*A New Focus on Groundwater–Seawater Interactions*
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# Regional assessment of groundwater discharge into seas: present-day concepts and methods

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**Abstract** Studies of groundwater discharge into the seas and oceans are part of a complex hydrological–hydrogeological problem of underground water exchange between land and sea. Submarine discharge into seas and oceans is the least studied element of the present and prospective water and salt balance of the seas. Primarily, this is because groundwater inflow is the only water balance component that cannot be measured, and data needed for a well-grounded calculation of a water balance underground component are often missing. Therefore, it is important to determine this directly by hydrogeological methods. These methods permit areas of submarine groundwater discharge to be singled out and quantitatively characterized and, in some cases, make it possible to calculate the value of groundwater discharge causing these anomalies. The results of estimating the groundwater discharge to some seas and major lakes are considered.
**Key words** groundwater discharge; water balance; subsurface water exchange; subaqueous groundwater

The theory of subsurface water exchange between land and sea is closely connected with the general theory on groundwater flow, and began its development as a branch of hydrogeology during the mid-20th century. Concrete investigations of submarine groundwater discharge and, in particular, the intrusion of seawater into coastal areas have been carried out much earlier, for example, during the exploration for groundwater in coastal areas. However, the study of water exchange between land and sea at regional and global scales began relatively recently in conjunction with the need to obtain a reliable assessment of the role of groundwater in the water and salt balances of particular seas, and in global water circulation.

Investigations of the hydrogeological cycle, water balance and water resources of particular regions, sea basins, continents, and the Earth as a whole, have been hampered due to the absence of sufficient quantitative data on the subsurface water exchange between the land and the sea. The problems occurring in recent decades in inland seas and lakes have also brought to the fore the task of direct measurement and quantitative assessment of the role of submarine groundwater discharge in the water and salt balances of these water bodies. The poor knowledge of submarine water and chemical discharge is partly due to the difficulty in measuring these elements of the water balance directly. Until recently they were determined by calculating the discrepancy in the water balance equation. As a result, the final values included all the errors arising from the measurements of the rest of its terms. The prediction of changes in the water, salt and hydrobiological regimes of some water bodies, and the analysis of measures for their maintenance and protection requires a comprehensive study of the water exchange between the land and the sea.

The achievements of marine geology in obtaining geophysical data and unique deep-drilling data have allowed the analysis of this information in terms of the distribution and conditions of occurrence of submarine waters, their features, specific circulation, and verifying the parameters of their interaction with rocks, the sea and groundwaters of the land, as well as their influence upon biota. All this substantiates the need to investigate the role of submarine groundwater, not only in the water balance of the seas and oceans, but also in the geological processes occurring at their floors. In the other words, an independent branch is being formed in general hydrogeology – *marine hydrogeology*. This paper presents the scientific fundamentals of a large section of marine hydrogeology, dealing with the study of subsurface water exchange between land and sea. Special attention is paid to regional assessment and the identification of regularities in submarine groundwater discharge to seas and oceans, because these processes are manifested everywhere and can exert a significant influence upon the water and salt balances of individual water bodies or their parts. The intrusion of seawaters into coastal shores is also an element of subsurface water exchange between land and sea, but it has only a limited character and is activated under the presence of human activity.

The present-day achievements of marine geology and geophysics make it possible to perform hydrogeological zoning of the bottom of the seas and oceans, and to distinguish hydrogeological structures having or not having analogues on the continents. Of special interest in this respect are the most studied structures in the shelf areas of seas and oceans where geo-structural, hydrodynamic and hydrochemical features of water exchange between land and sea are very clearly manifested (Korotkov *et al.*, 1980; Zektser *et al.*, 1984). The factual data on the distribution and the features of groundwater migration at different depths have allowed the quantitative assessment of groundwater flows in the covers of the Earth's crust, and of their role in different geological–hydrogeological processes (Kononov, 1983; Zverev, 1993; Dzhamalov *et al.*, 1999; Shvartsev, 1999).

As mentioned above, a new scientific branch has been formed at the intersection between two allied sciences – *marine hydrogeology*. It has its own subject and objectives, aims and investigations. A system of the basic concepts and terms of this new science and its related definitions are given below. In the future, the proposed conceptual-terminological base will be improved in accordance with development of the science itself. Some concepts were defined using particular terminology used for the study of groundwater flow on the land (Zektser *et al.*, 1984).

The general concepts and terms of marine hydrogeology are as follows:

- *subaqueous* or submarine *groundwater* is the water enclosed in rocks composing the bottoms of large lakes, seas and oceans;
- *submarine groundwater flow* is the groundwater movement in rocks under the bottom of lakes, seas and oceans, occurring as the result of the general water circulation and geodynamic processes in the Earth's crust;
- *submarine ionic or chemical discharge* is the transfer of salts and chemical elements, dissolved in submarine groundwater, to lakes, seas and oceans.

The general term "*submarine groundwater flow*" is defined as the water exchange between rocks, composing the bottom (floor), and the marine basin. *Submarine groundwater discharge* implies an influx (discharge) of groundwater, generated on land, directly to the sea. The reverse process is the *penetration (intrusion) of seawaters* into the shores and aquifers of the land under the influence of different natural and artificial factors. All these processes in combination define the term "*subsurface water exchange between land and sea".*

The quantitative characteristics of the subsurface water exchange between the land and sea can be represented by, besides absolute values, such specific indices as *modulus* and the *linear flow rate* of groundwater discharge to the sea, as well a modulus of submarine groundwater discharge. The *modulus of groundwater discharge to the sea* is understood as losses of groundwater flow to the sea from a drainage area of 1 $km^2$, the discharge from which is directed directly to sea. The *modulus of submarine groundwater discharge* is defined by the characteristics of groundwater flow rate from an area of 1 $km^2$ of aquifer discharge on the sea bottom. The *linear groundwater discharge to the sea* is defined as the losses of groundwater flow per one width unit of its front or the shoreline of the sea. The linear discharge can also characterize seawater intrusion into the shore.

By analogy with groundwater discharge to sea, it is reasonable to introduce specific characteristics for the submarine chemical discharge. The term *chemical discharge* insufficiently reflects the essence of the physical-chemical processes of the transfer of dissolved salts with groundwater, but it is already used in literature and it is unfeasible to replace it. In this case, the amount of dissolved salts or particular chemical elements (compounds) transferred with groundwater directly to sea from 1 $km^2$ of drainage area, will be termed as a *modulus*, and the amount from a width unit of groundwater flow front or from 1 km of the shoreline will be defined as *linear losses of submarine chemical discharge.*

Groundwater is discharged to lakes, seas and oceans in the form of:

- juvenile waters during the degassing of the Earth's mantle;
- sedimentation waters at the expense of their expulsion during lithogenesis of marine sediments;
- subsurface component of the total river discharge (river low water runoff);
- direct groundwater discharge to seas not involving the river network.

The juvenile water discharge represents a "subsurface" component of the water balance of seas and oceans. The quantitative assessment of the volume of juvenile waters discharged to the seas is presently rather difficult. As reported by Timofeev *et al*. (1988), the amount of juvenile waters at the present-day phase of the Earth's evolution usually does not exceed 5% of the total hydrothermal discharge from volcanic areas. The isotopic composition of inert gases indicates that major volatile substances, including hydrogen, were degassed at the initial phase of the Earth's evolution (Verkhovsky *et al*., 1985). However, the complete degassing of the mantle has not yet happened and the current emission of the mantle hydrogen and methane through rift zones confirms this (Kononov, 1983). In the current geological epoch the juvenile gas- and water-containing fluids are associated with rift zones; the mid-oceanic ridges play a leading role. According to Vinogradov (1967), the annual amount of juvenile water, contributed from volcanoes, hot springs and deep-seated faults, does not exceed 0.5–1.0 $km^3$ (an extremely small value for the current balance of the World's Oceans).

The methodical procedure of calculating groundwater discharge drained from rivers, which in the water balance equations is included in total river runoff, is presently well worked out. It should be taken into account that approximately one third of the water discharge from rivers flowing into the seas is generated at the expense of groundwater drained from the zone of intensive water exchange.

The waters in the underground part of the hydrosphere can be subdivided into: (1) *groundwater of the land* that has an unsaturated zone in the upper part of the hydrogeological cross-section and is linked with the atmosphere, and (2) *subaqueous groundwater* under the bottom of large lakes and seas and hydraulically linked with the waters of these water bodies. The most widely distributed type of underground water is subaqueous water, i.e. submarine waters occurring under the bottom of seas and oceans, the hydrodynamics and hydrochemistry of which are largely determined by their interconnection with seawaters. The submarine waters are subdivided into *infiltration waters* that are generated on land at the expense of precipitation and surface runoff, *sedimentation waters* that are formed directly within the marine area due to accumulation of sediments and their subsequent diagenesis and katagenesis, and *juvenile waters* that are connected with the degassing of the mantle.

The infiltration waters discharging from the land are mainly distributed in the shelf zone. Their current filtration recharge per unit time is much higher than the amount of recharge from sedimentation waters during sedimentary processes. Therefore, when conditions are favourable, the tongues of the confined filtration waters can intrude far into the sea area, reaching the continental slope and displacing the sedimentation waters. The results from drilling of the sea bottom have provided vivid evidence of the intrusion of fresh or low-mineralized groundwater formed on land (initial reports of the Deep Sea Drilling Project). The constant interaction between infiltration water, sedimentation water, and directly with seawater leads to the gradual equalization of the chemical composition and mineralization of submarine groundwater of different origin, owing to the convective–diffusive processes and physical-chemical reactions. It is possible that at certain depths a transient zone exists, the spatial characteristics of which are, to a great degree, determined by hydrodynamic and physical-chemical gradients of the counter-moving submarine groundwater, and, depending on the geofiltrative properties of the water-bearing rocks, the groundwater of different genesis may have a by-layer occurrence.

The specific features of the interaction between unconfined filtration water flow and seawaters are considered below. Theoretically, if the filtration properties are homogenous, the shallow groundwater would be entirely discharged in the area of the sea and groundwater line (coastal zone). When a sufficiently thick shallow aquifer has a close hydraulic linkage with seawater, usually in the coastal zone, a counter seawater flow is formed, which restricts the shallow groundwater current and causes it to wedge out and, hence, the discharge has a greater velocity. The velocity of the discharging shallow groundwater in this zone can be several times greater than the average velocity of the filtration flow above the shoreline or the tidal zone. Such occurrences are true only for ideal homogenous aquifers. In nature, the shallow aquifers are usually heterogeneous, whether for lithological composition and/or for filtration qualities. Closer to the shoreline, the filtration properties of such sedimentary confined/unconfined aquifers are, as a rule, decreased due to the presence of clayey materials and increased water pressure head. The entire submarine discharge of infiltration flow occurs not only in the narrow coastal or tidal zone, but also at a distance of several kilometres offshore. At the same time, the results of the direct measurements show that a considerable part of the total shallow groundwater filtration flow is discharged in the coastal zone with a width of several hundreds of metres.

The shallow groundwater of the land, like confined groundwater, transforms its composition and mineralization during submarine discharge because of mixing and physical-chemical reactions with seawaters. However, due to the agricultural and industrial development of many coastal areas, the composition of natural (including shallow groundwater) waters is subject to significant changes. The nitrate concentrations in shallow groundwater during submarine discharge in some coastal areas of the USA, Australia, islands of Jamaica and Guam vary from 20–80 mg/L to 120–380 mg/L. Such high concentrations of biogenic elements in the submarine waters cause the anomalous growth of biomass in the seawater, the appearance of specific species of microorganisms and algae, which, in turn, can serve as indicators of submarine discharge of groundwater of a certain composition. In the other words, the intensive human activity in the coastal drainage areas causes direct changes in shallow groundwater composition and exerts a significant influence upon the environmental state of seawaters due to the transfer of biogenes, pesticides, heavy metals and other toxic substances.

Submarine discharge of confined groundwater takes place through submarine springs usually associated with tectonic disturbances and the areas with developing fissured and karst rocks, as well as through seepage via low-permeability covers of aquifers and sea-bottom sediments.

It is important to analyse the principal possibility of a hydrodynamic interconnection between hydrogeological structures of the land and adjacent parts of oceans. It is acknowledged that the shelf and continental slope are parts of the land, which do not continue on the ocean bottom. A continental slope usually represents a tectonic flexure, within which the thickness of sedimentary rocks sharply reduces until the full wedging out and disappearance of some beds (Lisitsyn, 1978). In other words, the hydrogeological structures of continents and oceanic depressions are dissociated tectonically, and the boundary between them runs along the continental slope. In this case, the submarine infiltrating waters, formed on the land, are wedged out mainly within the shelf and continental slope. The submarine groundwater discharge in the shelf and continental slope is considerably favoured by the existing submarine canyons, i.e. deeply entrenched erosional valleys stripping not only Quaternary, but also more ancient rocks.

The interaction between the infiltration and sedimentation waters in the shelf has not been fully studied until now. Some researchers consider that elision processes, i.e. the pressing-out of water from clayey sediments during the compaction and diagenesis of the latter, play a leading role in all the phases of the formation of artesian basins. However, the modelling of the gravitational consolidation of clayey rocks has shown that with real initial parameters the pressure distribution in clayey strata is controlled by the conditions at their upper and lower boundaries (Dyunin, 2000). The determining influence upon the pore pressure distribution is exerted by the permeability of clays and the velocity of their sedimentation. In the actual conditions of the seas and oceans, the sedimentation velocity of clayey rocks seldom exceeds $10^{-3}$ m/year, and their permeability is usually very small and can increase with depth due to the formation of macro- and meso-jointing during lithogenesis. In these cases, according to the data from the model, the pore pressure distribution in the clayey strata actually has a linear character and depends on a ratio of the pressures at the upper and lower boundaries of clays. The hydrostatic pressure of the clayey strata in the upper cross-section of marine sediments increases with depth. The pressure is almost always higher at the base than at the strata roof. Therefore, the submarine sedimentation waters, pressed out during clay consolidation, move predominantly from underneath upward into the source sea basin.

It should be noted that the upper part of the cross-section of the bottom sediments is mainly composed of sedimentary clays with anomalously high moisture and porosity (to 80%) and a low density (1.2–1.3 g/cm$^3$). The resultant changes in their physical properties with depth are chiefly caused by compressive (gravitational) consolidation. The most intensive reduction of the porosity and moisture of clayey rocks take place within the first tens and hundreds of metres and gradually the effect diminishes with greater depth. Thus, within the first 100 m of depth, the clays lose more pore water than within the next 100 m, and at a depth of 300–500 m, the loss amounts to 70–80% of the initial moisture volume. Below that, the clay consolidation rates progressively slow down. Thus, a decrease in the porosity and moisture of clays with depth occurs in relation to an exponential dependence on the rate at which the major pore sedimentation waters are pressed out during the initial steps of sediment consolidation and then discharged to the source basin. In general, the compression regime of rock consolidation depends on the lithological composition, and on the ratio of pressure and temperature, which determines the physical-chemical and mineralogical processes of diagenesis and lithification of the sediment (Dzhamalov *et al*., 1999).

The vertical filtration of sedimentation waters provides their constant linkage with seawaters in this case. The water exchange between compacting sediments and the sea basin is accompanied by salt exchange. The invariable composition of the seawaters during the recent geological epochs and salt exchange between the sedimentation and seawaters may cause the mineralization and salt composition of these waters to be similar. This is confirmed by the drilling experiences from the ship "Glomar-Challenger", when the boreholes, drilled into the ocean bottom are stripped at depths to several hundreds of metres from the bottom surface, the waters have a total salt concentration and a content of basic components almost similar to those in the modern seawater (initial reports of the Deep Sea Drilling Project).

One specific feature of submarine sedimentation waters is the invariability of their chemical composition. In submarine groundwater of the infiltration type one can observe a change in the chemical composition and mineralization, both in area and in section. However, in the submarine waters of the sedimentation type in the upper part of the geological cross-section, the regional hydrochemical zonality is actually absent.

The data from sea-bottom drilling indicates that the similarity of the chemical compositions of submarine and seawaters is most plainly apparent in areas with slow sedimentation rates. In other deeper parts of the oceans, a substantial change is often observed in the concentrations of some chemical elements in the submarine sedimentation waters. Namely, the Ca concentration usually increases, whereas concentrations of Mg and K decrease with depth. According to McDuff & Gieskes (1976), the breakdown of basalts in the deep parts of the oceanic depressions and the breakdown, though to a lesser degree, of dispersed volcanic material and carbonates in the sedimentary rocks are the main reasons for the increase of dissolved Ca and the decrease of Mg in the submarine waters.

Of greatest interest, in the hydrogeochemical respect, are the areas with modern submarine volcanism in the zones of the median oceanic ridges, where the major juvenile submarine waters are probably discharged. The magma in these regions is effused onto the ocean bottom or close to it, causing a powerful heat flux. The young oceanic crust is highly fissured because of the processes of cooling, compaction and extension. The seawater saturates the fissured zone and cools the magmatic body, solidifying it. The hydrothermal solutions of the rift zones are usually enriched with $CO_2$, $^3He$, $H_2$, metals and other components. The temperature of these solutions can approach the magmatic solidification point (980°C), but close to the bottom surface it is usually around 10–30°C. At higher temperatures, the water has low values of density and viscosity, causing active convection and an increased ability to penetrate into rocks, to dissolve and leach water-bearing rocks. The thermal gas- and water-containing fluids, enriched with different chemical elements, serve as the basic source of polymetals. The isotopic compositions of carbon and helium in the hydrothermal solutions often indicate the age of these elements. The fluids of the oceanic rift zones represent a mixture of juvenile and, chiefly, seawater; due to the contact with the magma, the temperature in the latter increases and chemical composition changes.

The conceptual model of the water exchange between land and sea under consideration is based on the analysis of up-to-date information, and makes it possible to formulate the following conclusions that can be used as the methodical basis for creating regional mathematical models of the formation, distribution and migration of submarine groundwater:

- Submarine waters are subdivided into infiltration, sedimentation and juvenile waters. The infiltration waters reside only within shelf areas and are entirely discharged to the continental slope. The sedimentation waters are generated everywhere on the bottom of seas and oceans, but prevail within the floor of the World Ocean. The juvenile waters are mainly found in the zone of mid-oceanic ridges and their role in the current water balance of the World Ocean is not significant.
- The predominant type of submarine groundwater discharge is seepage from below. The constant interaction of sedimentation and seawaters due to the vertical water exchange makes their mineralization and salt composition similar (if there are no additional salt sources).
- According to the conditions of the formation and distribution of different types of submarine waters, the bottom of the oceans is subdivided into shelf, floor and mid-oceanic ridges, which differ from each other by peculiar hydrodynamic and hydrochemical regimes of interaction of submarine waters with groundwater of the land, rocks and seawaters.
- Submarine waters serve as the basic agent and medium of the migration of chemical elements in the Earth’s crust. Due to the higher mineralization of groundwater compared with surface water, the influence of submarine chemical

discharge upon the salt balance of seas (especially of inland ones) can be significant. The migration of chemical elements with submarine waters is most boldly distinguished in the zone of mid-oceanic ridges, where, due to the convection of seawater, the active leaching of young basalts and thermal enrichment by gas- and water-containing fluids with different components, takes place.

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