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NEW RESULTS OF CALCULATION OF WATER BALANCE OF THE BALTIC SEA

The Baltic Sea belongs to typical semi-enclosed seas which means that its water balance is shaped by fresh waters (precipitation and evaporation as well as inflow of river waters from the catchment area) as well as by inflows of salty waters, mainly durig sea (ocean) storms. The knowledge of water balance is therefore indispensable to properly evaluate the state of the sea environment and the degree to which it is endangered. It is only natural that studies on water balance of the Baltic Sea have already a very long tradition. Eighty years ago a professor of geography at the University in Kiel, Otto Krümmel, at a lecture delivered at the Institute of Sea Studies at the University in Berlin (5th—6th March, 1903), presented an attempt at estimating elements of the balance and total outflow from the Baltic Sea to the North Sea (Krümmel, 1904). This happened a year after the International Council for the Exploration of the Sea (the Council exists to the present day) had been established in Copenhagen. The Council contributed greatly to the development of Baltic Studies. It is also worthwhile mentioning a paper by Alfred Rundo, presented in 1922 at a yearly session of the Russian Hydrological Institute in Petrograd (at present the State Hydrological Institute in Leningrad). This outstanding Polish hydrologist outlines the development of knowledge of the Baltic Sea over 200 years and calls on scholars to undertake balance studies of the sea (Rundo, 1922). The paper was published in Polish (Rundo, 1977).

In the period between the two world wars the problems connected with the water balance of the Baltic were undertaken by Hydrological Conferences of the Baltic Countries. In 1930 at the 3rd Conference in Warsaw A. Rundo presented the state of knowledge of river inflow to the sea and appealed to develop organized balance studies (Rundo, 1930). The appeal was accepted and as early as at the next (4th) Conference in Leningrad in 1933 Sokołowski for the first time presented an equation comprising the balance of fresh waters (Sokolovsky, 1933). Until 1939, a few contributions concerning the problems of water balance of the Baltic Sea were published.

Relatively rich material compiled in the period between the Wars allowed scholars to continue further research. In 1952 Willi Brogmus of the Institute of Sea Studies in Kiel presented the so-called revision of water balance of the Baltic Sea (Brogmus, 1952). Brogmus' work constituted a turning-point in studies of balance of the Baltic; it was based on new observational material, at least with reference to such elements as precipitation and river inflow. Although the material was far from being homogenous (Brogmus utilized all data from various periods) the results obtained, with some reservations, can be considered as mean multi-year values. Brogmus' unquestionable contribution was an attempt to consider the role of water exchange between the Baltic and the North Sea in the balance which was based on the analysis of differences in salinity of both seas. The basis assumed for calculation arouses considerable reservation; however, the attempt is worth mentioning and results of calculation point to the order of dimension of that important balance element. Besides, quite soon Klaus Wyrtki (1954), on the basis of the material collected before the war and utilizing Brogmus' calculations, made a detailed analysis of the balance elements over yearly and multi-year periods, throwing new light on the issue of the formation of water balance of the Baltic Sea. Brogmus' and Wyrtki's works became a basic source of information on water balance of the Baltic Sea and constituted a recapitulation of studies lasting the whole first half of the 20th century.

New balance studies could have been undertaken only after development of organized co-operation within the Conference of Baltic Oceanographers. At the 5th Conference in Leningrad (1966) the Polish delegation presented a paper pointing to seasonal variability of river inflow and called on scholars to undertake studies on water balance of the Baltic Sea (Majewski, Mikulski, 1966). After a few years of consultations at various meetings of the Baltic countries, the first meeting of experts on water balance of the Baltic Sea took place in Gdynia in 1971, where a programme of co-operation presented by the Polish side was accepted, division of tasks was made and a representative of Poland, Professor Zdzisław Mikulski, was appointed chief co-ordinator of the project. The project was included in regional co-operation of the Baltic countries within the International Hydrological Decade (1965—1974) and later on it was continued under the UNESCO International Hydrological Programme (Mikulski, 1974). Assumptions of the project and initial results were presented many times by the chief co-ordinator at various international meetings. The work of experts on water balance of the Baltic Sea took more than 10 years; altogether there were 7 general meetings and 3 ad hoc meetings of the working group concerned with the co-called pilot study year 1975—1976 (Mikulski, 1975). A final report containing synthetical results of the research is in preparation.

This article presents preliminary results of studies on water balance of the Baltic Sea. The studies proper were preceded by subdividing the sea into separate regions (sea areas) together with a correction of their area and capacity made by a Swedish specialist (Ehlin, Mattisson, Zachrisson, 1974); also the contribution area of the regions and of the whole sea was established (Table 1, Fig. 1). The subdivision into regions

Table 1

Characteristic data of the Baltic Sea regions

Region	*Basin area* km2	*Sea area* km2	*Sea capacity* km3	*Maximal depth* m	*Mean depth* m
1. Gulf of Bothnia	269 950	36 260	1 481	146	40,8
2. Bothnian Sea	229 700	79 257	4 889	294	61.7
Sum 1+2	499 650	115 517	6 370	—	55.1
3. Gulf of Finland	419 200	29 498	1 098	123	37,2
4. Gulf of Riga	127 400	17 913	406	51	22,7
5. Baltic proper	569 973	209 930	13 045	459	62,1
Sum 1+5	1 615 223	372 858	20 919	—	56,1
6. Sund and Delts	27 360	20 121	287	38	14.3
Sum 1+6	1 642 583	392 979	21 206	—	54,0
7. Kattegat	78 650	22 287	515	109	23,1
Sum 6+7	106 010	42 408	802	—	18,9
8. Baltic Sea	1 721 233	415 266	21 721	459	52,3

was indispensable due to substantial differentiation of the sea and the necessity to treat separately the water balance of each region. That is why it was decided to additionally distinguish two small „transitional” regions, namely the Danish Straits and the Kattegat. The following balance equation was accepted (Mikulski, 1981):

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

supply of fresh water — exchange with the sea — difference in retention

where: P — precipitation to the sea surface, E — evaporation from the sea surface. L — inflow of river waters, H — total outflow from the

Baltic to the North Sea, M — inpourings of sea waters, ΔV — difference in retention in the sea.

The period 1951—1970 (later on extended till 1975) was accepted as a basis to calculate the so-called historical balance; the period was divided into two decades and the homogeneity of the basic data was maintained. It was also recommended to accept — as far as possible — the so-called comparative period (1931—1960) considered as a normal period in climatological studies. And in the period between July, 1975 and December, 1976 the aforementioned pilot study year was operative, which was essential for the explanation of various methodological problems and for estimation of the errors of balance calculations.

Poland as a co-ordinator of the project, undertook the task to calculate the river inflow from the whole catchment area to the Baltic Sea. The studies were based on long observational period in order to find out possible tendencies of changes in time. The calculation covered 17 representative rivers and in order to check the accuracy of calculations in the decades 1951—1960 and 1961—1970, sixty-five and seventy-one controlled rivers were assumed. The error of calculations was within the range of a few percent (exceptionally up to 10—13%). In the years 1921—1975 quite distinct stability of the volume of river inflow in individual decades was noted (Mikulski, 1982). In the yearly course of river inflow the highest values occur in spring (April—June) and the lowest usually in winter. A statistical analysis of the river inflow made with co-operation of specialists from GDR (Hupfer, Mikulski, Börngen, 1979) showed a dominant influence of the Gulf of Bothnia and the Bothnian Sea on the total inflow to the Baltic Sea: also a clearly different nature of the Gulf of Finland and of the „transitional" regions (the Danish Strats and the Kattegat) was demonstrated. The mean values for multi-year periods do not differ much from the ones accepted so far in balance calculations; a little bigger differences can be noted between the particular regions which are sometimes caused by anthropogenic influence.

Calculation of the value of precipitation to the sea surface was made by the Swedish Meteorological and Hydrological Institute (Dahlström, 1983). Abundant observational material was utilized here: over 200 observational posts in the years 1951—1970 and about 300 observational posts in the years 1931—1960. Special attention was paid to the correlation of the measured precipitation, thereby obtaining substantially higher values than before. Estimation of spatial distribution of precipitation was a serious problem due to the fact that in the majority of cases values were used previously recorded by the so-called coastal observational posts, placed on a wide strip of the Baltic coast. The distribution was estimated due to the existence of a number of posts on islands and due to installations of equipment on lightships and other ships. Therefore, an attempt could be made at determning the relevant dependences and distribution on the sea surface. The results obtained show much higher values of precipitation than the ones accepted in earlier studies which, as was already mentioned, were a result of introducing corrections of measured values of precipitation (always in the positive direction). This considerably changes the proportion of this element in the total balance. In the spatial distribution a growth of precipitation takes place from the Gulf of Bothnia to the Danish Straits and the Kattegat. In the yearly course a growth takes place from the minimum in March to the maximum in August (sometimes in July).

There were great difficulties in estimating the value of evaporation from the sea surface. There exist numerous indirect methods of calculating this element of the balance, not to mention direct measurements which in the case of a sea are extremely difficult to conduct. In this case we have to do with a vast sea surface and the only spots available to measure meteorological elementes used to calculate evaporation are quite numerous islands, lightships and other ships equipped with meteorological instruments for the necessary measurements. Such a method of calculation was utilized by West German specialists to calculate evaporation from the Baltic Sea surface adopting the so-called aerodynamical method. For comparative purposes the relatively new aerological method was used, i.e. the aerological network around the Baltic was used and on the basis of this, differences in content of water vapour in the air moving over the sea were estimated. However, this method proved to be unsatisfactory.

Non-homogenous measurement material which was available thanks to the aerodynamic method, although it was from over one century, as well as considerable methodological difficulties made the scientists undertake a great measurement effort during the pilot study year. Joint action of all the Baltic countries in effect gave 75% of the whole available material. Obviously, this material determined the results of calculation of evaporation in a multi-year period since even in the period accepted as a basis for calculating water balance, only 20% of the material was available.

The values of the results obtained are higher by over 10% than the previous ones. It is also worth mentioning that the highest values occur in September and November and even in December (according to the period). Besides, the lowest values do not occur in winter, as it is usually the case of inland waters, but in April and May. In the spatial arrangement evaporation grows from the Gulf of Bothnia to the Kattegat (Henning, 1983).

Much effort was made to establish variations of the level and capacity of the sea. This effort was undertaken by Soviet oceanographers (Lazarenko, 1982). First, the analysis of representativeness of the existing observational posts was made, choosing those posts (fifty-nine) which represented the changing level of the open sea and were not exposed to local influences. On the basis of this, mean daily level was calculated and later on monthly and yearly means of changes of water level in five regions of the Baltic Sea were established. Such calculations were not conducted in the Danish Straits and the Kattegat due to the lack of suitable observational material. Average sea level (with the exception of the two above-mentioned regions) for the period 1951—1970 was −7.8 cm. The highest yearly average level (3.4 cm) occurred in 1967 (an exceptionally wet year) and the lowest (−17.7 cm) in 1939 and (−17.4 cm) in 1960; variations of average yearly level amount only to 20.8 cm (in the studied period 1951—1970). The highest value of the average sea level (27.7 cm) was recorded in the Gulf of Bothnia and the lowest (−17.7 cm) in the Baltic Sea proper. The highest average monthly level occurred in January, 1975, excluding the Baltic Sea proper, where it occurred in January, 1976. Next, the lowest average monthly level occurred in March, 1960, and, excluding the Gulf of Finland and the Gulf of Riga, in December, 1959.

Finally, calculations of changes of sea retention were made by accepting areas of the regions with various water levels as constant. The greatest increase in capacity (172.0 km^3) took place in 1960 and in 1961 (163.7 km^3), the greatest decrease in 1976 (−162.4 km^3) and in 1959 (−144.7 km^3).

In the third pilot study year intensive measurements of currents in the Danish Straits were made in order to establish exchange between the Baltic and the North Sea. This operation was carried out by Danish oceanographers under the so-called Belt Project (Jacobsen, 1980). Analysis of the results obtained during the PSY showed that direct measurement of currents (given the present state of measurement techniques) cannot be a sufficient basis for estimation of the water exchange. Therefore, it was decided while determining the total water balance, to confine the studies only to estimations of differences of water exchange, the so-called net outflow to the North Sea, which were obtained as a result of balancing solely elements of fresh water.

An attempt was made to calculate the total water balance in the period 1951—1970 taking as the basis the area of the Baltic Sea without the Danish Straits and the Kattegat (regions 1—5). The balance equation at the beginning was presented in the following form:

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

The expression $(H-M)$ — difference between the total outflow from the Baltic Sea and the inflow of sea water — was treated as the net outflow. This value constitutes a closing of the balance equation; it is positive even in mean monthly values of the above-mentioned multi-year period proving that the Baltic Sea is really a sea with a positive balance. The highest values of the net outflow are recorded in spring, with the minimum (72.4 km³) in May and the maximum (1.1 km³) in July; a secondary minimum (7.6 km³) is recorded in December (Table 2, Fig. 2). Similar values were obtained while analyzing the multi-year period 1931—1960.

It is interesting to compare these values with those obtained by Brogmus (1952), referring to the area of the Baltic Sea excluding the Danish Straits and the Kattegat (Table 3). In the total balance those are similar values; considerable differences occur, however, with regard to individual balance elements. And thus the values of river inflow decreased; nowadays, they constitute only 91—92% of Brogmus' value. Precipitation constitutes at present 130—138% of Brogmus' value according to the period of balancing (1951—1970, 1931—1960); this is mostly due to the fact that nowadays corrected values of precipitation have been accepted. Then, evaporation did not undergo significant changes of sea retention, and its value is close to zero in the multi-year period and does not influence the balance total.

The final balance equation is presented as follows:

$$(P-E+L) \quad - \Delta V = (H-M)$$
$$224-184+436 \quad - \quad 5 = 471 \text{ km}^3 \text{ (1951—1970)}$$
$$237-184+428 \quad - \quad 0 = 481 \text{ km}^3 \text{ 1931—1960)}$$
$$172-172+472 \quad - \quad 0 = 472 \text{ km}^3 \text{ (Brogmus 1952)}$$

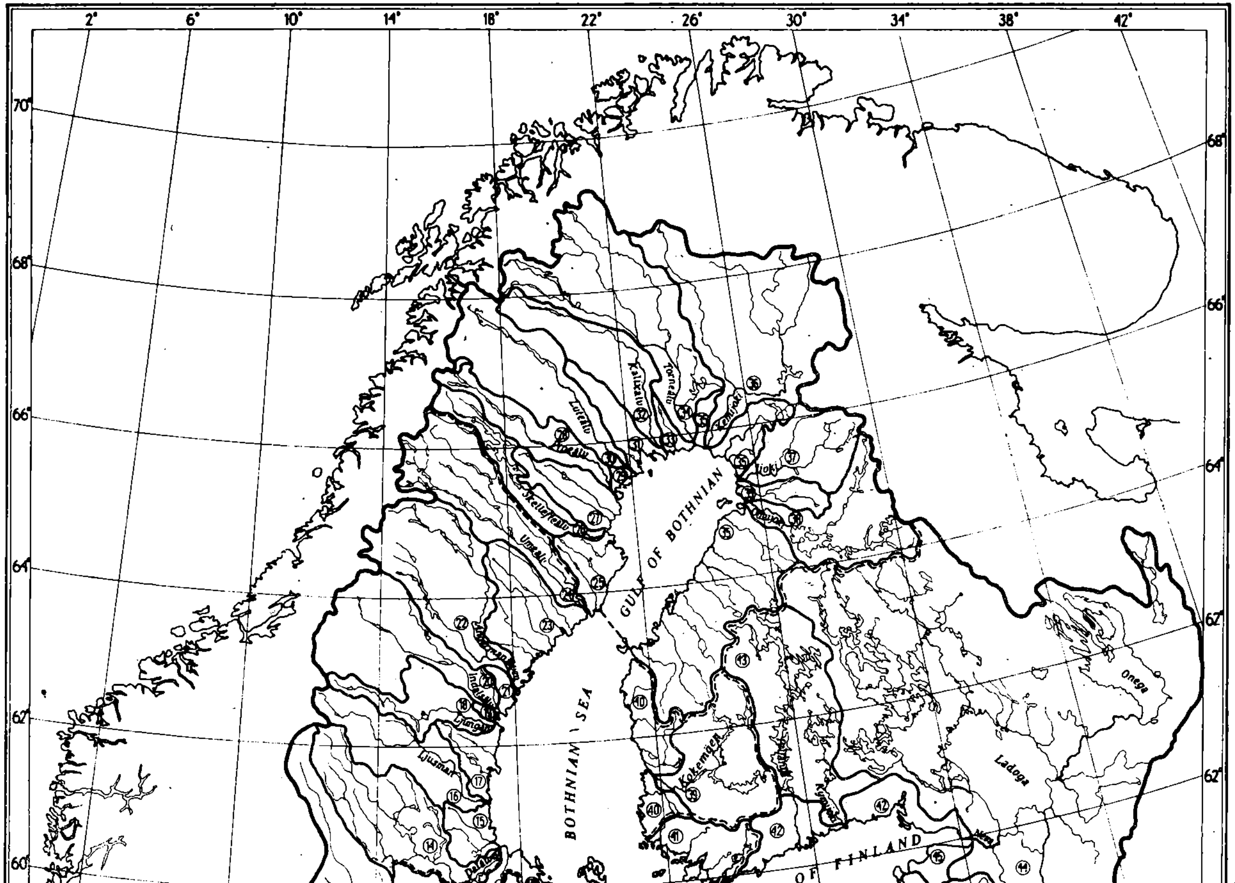
It should be stressed that the values accepted by Brogmus are only of approximate character. It also seems proper to take a stand on Brogmus' calculations referring to sea inflows and total values of outflow from the Baltic Sea connected with them. Brogmus followed Knudsen's generalization who estimated that the salinity of sea inflows (S_N) is on the average twice as high as the salinity of the water outflowing from the Baltic Sea (S_O).

$$S_N = 2\, S_O; \; (S_N = 17.4‰, \; S_O = 8.7‰)$$

Table 2

Water balance of the Baltic Sea in the years 1951—1970 (km^3, without Belts Sea and Kattegat; A = 372858 km^2)

Elements of Water Balance (km^3)	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	I—XII
Precipitation (P)	17.9	14.4	11.4	13.5	14.8	15.2	22.6	25.4	23.6	21.0	22.7	21.1	223.6
Evaporation (E)	13.7	12.7	8.9	4.7	4.8	5.0	13.1	16.7	23.6	22.7	26.0	25.1	184.0
River inflow (L)	23.7	22.1	28.7	45.9	64.3	53.9	39.1	35.9	32.6	32.3	30.7	26.9	436.1
$Q_0 = P - E + L$	22.9	23.8	31.2	54.7	74.3	64.1	48.6	42.6	32.6	30.6	27.4	22.9	475.7
Storage difference (ΔV)	−21.9	−28.1	−30.0	4.8	2.3	20.6	48.8	−5.8	10.0	0.9	−11.7	15.3	4.7
Inflow of fresh Water $Q_0 - \Delta V = H - M$	44.8	51.9	61.2	49.9	72.0	43.5	0.8	48.4	22.6	29.7	39.1	7.1	471.0


GULF OF BOTHNIAN
BOTHNIAN SEA
OF FINLAND
Onega
Ladoga
Kokemäen
Torneälv
Kalixälv
Luleälv
Skellefteälv
Umeälv
Indalsälv
Ljungan
Ljusnan

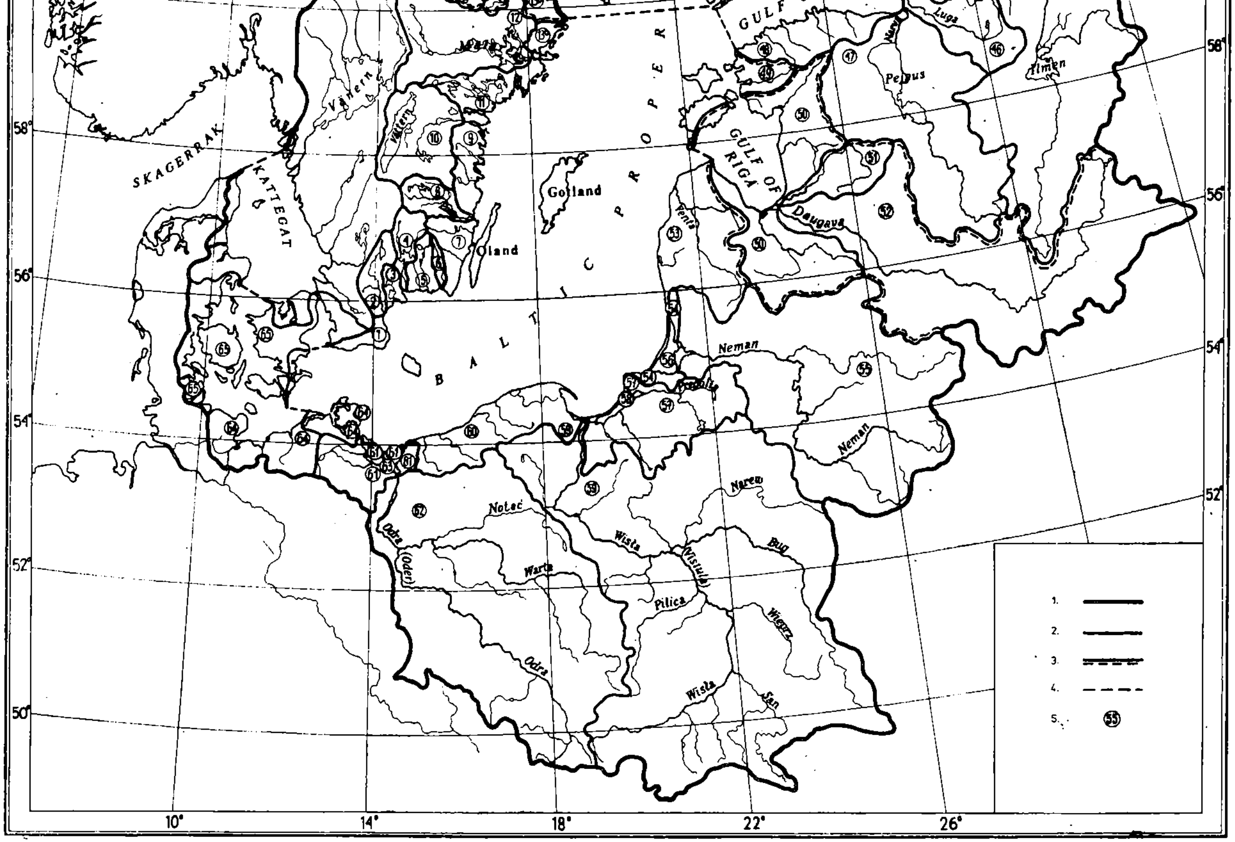


Fig. 1. Drainage basins of the Baltic Sea and its regions.

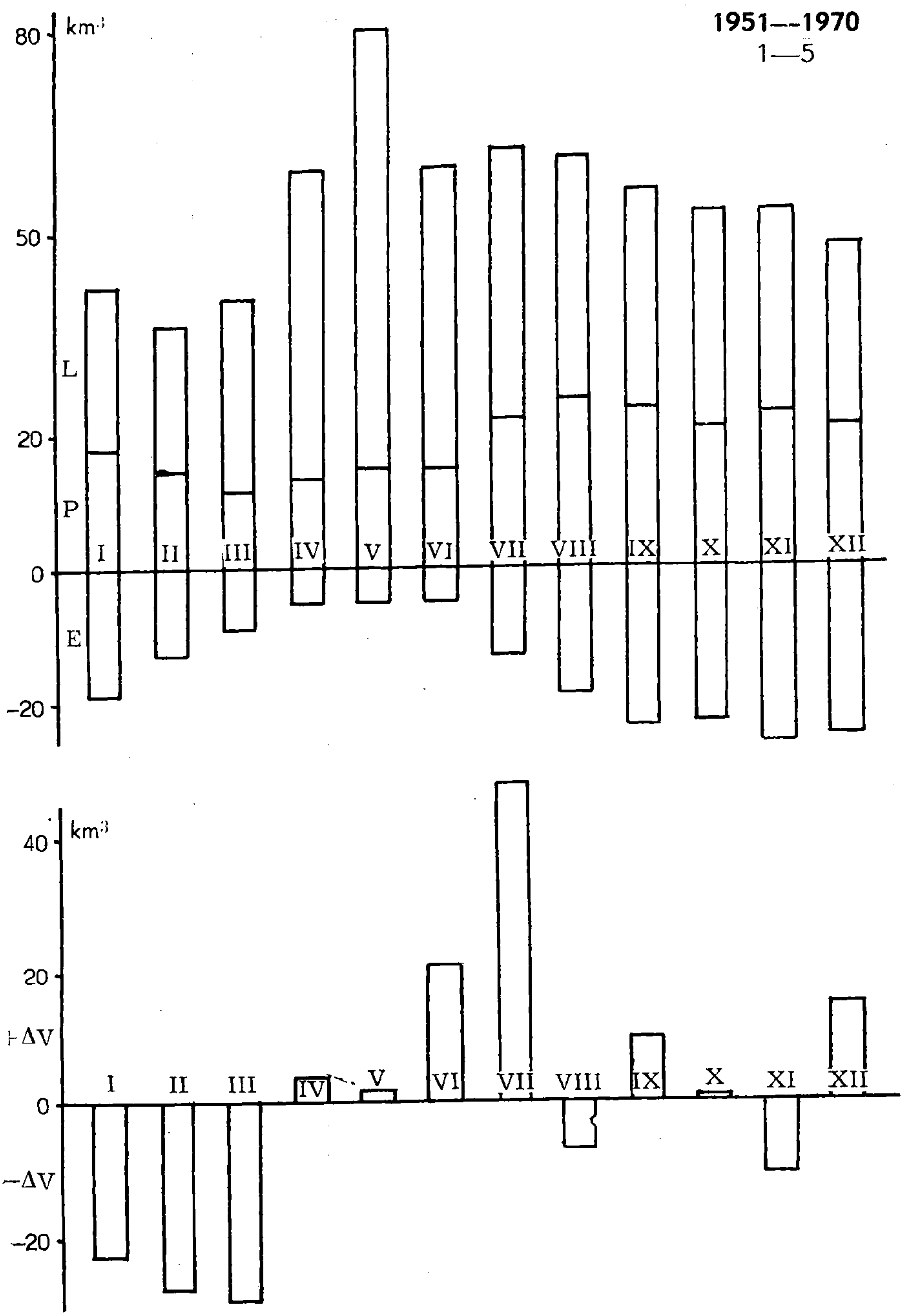


Fig. 2. Seasonal changes in the elements of water balance of the Baltic Sea in the years 1951—1970 (km³)

Table 3

Comparison of results of the Baltic Sea water balance (km³)

Elements of Water Balance	*Baltic Sea (without Belts Sea and Kattegat)* A = 372 858 km2					*Baltic Sea (without Kattegat)* A = 392 979 km2				
	1951/70	1931/60	Brogmus	1951/60 −Br.	1931/60 −Br.	1951/70	1931/60	Brogmus	1951/60 −Br.	1931/60 −Br.
Precipitation (P)	224	237	172	+52	+65	239	195	183	+56	+68
Evaporation (E)	184	184	172	+12	+12	193	250	183	+10	+12
River inflow (L)	436	428	472	−36	−44	444	436	479	−35	−43
$Q_0 = P - E + L$	476	481	472	+4	+9	490	491	479	+11	+13
Storage difference (ΔV)	5	0	0	+5	0	2	0	0	5	0
Inflow of fresh water $Q_0 - \Delta V = H - M$	474	481	472	−1	+9	485	491	479	+6	+13
Inflow from the North Sea (M)	(471)	(481)	(472)	−1	+9	(747)	(755)	(737)	+10	+18
Outflow to the North Sea (H)	(942)	(962)	(944)	−2	+18	(1232)	(1246)	(1216)	+16	+30
Balance total $P + L + M - \Delta V = E + H$	(1126)	(1146)	(1116)	+10	+30	(1425)	(1441)	(1399)	+26	+42

Therefore, the value of sea inflow (M) according to Brogmus is 472 km^3 (corresponding to the value of river run-off) and the total outflow from the Baltic Sea (H) is 944 km^3. Values obtained by Brogmus are compared with the present values in Table 3.

The results obtained give similar values. It should be stressed, however, that the values of H and M calculated in this way are only estimations. To calculate them properly, further detailed oceanological studies should be conducted on an appropriate basis.

A new study of water balance of the Baltic Sea was made for the first time on the basis of homogeneous observational material, in a monthly period, taking into account some more important regions of the sea. One should remember that the Baltic Sea, unlike many other seas, is composed of a few different regions that demand separate treatment. Here we have various balance systems, so the analysis of the results obtained can shed much light on the problem of water balance of semi-enclosed seas in general (Mikulski, 1981).

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