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ON THE GROUND-WATER DISCHARGE TO THE BALTIC SEA AND METHODS FOR ESTIMATING IT

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The methods for quantitatively estimating ground-water discharge to the Baltic Sea and the possibilities of applying these methods to investigations of the role of ground water in the water and salt balances of the Baltic Sea are discussed. The combined hydrological and hydrogeological method, the hydrodynamic method, and the method of the average long-term water balance of recharge areas are recommended for general quantitative estimation of ground-water discharge to the sea. Data on the ground-water discharge to the Baltic Sea from the zone of intensive circulation (relatively shallow aquifers) within the U.S.S.R. are presented. Certain conclusions are drawn, and objectives of future investigations are mentioned.

The problem of investigation and quantitative estimation of ground-water discharge to the seas has roused interest among hydrologists and hydrogeologists in recent years. At present, scientists all over the world have joined their forces in investigations of the water resources and water balance of continents, large areas and individual countries. Studies of ground-water discharge to the seas as a component of the total water balance and an important indicator of ground-water resources hold a prominent place among these investigations.

The ground-water discharge to the seas, or submarine ground-water discharge, is a poorly studied component of the water balance. The investigation and estimation of submarine ground-water discharge contribute to the solution of such important practical and theoretical problems as (1) the role of ground-water discharge in the total water and salt balances of the seas and in the hydrologic cycle; (2) the interrelationship between sea and ground waters in coastal areas; (3) the investigation and use of ground water discharging below the coastline for water supply; and (4) the effect of ground water on the formation of mineral deposits on the sea floor. In addition to other factors, submarine ground-water discharge often causes local temperature and hydrochemical anomalies in the sea water; therefore it should be taken into consideration in hydrological and particularly in water-balance investigations (Kudelin, Zektzer, Meskheteli & Brusilovsky 1971).

In many papers dealing with the water balance of seas and large lakes, the ground-water discharge is either not estimated at all or it is determined as the residual term of the average long-term water balance. In the latter case, the submarine ground-water discharge value includes all errors of the estimation of the other components of the water balance (precipitation, evaporation, and streamflow). As ground-water outflow to the seas is usually small compared to those of other elements of the water balance, it is important to evaluate it by direct methods that allow one to estimate quantitatively this element of the water balance and understand more profoundly the nature of the lack of balance of the water budget and the accuracy of estimating its separate elements. Hence arises the necessity to determine the ground-water discharge to seas by independent methods and to forecast it in case of changes of the other components of the water balance under the effect of natural factors and man's economic activity.

The above problems apply fully to the Baltic Sea and they are urgent, as a number of countries are carrying out large-scale investigations of the water balance of the Baltic Sea within the IHD programme.

This paper discusses qualitative and quantitative characteristics of the ground-water discharge to the Baltic Sea from the area of the U.S.S.R. and methods used to estimate it in the U.S.S.R. which may be used for the same purpose by other countries.

The ground-water outflow to the Baltic Sea has been studied by many investigators.

Gatalsky (1954) has found that in spite of the bed dipping towards the east and south (in the direction of the Middle Russian syneclise*), ground water flows under hydrostatic head to the west and north in the direction of the Baltic Sea.

Silin-Bekchurin (1958), considering the hydrogeological properties of the Cambrian rocks, states that the Gdov aquifer is drained towards the Gulf of

* A term suggested by Parlov in 1903 for structural features on the continental platform evidenced by distribution on the map rather than by measurable dip.

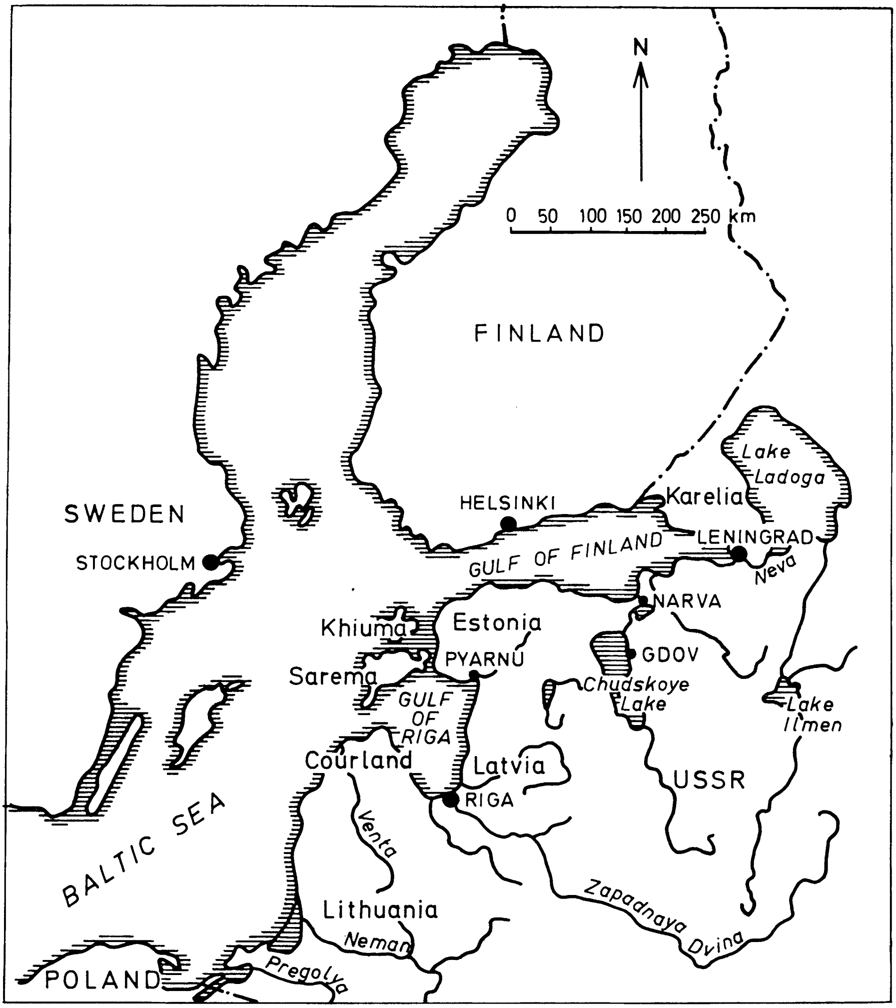

Fig. 1.
Map of the area of U.S.S.R. contributing ground-water flow to the Baltic Sea.

Finland, and around the Gulf of Finland a cone of depression may be drawn, opened in the direction of the Baltic Sea where the water of the Cambrian rocks discharges. The deep Silurian water moves in the U.S.S.R. northern area adjacent to the Baltic Sea in two directions – in the west towards the Gulf of Finland, in the east towards Chudskoye Lake, which is substantiated by the character of the distribution of piezometric levels. Silin-Bekchurin considers that in the lower Middle Cambrian aquifer system, ground water moves from the east, north–east and south towards the Gulf of Riga. Having examined the hydrodynamic conditions in the vicinity of the city of Pyarnu, Silin-Bekchurin concludes that on the Pyarnu Peninsula ground water is drained by the Pyarnu River and the Pyarnu Bay. However, despite the clearly expressed ground-water flow towards the Baltic Sea across the coasts of the bay, the ground-water discharge in the form of springs is absent and therefore groundwater discharges outside the coastal zone of the bays. Silin-Bekchurin suggests that the elevated ridge running in the northwestern direction through the central deep-water part of the Gulf of Riga is one of possible zones of ground-water discharge.

THE METHODS OF ESTIMATING THE GROUND-WATER DISCHARGE TO THE SEA

The ground-water discharge to the sea may be estimated quantitatively by several methods.

The combined hydrological and hydrogeological method

This method is as follows. Within the coastal area of the sea basin, average long-term ground-water discharges, expressed in litres per second per square kilometre, are determined for principal aquifers and aquifer systems. This is performed by separating stream hydrographs for a long-term period, obtained from stream gaging stations. The hydrographs are separated by applying routine procedures. Less detailed estimates may be based on the data on the low-water discharge of streams, draining the main aquifers of the coastal zone. Thus the first stage of ground-water discharge estimation incorporates determination of the average long-term values of ground-water discharge (expressed in $l/sec/km^2$) of the main aquifers and aquifer systems of the zone of intensive circulation (relatively shallow aquifers) occurring within the influence of drainage networks. The second stage starts with an analysis of the general geological and hydrogeological conditions of the area adjacent to the sea, ground-water contour maps of main aquifers, hydrogeological profiles and other data; then the areas from which ground water flows directly to the sea are distinguished and estimated (by a planimeter on maps). The third stage – the ground-water discharges of main aquifers, obtained by hydrograph separation at the first stage, are extended for the coastal areas distinguished (in keeping with the similarity of hydrogeological conditions). Finally, the ground-water outflow to the sea from the zone of intensive circulation is estimated by multiplying the ground-water discharges by corresponding coastal areas from which ground water flows directly to the sea.

This method was applied by Zektzer & Kudelin (1965) in estimating the ground-water discharge to the Baltic Sea from the area of the U.S.S.R. and to Lake Ladoga (Zektzer & Kudelin 1966).

The method has an important advantage – its application permits obtaining average long-term values of ground-water discharge to the sea by treatment of available long-term hydrological data. However, it should be noted that this method can be used only for areas with a well-developed drainage network. Besides, the combined hydrological and hydrogeological method permits determining only the outflow from the zone of intensive circulation that includes largely fresh ground water. Therefore it is advisable to use this method in combination with other methods, such as the hydrodynamic method or the average long-term water balance method.

The hydrodynamic method

This method is based on evaluating the discharges of ground-water flows directed to the sea by using hydrodynamic relationships. The flow discharge may be determined analytically and by mathematic modelling. By analysing the general structural and hydrogeological conditions of the part of the basin adjacent to the sea, the aquifers which discharge directly to the sea are distinguished. Then data on constants (thickness, coefficients of permeability and transmissibility, and the hydraulic gradient) of the main aquifers discharging to the sea are collected. For this purpose, the information on the wells situated in the coastal area is used, and there is no necessity to collect all available data; it is sufficient, using mathematic statistics, to determine the minimal number of wells whose data are needed for estimating the ground-water discharge.

The ground-water discharge is estimated analytically for each aquifer or aquifer system, after which the values obtained are added up.

Modelling may be successfully applied to determining the submarine ground-water discharge if sufficient data on regional conditions of ground-water movement in various aquifers and on the nature of their interrelationship are available. Construction of a model of the hydrologic cycle of the study area including submarine ground-water discharge is of interest.

The hydrodynamic method, as suggested by Dzhamalov (in press), may be used for estimating the discharge of confined ground water to the sea as a result of leakage through the semiconfining top of the aquifer and sea-bottom sediments. Such discharge is possible only in the coastal areas where piezometric levels are higher than the sea-water level. The method is as follows. Using well data, piezometric profiles of the aquifer under investigation are constructed for several stream tubes. These profiles are approximated in computers by curves of a certain type and then extended within the sea basin for maximum approximation to the sea-water level. Thus a zone of confined ground-water discharge of the aquifer under investigation in the coastal area is distinguished, and the leakage value is evaluated in computers using hydrodynamic relationships and data on aquifer constants or by modelling. This method has been effectively applied in estimating the ground-water outflow to the Caspian Sea from the Terek-Kuma artesian basin.

The average long-term water-balance method

This method is used for estimating the ground-water discharge to the sea from deep artesian aquifers having a distinct area of recharge. An average long-term water-balance equation is derived for the area of recharge. The value of deep percolation, i.e. the part of precipitation that recharges artesian water and, therefore, forms the deep ground-water outflow to the sea, is determined from average long-term values of precipitation, evaporation and streamflow. The method is somewhat limited. It is applicable to estimating the discharge of the aquifers which are safely isolated by impermeable layers from overlying and underlying aquifers, i.e. one should be sure that the water of the aquifers under investigation is discharged directly into the sea and that there are no leaks. This method may be effectively applied where the value of deep percolation being estimated exceeds the accuracy of evaluating the other terms of the water-balance equation (precipitation, evaporation, and streamflow).

The average long-term water-balance method and the hydrodynamic method have been used for estimating the ground-water discharge to the Gulf of Riga (Dzilna, Zektzer & Staprens 1968), the Caspian Sea (Zektzer, Ilyinskaya & Solopek 1967, Dzhamalov 1972), and Lake Balkhash (Akhedsafin & Shapiro 1970). Electrohydrodynamic analogy has been applied to estimating the ground-water discharge in separate coastal areas of the Caspian Sea (Askerbeili, Bulatov & Kyazimov 1968) and the Aral Sea (Pashkovsky 1969).

Some other methods

The above methods allow one, by analysis and treatment of available hydrologic and hydrogeologic information and without conducting expensive tests or expeditions, to quantitatively estimate the ground-water discharge to the sea.

Some other methods exist which permit locating areas of submarine ground-water discharge within a sea basin. They are based on detecting and studying anomalies of the sea water or bottom sediments, produced by discharging ground water. Anomalies of the electric conductance, temperature, salt content of sea water and those of the temperature and chemical composition of bottom sediments are observed. The anomalies may be located by electric profiling, infra-red imagery and tracer techniques.

Detection of physical and chemical anomalies of the sea water and bottom sediments allows one to locate the points of discharge of large submarine springs, which are important for studies of formation of mineral matter on the sea floor and also useful in water supply surveys.

All these methods call for labour-consuming expeditionary work. They are effective in locating concentrated points of submarine discharge of ground water and cannot be practically applied to general quantitative estimation of direct ground-water discharge to seas. Therefore these methods are not discussed here.

SOME RESULTS OF ESTIMATING GROUND-WATER DISCHARGE TO THE BALTIC SEA

The direct ground-water discharge to the Baltic Sea from the U.S.S.R. has been estimated by Zektzer & Kudelin (1965), to the Gulf of Riga by Dzilna, Zektzer & Staprens (1965), and Dzilna (1970). At present, these estimates are refined.

Within the area of the U.S.S.R., ground-water discharges to the Baltic Sea from two aquifer systems – the upper one, containing largely the fresh water of the zone of intensive circulation, and the lower one, containing mineralized water. The outflow from the zone of intensive circulation has been evaluated by the combined hydrological and hydrogeological method. The total area of the basin, the ground water of which discharges directly to the sea, has been obtained from an analysis of available hydrogeological data, i.e. ground-water contour maps and profiles which have been constructed for principal aquifers of the upper system. This area, determined by planimetering on maps of different scales, comprises separate coastal areas with different hydrogeological conditions. It includes the western coastal area of the Karelian Isthmus, the northern part of the Predglyntovaya Lowland, the western part of the Silurian-Ordovician plateau, the north–western margin of the Riga seaside plain, the coastal area of the Courland Peninsula, the Sarema (Ösel) and Khiuma (Dagö) Islands, and the western parts of the Borta, Miniya, Neman, and Pregolya

Table 1.
The direct discharge of ground water to the Baltic Sea from the zone of intensive circulation (within the area of the U.S.S.R.)

Area	Area contributing to ground-water discharge to the sea (km^2)	Average long-term ground-water discharge from the zone of intensive circulation (l/sec/km^2)	Direct discharge of ground water to the sea (m^3/sec)
1. The coast between the State border with Finland and the Neva River	1,200	2.1	2.6
2. The coast between the Neva River and Narva River	800	1.0	0.8
3. The coast between the Narva River and Keila River	1,400	1.6	2.2
4. The coast between the Pyarnu River and Keila River (seaside part of Silurian-Ordovician plateau, including islands)	4,900	3.2	15.7
5. The coast between the Pyarnu River and the Zapadnaya Dvina	1,200	2.6	3.3

River basins. The total area contributing to direct ground-water discharge to the Baltic Sea within the U.S.S.R. amounts to about 16,000 km^2.

In the north–western area of the European part of the U.S.S.R., the average long-term ground-water discharges (expressed in l/sec/km^2) have been determined using the combined hydrological and hydrogeological method of hydrograph separation (Zektzer 1968). The values obtained have been extended over areas with similar hydrogeological conditions, the ground water from which

Table 1 (cont.).

Area	Area contributing to ground-water discharge to the sea (km²)	Average long-term ground-water discharge from the zone of intensive circulation (l/sec/km²)	Direct discharge of ground-water to the sea (m³/sec)
6. The coast between the Zapadnaya Dvina and the Venta River	1,700	2.4	4.0
7. The coast between the Venta River and the northern boundary of the Neman basin	2,100	2.3	4.8
8. The western part of the Neman basin	2,000	2.0	4.0
9. The coast between the southern boundary of the Neman basin and the State border with Poland	700	1.6	1.1
Total:	16,000		38.5

discharges directly to the Baltic Sea. The estimates of the direct ground-water outflow to the Baltic Sea from separate areas of the zone of intensive circulation are presented in Table 1.

The total direct fresh ground-water discharge to the Baltic Sea within the area of the U.S.S.R. amounts to about 38.5 m^3/sec, or about 1.2 km^3/year. The largest outflow of the upper aquifers is from the coastal zone of the Silurian-Ordovician plateau and Khiuma (Dagö) and Sarema (Ösel) Islands which have significant fracturing and karstification, and large values of ground-water discharge (in l/sec/km^2).

Various aquifer systems contribute to the ground-water discharge to the Baltic Sea. They are Quaternary, Paleogene, Cretaceous, Upper Permian, Upper and Middle Devonian, Silurian, Ordovician, Cambrian-Ordovician, and Archean-Proterozoic. The methods applied permit estimating the ground-water discharge to the Baltic Sea for principal fresh-water aquifers (Table 2).

As seen from Table 2, the ground-water discharge to the Baltic Sea is primarily from the Quaternary (13.5 m^3/sec) and Ordovician (8.4 m^3/sec) aquifer systems; the Upper Permian and Cambrian-Ordovician aquifer systems yield the smallest amount (0.2 and 0.7 m^3/sec, respectively).

An analysis of the structural and hydrogeological conditions of the northwestern part of the Russian platform shows that the deep ground-water outflow to the Baltic Sea is from the Gdov aquifer, the water of which in the area of Estonia is freshened as a result of rainfall infiltration through "hydrogeological windows" as well as from the Paleozoic and Mesozoic deposits containing mineralized confined water. It may be supposed that the amount of deep-water discharge to the Baltic Sea is small compared with the outflow from the zone of intensive circulation. However, the deep ground-water discharge to the Baltic Sea may be estimated quantitatively only after special investigations.

In recent years, the conditions of the formation of ground-water discharge to the Gulf of Riga from the area of Latvia have been investigated (Dzilna et al. 1965, Dzilna 1970). The ground-water outflow has been evaluated by analytical computations of the ground-water flow rate with the hydrodynamic method using known hydrogeological constants of principal fresh-water aquifers. The ground-water discharge to the Gulf of Riga has been established to originate largely in the Quaternary and Shventoysko-Starooskolysky aquifers. On the eastern coast of the Gulf of Riga the Pyarnu aquifer, and on the southern coast the Amulsko-Saragaevsky aquifer occur. The total ground-water discharge to the Gulf of Riga from the above aquifers amounts to about 300,000 m^3/day, the largest part of the outflow being from the Shventoisko-Starooskolsky aquifer, which has a high permeability and great thickness.

Dzilna (1970) analysed qualitatively the conditions of ground-water discharge on the floor of the Gulf of Riga. There, Devonian deposits containing artesian water are overlain by morainic deposits 10–15 m thick with overlying clay-silt-like sediments. The moraine outcrops at the sea bottom along the eastern coast. Dzilna supposes that the water of the Shventoysko-Starooskolsky aquifer system is discharged as a result of leakage through the bottom moraine within a strip 3–5 km wide. The fresh water of the Pyarnu aquifer, covered by semipermeable Narva sediments, probably discharges within the strip of rocks

Table 2.
The direct ground-water discharge to the Baltic Sea from principal aquifer systems of the zone of intensive circulation (within the area of the U.S.S.R.)

Aquifer system	Area contributing to ground-water discharge to the sea (km^2)	Average ground-water discharge ($l/sec/km^2$)	Direct ground-water discharge to the sea (m^3/sec)
Quaternary	13,500	1.0	13.5
Paleogene	700	0.5	0.4
Cretaceous	2,000	1.2	2.4
Upper Permian	250	0.8	0.2
Upper Devonian	2,100	1.1	2.3
Middle Devonian	2,800	1.2	3.4
Silurian	3,900	1.5	5.8
Ordovician	4,900	1.7	8.4
Cambrian-Ordovician	1,400	0.5	0.7
Archean and Proterozoic crystalline rocks	800	1.8	1.4

steeply plunging to the west. Geophysical investigations have shown here a zone of tectonic disturbances in the basement that corresponds to the zone of higher fracturing in the Devonian deposits. This zone, situated 12–15 km off the coast, is probably the zone of discharge of the Pyarnu aquifer. In the eastern coast of the Gulf of Riga, the Pyarnu aquifer is overlain by thick Narva marls with clay interlayers that effectively hinder the discharge of the Pyarnu aquifer.

CONCLUSIONS

1. The quantitative estimation of the ground-water discharge to the Baltic Sea may be useful in solving a number of hydrological and hydrogeological problems, above all the role ground water plays in the water and salt balances of the Baltic Sea, its temperature and hydrobiological regimes, and in the formation of mineral deposits at the sea bottom, which could, in turn, reveal general regularities of ground-water discharge formation.

2. The ground-water outflow to the Baltic Sea may be estimated by the combined hydrological and hydrogeological method, the hydrodynamic method, and the average long-term water-balance method. These methods are based on available hydrogeological and hydrological information and permit estimating submarine ground-water discharge without expensive expeditionary work. The selection of which method to use depends on the knowledge of the study area and the availability of initial calculation materials. Simultaneous application of two or even three methods produces the most reliable results.

3. For locating ground-water discharge points below the coastline, geophysical and geochemical methods based on investigations of physical and chemical anomalies in sea water and bottom sediments may be used. The application of these methods requires much expeditionary work.

4. The ground-water discharge to the Baltic Sea from the zone of intensive circulation within the area of the U.S.S.R., estimated by the combined hydrological and hydrogeological method, amounts to 38.5 m^3/sec (about 1.2 km^3/year). It includes largely fresh ground water.

The ground-water discharge to the Baltic Sea from the zone of intensive circulation of the Baltic artesian basin, within which the principal part of submarine ground-water outflow is formed, amounts to about 35 m^3/sec or about 6.5 % of the total of fresh ground-water discharge of this basin (Zektzer 1968). The surface-water discharge to the Baltic Sea from the Baltic artesian basin amounts to 78.8 km^3/year. Thus the ground-water discharge to the Baltic Sea from upper aquifers amounts to about 1.5 % of the total stream-flow.

5. The investigations carried out permit one to roughly estimate the amount of salts transported to the Baltic Sea with ground water from the zone of intensive circulation within the area of the U.S.S.R. This estimate is based on the ground-water discharge value, obtained by the combined hydrological and hydrogeological method (Tables 1 and 2) and data on the chemical composition of the ground water of the coastal zone, obtained from sampling water-supply and observation wells and springs. The total value of salt transport to the Baltic Sea from the zone of intensive circulation amounts to about 500,000 t/year. About 200 tons of salts are discharged annually with ground water on every linear kilometre of the coast.

6. The value of ground-water discharge to the Baltic Sea (38.5 m^3/sec) is not all the submarine ground-water outflow, but only the flow from the zone of intensive circulation (largely fresh-water aquifers). It is, of course, the largest part of the submarine ground-water discharge. However, this value does not include the deep highly mineralized water and the outflow from the Gdov aquifer. Therefore the value of 38.5 m^3/sec may be regarded as minimal.

Subjects for further investigation of the ground-water discharge to the Baltic Sea are

(a) estimation of the ground-water discharge from the zone of intensive circulation all over the coastal area of the Baltic Sea;

(b) estimation of deep ground-water discharge where enough initial data are available for this purpose;

(c) investigation of the role of ground-water discharge in the formation of the water and salt balances of the Baltic Sea; and

(d) revealing the general regularities of submarine ground-water discharge, investigation of the effect of ground water on the formation of mineral deposits at the bottom, and studies of the water, salt, temperature and hydrobiological regimes of the Baltic Sea.

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