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DAY-TO-DAY VARIATION IN SEA LEVEL ALONG THE FINNISH COAST

by

EUGENIE LISITZIN

Institute of Marine Research, Helsinki

Abstract

In the paper the »renewal» time of the water in the Baltic and the Gulfs of Bothnia and Finland is computed on the basis of day-to-day changes in sea level for eight Finnish tide gauge stations. The results are compared with a number of older data for the interchange of water between the North Sea and the Baltic determined by other methods.

1. *Statistical results*

The danger of pollution in lakes and coastal sea regions is constantly increasing and is accompanied by a growing significance of the question of water mixing, water interchange and water renewal. There are several very different approaches to the closer study of this subject. Some of them require special instrumentation and extensive field work; in others interesting and valuable results may be achieved by using data already available as collected primarily for other scientific or practical purposes. For instance, sea level variations recorded at the tide gauges along the Finnish coast for a period covering on an average 40 years allow us to draw approximate, but valuable conclusions about water renewal in the Baltic and especially in the Baltic's extensive northern gulfs.

The positions of the Finnish sea level stations used in the following are given in Figure 1.

Changes in sea level in the Baltic sea basin are principally the consequence of the disturbing effects of different meteorological elements

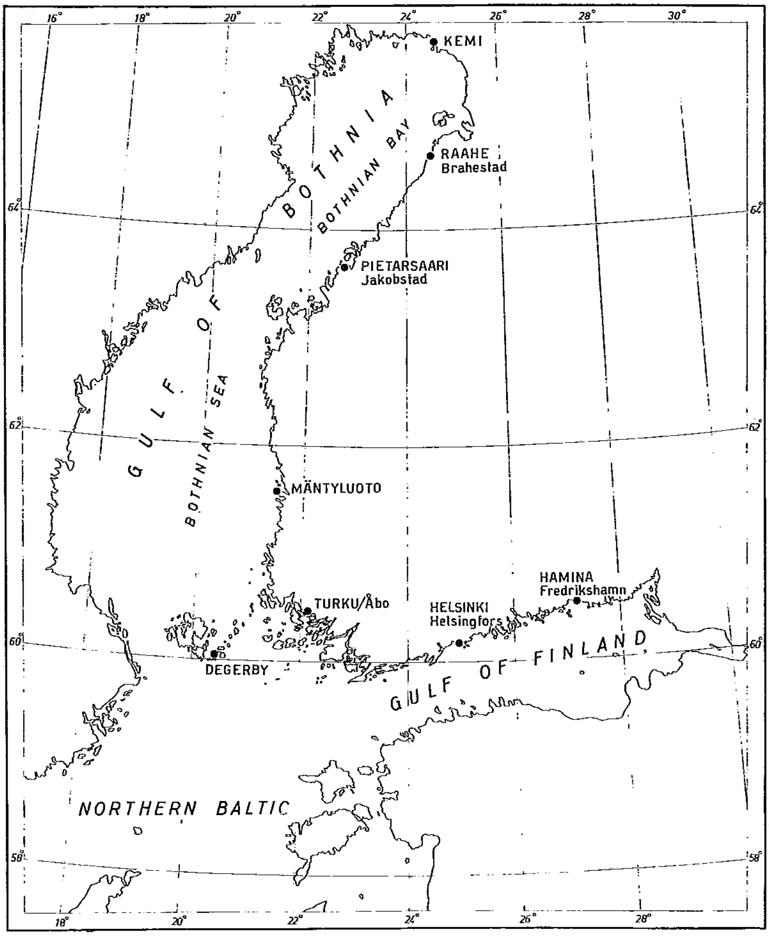

Fig. 1. The positions of the Finnish sea level stations used in this study.

upon the water surface. Among these elements atmospheric pressure and wind must be mentioned first. Along the Finnish coast the part played by astronomical tides contributes only a fraction to the total variations. A few examples may suffice to illustrate this fact. The height difference between the astronomical diurnal high and low water tides does not, even in the most favourable cases, exceed the following values [9, 10]:

at Kemi	6.5 cm
at Raahe	6.5 cm
at Mäntyluoto	3.5 cm
at Degerby	3.0 cm
at Hamina	15.0 cm.

The above maximum double amplitudes occur, however, only during fairly short periods each year in connexion with a more or less marked coincidence of the extreme amplitudes of all more pronounced diurnal waves. The average double amplitudes of the diurnal tides may be estimated as corresponding approximately to half of the maximum amplitudes mentioned above. It may, in addition, be pointed out that the semi-diurnal tides in the northern parts of the Baltic are considerably weaker than the diurnal tides, and the height differences caused by the former are, therefore, still less pronounced.

On the other hand, a study [12] concerning the annual pattern of the daily sea level ranges, based on sea level records for the 10-year period 1940—1949, has shown that the recorded mean ranges amount to:

at Kemi	21.0 cm
at Raahe	18.1 cm
at Mäntyluoto	12.1 cm
at Degerby	10.1 cm
at Hamina	20.8 cm.

For the Gulf of Bothnia, including Degerby, these ranges are roughly 6 times greater than the average double amplitudes of the astronomical tide, while for Hamina the ratio is slightly less than 3. The significance of the sea level variation due to meteorological factors compared with that due to astronomical tides is also clearly revealed by the results for the average frequencies of daily sea level ranges. These results show that height fluctuations greater than 10.0 cm per day occur over the days of the year as follows:

at Kemi	75 per cent
at Raahe	71 per cent
at Pietarsaari	48 per cent
at Degerby	36 per cent
at Hamina	78 per cent.

The increase of the percentage towards the inner parts of the Gulf of Bothnia and the Gulf of Finland is thus considerable. The above mentioned height difference limit of 10.0 cm which, with the exception of Hamina, is 1.5 to 3.0 times greater than the maximum double amplitude of the tides, and which roughly covers 4.5 (at Degerby) to 9.0 months per year, clearly indicates that the contribution of the astronomical tides to the range of total fluctuations in sea level is rather small. Of Hamina it may be added that daily sea level differences greater than 20 cm are recorded on 59 per cent of all days of the year and they thus cover more than 7 months per annum. This fact highlights the significance of meteorological disturbances compared with that of astronomical tides for the Gulf of Finland. The frequency numbers and the average height deviations refer, as mentioned, to the difference between the highest and the lowest sea level recorded during a day. No distinction was made on this occasion between water rise and water fall. For the same period, 1940—1949, the maximum range in sea level changes per day recorded at the various stations was:

Kemi	112 cm
Raahe	102 cm
Mäntyluoto	71 cm
Degerby	47 cm
Hamina	142 cm.

All these values are of a completely different magnitude from the maximum double amplitude of the diurnal tides. For Hamina the relevant ratio is less than 10, but for the other stations it varies between 15 and 20. These data thus accentuate once again the significance of meteorological elements, compared with astronomical tides, to the fluctuations of sea level in the Baltic.

There is, however, an important consideration which must not be overlooked. The extreme heights of sea level are, as a rule, of very short duration, covering a few hours or sometimes only a fraction of an hour, and they therefore hardly allow of a radical mixing of the water masses concerned. It must, moreover, be remembered that wind-driven water circulation is principally restricted to the upper water layers which, being less dense than the deeper water masses, render a thorough mixing improbable. The occurrence of bottom currents, deep water upwelling along the coast and other related compensatory processes may sometimes, however, contribute greatly to an acceleration of water mixing. Taking all these facts into account it seemed appropriate to choose a parameter other than the sea level range during a day as the basis for a more detailed study. The average daily sea level based on six recorded readings, together with its day-to-day changes, is a considerable improvement since it evens out the figures and thus eliminates the effect of the short lived extreme water heights. It thus provides a more reliable picture of the consecutive variations adaptable for a study of the processes characteristic of water interchange between separate sea basins. The effect of the astronomical tides is practically eliminated by the use of day-to-day changes in sea level. Since these tides are small, however, in comparison with the sea level variations caused by meteorological factors, this fact is of secondary importance.

All the results mentioned hereafter are based on the sea level records for the eight Finnish sea level stations given in Figure 1 during the 30 year period 1931—1960.

For our particular purpose it seemed preferable to study the positive day-to-day changes in sea level separately from the corresponding negative changes. The maximum and the average increase in sea level per day are, as a rule, slightly larger than the maximum and the average decrease. Since, in the long run, if we overlook the slight decrease in sea level caused by continuous land uplift, increase and decrease must balance each other, the inevitable conclusion is that the number of days characteristic by a positive change in sea level is somewhat smaller than the number of days with a negative change. In an extensive paper concerning variation in sea level in the Baltic, the number of days with an increasing sea level was estimated by Hela [5] as 166 per year, and the days characterised by a sinking water surface as thus 199. According to the results of the present paper the discrepancy between the periods of increase and those of decrease in sea level is somewhat less pronounced. As regards the particular tidal stations and the Finnish coastal region in general the following are the results for the number of days with an increasing and decreasing sea level respectively:

Station	Increasing	Decreasing
Kemi	180 days	185 days
Raahe	180 »	185 »
Pietarsaari	180 »	185 »
Mäntyluoto	178 »	187 »
Turku	172 »	193 »
Degerby	173 »	192 »
Helsinki	175 »	190 »
Hamina	176 »	189 »
Average	177 days	188 days

Tables 1 and 2 present respectively the positive and negative average monthly and yearly values of day-to-day variations. The former table thus refers to days with an increasing sea level, the latter to those characterised by a decrease in sea level. These tables indicate very clearly not only the general annual pattern of the changes and the slight differences between the corresponding positive and negative values, but also the considerable regional deviations occurring along the Finnish coast.

Table 1. The average day-to-day increase in sea level (cm).

Station	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	I–XII
Kemi	15.4	12.9	9.5	8.9	8.4	8.2	7.3	9.6	12.7	16.4	17.9	16.9	12.0
Raahe	13.9	11.0	8.7	7.9	7.0	6.4	5.6	7.1	9.7	12.1	14.3	13.9	9.8
Pietarsaari	10.7	8.7	7.6	6.5	5.6	5.2	4.7	5.5	8.1	9.8	11.2	11.0	7.9
Mäntyluoto	7.7	6.4	5.4	4.7	3.9	3.5	3.3	3.8	5.0	5.9	6.9	7.0	5.3
Turku	6.2	4.9	4.5	4.3	3.6	3.6	3.4	3.8	5.1	5.6	5.9	5.6	4.7
Degerby	4.9	3.9	3.9	3.3	2.7	2.5	2.5	2.6	3.2	3.6	4.1	4.2	3.4
Helsinki	8.3	7.5	6.4	5.9	5.3	4.8	4.5	5.4	6.9	7.4	8.2	7.4	6.5
Hamina	11.0	9.2	8.0	7.1	6.8	6.2	5.8	7.2	9.0	9.8	10.6	10.6	8.4
Average	9.8	7.7	6.8	6.1	5.4	5.0	4.6	5.6	7.5	8.8	9.9	9.6	7.2

Table 2. The average day-to-day decrease in sea level (cm).

Station	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	I–XII
Kemi	15.2	10.9	9.0	8.4	7.9	8.2	7.2	9.1	13.1	15.0	16.7	15.5	11.4
Raahe	13.4	10.0	8.4	7.8	6.9	6.2	5.3	7.1	9.8	12.3	13.3	13.5	9.5
Pietarsaari	10.9	8.6	7.4	6.5	5.4	4.8	4.4	5.9	7.7	10.0	10.3	10.5	7.7
Mäntyluoto	7.6	5.9	5.3	4.5	3.6	3.1	2.9	3.7	4.7	6.3	6.5	6.4	5.0
Turku	5.9	4.8	4.1	3.6	3.2	2.8	2.8	3.4	3.7	5.2	5.5	5.5	4.2
Degerby	4.3	4.0	3.5	3.0	2.8	2.2	2.2	2.4	2.8	3.5	3.4	3.7	3.2
Helsinki	8.2	7.0	6.1	5.1	4.8	4.4	4.2	4.7	5.5	7.2	7.2	7.8	6.0
Hamina	10.8	8.6	7.5	6.5	5.9	5.8	5.3	6.1	7.6	10.2	9.8	10.7	7.9
Average	9.5	7.5	6.4	5.7	5.1	4.7	4.3	5.3	6.9	8.7	9.1	9.2	6.9

The average sea level variation from one day to the next has a fairly pronounced annual pattern, with a maximum in late autumn or early winter and a minimum during the warm season. It can be estimated that in the northern parts of the Gulf of Bothnia the maximum monthly average in autumn is approximately 2.5 times as great as the corresponding minimum value in summer. Further south and progressing along the northern coast of the Gulf of Finland the ratio diminishes to less than 2. This fairly marked deviation shows the pronounced effect of the piling-up of water caused by wind during the stormy season of the year.

The day-to-day changes are, as might be expected, smallest in Degerby, and they increase gradually towards the north and east in the large gulfs which enclose Finland. The variations are, for instance, approximately 1.5 times as great at Mäntyluoto as at Degerby, while the ratio for Raahe, on the one hand, and Degerby, on the other, is almost 3, and for Kemi and Degerby more than 3.5. The day-to-day changes are practically twice as great at Helsinki as at Degerby. The ratio between the data for Hamina and Degerby is 2.5.

Table 3. The average maximum day-to-day increase in sea level (cm).

Station	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	I—XII
Kemi	47.8	36.4	27.0	26.8	26.7	24.6	23.3	29.6	40.9	49.2	55.6	47.5	36.2
Raahe	40.7	33.8	25.7	24.3	20.9	19.3	16.9	21.8	30.9	33.2	40.9	38.2	28.9
Pietarsaari	35.7	29.1	21.4	20.5	16.8	15.7	13.7	17.5	24.3	28.3	39.2	30.5	23.8
Mäntyluoto	24.8	18.7	16.4	15.4	11.7	10.3	9.8	12.4	15.7	18.8	21.2	19.3	16.2
Turku	19.8	14.4	12.9	12.7	11.1	10.8	10.9	13.6	16.6	16.4	19.3	16.2	14.6
Degerby	14.1	11.3	11.7	10.2	8.0	8.0	8.6	8.1	9.9	11.5	12.7	11.3	10.4
Helsinki	27.0	21.1	19.3	18.3	16.3	15.0	14.5	17.4	21.3	22.9	24.4	22.8	20.0
Hamina	36.7	27.4	24.4	23.1	20.6	19.0	18.8	22.7	27.3	30.2	33.7	31.8	26.3
Average	30.8	24.0	19.8	18.9	16.5	15.3	14.6	17.9	23.4	26.3	30.0	27.2	22.0

Table 4. The average maximum day-to-day decrease in sea level (cm).

Station	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	I—XII
Kemi	49.2	34.9	28.9	25.2	25.8	24.6	20.4	27.2	37.0	47.7	48.0	45.3	34.5
Raahe	43.0	31.8	27.4	22.3	20.3	17.6	14.0	21.6	27.9	35.9	37.3	37.5	28.0
Pietarsaari	32.4	27.5	22.5	19.1	15.9	13.8	11.2	16.8	22.3	29.0	28.9	28.2	22.3
Mäntyluoto	23.6	18.4	16.4	14.6	10.7	8.0	7.7	11.0	14.1	18.6	19.7	17.9	15.1
Turku	18.1	13.6	11.6	10.3	8.7	7.7	7.7	9.0	11.2	15.5	16.8	16.7	12.2
Degerby	12.9	10.4	10.4	8.2	7.2	5.6	5.4	6.3	7.6	9.6	10.3	10.7	8.7
Helsinki	23.9	19.7	16.7	14.2	13.6	11.4	10.9	12.3	16.3	23.4	21.8	22.4	17.2
Hamina	31.4	25.2	21.8	17.0	17.4	16.1	14.6	16.7	23.1	32.1	29.6	31.4	23.0
Average	29.3	22.7	19.5	16.4	15.0	13.1	11.5	15.1	19.9	26.5	26.6	26.3	20.2

Of the mean maximum daily increase and decrease in sea level during different months, it may be noted that the values have roughly the same features as those for the average day-to-day fluctuations. The results are presented in Tables 3 and 4. The first of these tables refers to the maximum recorded increase in sea level from one day to the next, while the second table gives the corresponding maximum decrease.

To obtain some idea of the absolute extreme values recorded during the period under review Tables 5 and 6 have been compiled. These tables, presenting respectively the maximum increase and decrease in sea levels during the different months, confirm the above results, but show, as might be expected, a less pronounced regularity in the general annual pattern of the data.

Table 5. The recorded maximum day-to-day increase in sea level (cm).

Station	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	I–XII
Kemi	113	79	59	70	64	52	47	47	68	83	85	72	70
Raahe	93	73	50	62	55	47	27	36	56	61	67	61	57
Pietarsaari	84	62	43	58	44	33	25	33	50	45	55	46	48
Mäntyluoto	46	36	35	34	26	20	26	28	34	43	43	32	34
Turku	37	29	22	31	20	20	25	28	46	32	41	29	30
Degerby	25	25	22	28	16	17	20	19	17	26	23	28	22
Helsinki	67	33	38	37	38	21	28	33	56	46	48	48	41
Hamina	87	54	52	40	60	32	34	42	75	60	60	67	55
Average	69	49	40	45	40	30	29	33	50	50	53	48	45

Table 6. The recorded maximum day-to-day decrease in sea level (cm).

Station	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	I–XII
Kemi	109	74	55	50	39	48	37	45	70	100	95	87	67
Raahe	96	70	53	47	45	33	24	38	52	80	82	73	58
Pietarsaari	77	61	39	43	32	25	21	27	33	74	49	50	44
Mäntyluoto	61	41	35	33	25	13	13	17	21	46	42	36	32
Turku	38	28	22	21	18	14	14	17	21	36	35	38	25
Degerby	26	18	18	18	12	9	9	12	12	19	19	20	16
Helsinki	38	46	26	27	28	18	18	26	39	44	51	53	34
Hamina	48	70	40	32	30	26	24	41	59	64	60	78	48
Average	62	51	36	34	29	23	20	28	38	58	54	54	41

Mention must be made in this connexion to the relative magnitude of the daily sea level ranges and the day-to-day variation, in order to get some idea of the degree of reduction in amplitude of the fluctuations when using the last-mentioned data. The ratios between the two sets of data indicate a marked regularity in this respect. The following are the ratios for the average and the maximun values (for the day-to-day changes the values refer to the increase in sea level) characteristic of the separate stations:

Station	Ratio for average change	Ratio for maximum change
Kemi	1.7	1.0
Raahe	1.8	1.1
Mäntyluoto	2.3	1.5
Degerby	3.0	1.7
Hamina	2.5	1.6

The above figures indicate that the deviation between the two sets representing the average changes is at its lowest in the innermost part of the Gulf of Bothnia and increases continually towards Degerby where it reaches the value 3.0. Progressing towards the east in the Gulf of Finland the ratio diminishes and is for Hamina slightly greater than for Mäntyluoto. As for the maximum changes, it may be noted that the ratio is approximately 40 per cent smaller than for the average changes.

The results given above may be supplemented by two additional Tables 7 and 8. Table 7 represents the sum of the average increase in sea level during the particular months and for the whole year; Table 8

Table 7. The sum of the average increases in sea level (cm).

Station	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Year
Kemi	229	156	136	132	124	129	113	138	197	251	256	247	2108
Raahe	205	149	129	116	108	101	86	104	151	193	204	210	1756
Pietarsaari	161	124	112	96	85	82	74	83	123	150	161	163	1414
Mäntyluoto	113	85	80	68	58	56	51	54	75	91	101	101	933
Turku	88	65	63	60	52	55	51	53	67	80	86	85	805
Degerby	65	54	54	47	43	42	40	36	47	54	58	60	600
Helsinki	121	99	93	82	79	75	70	76	94	110	116	116	1131
Hamina	161	122	116	102	97	96	88	99	126	149	156	160	1472
Average	143	107	98	88	81	80	72	80	110	135	142	143	1279

Table 8. The sum of the average decreases in sea level (cm).

Station	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Year
Kemi	243	162	146	126	124	113	108	149	186	245	258	245	2105
Raahe	216	148	137	118	106	86	82	114	140	190	203	211	1751
Pietarsaari	173	125	122	98	85	68	67	93	114	149	158	166	1418
Mäntyluoto	123	87	86	69	56	43	45	61	70	94	97	103	934
Turku	98	72	70	57	52	41	45	59	61	83	82	87	807
Degerby	76	57	61	46	42	28	33	42	43	56	54	63	601
Helsinki	133	103	100	80	76	62	66	78	89	114	112	121	1134
Hamina	174	126	121	100	96	82	84	102	119	157	152	165	1478
Average	154	110	105	87	80	65	66	87	103	136	140	145	1278

refers to the corresponding decrease. The tables show that there is only a slight discrepancy between the values for increase and decrease per annum, while the monthly data show more pronounced deviations. These deviations are obviously due to the general features of the annual pattern of sea level along the Finnish coast.

2. *Water renewal and water budget in the Baltic and its gulfs*

a. The Baltic Sea.

It might be rewarding to examine more closely the values for Degerby, since this sea level station, because of its central position only slightly north of the middle of the entire basin of the Baltic and its large gulfs, is fairly representative of the average conditions for the whole sea basin [13, 14]. For day-to-day changes, however, the use of Degerby records as representative of the entire Baltic may involve a certain amount of inaccuracy. The variation in sea level at an individual station is, without doubt, always greater than that for the sea basin as a whole. A comparative study has shown that a 20 per cent reduction of the data for Degerby is fair, if satisfactory values for the Baltic are to be achieved. According to Table 7 the sum of the increase in sea level amounts at Degerby to 600 cm per year, and the corresponding increase for the whole sea basin may thus be estimated as 480 cm per year. This height seems rather insignificant, when one considers that the average depth of the Baltic is approximately 60 meters. It implies, accordingly, that as an initial estimate a period of somewhat less than 13 years should be necessary for the more or less complete renewal of the water masses in the Baltic basin. This period is considerably shorter than, for instance, the renewal time for the Mediterranean and the Arctic Sea, for which basins the annual inflow and outflow are known. For the former the time estimated is 80 years; for the latter, 165 years [8]. Taking into consideration the fact that the volume of the Mediterranean is 184 times, and that of the Arctic Sea 738 times greater than that of the Baltic, a »renewal» period of 13 years seems to be reasonable, although it is not possible to draw final conclusions because of the pronounced differences in the structure of the transition areas of the particular basins. It is therefore difficult to decide whether the day-to-day variations give too short or too long a period for the renewal of the water in the Baltic. It must always be borne in mind that in connexion with perpetual sea level fluctuation a considerable part of original Baltic water may return even perhaps the next day to the sea basin, and it is therefore hardly logical to talk of a complete renewal of the water. It must, moreover, be emphasized that in speaking of the renewal of the Baltic water it must be remembered that the deepest areas in the basin, such as the Gotland deep, where the density of the water is considerably higher than elsewhere in the Baltic, will not share in the renewal, unless special conditions necessary for the renewal are fulfilled. As a rule an extremely marked inflow of water from the Danish Sounds, as a consequence of special meteorological and hydrographic conditions, is needed to effect such a renewal. According to a rough estimate made by HELA [6] the average length of the renewal period for the bottom water in the Bornholm basin is 15 years, and for that in the Gotland basin 30 years.

Considering the total area of the Baltic and its extensive gulfs, 365,000 km^2 in all, it may be computed that the average water quantity involved every year in the renewal of the Baltic is 1,754 km^3. This water volume is almost twice as large as the water outflow determined for the Baltic by BROGMUS [3] according to the following equation of the annual water budget:

$$\begin{array}{lllll} \text{run-off} & + \text{ precipitation} & - \text{ evaporation} & + \text{ inflow} & = \text{ outflow} \\ 472\text{ km}^3 & + \ 172\text{ km}^3 & - \ 172\text{ km}^3 & + \ 472\text{ km}^3 & = \ 944\text{ km}^3. \end{array}$$

The first three terms on the left were determined by Brogmus with great care on the basis of observed data, while the amount of inflow and outflow was calculated using data for the mean salinity of the surface and bottom current respectively, starting from the general assumption that the quantities of water and salt transported by the two currents correspond to a state of equilibrium, where neither the total water quantity nor salinity change. This procedure means that the inexactitude inherent in a considerable number of different data will be contained in the values for inflow and outflow.

Soskin and Rosova [15] proceeded quite differently: starting from current observations in the Danish Sounds made during the years 1898—1944, they achieved the following results for water interchange between the North Sea and the Baltic:

$$\begin{array}{lcl} & \text{interchange} & \\ \text{fresh water supply} + & \text{inflow} & = \text{outflow} \\ 473\ \text{km}^3 + & 1187\ \text{km}^3 & = 1660\ \text{km}^3. \end{array}$$

The results of the present paper compiled for fresh water from the data computed by Witting [18] may be presented as follows:

$$\begin{array}{lllll} \text{run-off} + & \text{precipitation} - & \text{evaporation} + & \text{inflow} & = \text{outflow} \\ 467\ \text{km}^3 + & 206\ \text{km}^3 - & 182\ \text{km}^3 + & 1263\ \text{km}^3 & = 1754\ \text{km}^3. \end{array}$$

The fresh water supply amounts in this case to 491 km^3. This implies that the relevent data compiled by three authors using different methods vary by less than 5 per cent. These differences are thus insignificant for the total result.

The results reported in the current paper are fairly close to the data given by Soskin and Rosova. This is encouraging since the computations involved are based on completely different observations. There are other facts, too, that support the validity of the present results. The ratio between outflow and inflow is 1.39. This ratio does not deviate very much from the ratios of the salinity of the bottom and surface currents in the transition area. According to Thomsen [16], for instance, the average salinity for the bottom current at the light-vessel »Gedser Rev» in the years 1931—1960 was 14.6$^0/_{00}$, while the surface current had a salinity of 9.7$^0/_{00}$. The ratio between these values is 1.50. This author also gives salinity values for the bottom and surface current at the light-vessel »Halskov Rev» in the Great Belt, with an average of 22.2$^0/_{00}$ respectively 15.2 and the ratio 1.46. The coincidence between the three ratios is evident. For the sound the ratio between the salinity at the bottom and the surface may reach the value 2 or even higher, but this cannot be taken as evidence against the results of the present paper, since in the narrow transition area the ingoing current, corresponding to a pronounced water increase in the Baltic, reaches the surface and the salinity of the inflowing water masses is in fact considerably lower than that of the bottom current.

It might also be of interest to know whether inflow and outflow computed on the basis of sea level data correspond to the water transport through the Danish Sounds determined by other methods. Our results imply that for the Finnish coast there are, on an average, 177 days of increase and 188 days of decrease in sea level. Sea level data, of course, present a simplified picture of the incoming and outgoing currents, for it is not possible to determine the relative strength of these currents, and figures refer only to the resulting quantity of the water transport. Only approximate figures, therefore, can be hoped for.

For the days characterised by an increase in sea level an average resulting inflow through the transition area of 82,588 m^3/sec may be assumed, while the mean fresh water supply amounts to 15,570 m^3/sec. The total water increase is thus 98,158 m^3/sec. As regards the days with sea level decrease, the resulting outflow in the transition area is 107,984 m^3/sec, reduced by fresh water supply to 92,414 m^3/sec.

HELA [5] has examined a case of continuous water decrease in the Baltic. This decrease covered the time from 12.00 on November 25 to 12.00 on December 3, and amounted to 20.7 cm, corresponding to 2.59 cm per day. This value is only slightly larger than the average decrease in sea level, which is 3.2 cm for Degerby, according to Table 2, but must be reduced, if it is to be representave of the Baltic as a whole, by 20%, resulting thus in 2.56 cm per day. By different methods the velocity of the water transport from the Baltic was computed by HELA [5] for the above mentioned period of 8 days. Some of these results may be mentioned here:

1. A method elaborated by JACOBSEN [7] led to an average water transport velocity of 52,500 m^3/sec.

2. According to a method described by BERGSTEN [2] the corresponding value is 167,000 m^3/sec.

The considerable discrepancy between these two results clearly illustrates the difficulties connected with the problem.

3. Hela's own computation resulted in a transport velocity of 90,100 m^3/sec, which is rather close to the value reached in the present paper.

In spite of their considerable differences the three velocities were averaged, to give a result of 103,200 m^3/sec. This value, too, tends to support the result of the present paper, the deviation being of the magnitude of 10 per cent.

b. The Gulfs of Bothnia and of Finland.

The next step was a study of the total increase, and consequently decrease, in sea level in the Gulfs of Bothnia and Finland. According to Table 7 there is at Kemi a total yearly increase in sea level of more than 21 m, at Raahe of more than 17.5 m. At Pietarsaari the increase amounts to somewhat more than 14 m, at Mäntyluoto it exceeds 9 m, while at Turku it is 8 m and at Degerby 6 m, reaching a height of more than 11 m at Helsinki and, finally, at Hamina a height of fully 14.5 m. For the three sea level stations situated in the Bothnian Bay the increase and decrease in sea level thus amounts, on an average, to 17.5 m per annum. This water quantity, if taken as representative of the western parts of the Bothnian Bay, too, must surely have a marked effect upon the exchange and renewal of water in this bay, where the average depth is approximately 42 m. The theoretical result is thus in this case that the water masses would be more or less renewed in a period of less than 2.5 years.

At this point it may be interesting to inquire into the question of whether and to what degree the renewed water in the Bothnian Bay is water originating from the North Sea and the Danish Sounds ot whether it is composed mainly of south Baltic or perhaps Bothnian Sea water. Unfortunately only an approximate answer can as yet be given to this question. The time of water transport in the Baltic from the Danish Sounds to Utö was computed by the author [11], by means of salinity and sea level observations, as roughly 10 months. AHLNÄS [1] for the same area gives a mean water transport value of 3.4 cm per sec, computed from the effect of five large inflows of North Sea water through the Danish Sounds and the salinity at Utö. This estimate corresponds to a period of slightly less than 8.5 months. VOIPIO [17], from salinity data, gives rates of water transport along the east coast of the Bothnian Sea during particular years for a period of 21 years. These rates may be averaged to a mean velocity of 4.2 cm per sec. If the velocity in the Bothnian Bay is taken to be of a similar rate, the time needed for the water to proceed from Utö to Kemi is 6.5 months. The total time for the distance extending from the Danish Sounds to Kemi would, according to these estimates be 15—17 months. This indicates that during the 2.5 years needed for the renewal of the water in the Bothnian Bay, a considerable quantity of North Sea, or let us say Danish Sound water may at least theoretically reach the region outside Kemi.

For the Gulf of Bothnia as a whole, with an average depth of 60 m, the mean increase in sea level may be estimated as 12.0 m per year. At a rough estimate, 5 years would thus be needed to renew the water in this gulf.

For the Gulf of Finland the renewal time seems to be still shorter. The average depth of this basin may be estimated as 38 m and the mean sea level increase as a good 11.5 m per year. The more or less total renewal of water in the Gulf of Finland may therefore be expected to take somewhat more than 3 years. Although the above results can only be considered as preliminary, they indicate that the renewal of the water in the two large gulfs enclosing Finland occurs considerably more rapidly than in the Baltic basin as a whole. It would, nevertheless, be wrong to talk of a total renewal of water in this connexion. With changing meteorological conditions the original water of the gulfs may return, at least in part, within a few days. On the other hand, in individual places where pollution of the water is very marked — as a result, for instance, of an industrial plant in the vicinity — rapid mixing with the uncontaminated or only weakly contaminated water of the surrounding region may be fairly effective.

It has been stressed several times that all the results arrived at above are only approximate estimates. The data on water salinity in different parts of the Baltic Sea collected in connexion with hydrographic cruises may offer an opportunity of checking the above results. There are, of course, considerable seasonal and occasional fluctuations in salinity and, in addition, there was in the 1940's a distinct tendency towards an increase in salinity in the whole basin. If only approximate results are required, the average data given by GRANQVIST [4] are sufficient for the computation of the salinity of the water masses penetrating into the separate parts of the Baltic. Insofar as we accept the hypothesis that salinity remains unchanged from one year to another, the higher salinity characteristic of the water entering the Baltic through the Danish Sounds and the separate basins through the corresponding transition areas must be counterbalanced by the fresh water brought into the region by river discharge, and as the consequence of the effect of precipitation minus evaporation. The fresh water value was computed by WITTING [18] and it is substracted from the total increase in sea level according to the results of this paper. If the total increase (in km^3) is Q, the salt water increase is $Q - Q_f$, where Q_f (in km^3) refers to the corresponding quantity of fresh water. Denoting the average salinity in the basin by S_a and the mean salinity of the sea water entering into this basin by S_b we get thus

$$Q \cdot S_a = (Q - Q_f) \cdot S_b$$

The values for the quantities Q, Q_f, S_a and S_b characteristic of the particular basins are given in Table 9.

Table 9. The total water increase (Q) in km^3, the increase in fresh water (Q_f) in km^3, the average salinity (S_a) in pro mille in the different basins and the mean salinity of the penetrating water (S_b) in pro mille.

	Q	Q_f	S_a	S_b
Bothnian Bay	649	124	3.5	4.3
Gulf of Bothnia	1243	226	5.0	6.1
Gulf of Finland	339	117	6.0	9.2

The salinity of 4.3‰ corresponding roughly to the salinity at a depth of 20 m at the hydrographical station F17 (63°34' N., 20°34' E.) in the Quark indicates that most of the water entering the Bothnian Bay is characteristic of this transition area. The salinity of 6.1‰ is also representative of the average conditions at a depth of 50—60 m in the region south and west of the Aaland Island. For the Gulf of Finland, which unlike the Gulf of Bothnia is an immediate continuation of the Baltic proper, the salinity of the penetrating water has a slightly lower value than that of the surface water at »Gedser Rev». The salinity correspond, on the other hand, to that typical of the bottom layers in the vicinity of the approaches to the Gulf of Finland. In all the three cases considered above, the salinity of the penetrating water is closely related to that of the deep water in the corresponding transition areas.

The above attempt — to compute, on the basis of day-to-day changes in water level, the »renewal» time of the water in the Baltic and its large northern gulfs — must be considered as an initial estimate. It has always to be borne in mind that the water in a basin can never be completely renewed. The figures arrived at in this paper may, however, be used as an indication of the period necessary for a more or less total renewal of the water in the research areas.

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