approval of its good prospects for groundwater production), with a total water flow rate of 7,800 m^3/day, its operational life is estimated to be 3 years, determined by the time the maximum permissible drawdown is reached. During this period, no increase in water salinity above the permissible values is predicted to occur at this water intake. So, the salinity would be below 1.5 g/dm^3.

Forecast of a hypothetical relocation of the water intake to a greater distance from the Bug Estuary

If the linear series of wells is extended from the Balabanivka-Sviatotroitske site along the Zhovtneve reservoir to the Ingul River valley, it would be possible to extract over 17 thousand m^3/day of groundwater for 600 days without exceeding the permissible drawdown of 20 m and salinity of 1.5 g/dm^3 (point 1 on the graph in Figure 6c), as well as 32 thousand m^3/day for 100 days (point 2 on the graph in Figure 6c). It should be noted that the hydrogeological parameters used in the model should be validated by the results of groundwater pumping tests.

Figure 6c illustrates the dependence of the operational life (until the maximum permissible drawdown of 20 m is reached) on the total flow rate for the forecast water intake extended from the Balabanivka-Sviatotroitske site to the Ingul River.

Forecast of local water supply in Mykolaiv during military operations or emergencies of anthropogenic or natural origin

Lessons learnt from military operations show that Ukraine needs to create a tiered water supply system (centralised and local). During military operations, the norm for water supply per person is 5-7 litres per day. One pumping station for local water supply (called a water buvette) can meet the needs of up to 5,000 people. Based on the population of Mykolaiv,

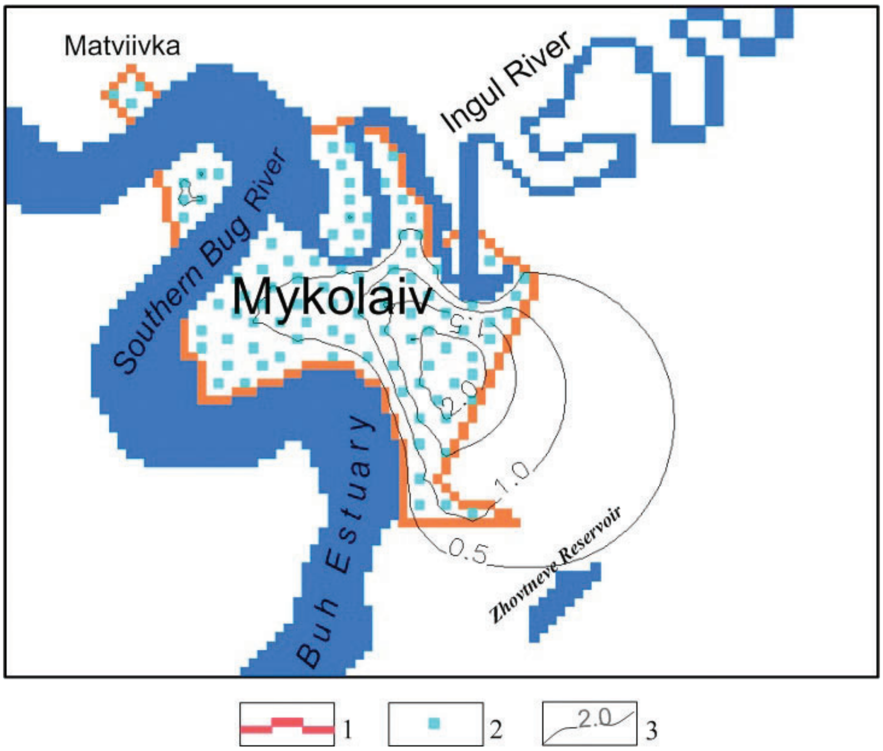

Fig. 7 - Contour map of the modelled groundwater drawdowns in the Upper Sarmatian aquifer under the influence of water extraction from the local water intake wells (pumping stations) in the city of Mykolaiv: 1 - Mykolaiv city boundary; 2 - pumping station (water buvette) planned; 3 - drawdown contour, m.

Fig. 7 - Curve di abbassamento modellate per l'acquifero Upper Sarmatian sotto l'influenza dell'emungimento dai pozzi della città di Mykolaiv: 1 – confini urbani di Mykolaiv; 2 – campo pozzi previsto; 3 – curve di abbassamento, in m.

95 such local pumping stations with a total flow rate of 3.3 thousand m^3/day should be built in different parts of the city, which is quite realistic. In the modelling scenario presented below the location of the pumping stations was chosen assuming an even distribution across the city, which is determined by the existing military situation. It should be emphasized that this is only a hypothetical model distribution, while the actual location of the pumping stations should be clarified with the involvement of local authorities and specialists who would implement these management decisions. Figure 7 shows the impact of this water extraction on the drawdown of the Upper Sarmatian aquifer, which was obtained using the previously described model.

It can be seen that the maximum drawdown of groundwater levels is 2.0 - 2.5 m, which is quite low with respect to 20 m. However, given the quality composition of groundwater, especially its salinity, special water treatment is definitely required before it can be supplied to consumers. The point is that a local water supply network should be available in all districts of the city. The local water intake wells (pumping stations) near the Bug Estuary already have a salinity of more than 1.5 g/dm^3, so this water needs to be treated (desalinated) before it is consumed.

As mentioned above, the water and hydrogeological conditions of the investigated water intake sites within the Mykolaiv groundwater field do not allow their continuous use for supplying water to Mykolaiv. Thus, the archive material (Kapinos et al., 1977) on the chemical composition of water in various aquifers within the Southern Bug-Dnipro interfluve was analysed. The area was chosen due to its large distance from the Bug Estuary and its location on the same bank of the Southern Bug River, as the city. This location has the potential to facilitate the delivery of water to the city. The analysis revealed that the water of Neogene aquifer has the lowest total salinity in this area, ranging from 0.278 to 6.910 g/dm^3, with an average of 1,270 g/dm^3. As already indicated, the water with least salinity is associated with the Southern Bug River basin.

The wells in Matviivka are the most promising, with a total salinity of 0.3-0.7 g/dm^3 (Fig. 8). The position of the Matviivka village in relation to Mykolaiv city and the Southern Bug River is shown in Figure 1. Matviivka was previously a settlement in Novoodeskyi district and now it belongs to the Central district of Mykolaiv city. This site is also attractive because the wells would be located upstream of the Southern Bug River and water would be extracted from the upper part of the aquifer. Similar measures have been recommended for the system of the Balasore coastal groundwater basin in Orissa, India (Rejani et al., 2008), and are also common for water quality improvement (Hussain et al., 2019; Prusty and Farooq, 2020).

These recommendations are consistent with the results presented in Figure 7. Both wells were taped into the Neogene aquifer and are currently in operation with flow rate of 20 m^3/day. However, this value needs adjustment, which can only be done once military operations have ceased. It is important to note that water salinity increases in the north-eastern direction. Therefore, in the event of drilling and intensive operation of additional wells, hydrogeological modelling is required to estimate the rate and timing of intrusion of highly saline water into water intake wells located along the Southern Bug River.

It should be mentioned that the water from wells in the villages of Troitske, Novoshmydtivka (located approximately

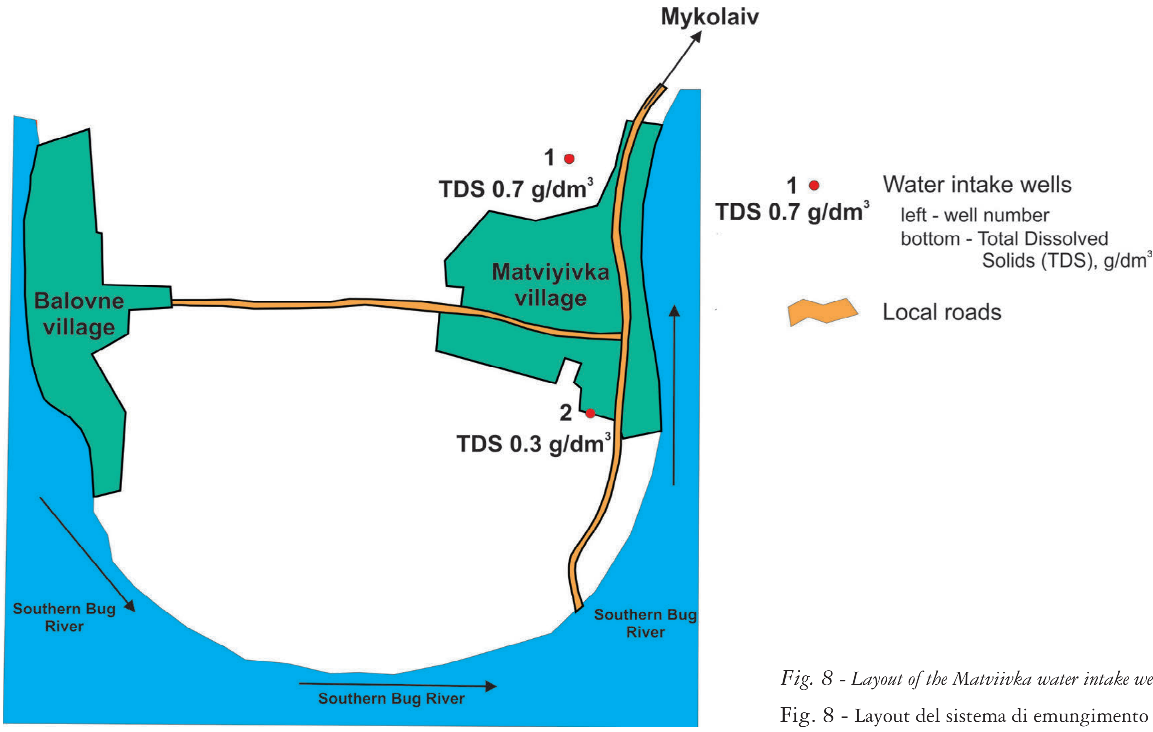

Fig. 8 - Layout of the Matviivka water intake wells.

Fig. 8 - Layout del sistema di emungimento di Matviivka.

45 km from Mykolaiv), as well as Novosilya, Mykolaivka, Lozove (located over 100 km from Mykolaiv), have a salinity below 1 g/dm^3. However, the greater distance from Mykolaiv makes them less attractive for supplying water to the city. These distant settlements could be considered as a potential reserve source of drinking water if more detailed hydrogeological studies show that the Matviivka wells cannot be used for Mykolaiv's water supply due to the possible deterioration of water quality as a result of intensive water extraction.

Conclusions

This study was focused on the use of groundwater for the centralised water supply of Mykolayiv in peacetime, as well as on the creation of a network of local drinking water supply (pumping stations) for conditions of natural and technogenic emergencies or military operations.

In conclusion, the following points can be emphasised:

1. A partial water supply of Mykolaiv from groundwater can be realised in case of prospecting and further exploration of new promising sites located at a distance of 6-7 km or more from the Bug Estuary. According to a preliminary estimate, this could amount to 7000 m^3/day, covering about 7% of Mykolaiv's drinking water needs.
2. The development of the Balabanivka-Sviatotroitske site in the Mykolaiv groundwater field is promising: the operational groundwater reserves of the Upper Sarmatian aquifer have previously been estimated at 7,800 m^3/day. It is worth considering the possibility of extending the linear series of wells from the Balabanivka-Sviatotroitske site to the Ingul River valley and adjusting their distance from the Estuary.
3. It would be necessary to have a tiered system of water supply that is as resilient as possible to any kind of emergency, including war. Such a system should include the following elements:
   - in case of centralised water supply, at least two water sources (one of which should be a groundwater source), a reserve power supply system, and the most protected water intake and water treatment system. If necessary, a water quality improvement system must be included;
   - in case of local drinking water supply, a system of pumping stations (water buvettes) with maximum protection for machinery and people queuing for water, provided by an autonomous reserve power supply for pumps that duplicates the central power supply and, where appropriate, facilities to improve water quality. Wherever possible, pumping stations and bomb shelters should be located close to each other so that water can be supplied from the pumping station to the bomb shelter;
4. Given the risk of increased groundwater salinity during the operation of water intakes, special water treatment should be considered before it is delivered to the consumer.

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Competing interest
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author contributions
V. Shestopalov: Scientific supervision of studies; Yu. Rudenko: analysis and schematisation of geological and hydrogeological conditions, development of the calculation scheme, writing - original draft of the paper, review and editing; I. Koliabina: processing and interpretation of data on water quality and water chemistry, writing - original draft of the paper; B. Stetsenko: hydrogeological modelling; K. Yaroshenko: collection and processing of data on water chemistry. All authors have read and agreed to the final version of the manuscript.

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