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SUBMARINE DISCHARGE OF UNDERGROUND WATERS: RESEARCH EXPERIENCE,EXPLORATION PRACTICES, METHODS AND TECHNOLOGIES FOR POSSIBLE USE

In view of the need to solve problems related to the population's access to sufficient drinking water, the search for submarine discharge zones is currently the most important economic task. Infiltration waters generated within the land, being filtered through bottom sediments, are directed to the seas and oceans and are irretrievably lost for practical use. According to numerous data on the dynamics of underground water supply systems, the movement of underground flows in coastal areas under undisturbed conditions is always directed towards the sea, where discharge is carried out. Infiltration waters flowing from the land to the seabed are predominantly distributed in the shelf zone, but under favorable conditions (tectonic disturbances, paleo-river beds, etc.) their flows can reach the continental slope, so significant areas of the ocean shelf deserve to be explored for fresh and slightly salty, brackish water. In some countries, they are already used to provide water supply.

The article assesses the feasibility of practical use of subaquatic waters using specific examples. It analyzes hydrogeological potential, economic factors, and presents technical concepts for water intake, transportation, and treatment. Based on these factors, we are analyzing the possibility of replacing the seawater

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desalination process with its extraction from submarine underground horizons on the shelf. The article provides a comparative assessment of energy consumption obtained from fossil fuels in the process of seawater desalination and its extraction from underwater horizons. The material presented in the article shows that there are no insurmountable obstacles to the use of submarine discharge waters as an additional source of drinking water.

Keywords: *submarine groundwater discharge (SGD), water intake schemes.*

Introduction

Access to sufficient drinking water is a basic human need that is crucial for social and economic development. Today, many countries are experiencing water shortages, and forecasts predict an aggravation of the situation in the future due to population growth, urbanization, and climate change. Therefore, the use of submarine groundwater discharge (SGD) as an additional source of drinking water is becoming increasingly relevant. For example, according to some authors [9], groundwater runoff into the seas and oceans is comparable to surface river runoff. Given that more than 40 % of the world's population lives or works in the 100-km coastal zone of oceans and seas, the demand for fresh water will become more acute in the next decade, so large areas of the world's ocean shelf deserve increased attention in terms of finding submarine sources of fresh water. The outlets of submarine sources with significant flow rates are known, and their search, exploration and use in economic activities in many regions has already become a reality, although generally accepted methods of industrial extraction of fresh water from submarine discharges of various types have not yet been developed. After all, each type of submarine unloading requires specific technical equipment.

Currently, submarine unloading is divided into the following main types:

- discharge of water from fractured karst carbonate reservoirs;
- subsurface runoff from rivers and river valleys;
- area seep below sea level;
- runoff of water from deep aquifers.

The world has already accumulated some experience in the extraction of fresh water for each type of discharge.

Discharge from fractured karst carbonate reservoirs is the most numerous groups of underwater sources. It is often used in coastal regions to supplement drinking water supplies. This type is widespread mainly in the Mediterranean, on the coast of which there are many underwater springs associated with karstic massifs of Mesozoic limestone, where during the Messinian stage (from 5.9 to 5.3 million years ago) there was a decrease in the level of the Mediterranean Sea, which led to the formation of a network of karst caves that are hundreds of meters below the current level.

Sea water enters the catchment system through the caves, so the karst springs are brackish, which limits their use for water supply. They mostly extend along the northern coast of the Mediterranean Sea, where 40 large springs have been described (Fig. 1) [24].

Numerous attempts to take water from these sources using dams, flexible or rigid catch basins, and water diversions have failed [26]. Usually, the principle was to artificially increase the pressure in order to reduce the boundary between fresh and seawater and reduce salinity (Fig. 2).

In Cassis and Marseille (southeastern France), the Porte Miou and Bestoin springs are the outlets of an important karst aquifer, where a cave system of underwater galleries has been explored since the 1950s. In the 1970s, the first dam was built in Port Miu Cave

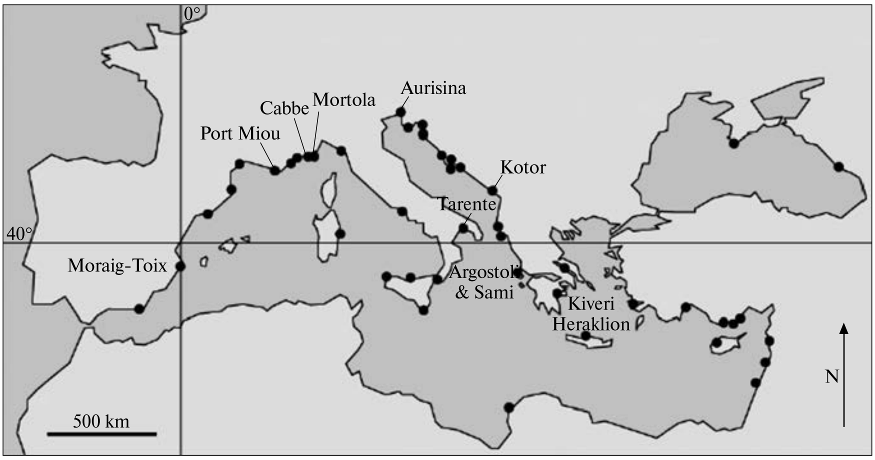

Fig. 1. The main underwater or coastal karst springs in the Mediterranean Sea [24]

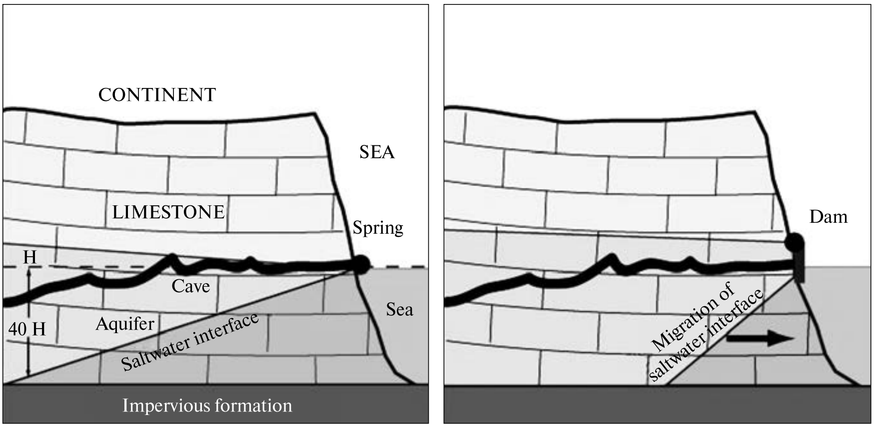

Fig. 2. The principle of increasing water pressure to reduce salinity, E. Gilli (2015)

to prevent saltwater intrusion, but although salinity decreased significantly, it was still too high for use at 179 m below sea level (Fig. 3) [33].

The Cabbe-Massolins underwater springs are confined to karst cave systems stretching in the southeast of France, combining several outlets of brackish water, the total flow rate of which is estimated at 250 l/s, the catchment area is 25 km^2 of the karst system. Structural analysis and study of salinity changes depending on the amount of precipitation measured at different meteorological stations [25] allowed to estimate the catchment area outlined by indicator dyes [23, 30]. Fig. 4 shows a cave selected as an experimental site to study the effect of an artificial increase in pressure on the salinity of the source [27]. Despite attempts to isolate the cracks from which salt water was oozing, it was not possible to significantly increase the head pressure by more than a few cm. Meanwhile, the presence of the dam has reduced salinity compared to what was observed in 1995—1996, when the average salinity value was 20 g/l with a minimum value during floods. After the dam was built, the average salinity was 3.2 g/l.

In 2003, the Nymphaeum experiment was conducted in Mortola (Italy). The spring is located in the open sea at a distance of 800 m from the shore at a depth of 36 m, at the

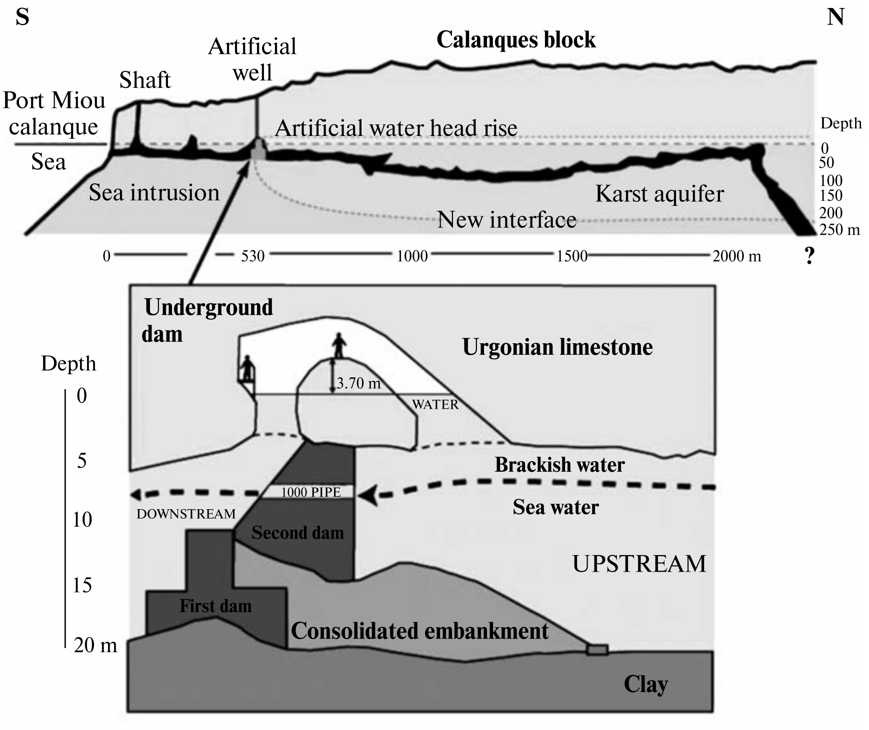

Fig. 3. Port Miu Underground Dam [33]

base of a limestone ledge. Calvino and Stefanon [19, 20], placed the pipe in the main waterway of the gryphon. The pipe worked for several months, but the water remained brackish and unsuitable for water supply. In 2003, the submarine source was covered with a «tulip» system, a plastic dome with a vertical steel pipe. A flexible hose at the top of the dome fed a tank on a raft (see Fig. 4).

This drainage system did not completely isolate the submarine discharge from seawater, which led to an increase in salinity. In addition, replacing the 36-meter-high seawater column above the spring with a lower-density brackish column in the pipe changed the hydrodynamic behavior of the spring. The decrease in seawater pressure above the outlet led to an increase in subsea unloading due to cracks formed near the main source and additional seawater inflow. Depending on the hydrological conditions, such aspiration can cause an increase in salinity of up to 18 g/l [30].

It should be noted that in places where the coastal karst aquifer is not saline, isolation of the source from seawater gives good results (Aurisine — Italy, Kotor — Montenegro, Anavalos-Kyveri — Greece (Breznik M., 1998). However, in most cases, such as Port Miou, Kabbeh, etc., water quality remains below standards, and the catchment area at the outlet of the karst aquifer is not efficient. In such circumstances, desalination plants are more suitable for producing fresh water, as seawater itself is an important potential resource in all coastal areas where the population is experiencing a shortage of drinking water.

Submarine springs flowing from karstic limestone massifs are also well known on the Black Sea coast. In the Caucasus, these are Mesozoic and Paleogene limestones, and in the Crimea, they are most often Upper Jurassic. Submarine springs of this type

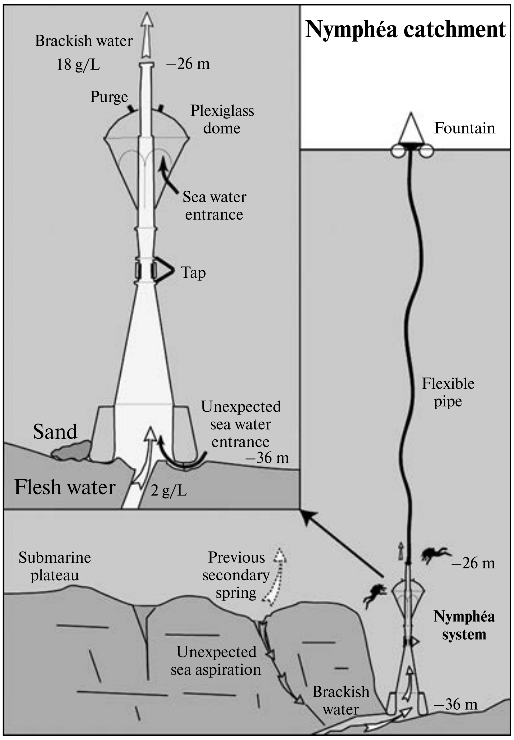

Fig. 4. The catchment system of the Nymphaeus experiment [24]

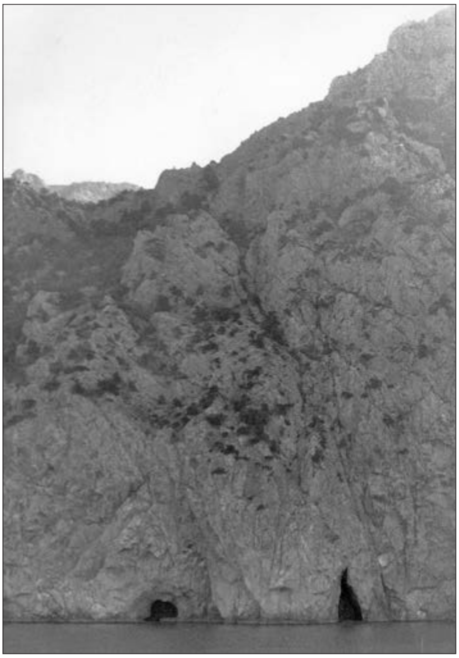

Fig. 5. Cape Aya (photo from the sea)

are well established on the coast from Balaklava to Feodosia. According to V.I. Lyalko and E.F. Shnyukov [7, 14], submarine discharge of water in the amount of up to 700 thousand m^3/day is possible in the area from Balaklava to Simeiz. Several submarine springs have long been known on Cape Aya and in the Batyliman rocks. It is a steep ridge of Jurassic limestone 150—300 m above sea level, sinking to depths of 17—40 m. In the western part of the ridge, there is a series of surface and underwater grottoes that penetrate 20 m or more into the rocks (Fig. 5).

A survey of the mouths of some canyons adjacent to the southern coast of Crimea showed the presence of submarine discharge of fissure-karst or fissure waters in the Balaklava, Kastel and Sudak canyons, which cut through Middle and Upper Jurassic limestone. These materials were obtained during the 37th voyage of the Akademik Vernadsky vessel [10, 11]. Subsequent expeditions revealed desalination of seawater at the bottom of canyons on the continental slope of Turkey and in the extreme northwest of the Turkish shelf, in a canyon on the Bulgarian shelf, and signs of desalination were also found in the canyons of the northwest Black Sea. Taking into account the fact that the southern regions of Ukraine have limited groundwater resources, and deterioration of their ecological and hydrogeological condition has led to depletion and pollution in some areas, the priority of increasing the resource base due to submarine groundwater is both a matter of the present and of long-term strategic intentions to provide water to coastal communities. The use of subsea sources for water supply is efficient and environmentally friendly. Unfortunately, there are no examples of using these waters for economic needs yet, but some developments are available.

Here are the technical solutions for submarine unloading proposed by the NIPIOKEANMASH Institute with participation of the VMGOR of the National Academy of Sciences of Ukraine for the specific conditions of the Balaklava-Foros test site.

Grotto № 1 on Cape Aya is a semi-submerged cave 41.5 m long, 8.47 m wide at the entrance, 3.6 m wide at the dead end, 8.5 m deep at the entrance, and 1.98 m deep at the dead end.

The largest recorded flow rate is 3800950 m^3/day. According to preliminary estimates, this water can be used for drinking water supply.

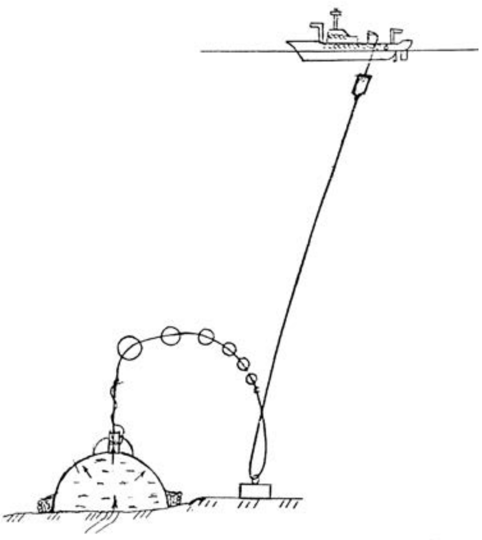

Fig. 6. A set of equipment for the experiment in Grotto № 1 (see numbers in text)

The complex for experimental work on the extraction of water from the grotto (Fig. 6) is designed to test the technology of sampling fresh water from a semi-flooded grotto. The technology involves hermetically closing the grotto opening, pumping out salty seawater, accumulating fresh water and pumping it out for transportation to the consumer. The complex includes a pumping station mounted on the boat, which is located in the grotto only during the experiment, and at other times in the port-shelter.

The boat (3) is equipped with: pump (4), winch (5), diesel generator (6), anchor, rescue equipment. To cover the grotto during the experiment, the boat has a shield (1) with a hollow cuff (2) made of rubberized fabric. To fix the shield in the grotto, spreader bars are installed on it. To isolate the water basin, the shield has a sealing cuff that is filled with water at a level of +1.0...+1.5 m above sea level. The 1015 Pa pressure support ensures a tight fit of the shield cuff to the walls and bottom of the grotto.

The set of equipment for trial industrial operation consists of two main components: a dam (1) and a water supply line (2) (Fig. 7).

The volume of submarine unloading of fresh water from the Balaklava-Foros site is 80—100 thousand m^3/day [14]. The springs are probably located in the bed of the underwater canyon, 15 km away from the coast. The slopes of the canyon are very steep and are composed of limestone. Abnormal salinity values were detected at the Alushta and Yalta sites and Sudak Canyon. The depth of possible springs is 100—350 m.

The proposed set of equipment for the experimental operation of bottom sources (Fig. 8) serves to test the technology of water extraction from previously explored sources. The technology involves lowering a pumping station from a support vessel to the explored source, sealing the well by creating a closed cavity with a pressure lower than the external hydrostatic pressure, and pumping fresh water, which is supplied to the floating buoy and from it to the water carrier. Power is supplied from a supply vessel or water carrier.

Underbed runoff and the runoff of river valleys. Each river carries its channel runoff, or surface water flow. The river usually flows in a bed composed of fairly thick alluvial deposits, mostly sands. In this alluvial bed, an underground underwater stream moves,

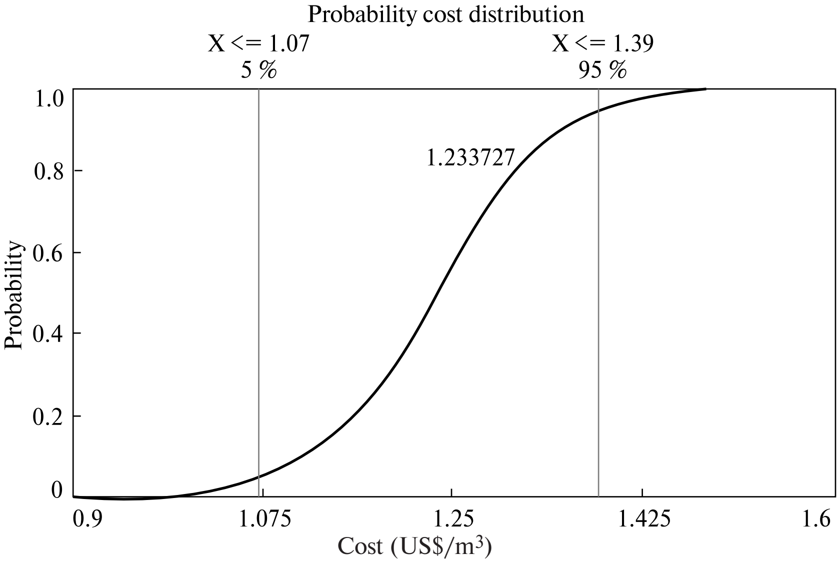

Fig. 7. A set of equipment for the experimental and industrial exploitation of fresh water from the grotto near Cape Aya [11] (see numbers in text)

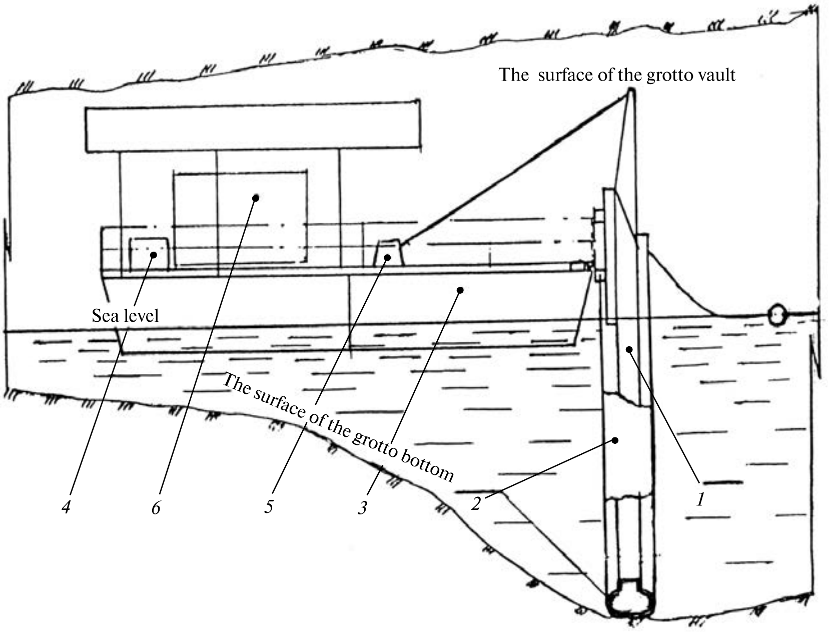

Fig. 8. A set of equipment for conducting an experiment on water extraction from bottom sources

which is the undercurrent. Whereas river flow is normally intercepted and diverted for water supply and other purposes, subcurrent flows further into the sea via paleo-river channels. They often seem to be sealed from above by silt, sometimes quite thick, and waters of the undercurrent reach the seabed surface only in certain places.

Often, river mouths are extended by underwater canyons with numerous submarine springs. This led to the idea of the possible role of canyons as aquifers. Such crevicescanyons were discovered on the continental slope of the Black Sea during marine expeditions [10, 11, 14]. Most likely, rivers and canyons are laid over large disturbances. A survey of the upper reaches of some canyons adjacent to the southern coast of Crimea confirmed this idea and showed the presence of submarine discharge in them [13, 14]. Such underwater canyons are also known in many other aquatic areas. For example, a 70-meter-deep canyon where submarine unloading was discovered stretches from the mouth of the Ganges River to the Bay of Bengal for a distance of 1600 km, and is 700 km wide. Submarine springs with huge flow rate have been discovered in the Amazon Delta. L.I. Lvovich [8] calculated the water balance and estimated the sub-stream runoff at 25—30% of the river runoff, so even its partial use will be a significant addition to the water balance of coastal areas. Therefore, it is important to study paleo valleys in the shelf zones of the World Ocean.

For example, the EU-funded project PALAEAUX (2008) Management of Coastal Aquifers in Europe focused on the study of paleo aquifers (deep groundwater of paleoshelfs) and their current distribution on a continental scale. The importance of such studies lies in the fact that groundwater indicators of the coastal plains and the continental shelf reflect the climatic and environmental conditions of the period of their formation. In certain areas, their potential is estimated to be a source of good quality drinking water that has not been subjected to industrial-era pollution. The results are summarized in the work of W.M. Edmunds [22], which collects data on submarine waters throughout Europe from the Baltic Sea to the Canary Islands.

In Ukraine, some attention has been paid to the study of paleo-oceanic sites on the shelves of the Black and Azov Seas. The 5th voyage of the R/V Kyiv was devoted to this topic, during which the study of different ages of Quaternary palaeodunes on the shelf of the northwestern Black Sea and their undercurrent of fresh water was carried out. Submarine unloading of underwater runoff also takes place in the Sea of Azov, especially in such rivers as Don and Kuban. The semi-depleted small rivers of the Northern Azov Sea have not yet been studied, although undercurrent flow in paleo-rivers is likely here as well. Numerous paleo-riverbeds of Don have been studied by various methods for a long time.

The Paleo-Don flowed in different channels at different points in its Quaternary history, but invariably entered the Black Sea through the Kerch Strait, creating a well-developed channel vantage point. Well 17, drilled in the Sea of Azov, hit one of the Don's fossil beds and passed through tens of meters of alluvial sands [16]. As a result of drilling, fresh water was released from the drill pipes. The well is located 50 km north of the Kerch Peninsula (from Bulganak Bay).

Literature data on the groundwater dynamics of artesian basins opening toward the sea indicate the movement of groundwater flows toward the sea or ocean. Such basins cover the coastline of many water areas. Very often, even in an arid climate, freshwater plants can be seen near the shores, which indicates the area-wide rise of freshwater in certain aquifers. However, the scattered nature of this type of unloading has not found its practical application on the farm.

The flow of water from deep aquifers is most often caused by tectonic disturbances of geological strata on the seabed. The main task is to look for larger migration zones, sources where water can be extracted, rather than area-based groundwater discharge. The outlets of such submarine waters with a huge flow rate are located in the Atlantic Ocean near Florida. Here, many ships are bunkered right in the sea. Such sources are found in Indonesia (Java and Madura), off the Pacific coast of North America, in the Gulf of Carpentaria (Australia), where local fishermen receive fresh water from submarine sources, inserting a bamboo pipe into the griffin, and in the Persian Gulf (Bahraini Islands) rubber hoses with floats are brought to the surface of the water where fresh water is always in excess.

According to the literature, one of the wells drilled offshore Australia at a water depth of 48 m uncovered a chalk aquifer with a good water flow rate at a depth of 1200 m. In the United States, a 9-meter-high freshwater fountain was produced near Florida, 43 km offshore.

In the absence of artesian upwelling and related sources, as in the case of subcreek flow waters, aquifers can be uncovered by drilling.

F.A. Kohout, et al. [29] report the results of a study on Nantucket Island (Massachusetts, USA), where fresh water was discovered during deep drilling on the coast. Based on these findings and geological mapping of the area, the authors argue that fresh water exists far from the island's shore and suggest a generalized hypothesis about the widespread presence of submarine water on continental shelves. This work resulted in an offshore drilling program on the continental shelf off the coast of New England. The results of the research are published in the work of Hathaway J.C., Poag C.W., Valentine P.C., et al. [28], which reports the detection of fresh water in a number of aquifers at a distance of more than 100 km from the coastline, with a gradual increase in salinity to the outskirts of the continental shelf and a maximum salinity at a distance of 130 km. Later, M. Person, et al. [32], on the basis of drilling materials, found very low salinity values in the sandy deposits of the Nantucket shelf, which made it possible to conclude that freshwater lenses are stretching far into the sea.

F. Ruden [35] gives data on the salinity of waters from drilling on land (near the sea in Tanzania) and comes to a similar conclusion that water with low salinity is likely to be found in the channel between the mainland of Tanzania and Zanzibar. Similar studies were conducted by the US Geological Survey east of Jacksonville (Florida) [21]. The measured pressure, low salinity, and the depth at which water was found made it possible to discover larger aquifers than those anticipated when studying deep onshore wells. According to F.T. Manheim [31], fresh and brackish water off the coast of Florida is found 120 km from the coastline.

If the prospects for discovering sufficiently large volumes of high-quality fresh water are favorable, a technical concept is drawn up and evaluated from an environmental point of view. T.H. Bakken, et al. propose reverse osmosis technologies to be used for groundwater treatment [18]. The proposed treatment solution is based on traditional technology, which can be used to treat water of any quality. The solution to such a problem usually includes the steps listed in the table.

The cost of water purification depends on its salinity, which in turn determines the amount of energy required for purification, but also affects the level of greenhouse gas emissions if fossil fuels are used. The cost of treated water is affected by intermediate stages. So, in the absence of a stage of filtration through sand, the cost price is reduced by 0,15 $ per 1 m^3 of water. If the source water does not require desalination, i.e., has a salinity that meets drinking water standards (<0,5%), so the treatment costs are significantly reduced.

The above shows that submarine groundwater can be a realistic alternative to freshwater supply. On the basis of the proposed technical concept, the costs of investment and production of groundwater in USD were estimated per 1 m^3, the components of which are

- 56 days of drilling on a barge with a modular drilling rig;
- two subsea units for two subsea water intake wells with a total of 40.5 m^3 of water per day (45 m^3, 90 % utilization rate); it also includes the costs associated with logistics, drilling, power supply, as well as barge and mooring services;
- the offshore pipeline from the well to the treatment plant was modeled from 1 to 15 km;
- the cost of treatment facilities varies depending on the salinity level of submarine water and the required number of associated treatment stages (see Table).

For a correct assessment of investment costs for the extraction of submarine groundwater, it is necessary to compare them with the cost of seawater desalination [17, 37]. However, much higher estimates of operating costs were used for the water treatment process [18]. The modeling showed that the use of submarine groundwater would be more economically competitive than seawater desalination. Calculations gave the expected unit cost of 1.23 \$/m^3. Given the uncertainty in the estimates presented, the Monte Carlo simulation gives a 90% probability that the unit costs will be between 1.07 and 1.39 \$/m^3, respectively (Fig. 9). This almost corresponds to the proposed feasibility criterion of 1.141 \$/m^3 [30], as the average cost is 1.462 \$/m^3, obtained from a large database of three desalination plants operated on the basis of reverse osmosis.

It was found that the «subsea component» is only 1/10 of the total unit cost, taking into account both amortized capital costs and operating costs, which means that subsea technologies do not represent serious additional economic costs for investors. It is believed that the dominant cost factor is the salinity (desalination) of subsea groundwater, which affects energy consumption and, consequently, the cost.

To date, generally accepted methods of hydrogeological study and industrial extraction of submarine freshwater have not yet been developed.

Many countries are developing modern technical methods of extracting «water under water». A patent was granted in Japan for an original method of extracting fresh water from a submarine source. The authors of the patent propose to control and separate fresh and seawater directly at the bottom of the sea. A fully automated installation with sensors that continuously measure the salt composition of the water is installed above the source. If the salinity exceeds the permissible value, the water supply to the consumer is automatically stopped and the water is discharged into the sea until its quality is normalized.

Italian experts have proposed using a special bell to collect water from submarine springs, which is installed on the seabed, covering the source. The bell is equipped with

Stages of underwater groundwater treatment [18]

Purification technology	Type of pollution
Filtration through the sand	Mechanical impurities
Reverse osmosis	Chlorides and other dissolved salts, metals and radionuclides
Aeration	Removal of volatile substances (H_2S and CH_4), increase of dissolved oxygen
Remineralization	Balancing the desired trace elements and metals
Chlorination or UV treatment + chlorination	Removal of microorganisms

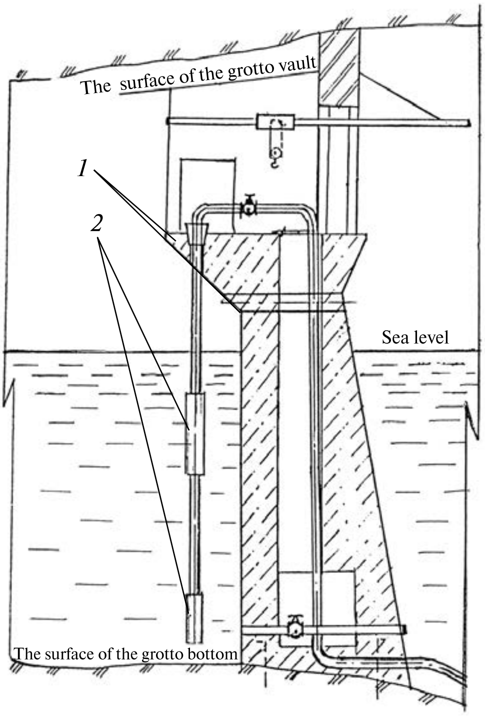

Fig. 9. Probability distribution curve (accumulated percentages — data sample) expressed in terms of specific costs of produced drinking water. The curve is built on the basis of thousands of simulations (Monte Carlo simulation) [18]

special safety valves that control water flow and quality composition. In the absence of natural outlets of fresh water, aquifers can be opened by drilling.

Given that more than 40% of the world's population is located within 100 km of the coastal zone, the demand for fresh water will become more acute in the coming decades, so it is necessary to more widely use traditional and new (subaqueous) sources for water supply.

The southern regions of Ukraine have limited groundwater resources. The deterioration of the ecological and hydrogeological situation in the southern part of Ukraine is also facilitated by the violation of the groundwater exploitation and protection regime, which has led to its depletion and pollution in some areas of the territory. That is why increasing the resource base through submarine groundwater is both a matter of the present and of long-term strategic intentions to provide water to coastal communities in the southern regions of Ukraine that have a low level of water supply.

At the same time, karst and fractured karst waters are found in areas of carbonate rock development, mainly in the Mountainous Crimea. For flat coastal regions, the northwestern shelf with a developed system of paleo valleys of rivers, including such large ones as Dnipro, Dniester, and Danube, has the greatest potential. Submarine unloading of underwater runoff also occurs in the Sea of Azov, especially in the paleodelta of rivers such as Don and Kuban. While drilling from the R/V Geokhimik in the Sea of Azov north of the Kerch Strait, one of the wells discovered fresh water from alluvial deposits of the Paleo-Don. Unloading due to the area elevations below sea level requires a detailed study to identify underwater aquifers.

Sub-channel runoff waters are very often blocked from above by silt, sometimes quite thick, and can appear directly on the seabed surface only in certain places. According to L.I. Lvovich [8], subcreek runoff is 25—30 % of the river runoff. So, if we take the runoff of large rivers of the north-west of the Black Sea at 70 km^3/year (without the Danube), and the Crimea — at 3 km^3/year, the volume of underwater runoff will be approximately 17—18 km^3/year. Even its partial development will be an important addition to the water balance of southern Ukraine.

As noted above, one of the most important tasks in the development of marine hydrogeology in the context of studying groundwater flow to the sea is the development of new methods for finding submarine groundwater outlets. At the same time, as our research shows, each type of submarine unloading requires the use of specific research methods. It should be noted that the scientists of the Department of Earth Sciences of the National Academy of Sciences of Ukraine have accumulated considerable experience in developing certain research methods.

A group of researchers of the Institute of Geological Sciences of the NAS of Ukraine (IGS) V.I. Lyalko, et al. (1977) noticed that the unloading of submarine sources due to the temperature difference between sea and groundwater causes the formation of a temperature anomaly that can be used to determine the intensity of underground unloading in the location of study. These ideas were used in geothermal studies of the coastal zone of the Black Sea near the town of Foros in the south-west of Crimea. The study of the seabed temperature field made it possible to determine the location and flow rate of submarine sources. The new methodology greatly facilitates and accelerates hydrogeological exploration of submarine waters in the south [7].

The study of the distribution of uranium, radium, and radon in surface watercourses made it possible to apply the results obtained in marine hydrogeology. It was found that the specific radiochemical composition of groundwater in the Mountainous Crimea makes it possible to identify areas of discharge on the shelf. One of the most informative was ^{222}Rn. In places of concentration of submarine unloading, an inverse relationship between the salinity value and the concentration of ^{222}Rn in seawater was clearly observed.

The radiogenic isotope method can be used both to find open submarine outlets and to find places where fresh groundwater enters the marine environment through extracting pore water samples from the bottom sediments of the offshore zone.

Field experiments designed to test the technology of fresh water extraction from a semi-submerged grotto near Cape Aya were conducted by Ukrainian scientists from the Institute of Geology of the National Academy of Sciences of Ukraine, MDI and the State Institution «Department of Marine Geology of the National Academy of Sciences of Ukraine». They included measurements of current velocity, salinity, turbidity, temperature, silicic acid and phosphate content by towing hydrological and hydro-optical probes of their own production (at a depth of ~0,1—0,2 m, along the coastline 5 m from the shore), which, according to the authors, allows them to quickly detect traces of submarine discharge [4]. However, the research was concentrated in the area of the already known and well-described karst cavity near Cape Aya with powerful submarine groundwater outlets. In addition, the data obtained as a result of field surveys in the cavity area and towing along the coastline require special processing, including numerical modeling.

The essence of the freshwater extraction technology implemented by the VMGOR staff of the National Academy of Sciences of Ukraine was to seal the grotto opening, pump out salty sea water from it, accumulate freshwater and extract it for transportation to the consumer (see Fig. 7).

The applied methodology may be acceptable to a certain extent for a region where submarine discharge may exist due to underground flow of fracture and karst water. The use of the aforementioned methodology in places of possible seepage through bottom deposits seems questionable.

Conclusions

Notwithstanding the growing interest to the problem of submarine discharge of fresh groundwater in Ukraine and worldwide, the issue of comprehensive study of groundwater flow, including areas of its discharge and quantification, remains open. There are also no established technical concepts for the arrangement of water intakes, transportation of subsea water, and its treatment, as it is obvious from the above examples and our research that each type of subsea unloading requires specific approaches and methods for the use of fresh water. As for the shelf and coastal zone, hydrogeological exploration is a problem all over the world. It is much lower than the exploration of the adjacent land. One of the reasons for this situation is insufficient attention to hydrogeological drilling in offshore areas and methodological support for these works. There are also fundamental differences in the conditions of groundwater formation on land and offshore. Thus, in submarine conditions, there is no aeration zone, fresh groundwater supply area, etc. The direction of groundwater movement in the coastal and marine zone can be reversed.

The peculiarity of hydrogeological research in water areas is that in most cases it is not possible to directly observe geological objects, water manifestations and make measurements that are performed in land conditions. This feature can be fully attributed to the deepwater part of the shelf and partially to the coastal zone. Therefore, the basis of hydrogeological research should be instrumental methods and technologies for studying physical and chemical anomalies formed as a result of groundwater movement through the seabed.

At the same time, the main types of survey work in offshore waters are significantly complicated: route surveys and testing of water points, mapping drilling, routine observations and a number of others. The cost of hydrogeological research increases by orders of magnitude. In this regard, the cost of water produced offshore is also increasing. Nevertheless, despite all the difficulties, offshore groundwater can become an alternative to drinking water supply for the population of coastal areas in case of depletion of onshore resources. No doubt, submarine waters are not the answer to the global water crisis, but they have strategic value in the long run.

In addition to subaqueous waters, submarine sources of karst origin, the most common group of underground sources, may be promising in terms of additional water supply in coastal areas. Their characteristic features are sharp drops in piezometric pressure, which leads to the inflow of seawater into karst channels and an increase in salinity of these sources. The delicate balance between salty seawater and desalinated subsea water is an obstacle to the exploitation of subsea discharge waters.

The examples discussed in this article show that the equilibrium system is shifting toward increased salinity. This problem can be solved by combining technical equipment of the water intake with desalination plants, and thus the required volume of water for drinking water supply can be achieved.

In Ukraine and around the world, due to the significant anthropogenic impact on open water areas, the role of fresh groundwater, including submarine waters, in the total resources in the water balance has increased substantially. Therefore, there is a need for a regional assessment and forecast of existing fresh submarine water resources with estimates of their possible catchment areas, which directly forms the total groundwater resource.

Therefore, taking into account the geological and structural features of each particular region, geomorphological and hydrogeological features of the coastal zone and the adjacent shelf, which determine the nature and conditions of subterranean flow under sea level, as well as the presence of various types of subsea discharge, it is necessary to develop new integrated technologies to search for additional freshwater resources in offshore areas. Use of a part of the groundwater runoff that is discharged into the sea will expand the resource base for water supply to communities in the southern regions of Ukraine. At the same time, basic scientific research and its practical results should become part of Ukraine's contribution to solving the common global international problem of freshwater shortages.

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СУБМАРИННЕ РОЗВАНТАЖЕННЯ ПІДЗЕМНИХ ВОД: ДОСВІД ДОСЛІДЖЕНЬ, ПРАКТИЧНІ ПІДХОДИ, МЕТОДИ ТА ТЕХНОЛОГІЇ МОЖЛИВОГО ВИКОРИСТАННЯ

У зв'язку з необхідністю вирішення проблем забезпечення населення достатньою кількістю питної води пошук зон субмаринного розвантаження на даний момент є найважливішим народногосподарським завданням. Інфільтраційні води, що утворюються в межах суші, фільтруючись через донні відкладення, спрямовані в моря та океани і безповоротно втрачаються для практичного використання. Згідно з численними даними про динаміку систем підземного водопостачання, рух підземних потоків у прибережних районах у непорушених умовах завжди спрямований у бік моря, куди і здійснюється скид. Інфільтраційні води, що стікають із суші на морське дно, поширені переважно в шельфовій зоні, але за сприятливих умов (тектонічні порушення, русла палеорічок тощо) їхні потоки можуть виходити на материковий схил, тому значні площі океанічного шельфу заслуговують на вивчення з метою пошуку прісних і солонуватих вод. У деяких країнах вони вже використовуються для забезпечення водопостачання. У статті на конкретних прикладах оцінено доцільність практичного використання субаквальних вод. Проаналізовано гідрогеологічний потенціал, економічні чинники, надано технічні концепції забору, транспортування та очищення води. Виходячи з цих факторів, аналізуються питання щодо можливості заміни процесу опріснення морської води на видобуток її з підводних підземних горизонтів на шельфі. У статті наведено порівняльну оцінку споживання енергії, отриманої з викопного палива в процесі опріснення морської води та вилучення її з підводних горизонтів. Наведений у статті матеріал показує, що для використання підводних скидних вод як додаткового джерела питного водопостачання немає непереборних перешкод.

***Ключові слова*:** субмаринне розвантаження підземних вод, схеми водозабору.