551.465.12

WATER BALANCE OF THE SEMI-ENCLOSED SEAS

by

ZDZISŁAW MIKULSKI

Institute of Physico-Geographical Sciences
University of Warsaw, Poland

Abstract

Semi-closed seas are peculiar hydrographic entities that occur on the border between inland waters (fresh) and sea waters (salt): they are usually referred to as brackish waters. Their hydrologic character is determined by the water balance, taking into consideration river waters supply as well as inflow from open seas and oceans. The most important semi-closed seas of the world and the character of their water balance are given in the table. Pattern of the components of the water balance of those seas was analysed taking the Baltic Sea, being the most explored sea, as an example. The necessity of invenstigating the water balance of the semi-closed seas was indicated, in consideration of their growing pollution.

1. *Introduction*

The notion of the ''semi-closed sea'' is relatively new in the scientific literature and its appearance is due rather to the specific hydrologic character than to morphometrical characteristics. It can be both an inland sea (mediterranean) with limited contact with open sea or ocean and a coastal sea (fringing) having direct contact with the ocean. Presence of those seas is accounted for by the diversified coastline of the continents. Here is a list of the semi-closed seas divided into drainage basing of the three oceans (Table 1). At least a dozen semi-closed seas can be found on the Earth, not mentioning smaller bays, lagoons and coastal lakes of similar character.

Semi-closed seas are peculiar hydrographic entities that occur on the border between fresh and salt waters, and their salinity is usually small; that is why they are usually refered to as brackish waters. The hydrological environment of those seas is subjected to two basic hydrological factors: inland (fresh) water inflow and sea (salt) water inflow. The former is of continuous character with varying intensity throughout the year and usually small amplitude. The latter factor is sporadic and occurs under favourable weather conditions; often it is quite violent and supplies considerable amounts of water thus affecting the sea level.

Tab. 1. Semi-closed seas of the world and their basic characteristics

Continent	Name of sea	Morfometric features area (km^2)	volume (km^3)	mean dept (m)	Connection with ocean (sea)	Water balance
	A. Pacific Ocean					
Asia	Yellow Sea	417.000	17.00	40	East China Sea	+
Asia	Sea of Japan	1.007.700	1.360.400	1350	Pasific Ocean	+
Asia	Sea of Okhotsk	1.527.600	1.280.100	838	,, ,,	+
North America	Gulf of California	162.200	131.900	813	,, ,,	—
	B. Atlantic Ocean					
North America	Gulf of Mexico	1.600.000	2.332.000	1500	Atlantic Ocean	—
North America	Gulf of Saint Lawrence	237.800	30.200	127	,, ,,	+
North America	Hudson Bay	1.232.300	157.700	128	,, ,,	+
Europe	White Sea	90.000	8.000	89	Barents Sea	+
Europe	Baltic Sea	415.300	21.700	52	North Sea	+
Europe	Mediterranean Sea	2.501.500	3.842.200	1540	Atlantic Ocean	—
Europe	— Adriatic Sea	139.300	330.00	237	Mediterranean Sea	—
Europe	— Black Sea	420.300	547.000	1300	,, ,,	+
	C. Indian Ocean					
Africa	Red Sea	437.900	215.600	491	Indian Ocean	—
Asia	Persian Gulf	238.800	6.000	25	,, ,,	—

Mutual and extremely changeable relations between those factors is characteristic of the hydrological environment of the semi-closed seas, therefore those seas differ considerably from each other. Also in one and the same sea, the relations between the two factors can be different — in time as well as in various parts of the semi-closed sea; therefore in the seas with varied coastline, various parts are characterized by diversity of the marine environment. This in particular refers to the salinity of the water. The parts situated in the vicinity of the straits connecting the inland sea with the ocean, have the salinity approximating that of the ocean, whereas the parts situated close to the river mouths are considerably desalted. Sea inflows that occur mostly in the sea depths and supply waters of higher density, cause higher salinity and its clear vertical gradient affecting substantially a number of processes. Inland waters discharged into the sea supply certain quantities of heat affecting this way changes in the thermal organization of the sea and the pattern of the thermal structure — different from that in open seas. The inland waters play also an important role in chemical and biological processes, supplying big quantities of dissolved and suspended matter. The inland seas are characterized by prevalence of sediments of land origin, the so-called terrigenic sediments, made in result of settling of the suspended matter and precipitating of the dissolved matter, supplied with the fluvial waters. Intensive growth of river pollution causes a growth of sewage load discharged into the sea and deposited in great part in the sea depths.

The above discussed forming of the marine environment by varied mutual arrangement of the two factors — land and oceanic — is expressed by means of the water balance of the semi-closed seas pointing to the role of individual elements of the balance in the process of the water exchange in the sea. The water balance of semi-closed seas is affected by the following factors: surface and sub-surface water inflow from the drainage area (L), precipitation over the sea (P), evaporation (E), ocean water inflow (M), possible excess waters (H) are drained into the ocean, and the decreace or increase of water in the sea is termed storage difference (ΔV). Precipitation and evaporation are referred to jointly as "vertical water exchange" and water inflow from the drainage area and water exchange with the ocean are treated as "horizontal water exchange". The complete water balance equation is as follows (MIKULSKI [9]):

$$(P - E) + (L + M - H) = \Delta V$$

vertical exchange	horizontal exchange	storage difference

This equation can also be put in another form, *i.e.*

$$(P - E + L) - (H - M) = \Delta V$$

fresh water supply	exchange with ocean	storage difference

Both forms of the equation can be given either in volumetric units (km^3) or as depth of the sea water layer (cm); in the latter case the storage diffenrence is defined by the water-level difference (ΔR).

2. *The vertical water exchange*

The analysis of the water balance of the semi-closed seas should be begun with discussing the vertical water exchange. Two factors are invloved here, namely: precipitation over the sea and evaporation from the sea surface. Both of these factors usually play a minor role in the water balance as their impact is contrary and mutually neutralized. Usually growth of precipitation (in the ingoing part of the equation) is accompanied by growth of evaporation (in the outgoing part). Only in case of the seas situated in the intertropical climatic zone, the vertical exchange can exceed the horizontal exchange.

Precipitation over the sea is a component difficult to be measured directly; measuring it is still hindered by lack of observation posts in the open sea. Trial measurements on ships do not give satisfactory results; also there do not always exist possibilities of measurements on islands or on parts of the land protruding into the sea. Most often the data obtained from on-shore posts are used; their extrapolation demands knowledge of spatial distribution of precipitation over the sea — which is different from the distribution over the land. Radar measurements of precipitation over the sea are of some help here, especially in order to define the precipitation area, *i.e.* the spatial distribution and changes in relation to precipitation over the coast-line. When studying the water balance of the Baltic Sea, the observations specially made for that purpose on numerous islands were used and conclusions drawn form that analysis were extrapolated over the whole surface of the sea.

Another equally difficult problem when estimating this component is to define the actual value of precipitation in place of the measured one. There still does not exist a univocal attitude to the question of the value of corrections, not only with reference to the sea conditions but also to the land conditions despite the fact that measuring experiments have been conducted on land for many years. Within the Baltic research project were accepted the values of corrections and thus estimations of the values of actual precipitation as given by individual countries participating in the project concerned with the Baltic water balance. Those values of precipitation were accepted as the initial values for further calculations of the precipitation over the sea.

Evaporation from the sea surface is the least known component. The estimations of its value, given by various authors, differ considerably from each other. As there exists no possibility of measuring evaporation directly, it is necessary to seek empirical methods enabling a rough estimation of this component on the basis of climatological or aerological data. Few existing methods of this kind can only be used for vast sheets of water. The mentioned aerological method was used for the first time by PALMÉN and SÖDERMAN [14] for estimating the evaporation from the Baltic Sea surface. Attempts at using it in the studies of the water balance of the Baltic have not given satisfactory results so far. That is why it was decided to use ship observations in the so-called aero-dynamic method first of all because bigger measuring material (though not very homogenous) was available.

A big contribution to the estimation of the vertical exchange in the water balance of the Baltic was made by Simojoki [18]. His calculations of the precipitation value (based on 50 years' data) and estimation of the value of evaporation from the sea surface concerned individual regions of the Baltic. These results were later on frequently quoted in literature. However, initial results obtained within the Baltic research project and concerning the vertical water exchange show a bigger role of this exchange in the water balance of the sea that it had been believed until that time, and even i some periods evaporation may exceed river inflow.

3. *The horizontal water exchange*

The horizontal exchange in the semi-closed seas is a most complicated process. On one hand, it is a constant process, though clearly changing in time and space as individual seas are variously supplied with fluvial waters. On the other hand, contacts of those seas with oceans afford possibilities for more or less intensive oceanic inflows which, though sporadic, can sometimes bring large quantities of water and affect decisively (even though momentarily) the shape of the water balance as well as the degree of salinity of the sea water, especially in the vicinity of the straits connecting the semiclosed sea with the ocean.

River inflow — in humid climate — is usually the most important source of water supply to the sea, especially in case of an inland sea with a big drainage area. To estimate the river inflow is not very difficult provided there exists a sufficient measuring network in the drainage area and, especially, measurements of the water flow at the river mouths are made. The starting point for such estimations is the division of the sea drainage area into hydrographic regions that are characterized by the structure of fluvial outflow, *i.e.* such regions in which the unit flow is similar within a region. Regions delimited in this way can be represented by one (or more) rivers hydrometrically controlled. In other words, rivers representative for a region are chosen; to them is assigned a certain part of the drainage area whose rivers falling into the sea are characterized by similar value of unit flow. It is desirable that the limits of such regions are the same as those delimiting sections of the drainege areas (so-called drainage sub-areas) of the formerly defined sea regions. Such a procedure is particularly recommended when there occurs a big number of small rivers and in order to take them all into account it is necessary to do laborious and detailed calculations of the inflow. Due to simplification of calculations, in case of the Baltic, a considerable mechanization of arithmetical operation could have been introduced which made it possible to calculate the inflow for each month and year within the 50-year period (1921—1970), with division into decades and other required characteristic periods for each the defined sea region separately. This enables a detailed analysis of the role of the fluvial inflow in the water balance generally.

The knowledge of the value of fluvial inflow simplifies estimations of inflow of solid matter that is carried by the rivers to the sea. River measurements of various forms of river rubbles — dragged, floating and dissolved — particularly at the river mouths, allow to estimate full load of the rubble carried to the sea.

Subsurface inflow into the sea is a separate and little known promlem. However, attempts at estimating this inflow made here and there show its insignificant share in the total mass of water supplied by rivers. Certainly, development of hydro-geological methods of investigation and advancement of estimation methods may give more reliable results. It is necessary to remember that hydro-geological conditions — different in various regions of the world — are of big importance in the subsurface inflow. Therefore, undue generalization of the problem may in a specific case lead to big errors in estimating this component of the water balance.

However, the most difficult component of the water balance of the semi-closed sea to be estimated is the *oceanic water inflow*. In case of the seas with relatively easy contact with the ocean, this element may decisively affect the water balance and the degree of the sea salinity. The marine environment of such seas can be similar to the oceanic environment; and vice versa — marine environment of the seas with small acces of oceanic waters is similar to the environment of coastal lakes.

In the straits connecting the semi-closed sea with the ocean, the water masses move either towards the ocean or towards the sea. This movement is mainly determined by difference in water level in the sea and the ocean and by anemobaric conditions. Various degree of salinity of the seas can cause simultaneuos two-way movement: heavier, saltier oceanic waters move towards the sea in the lower regions whereas brackish waters are in the upper regions. Also anemobaric heterogeneity in the straits region can cause two-way movement of the water masses — at the two opposite banks. For those reasons, movement of water masses in the water balance of the semi-closed seas is usually considered jointly, as component of horizontal exchange.

Evaluation of this component is extremely difficult: it is not always possible to make direct measurements, not mentioning high cost of such measurements. Most often estimated calculations are made by evaluating the size of exchange from the difference of water level between the sea and the ocean. Often the relation of the exchange to the current anemobaric situation is indicated, *i.e.* air-pressure, force and direction of winds. In case of the Baltic the best effects were received by comparing the results obtained from indirect methods with the results of measuring water movement in the straits. Still, however, new methods and solutions are sought.

When analysing the value of water exchange in the straits, it is necessary to remember that not always and not the whole mass of oceanic water reaches the depths of the semi-closed sea and having passed the straits region, returns to the ocean since often a complicated system of the straits is unfavourable for the oceanic waters to move further towards the semi-closed sea. On the contrary, the resistance of the sea water makes the oceanic waters return. An excellent example is the water exchange in the Danish Straits — in case of the Baltic Sea (Remane and Schlieper, [15]).

4. *Changes of the water-level*

Forming of the water balance results in an adequate waterlevel, indicating the specified sea capacity, *i.e.* the quantity of water stored in the sea. Changes of the water-level in the accepted balance periods or, more precisely, differences of the water-level at the beginning and at the end of the balance period, are in the water balance equation the so-called *storage difference* being the closure of the water balance equation. Positive value of the difference indicates and increase of the quantity of water in the sea during a balance period whereas negative value indicates a decrease of the water quantity.

As discussed in the above paragraph, changes of the water-level are an essential component of the water balance of the sea and their value should be calculated very precisely as each — even very small change of the level — signals a big change of sea retention. Marigraphic records of the chosen representative posts for individual regions of the sea are used as a basic for calculations. Each region can be characterized by different values of the changes with relation to the reasons that cause them. When analysing the marigraphic records, short-duration changes should be disregarded as usually caused by local factors and long-duration changes should be taken into account as they are a result of forming of the water balance of the sea.

From the hydrological point of view, seas with positive and negative balance are distinguished. The former are characterized by overbalance of supply over outflow of water (within a year) and excess water flows away to the ocean; these are mainly seas situated in the temperate and Arctic zones (small loss for evaporation). The Baltic belongs to such seas. In the seas with negative balance there is an overbalance of outflow (mainly evaporation) over supply; the balance difference is compensated by constant inflow of oceanic waters. This is a characteristic feature of the Mediterranean Sea (GIDROLOGIA SREDIZIEMNOGO MORIA, [6]) According to the estimations, but of the semi-closed seas of the world given in Table 1, seas with a positive water balance are more common. Discussing, however, the water balance of individual regions of those seas, it is possible to find various balance structures in one and the same sea.

Calculation of the water balance of the semi-closed seas should be based on independent estimation of each balance component separately. Such a procedure allows to estimate the precision of balance calculation. This is also a useful way to correct — from the balance difference — one of the components estimated with least precision; most often this concerns water exchange between the sea and the ocean.

An important indicator of hydrological regime of the semiclosed seas is intensity of entire water exchange in the sea. Entire exchange is defined by means of proportion between the capacity of the sea basin and the value of balance total. The value of the exchange can vary considerably. Exceptionally frequent exchange takes place for instance in the Persian Gulf — every two-three years (SEIBOLD [17]); the Adriatic is also characterized by intensive exchange (ZORE-ARMANDA, [26]). The Baltic, in turn, exchanges its water every about 40 years and the Mediterranean Sea every 75 years (WÜST, [25]). Very slow exchange takes place in the Black Sea, namely every 2,600 years (NEUMANN and ROSENAN, [12]). It is certainly a theoretical exchange, since practically the exchange does not comprise the whole mass of water.

5. Studies of the water balance

In studies of the water balance of the semi-closed seas methodological difficulties of various kinds are often encountered which should be eliminated by means of detailed study. They also concern the above mentioned problem of calculation precision. Within the Baltic cooperation a special research project was launched under the name "Pilot Study Year". This project, carried out in the period between July 1975 and December 1976, enabled working up of a short-period balance, checking of various methods of calculation and estimation of their precision (MIKULSKI [10]). Thanks to this project the calculation of the historical water balance could have been started within the accepted balance periods.

Water balance of the semi-closed seas has its history originating mainly from the studies connected with the Baltic. The Baltic is one of the best investigated seas of the world. The beginnings of the research work of the Baltic date back to 1902 when the International Committee for Northern Seas Research was created (later changed to the International Council for Sea Research). The first estimation of the water balance of the North Sea and the Baltic were made by Krümmel who delivered in March, 1903 a lecture in the Institute of Sea Research at the University of Berlin (Krümmel, [8]). His estimation of the value of the balance components was very approximate. He assumed relatively high value of precipitation and small quantities of fluvial inflow and evaporation; he did not take into consideration inflows from the North Sea. The balance total obtained by him was the lowest of all later balance calculations. Further development of research concerned mainly calculation of some of the balance components.

The Hydrologic Conferences of the Baltic Countries initiated in 1926 and later on the famous Rundo's address at the 3rd Warsaw Conference (Warsaw 1930) with an appeal to launch a project of the water balance study of the Baltic resulted in initiation of organized studies on this problem. Finally, at the 4th Conference (Leningrad 1933) (Sokolowski [19]) presented his version of the water balance equation in which he took into account the resultant of the water exchange with the ocean calculated from the balance difference. Sokolowski's work closed the 30-year period of theoretical calculations of the water balance of the Baltic until II World War. In all that period, oceanic water inflows, mentioned only in Sokolowski's equation, were disregarded.

Owing to the research organized within the Hydrologic Conferences of the Baltic Countries, for the first time reasonably homogenous measuring material was collected which allowed Brogmus to make a full account of the water balance of the Baltic — estimations of oceanic inflows included (Brogmus [2]). Two years later Wyrtki [24] made a detailed analysis of changes in balance components; his studies presented the problem of water balance of the Baltic in a new aspect. Brogmus's and Wyrtki's studies are so far virtually the basic information sources concerning the total water balance of the sea; they constitute a recapitulation of half-a-century old studies on the water balance.

Soon, studies of water balance of other semi-closed seas started to appear, in particular of the Mediterranean and the Black Seas, made by Wüst [25], Neumann and Rosenan [12]and Carter [3]. Later on Tixeront [23] and Owczynnikow [13] wrote papers on those seas. Many methodological issues connected with forming of either positive or negative water balance of the seas were discussed by Guilcher [7]. Then Seibold [17] made an interesting comparative study of the seas situated in humid and dry climatic zones. It is

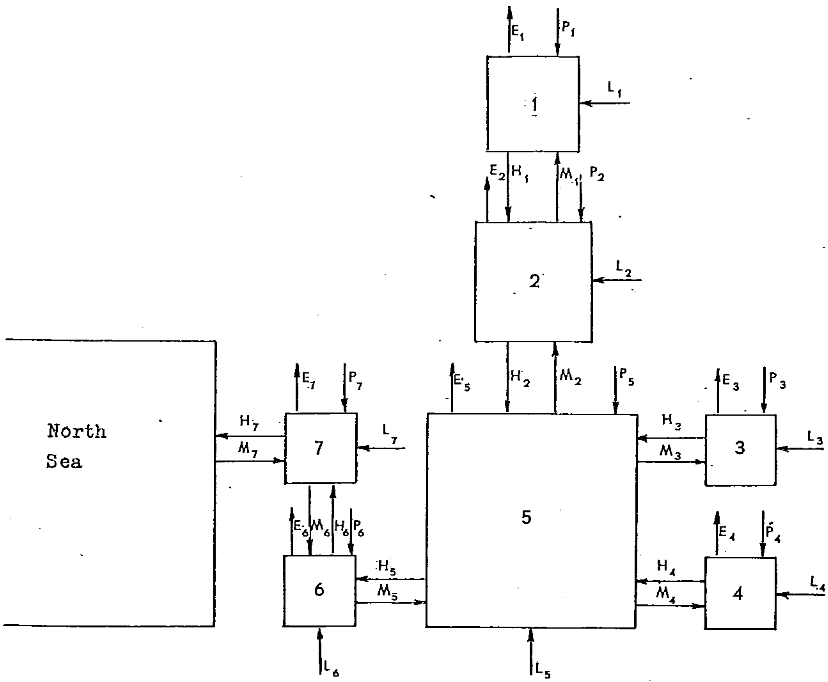

Fig. 1. Scheme of the water balance of the Baltic Sea and its transition area.

Subregions: 1. Bothnian Bay, 2. Bothnian Sea, 3. Gulf of Finland, 4. Gulf of Riga, 5. Baltic Proper, 6. Belt Sea, 7. Kattegat

Legend: P — precipitation, T — evaporation, L — river inflow, H — outflow, M — inflow from subsequent subregion

worth noting that a special symposium was organized by the International Association of Scientific Hydrology with cooperation of the following international associations: Physical Sciences of the Ocean (IAPSO) and Meterology and Atmospheric Physics (IAMAP). The symposium was organized together with XV General Assembly of the International Union of Geodesy and Geophysics (UGGI) in Moscow in 1971. Lectures delivered there made substantial contribution to the knowledge of forming of water balance of those specific hydrographic entities and indicated possibilities of estimating balance components. The fact of publishing the results of several years' studies on the southern seas of the USSR, like the Sea of Azov, the Caspian Sea and the Aral Sea, should be mentioned. Possibly for the first time calculations of their water balance and salt balance were made as well as attempts at forecasting their balance structure (SOVREMENNYJ I PERSPEKTIVNYJ..., [20]). There were also attempts at formulating mathematical models of the water exchange in the Baltic Sea (BOLIN, [1]; SVANSON, [21].

Studies on the semi-closed seas are becoming a more and more urgent problem. Growing exploitation of the seas and their growing pollution require an urgent description of the water balance as a basis of all further scientific and economic ventures since the water balance should be a basis for control and prognosis of the state of sea pollution. It seems that all those circumstances should decisively activate regional hydrological cooperation comprising the drainage areas of the chosen semiclosed seas of the world (FALKENMARK and MIKULSKI, [5]).

An example of organized studies on semi-cloced seas is the international research project under the name "The Water Balance of the Baltic Sea" undertaken by all Baltic countries on Poland's initiative as a continuation of studies started within the Hydrologic Conferences of the Baltic Countries in the period between the two World Wars (FALKENMARK and MIKULSKI, [4]). This project is considered by UNESCO an example of regional hydrological cooperation and a model for other semi-closed seas of the world. The research within the Baltic project carried on since 1971 and aiming at new historical formulation of the Baltic water balance is approaching the end. The result will be a joint monograph to be published in 1981. Further intended research in this field will concern the present operative water balance.

An important element in this research is estimation of long-period changes of balance components with regard to economic activity of man. Knowledge of the changes and their trends can contribute to working out of a prognosis of forming of the water balance. The purpose of the operative balance should be a constantly corrected prognosis enabling also to foresee the ecological situation in the marine environment. Therefore, the operative water balance will be in future a basis for preservation of the marine environment from pollution.

REFERENCES

1. BOLIN, B., 1972: Model studies of the Baltic Sea. *Ambio Special Rep.* **1**, 115—119.
2. BROGMUS, W., 1952: Eine Revision des Wasserhaushaltes der Ostsee. *Kieler Meeresforschungen,* **9**, 15—42.
3. CARTER, D. B., 1956: The water balance of the Mediterranean and Black Seas. *Climatology,* **11**, 123—174.
4. FALKENMARK, M. and Z. MIKULSKI, 1974: *Hydrology of the Baltic Sea.* General background to the international project. Stockholm—Warszawa, 51 pp.
5. —»—, 1975: The Baltic Sea — A semienclosed sea, as seen by the hydrologist. *Nordic hydrology,* **6**, 115—136.
6. *Gidrologia Sredizіemnogo moria,* 1976: Burkov, B. A. (ed.). Leningrad, 376 pp.
7. GUILCHER, A., 1965: *Précis d'hydrologie marime et continentale.* Paris, 390 pp.
8. KRÜMMEL, O., 1904: Die Deutschen Meere im Rahmen der internationalen Meeresforschung. *Veröffentl. d. Inst. f. Meeresk. u.d. Georg. Inst. d. Univ. Berlin,* 6.
9. MIKULSKI, Z., 1974: Water balance of the Baltic Sea (Cooperation of the Baltic countries). *J. Hydrol. Sci.,* **1**, 89—107.
10. —»—, 1975: Pilot study year on the water balance of the Baltic Sea (1975—1976). *Ibid.,* **2**, 119—124.
11. —»—, 1976: Water balance of the semi-enclosed seas, with the Baltic and the Black Sea as examples. *Czas. Georg.,* **47**, 225—236. (in Polish).
12. NEUMAN, J. and N. ROSENAN, 1954: The Black Sea: energy balance and evaporation. *Trans. Am. Geoph. Union,* **35.**
13. OVCHINNIKOV, I. M., 1974: On the water balance of the Mediterranean Sea, *Okeanologia,* **14**. 250—255. (in Russian).
14. PALMÉN, E. and D. SÖDERMAN, 1966: Computation of the evaporation from the Baltic Sea from the flux of water vapor in the atmosphere. *Geophysica,* **8**, 261—279.
15. REMANE, A. and C. SCHLIEPER, 1971: Biology of brackish water (2nd rev.ed.), *Die Binnengewässer,* **25.**
16. RUNDO, A., 1930: Sur l'evaluation de l'apport des eaux fluviales à la Baltique. *III Conf. Hydrol. d. Etats Balt. Warszawa.*
17. SEIBOLD, E., 1970: Nebenmeere im humiden und ariden Klimabereich. *Geol. Rund.,* **60**, 73—105.
18. SIMOJOKI, H., 1949: Niederschlag und Verdunstung auf dem Baltischen Meer. *Fennia,* **71.**
19. SOKOLOVSKI, D. L., 1933: Über die Wasserbilanz der Ostsee. *IV Hydr. Konf. d. Balt. Staaten. Leningrad.*
20. Sovremennyj i perspektivnyj vodnyj i solevoj balans jushnych morej SSSR, 1972, Simonov, A. I., Goptarev, N. P. (eds), *Trudy GOIN,* **108**, 236 pp.
21. SVANSON, A., 1972: The water exchange of the Baltic. *Ambio Spec. Rep.,* **1**, 15—19.
22. Symposium on water balance of semi-enclosed seas bays, 1971: *Proces—Verbaux,* **12**, 114—121.
23. TIXERONT, J., 1969: Le bilans hydrologique de la mer Noire et de la mer Méditerranée. *Bull. Int. Ass. Sci. Hydr.,* **14**, 61—69. (Cahier, Océanographique, 12, 1970, 227—237).
24. VYRTKI, K., 1954: Schwankungen im Wasserhaushalt der Ostsee. *D. Hydr. Zeit.,* **7**, 91—129.
25. WÜST, G., 1952: Der Wasserhaushalt des Mittelländischen Meeres und der Ostsee in vergleichender Betrachung. *Geof. Pura e Appl.,* **21**, 7—18.
26. ZORE-ARMANDA, M., 1969: Water exchange between the Adriatic and the Eastern Mediterranean. *Deep-Sea Res.,* **16**, 171—178.