Interaction of fresh and submarine saline groundwater in the coastal zone of the Sea of Okhotsk and the Sea of Japan

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Abstract. The multidirectional interaction of fresh groundwater of land with a mineralization of 0.1 – 0.2 g/dm³ and submarine saline groundwater in the coastal zone of the western coast of the Sea of Okhotsk and the Sea of Japan has been characterized. The main hydrochemical background in the coastal zone of the seas is created by ultra-fresh and fresh hydrocarbonate groundwater of land in the free gravity runoff zone. The main types of submarine groundwater are silt sediment waters, pore-stratal and fissure-stratal waters of sedimentary rocks, fissure and fissure-vein waters of effusive, metamorphic and intrusive rocks. With the salinity of the modern sea waters within the range of 30–34.4 g/dm³, a decrease is traced from 27–30 g/dm³ in the sediments of the Upper Miocene-Holocene aquifer complex to 14–20 g/dm³ in the sediments of the Oligocene-Lower Miocene complex. Fresh groundwater of volcanogenic hydrogeological basins, the deposits of which have been explored in basalts, are distinguished by special advantages. These waters do not have environmental restrictions for drinking, they belong to the highest class and their resources may well be involved for a worthy use within the region and beyond.

1. Introduction

The main hydrochemical background in the coastal zone of the seas is created by ultra-fresh and fresh hydrocarbonate groundwater of the free gravity runoff zone. For a territory with a natural regime of groundwater, changes in the chemical composition are seasonal with insignificant fluctuations in the concentrations of cations and anions [1–6].

The main area of the seabed is occupied by deposits represented by sedimentary, partly volcanic-sedimentary rocks of the Late Cretaceous-Cenozoic age. The thickness of the sedimentary cover in the depressions reaches 12 km. It is composed mainly of sedimentary, partly volcanic-sedimentary rocks of the Late Cretaceous-Cenozoic age. Among the submarine hydrogeological structures, there are submarine basins of the sedimentary cover (artesian basins), submarine massifs of fissure and fissure-vein waters (hydrogeological massifs), and submarine volcanic basins.

The sedimentary cover of the North Sakhalin submarine artesian basin has been dissected by oil hydrogeologists into five aquifers; the upper three hydrogeological complexes have been studied to some extent. These complexes differ in the structure of reservoirs, filtration characteristics of rocks,
water salinity and hydrodynamic regime. Almost all terrigenous rocks of the sedimentary cover with an increase in the depth in the section of the artesian basin lose their porous capacitive properties. Under the sea waters there are various strata of rocks, which are saturated with groundwater of different phase state and degree of connectivity. The main types of submarine groundwater are silt sediment waters, pore-stratal and fissure-stratal waters of sedimentary rocks, fissure and fissure-vein waters of effusive, metamorphic and intrusive rocks [7, 8]. They are classified as follows:

- sedimentary sea waters accumulating during the formation of sedimentary or sedimentary-volcanic strata;
- fissure-vein waters, which under high pressure penetrate into the subsoil through ruptured faults associated with volcanic or tectonic activity;
- The most developed are the pore waters of bottom sediments and deposits. Subordinate are fissure waters – in the weathering crust of consolidated rocks and fissure-vein waters of large faults.

The neotectonic activity of the region contributes to the formation of faults in the Holocene and Pleistocene and the renewal of faults that were formed at the early stages of the geological development of the territory.

The conditions for the formation of the chemical composition of submarine groundwater are common to all hydrogeological subdivisions of the shelf in the water area of the seas [2, 7, 8, 9]. They are caused by the burial of marine sodium chloride waters in the strata of rocks in the process of sedimentation (sedimentary groundwater).

2. Results and discussion

The mineralization of modern sea waters is in the range of 30–34.4 g/dm$^3$. The Upper Miocene-Holocene aquifer (N$_2$-Q) is distinguished by a zone of development of waters of marine origin with a mineralization of 27–30 g/dm$^3$. The ionic composition of these waters is sodium chloride.

The sediments of the Lower-Middle Miocene aquifer (N$_1^{1-2}$) are characterized by a zone of saline waters with a mineralization of 20–27 g/dm$^3$. The composition of the waters is predominantly sodium chloride.

In the sediments of the Oligocene-Lower Miocene aquifer (P$_3$-N$_1^{1}$) with hydrodynamic conditions of very hindered water exchange, a further decrease in mineralization to 14 g/dm$^3$ is observed with the spread of a hydrochemical zone of slightly saline waters (14–20 g/dm$^3$). In the composition of these waters, a decrease in the concentration of chlorides (up to 7 g/dm$^3$) and sulfates (up to 5–10 mg/dm$^3$) and an increase in the content of hydrocarbons (up to 2–3 g/dm$^3$) are observed.

On the shelf of the northern part of the Sea of Okhotsk, there are numerous local areas of desalination of sea waters, accompanied by an increase in the concentration of biophilic elements [2]. For the most part, desalinated bottom waters contain an excess of $P_{tot}$, $N_{tot}$, Si. Desalination of the bottom water layer is a direct indicator of the modern discharge of fresh groundwater of land onto the shelf [2].

At the bottom of the Sea of Okhotsk, local methane outcrops were recorded represented by two types: with the formation of “torches” – hydroacoustic anomalies reflecting the flows of gas bubbles, and without that [9]. Most of the torches are located within the North Sakhalin and Deryuginsky troughs.

Recycling hydrogeological systems have been identified in many points of rift valleys in hydrogeological massifs and volcanogenic basins, where sea waters interact with hot volcanic (lava) chambers along fault zones under high pressure, resulting in the formation of thermal groundwater outlets and ore structures enriched with sulfides of iron, zinc or lead (“black smokers”) or compounds of silicon and barium (“white smokers”) [7].

Fresh groundwater of the coastal sea zone serves as the main source of resources for drinking and technical water supply to settlements on the coast of the Sea of Okhotsk and the Sea of Japan [10, 11, 12].

The structure of actual volcanogens involves the Middle and Lower Jurassic, Cretaceous, Paleogene, Neogene and Neopleistocene effusive formations of various compositions.

Research carried out by N.V. Boldovsky [1] identified 37 subdivisions among aquifers, complexes and fracture zones, of which 16 were among volcanogenic formations. In this territory, effusive and
volcanogenic-sedimentary formations of predominantly Cenozoic age are developed, in which the outpouring of basalts predominates [1, 4, 5, 8, 10]. The structural features of volcanic structures determine the very complex nature of the distribution of aquiferous and impervious zones and horizons in them.

The diverse hypsometric position, the variegated mosaic distribution of aquiferous and impervious zones and horizons over the area and depth determine the complex placement of reservoirs, the directions and velocities of groundwater movement in volcanic structures, determine the peculiarities of the formation of groundwater resources and the complex interaction of fresh groundwater and saline waters near the coast.

The depth of circulation of fresh fissure-vein waters along tectonic faults reaches 2-3 km, which is confirmed by the presence of sources of thermal waters within the region [12].

The most studied hydrogeologically is the East Sikhote-Alin volcanogen and especially the Cenozoic basalt covers, the groundwater of which is supplied to the cities of Sovetskaya Gavan and Nikolayevsk-on-Amur, settlements Vanino, De-Kastri and other localities.

Fresh groundwater is discharged in the form of springs with a flow rate of often several hundred liters per second. At low tides, on the draining coast, among the pebble deposits, there are numerous outflows of fresh water with flow rates of 0.1–0.2 l/s [1, 5]. Subaqueous discharge of fresh groundwater on the seabed was studied at depths from 1 to 12 m in the coastal zone from the coast at a distance of up to 1000 m from the coast in the Tabo-Chikhachev bay of the Tatar Strait along the coastline with a length of 32 km. In the Tabo bay, such discharge at the bottom was recorded in the form of gas plumes, up to 1 cm in height [1, 5, 6].

In the area of De-Kastri settlement groundwater of the Eocene-Miocene aquiferous volcanic complex are fresh hydrocarbonate ones with a mixed cationic composition and only near the coastline of the Tatar Strait bays during the operation of wells there are more mineralized waters of chloride-hydrocarbonate or chloride composition [3, 5, 12]. Mineralization of water varies from 0.074 to 0.109 g/dm³. The total hardness of water (carbonate) varies from 0.8 mg-eq/dm³ to 1.0 mg-eq/dm³. The reaction of the medium in groundwater varies from slightly acidic to slightly alkaline with an average pH value of 6.4–7.3. In general, groundwater meets the standards for drinking, has favorable organoleptic properties, is epidemiologically safe and is suitable for water supply.

The complex hydrogeochemical conditions of the water intake area of the De-Kastri CHPP are caused by the proximity to the sea coast of the Somon bay [3, 4, 6].

At low tides on the draining coast, among the pebble deposits, there are numerous outflows of fresh water with flow rates of 0.1–0.2 l/s. The value of subaqueous discharge of fresh groundwater into the water area of the bay or through beach pebbles, according to N.V. Boldovsky [1] reaches 10 l/s, the flow modulus from the area of river basins is 2.88 l/s*km², and the linear underground runoff of the coastal zone is 4.2 l/s*km.

At the site of the De-Kastri oil terminal, fresh groundwater is discharged subaqueously, as well as in the form of springs and seeps in coastal ledges along the Chikhachev bay and the Severnaya bay; partly to the local hydrographic network – a small nameless stream near the northern end of the site. The total salinity of fresh groundwater in observation wells 1, 2, 3, 4, 5, 6, 7 was not much more than 0.1 g/l; and in wells 8 and 9 – 0.2–0.3 g/l.

The subaqueous discharge of fresh groundwater in the Tabo-Chikhachev bay of the Tatar Strait was mapped by N.V. Boldovsky and K.P. Karavanov [1] at depths from 1 to 12 m in the coastal zone from the coast at up to 1,000 m along the coastline over a distance of 32 km. In the Tabo bay, such discharge at the bottom was recorded in the form of gas plumes of up to 1 cm in height. The mineralization of sea waters in the Tabo bay is 26.1–29.6 g/dm³, while the mineralization in the Tatar Strait is 31–33 g/dm³.
Several aquifers are widespread within the Soviet-Gavan volcanic hydrogeological basin, among which the most important are the complexes of Pliocene-Lower Neopleistocene basalts and andesite-basalts and Miocene basalts [4, 5, 8]. Basalt cover up to 500 m thick consists of a number of lava flows, each 10–20 m thick. Usually the upper part of the lava flow is large-porous (cavernous) and fractured, the middle part is characterized by lower porosity and low fracturing, the lower part is dense lava varieties. The aquifers are porous and highly fractured basalt varieties, which contain the main groundwater resources.

In river valleys, the depth to groundwater is from 1–5 to 20 m, in flat watersheds and elevations groundwater occur at a depth of 30–40 to 60 m. The waters are usually pressurized, there are some gushing wells. Their flow rate reaches 75 l/sec with a decrease in the level by 2.4 m (the valley of the Bolshaya Egge River).

In terms of chemical composition, underground waters of basalts are hydrocarbonate calcium-magnesium or magnesium-calcium in character with mineralization up to 0.2 g/dm$^3$. In the coastal zone of the sea, underground water mineralization in basalts increases to 0.3–0.5 g/dm$^3$, and the chemical composition of the waters becomes chloride-hydrocarbonate with a mixed cationic composition.

The complex hydrogeochemical conditions of the interaction of underground and sea waters in the areas of some intakes of drinking underground water are caused by the proximity to the sea coast. Cases of salt water intrusion to drinking (fresh) underground water intakes were recorded, as a result of which the operation of the wells was terminated.

At the Bolshaya Egge site of the Sovgavan field, with an increase in water withdrawal from 9.7 thousand m$^3$/day to 10-11 thousand m$^3$/day, the quality of groundwater for the period from 1975 to 1978 began to gradually deteriorate by a growing concentration of chlorides. With fresh groundwater mineralization of about 0.1 g/dm$^3$ in 3 water intake wells, mineralization increased to 0.52–1.43 g/dm$^3$, and the average increased to 0.24 g/dm$^3$. This testifies to the pulling of saline groundwater to the water intake, although a dynamic equilibrium is maintained during the withdrawal of groundwater by levels in the wells during water withdrawal within the approved reserves (9.7 thousand m$^3$/day). The share of attracted saline groundwater does not exceed 1-2 % in the volume of water withdrawal, but they significantly change the quality of drinking water and the process of deterioration of their qualitative composition progresses [11].

3. Conclusion
In the coastal zone of the seas, groundwater of high quality, meeting the standards and regulations and the requirements for drinking without preliminary purification in terms of medical and biological indicators, are of particular importance [3, 6, 12]. It is necessary for the current provision of the public with high-quality bottled drinking water, for water supply in case of an emergency and for export opportunities to designate already known deposits or set the task of identifying and assessing high-quality natural groundwater that does not require special treatment. Fresh groundwater of volcanogenic hydrogeological basins, the deposits of which have been explored in basalts in the areas of Nikolayevsky-on-Amur, Sovgavan, Vanino, De-Kastri and other places, are distinguished by special advantages. These waters do not have environmental restrictions for drinking, they belong to the highest class and their resources may well be involved for a worthy use within the region and beyond.

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