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CURRENTS IN THE SUUR STRAIT AND THEIR ROLE IN THE NUTRIENT EXCHANGE BETWEEN THE GULF OF RIGA AND THE BALTIC PROPER

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Abstract. Investigations of currents, winds, and some hydrophysical and hydrochemical parameters in the sea water were carried out in the Suur Strait within the Gulf of Riga Project in 1993—94. One of the aims of the project was to quantify the water and nutrient exchange between the Gulf of Riga and the Baltic Proper.

The water flow in the strait was found to be uniform, but the temporal variability of the currents was quite complex. The currents are governed mostly by the wind stress and the differences in the sea level. The maximal measured velocities were up to $1\ \mathrm{m \cdot s^{-1}}$, the averages being about $0.19\ \mathrm{m \cdot s^{-1}}$. The total volume of the water running through the strait in both directions is about $100\ \mathrm{km^3 \cdot yr^{-1}}$. According to previous studies the outflow ought to be predominant under typical conditions. However, in our case the net exchange was $29—37\ \mathrm{km^3 \cdot yr^{-1}}$, directed into the Gulf of Riga. The analysis showed the behaviour of spectra to follow the "$-5/3$ law". The only significant peak above the background spectra is at 12.5 h (M_2-tide) and some insignificant maxima were found at 1.5, 4.8, 27, and 30 hours and 3—4 days. The correlation between the winds and currents was 0.85 in autumn 1993, but evidently both the winds and sea levels should be considered in the further studies. Besides the seasonality the nitrogen regime in the Suur Strait area is influenced by the currents: outflowing currents rise the nitrogen contents; the rise in phosphorus contents is mostly related to storm events. The field work will be continued up to the end of 1995 followed then by thorough interpretation and modelling. The future aim is to present more precise water flow and nutrient exchange characteristics in the strait and to work out a model for calculating the water exchange from the wind- and sea-level data and a balance model for water and nutrients in the Gulf of Riga.

Key words: currents, spectra of currents, water exchange, nutrients, Gulf of Riga.

INTRODUCTION

The measurements of currents and nutrient contents in the Suur Strait are far more important than it provisionally might be seen. Namely, a considerable portion of the water and nutrient exchange between the Gulf of Riga and the Baltic Proper proceeds through this strait.

The Gulf of Riga is a semi-enclosed water body with an area of $17\,913\ \mathrm{km^2}$, a volume of $406\ \mathrm{km^3}$, and the maximal depth of 52 m (Baltic

Marine Environment..., 1986). It is hardly connected via the straits with the Baltic Proper (being thus a kind of smaller counterpart of the Baltic itself). The main connection, the Irben Strait, has a width of 27 km, sill depth of about 21 m, and an area of the cross-section of 0.37 km^2. The Suur Strait is 6 km wide and its maximal depth is 20 m. (The minimal sill depth, about 5—6 m, is located to the north of the strait, but it still belongs to the system of these straits.) The cross-section area is 0.04 km^2, which is about 10 times less than in the Irben Strait. However, according to our preliminary estimations as well as previous ones, the share of the strait in the water renewal of the Gulf of Riga is probably more than 20%.

Ecologically the Gulf of Riga acts as a transition zone between the heavily loaded riverine inflow and the less polluted waters of the Baltic Proper. The nutrient conditions therefore differ substantially from those of the Baltic Proper featuring especially high nitrogen contents and hypothetical phosphorus-limiting conditions for phytoplankton. The influence of the heavily polluted Gulf of Riga on the water quality of the Baltic Proper depends on the efficiency of nutrient trapping within the Gulf and on the intensity of the water exchange processes via the straits. In our case also the interactions with the waters of the Väinameri area, which seems to be another transition zone, should be considered.

The first dated measurements of currents in the Suur Strait were performed by Mey (1922). Mardiste (1976; Мардисте, 1975) investigated the hydrological features of the Väinameri, including the currents in the straits. He (Mardiste, 1976) and Petrov (Петров, 1979) also proposed estimates of the water exchange through this strait. According to Mardiste the net exchange was about $-50\ \mathrm{km^3 \cdot yr^{-1}}$ and according to Petrov $-38\ \mathrm{km^3 \cdot yr^{-1}}$ (outflows both). At the same time the net exchange via the Irben Strait was found to be $6\ \mathrm{km^3 \cdot yr^{-1}}$ by Petrov and the net exchange of the Gulf of Riga (no differentiation between two straits) $-32\ \mathrm{km^3 \cdot yr^{-1}}$ according to Pastors (Пасторс, 1963). Still, these studies were carried out nearly 20 years ago and were based on a relatively small amount of field data and some indirect estimations (e.g. empirical relationships between the winds and currents, volume changes calculated by sea-level data, etc.). The number of the nutrient analyses made on this strait for the period 1968—92 is only 30 while several hundred analyses were made for the Väinameri (except Matsalu and Haapsalu bays).

As access of western researchers to the Gulf of Riga was prohibited for a long time, the scientific information on the Gulf remained relatively deficient and difficult to use. Therefore, extensive investigations within the framework of the international Gulf of Riga Project were started in 1993. One sub-project deals with the problems of water and nutrient exchange and the aim of the sub-sub-project under discussion has been set to investigate the currents and matter exchange in the Suur Strait. Simultaneously with our investigations in the straits research work was carried out by other working groups as well, e.g. expeditions of the Finnish R/V *Aranda* and the Estonian *Kiir* in the open part of the Gulf of Riga.

In this paper the first results of our nearly two-year-long work are presented. Some preliminary information was presented already in papers by Astok et al. (1995) and by Suursaar & Kullas (1995). The field work will be continued up to the end of 1995, followed by careful data processing, interpretation, and modelling. Thus, the aim of this paper is to: (1) present some introductory information on the project, (2) investigate the features and variability of the currents in the strait, (3) describe the nutrient regime, especially its relationships to the hydrophysical processes in this area, and (4) discuss the preliminary estimates of the water exchange via the strait.

FIELD MEASUREMENTS

The main part of the field work was done in five expeditions, each lasting two to four weeks (see also the Table). In order to investigate the currents and the water exchange through the Suur Strait (Fig. 1) two recording current meters (Aanderaa RCM-7 and RCM-4) were used, providing data on the directions and velocities of currents as well as water temperatures and salinities. Between the expeditions one current meter was usually left in the strait for autonomous long-term recordings. (The long-term recordings were actually carried out for a longer time than reflected in the Table, but the recordings were partly lost due to different technical problems.) The recording interval was usually set on 10 min, except the third expedition (5 min) and the long-term measurements after the fifth expedition (30 min). During the first four expeditions both the current meters were moored at the same place in the strait (58°33′0 N and 23°27′8 E), about a mile from Viirelaid Isle. The upper current meter was at a depth of 3—6 m and the lower one at about 12 m. During the fifth expedition both the instruments were moored at 6 m, but one was at the opposite side of the strait, about a mile off Virtsu coast (58°33′9 N and 23°29′2 E). The spatial structure of the currents was also investigated by salinity, temperature (CTD), and velocity profilings that were carried out along the cross- and longitudinal sections of the strait in spring and autumn 1993.

Another task was to follow the nutrient fluxes in the strait and to update the matter balance of the Gulf of Riga. Therefore, water samples for analysing nutrient contents (P_{tot} and N_{tot}) were collected on board of R/V *Junga* (first through fourth expeditions) and *Lest* (fifth expedition). The samples were taken using Nansen bottles three times a day at two layers (0—1 and 12—16 m), mostly at the station of Viirelaid. Components of nutrients ($P\text{-}PO_4$, $N\text{-}NO_2$, $N\text{-}NO_3$, $N\text{-}NH_4$) were measured in the similar

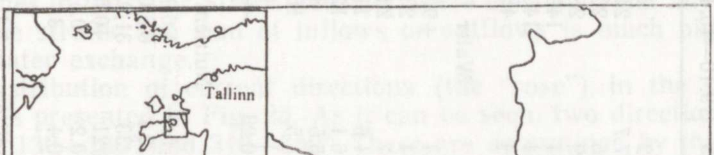

Fig. 1. Suur Strait area. Locations of Viirelaid (x) and Virtsu (+) mooring stations and the cross section (–).

Measurements in the Suur Strait in May 1993—Nov 1994

	Expedition code[a], year, and date							
	E1 1993 5—28. 05	E2 1993 19.10—15.11	E3 1994 24. 01—8. 02	L3 1994 4—24. 03	E4 1994 9. 05—2. 06	L4a[b] 1994 2. 06—2. 09	L4b[b] 1994 2. 06—2. 09	E5 1994 21.10—19.11
No. of mooring stations	2	2/1	2	1	2	1	1	2
Current measurements, days	17.7	24.2	11.0	19.9	22.9	35.8	55.4	15.9/29.3[c]
CTD (ACM) profilings	46	20	—	—	—	—	—	—
O_2/T profilings	19	28	5	—	15	—	—	23
No. of P_{tot} analyses	104	140	72	3	130	—	—	152
No. of N_{tot} analyses	104	140	72	3	130	—	—	152
No. of other nutrient analyses	44	48	40	12	104	—	—	134
Water flow characteristics								
Max. velocity, $cm \cdot s^{-1}$	+54	+90	−24	−33	+46	−79	—	+95
Mean velocity of inflow, $cm \cdot s^{-1}$ [d]	14	23	6	7	14	23	21	15
Mean velocity of outflow, $cm \cdot s^{-1}$ [d]	7	23	7	10	10	14	22	22
Duration of inflows, days [d]	11.6	11.3	9.8	5.4	21.1	44.4	11.1	4.7/12.1[c]
Duration of outflows, days [d]	6.1	12.9	1.2	14.5	1.8	14.3	21.5	11.2/17.2[c]
Estimate of water inflows, km^3	5.5	8.8	1.8	1.1	10.3	31.8	8.2	8.4
Estimate of water outflows, km^3	1.5	10.4	0.3	4.5	0.3	6.2	16.0	13.6
Correction coefficient, k	1	1	0.9	0.9	1	0.9	1	1
Estimate of net exchange, $km^3 \cdot day^{-1}$	+0.23	−0.07	+0.14	−0.17	+0.44	+0.44	−0.24	−0.16
Nutrient statistics (in μM)								
P_{tot} average (surface/bottom)	1.1/0.9	1.6/1.5	1.4/1.8	—	0.8/0.8	—	—	1.3/1.4
P_{tot} st. dev. (surface/bottom)	0.4/0.1	0.8/0.7	0.2/1.1	—	0.2/0.2	—	—	0.4/0.6
N_{tot} average (surface/bottom)	51/33	31/25	43/36	—	22/20	—	—	35/33
N_{tot} st. dev. (surface/bottom)	38/21	10/5	22/7	—	6/5	—	—	5/6
PO_4 average (all data)	0.2	0.5	0.8	—	0.1	—	—	0.6
NO_3 average (all data)	<0.4	3	11	—	0.4	—	—	6

Notes: [a] Letter E in the code designates a complex expedition, and L marks measurements between the expeditions;
[b] L4a, cuts of proper data; L4b, cuts of records where the flow characteristics are estimates by partly invalid data;
[c] For Virtsu and Viirelaid stations separately;
[d] Weighted mean (if two current meters were used).

way at least on one particular day of a week during the expeditions. The chemical analyses were performed by the laboratory of the Environmental Engineering Institute, Tallinn Technical University. Altogether about 1600 analyses of nutrients were made in 1993—94. In addition, regular vertical soundings of O_2 and temperature were performed using a Marvet Fluids analyser and Secchi measurements of water transparency were carried out. During the autumn expedition in 1993 and since autumn 1994 the Aanderaa automatic weather station was erected on Viirelaid Isle providing data on wind directions, speeds, gusts, and air temperatures every 10 min. The meteorological data from the weather station of Virtsu (having resolution of 8 h) could be used for earlier expeditions.

In conclusion it could be said that these are evidently the most extensive investigations ever made in this part of the sea, including the unique expedition in winter 1994, when the current meters were "hanged" from the ice cover and the water samples were taken regularly from the ice as well.

RESULTS AND DISCUSSION

1. Spatial and temporal variations of currents

The main driving force of currents in the Suur Strait is said to be the (mainly local) wind force: usually W—NE winds give rise to SSE currents and E—SW winds evoke NNW currents (see e.g. Mardiste, 1976). The second important factor is the sea-level differences caused by the large-scale wind and pressure fields above the Baltic Proper. Third comes the positive fresh-water balance caused by the riverine inflow averaging about 32 km^3 a year. As the SW winds and anti-cyclonic general circulation scheme statistically prevail in the Baltic, it could be presumed that the inflowing currents should prevail in the Irben Strait and the outflowing ones in the Suur Strait. Actually, there does not exist any constant flow in the straits: the sum of inflows or outflows is much bigger than the net water exchange.

The distribution of current directions (the "rose") in the station of Viirelaid is presented in Fig. 2*a*. As it can be seen, two directions clearly prevailed: 130—160° and 340—350°. These are determined by the position and bottom topography of the strait. The difference in these lines (about 10—20°) could be explained by the influence of Viirelaid Isle. The rose built for the eastern (Virtsu) station in autumn 1994 (Fig. 2*b*) shows the same directions for the outflow, but 160—180° for the inflow, i.e., unlike the previous ones the rose is bent out in the opposite direction. The inflowing currents prevailed in 1993—94 (at least during our expeditions). According to the former studies the outflow from the Gulf of Riga should be bigger. One explanation could be that there were quite abnormal weather conditions during the expeditions in 1993: Fig. 2*c* shows the long-term average wind-rose in Virtsu (a similar rose has also been used by Mardiste and Petrov in their water exchange calculations), and Fig. 2*d* shows the wind rose in autumn 1993, when winds between S and W must have strongly prevailed in typical conditions.

Some flow statistics are presented in the Table. According to our investigations the weighted gross-mean velocity module in the Suur Strait is 19 cm · s^{-1}. This value is generally in accordance with previous studies (e.g. Mardiste, 1976). According to Petrov (Петров, 1979) the mean velocities in the Irben Strait are about 6 cm · s^{-1}. Thus, the smallness of the Suur Strait compared to the Irben Strait is somewhat compensated by the larger velocities. The maximal velocities reported so far for the Suur Strait were presented by Mey (1922) as 103 cm · s^{-1}. Evidently, the longer

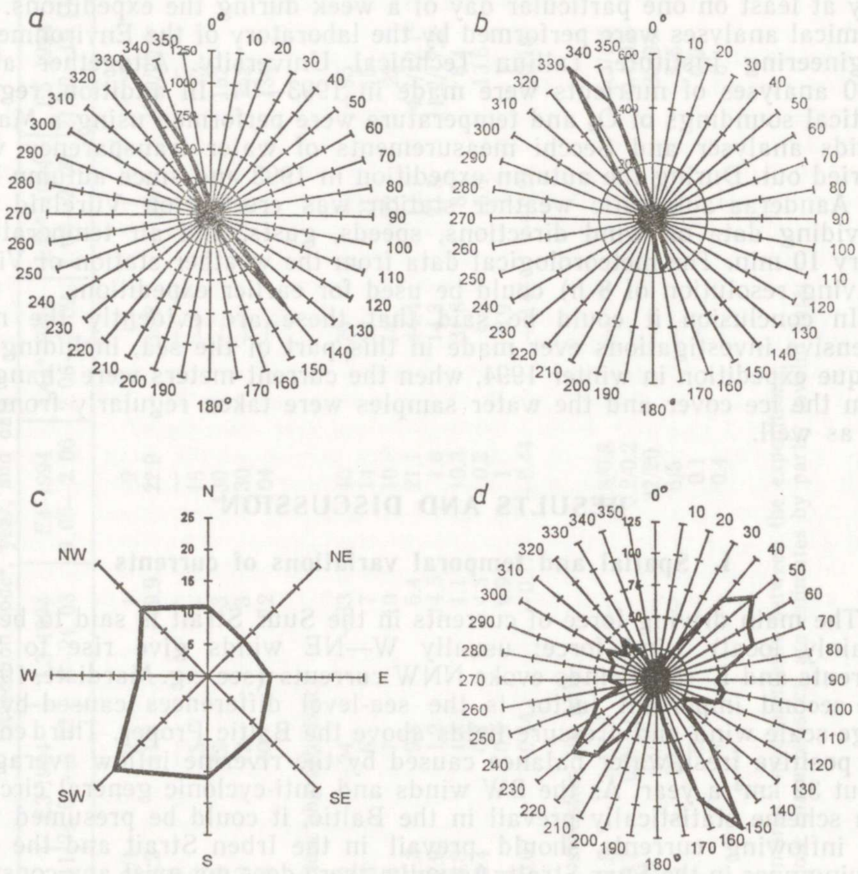

Fig. 2. The distribution of current directions in Viirelaid station, 6 m, 31 Oct—16 Nov 1994 (*a*); Virtsu station, 6 m, 31 Oct—16 Nov 1994 (*b*); long-term mean distribution of wind directions at Virtsu (*c*); wind directions in Viirelaid Isle in Oct—Nov 1993 (*d*).

the period we measure (especially during the autumn storms), the bigger is the chance to "beat" the record. The maximal values measured by our team were 92 cm · s^{-1} for the outflowing current and 95 cm · s^{-1} for the inflowing current. (Unfortunately, the almost 2-month-long records of the dramatically stormy autumn of 1994 were lost.) During the storm on 9—14 November 1993 the volume of the outflow was about 8 km^3. For comparison: the mean total river inflow to the Gulf of Riga is about 32 km^3 a year, the Pärnu River has an annual runoff of about 2 km^3.

Spatial structure of currents. Generally, it is too much to assume that the water flow in the straits is isotropic in three dimensions. On the other hand, it would be too tedious to follow all the flow structures under all possible conditions. Therefore, it is important to find out whether we can assume the flow to be nearly uniform over the entire cross section, or whether we should find out certain relationships between the currents measured in some point and the water flows over the whole cross section. In that sense the Suur Strait is a much "easier case" than the Irben Strait, as in the latter both inflows and outflows can be simultaneously observed in different parts of the strait. In general the vertical distribution of velocities (epure) is not linear, as it also appeared from velocity

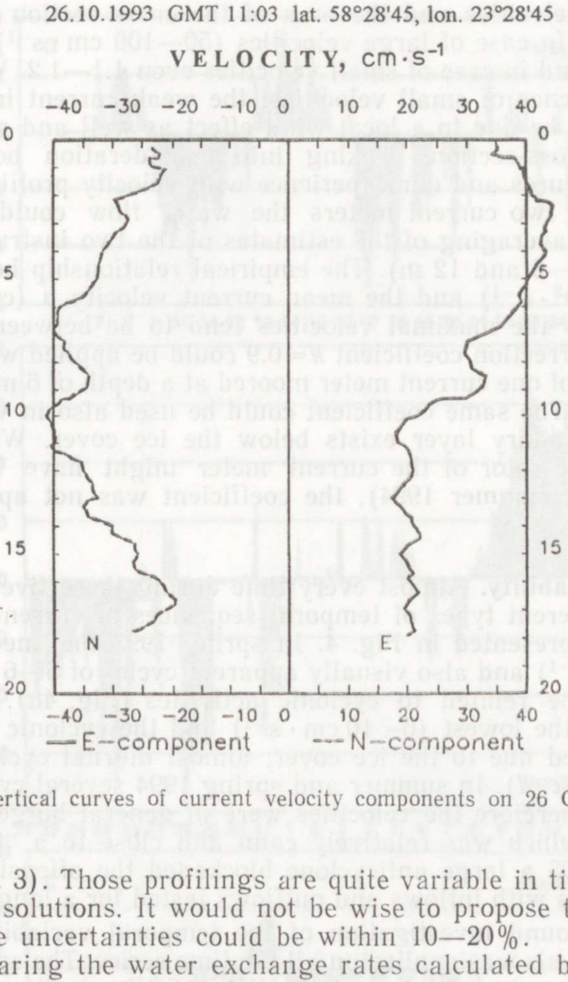

Fig. 3. Vertical curves of current velocity components on 26 Oct 1993.

profilings (Fig. 3). Those profilings are quite variable in time and do not show any firm solutions. It would not be wise to propose too pretentious formulas as the uncertainties could be within 10—20%.

When comparing the water exchange rates calculated by two parallel instruments it appears that the bigger the velocities are, the less is the difference. In winter 1994 the mean daily water exchange was 0.1 and 0.19 $km^3 \cdot d^{-1}$ according to the upper and lower current meter, respectively (the difference between the bigger and smaller value is 47% from the bigger one). In spring 1993 the corresponding figures were 0.32 and 0.25 $km^3 \cdot d^{-1}$ (the difference is 22%); in spring 1994, 0.58 and 0.47 $km^3 \cdot d^{-1}$ (18%). In autumn 1993 the difference (0.92 and 0.77 $km^3 \cdot d^{-1}$) was 17% only for the 7.7-day period when both the current meters were in order. In autumn 1994 the figures for the common period were −0.49 $km^3 \cdot d^{-1}$ according to the western current meter and −0.38 $km^3 \cdot d^{-1}$ for the eastern one, producing a difference of 23%. The corresponding correlation coefficients were good lying between 0.69 and 0.88, testified also by vector plots. Therefore we can assume that the flow is mostly unidirectional over the whole cross section and velocity differences averaging around 20% may occur in different layers and parts of the strait. Still, there is a need to specify the spatial differences over the cross section in the expeditions planned for 1995.

Mardiste (Мардисте, 1975) proposed two different regression models for calculating the inflows and outflows from the surface current measured in the middle of the strait. However, a shortcoming seems to be big intercepts of regression lines, producing in case of zero velocities simultaneously 0.09 $km^3 \cdot d^{-1}$ of inflows and 0.18 $km^3 \cdot d^{-1}$ of outflows. In the case of medium velocities ($v = 20-25$ $cm \cdot s^{-1}$) it is possible to simply multiply the velocities and the area of the cross section for getting the flow volumes. In case of large velocities (50—100 cm · s^{-1}) the coefficient is 0.85—0.95 and in case of small velocities even 1.1—1.2. We do not agree to such preference of small velocities: the weak current in the middle of the strait may be due to a local wind effect as well and not to represent the whole cross-section. Taking into consideration both the abovementioned features and our experience with velocity profilings and measurements with two current meters the water flow could be calculated simply by the averaging of the estimates of the two instruments (located at depths of 3—6 and 12 m). The empirical relationship between the flow volume Q ($km^3 \cdot d^{-1}$) and the mean current velocity v ($cm \cdot s^{-1}$) is then $Q = 0.035\,v$. As the maximal velocities tend to be between the depths of 2—7 m, the correction coefficient $k = 0.9$ could be applied when calculating from the data of one current meter moored at a depth of 6 m (consequently, $Q = 0.0315\,v$). The same coefficient could be used also in winter, when an additional boundary layer exists below the ice cover. When there were doubts that the rotor of the current meter might have been entangled (autumn 1993, summer 1994), the coefficient was not applied (see also the Table).

Temporal variability. Almost every time during these five expeditions we registered different types of temporal sequences of current vectors. Some of them are presented in Fig. 4. In spring 1993 the medium velocities (10—14 cm · s^{-1}) and also visually apparent cycles of 5—6 days prevailed, which could be related to cyclonic activities (Fig. 4*a*). In winter the velocities are the lowest (6—10 cm · s^{-1}) and the cyclonic movements are less represented due to the ice cover; almost diurnal cycles could rather be seen (Fig. 4*c*, *d*). In summer and spring 1994 several cyclones occurred in sequence, therefore the velocities were in general bigger than those in spring 1993, which was relatively calm and close to a "typical spring". In autumn 1993 a large anticyclone blockaded the offensives of cyclones and the periods with inflows and outflows lasted for a long time (Fig. 4*b*).

For a profound investigation of the temporal variability of currents spectrum analysis was applied on all the time series. The spectra presented in Fig. 5 were calculated from the NNW—SSE-velocity component. The variance of this axial component of the velocity vector fluctuations comprises about 92—97% from the total variance, leaving only a small share for the perpendicular component. The values presented are the calculated ones (not smoothed) and normalized so that the total energy is equal to 100(%). As the measuring interval was 10 min, the harmonic of the shortest term could have a period of 20 min (72 cycles per day). All the spectra show a decreasing kinetic energy with an increasing frequency. The "red-noise" (or background) spectra will follow the so-called −5/3 law if the logarithmic scales are applied (i.e. the slope is −5/3; see e.g. Ozmidov, 1965). The feature is apparent in its purest way in Fig. 5*d*, *e*. The slope is not so steep in frequencies less than 1 cpd (cycles per day) and more than 30 cpd in some cases. The isolated peaks arising above the backround spectra of currents mark the energy concentration in the motions at those frequencies. The spectra calculated from the wind data (two components) in autumn 1993 showed similar background spectra up to 30 cpd, but no considerable peaks appeared. The investigated spectra of the ENE—WSW (perpendicular) velocity component of currents did not show so steep slopes of background spectra (due to narrowness of the strait the share of large-scale motions is relatively small) and absence of significant peaks (see also Fig. 5*f*).

According to literature (e.g. Mälkki, 1975) the inertial motions (having a period of about 14 h in our latitude) and the diurnal (K_1, O_1) tides

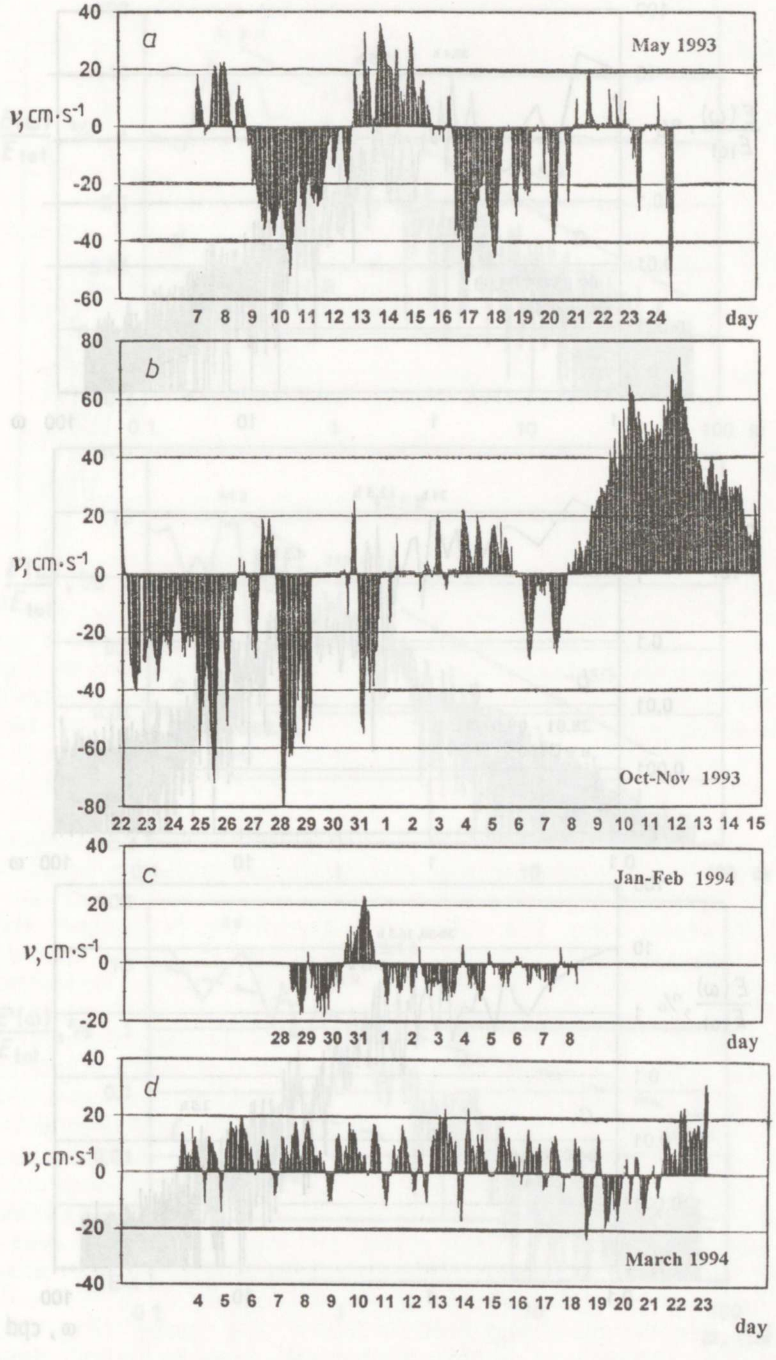

Fig. 4. Temporal sequences of NNW—SSE components of velocity vectors: 7—25 May 1993, 12 m (*a*); 22 Oct—15 Nov 1993, 6 m (*b*); 28 Jan—8 Feb 1994, 3 m (*c*); 4—23 March 1994, 6 m (*d*).

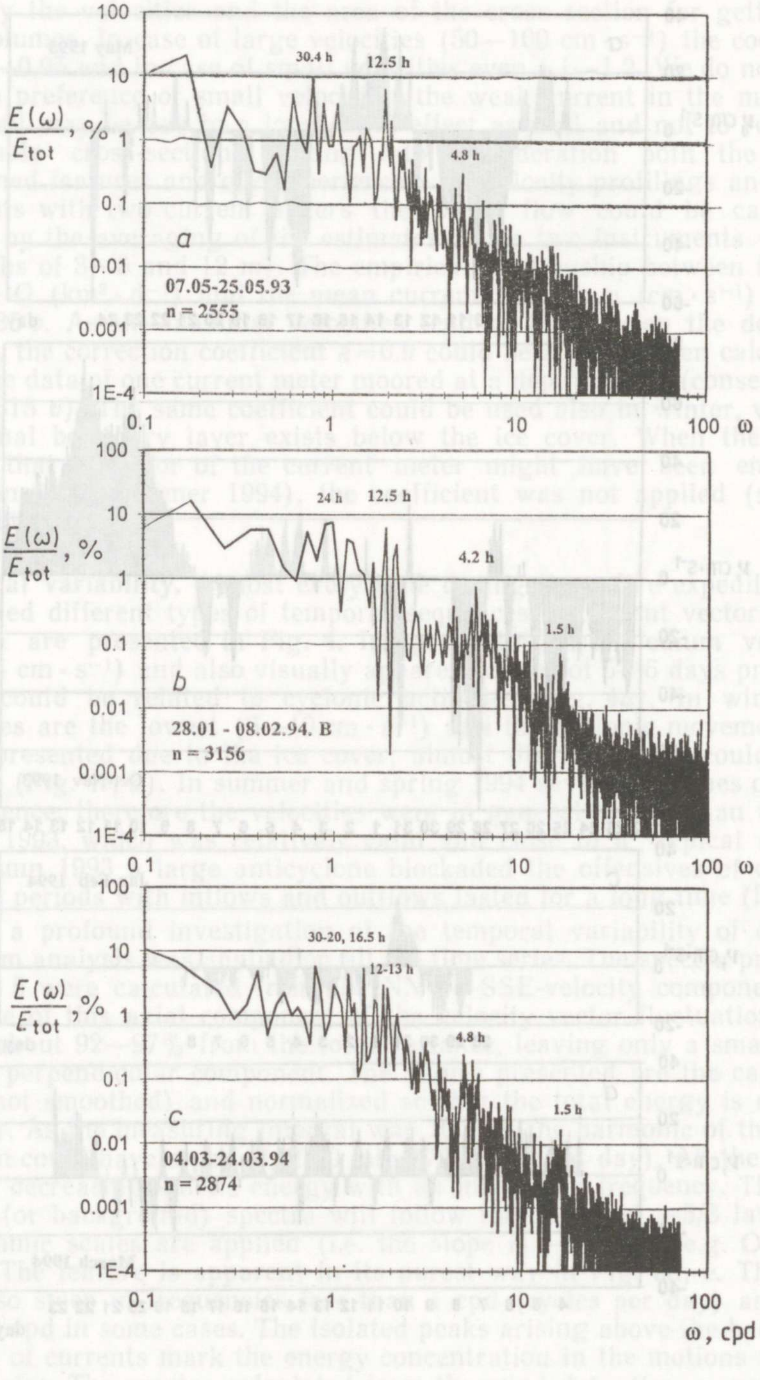

Fig. 5. The normalized energy spectra calculated from NNW—SSE components of current velocity fluctuations of different expeditions in 1993—94. The letter B in legend means near-bottom (12 m) series. The periods of prominent peaks are marked above the graphs; the slope proportional to −5/3 at *d* and *e*, and the approximate position of the respective spectra of the ENE—WSW component is shown in *f*.

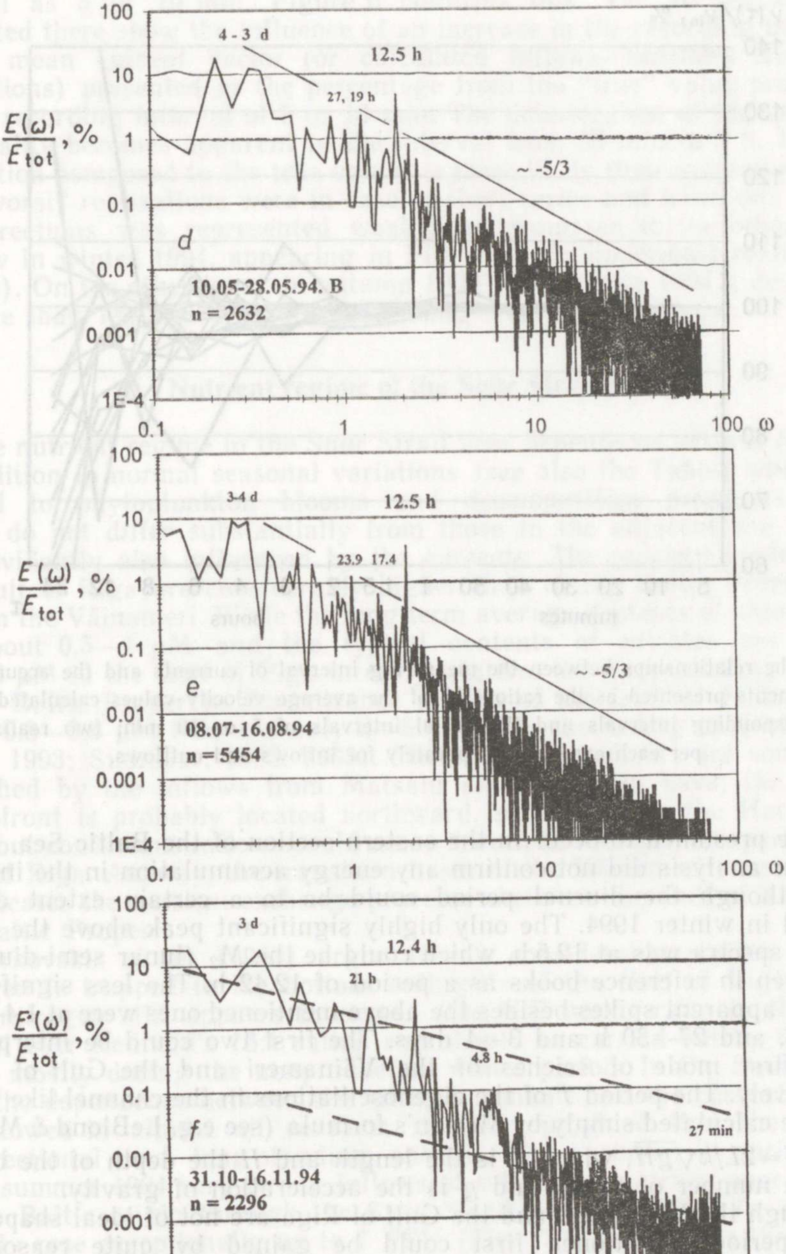

Fig. 5. Continued.

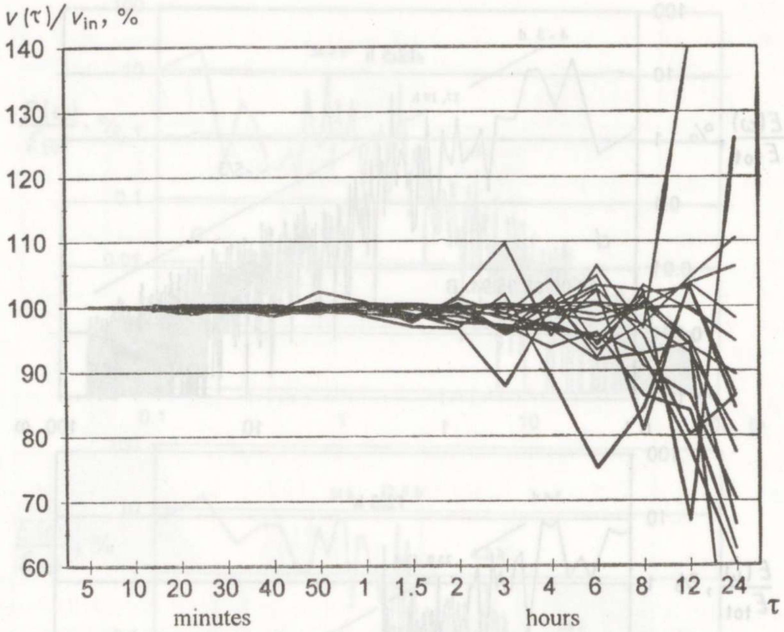

Fig. 6. The relationships between the measuring interval of currents and the accuracy of measurements presented as the ratio (%) of the average velocity values calculated using the corresponding intervals and the initial intervals of 5 or 10 min; two realizations per each expedition separately for inflows and outflows.

could be presumed to occur in the eastern section of the Baltic Sea. However, our analysis did not confirm any energy accumulation in the inertial period though the diurnal period could be to a certain extent differentiated in winter 1994. The only highly significant peak above the background spectra was at 12.5 h, which could be the M_2 (lunar semi-diurnal) tide given in reference books as a period of 12.42 h. The less significant, but still apparent spikes besides the above-mentioned ones were at 1.4—1.6, 4.5—4.8, and 27—30 h and 3—4 days. The first two could be interpreted as the first mode of seiches of the Väinameri and the Gulf of Riga, respectively. The period T of the eigenoscillations in the channel-like basin could be calculated simply by Merian's formula (see e.g. LeBlond & Mysak, 1978) $T=2L/k\sqrt{gH}$, where L is the length and H the depth of the basin, k is the number of mode, and g is the acceleration of gravity.

Though the Väinameri and the Gulf of Riga are not of ideal shape, the seiche periods mentioned first could be gained by quite reasonable generalized basin measures of $L=20-30$ km and $H=6-10$ m, and the second ones by $L=110-130$ km and $H=18-22$ m.

Seiches are the most apparent in winter and spring (Fig. 5*a*, *c*), in other seasons the strong cyclonic movements tend to overshadow them. Also the peaks at 27 and 30 h (Fig. 5*a*, *c*, *d*) could be seiches, but in the system of the Gulf of Finland—Baltic Proper. (The corresponding well-known seiche has a period of 27.4 h.) Or, they could be low-frequency effects generated by the interaction between the cyclonic forces with the bottom topography of the shallow coastal zones. The peaks at 3—4 days (Fig. 5*d*, *f*) are of atmospheric cyclonic origin.

The given spectra show that the most substantial portion of the kinetic energy lays in the low frequencies. For investigating merely the water exchange it is not necessary to measure currents with such a small time interval as 5 or 10 min. Figure 6 confirms this. The 16 realizations presented there show the influence of an increase in the recording interval on the mean current vector (or calculated inflows—outflows over the expeditions) presented as the percentage from the "true" value produced by the recording interval of 5 or 10 min. The deterioration of the measuring quality becomes apparent in the interval from 50 min to 2 h. Underestimation compared to the true values is more likely than overestimation. The "worst" realizations were in case of short series and when one of the two directions was represented weakly as compared to the other (e.g. outflow in winter 1994, appearing in Fig. 6 as the uppermost realization at 12 h). On the other hand, in autumn 1993 and summer 1994 a deviation of more than 1% appeared only beginning from a 2-h interval.

2. Nutrient regime of the Suur Strait area

The nutrient regime in the Suur Strait area depends on several factors. In addition to normal seasonal variations (see also the Table) which are related to phytoplankton blooms and decomposition processes (and which do not differ substantially from those in the adjacent sea areas) it is evidently also influenced by the currents. The nutrient contents in the Gulf of Riga are considerably higher than in the Baltic Proper and even in the Väinameri. While the long-term average contents of phosphates are about 0.5—1 μM and the typical contents of nitrates are about 10—15 μM in the Gulf of Riga in early winters, the corresponding values in the Baltic Proper in the entrance section of the Gulf of Finland are about 0.3—0.6 μM PO_4 and only 3—5 μM NO_3 (according to Yurkovskis et al., 1993; Suursaar, 1992, 1995). These sharp gradients are somewhat smoothed by the inflows from Matsalu and Haapsalu bays; the major chemofront is probably located northward, somewhere in the Hari Kurk area, but continuous inflows could move it even to the northern part of the Gulf of Riga. Anyway, the transition basin of the Väinameri considerably complicates the nutrient exchange processes between the Gulf of Riga and the Baltic Proper.

Yurkovskis et al. (1993) argue that a considerable portion of the nitrogen is trapped to the bottom sediments of the Gulf of Riga. However, nitrogen still appears in excess (the N:P molar ratio in the Gulf is well over Redfield's 16:1 ratio) and should be carried out by the currents, mostly during the nonproductive winter period. In the Suur Strait area the dependence between the nitrogen content and the currents could be followed in almost all seasons; however, provided that the flow is unidirectional and long-standing enough. For example, in spring and early summer 1994 very strong inflows of saline and nutrient-poor waters of the Baltic origin through the Suur Strait occurred (Fig. *7c*, *d*). The salinity rose exceptionally up to 7 PSU (Fig. *7a*). As soon as the inflow abated, the salinity dropped and the nitrogen content jumped up (note the dates 15—16 May, 20 May and 31 May—1 June in Fig. *7a*, *b*, *c*, *d*). A close negative correlation can be observed between Figs. *7a* and *7b*. The same phenomena, though not so prominently, could be followed during some other expeditions, too. Consequently, the nitrogen regime in the Suur Strait area depends on the direction (and duration) of currents.

The binding and releasing processes of phosphorus are allegedly almost balanced in the Gulf of Riga (Yurkovskis et al., 1993). According to our investigations a strong release of phosphorus compounds with the suspended material took place in the Suur Strait area during (autumn) storms. Figure *8b* shows a gradual increase in the phorsphorus contents after each storm event, marked by gaps in the sampling schedule. A simultaneous decrease in the water transparency is displayed in Fig. *8a*.

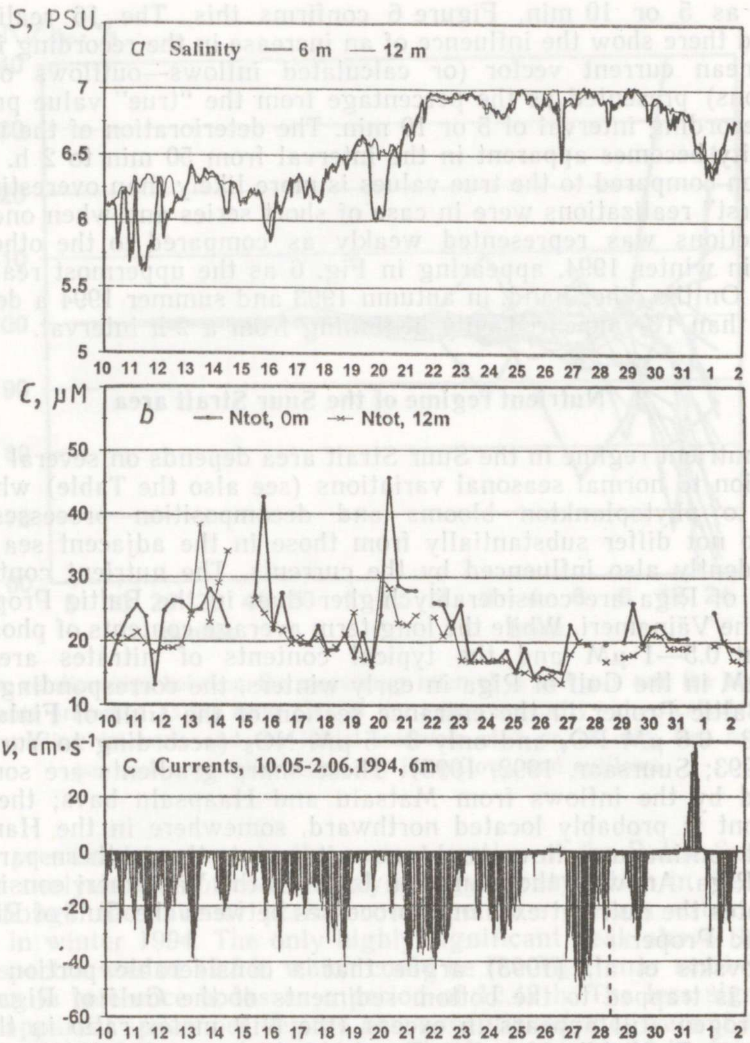

Fig. 7. Temporal variations in salinity (*a*), total nitrogen contents (*b*), and NNW—SSE components of velocity vectors (*c* and *d*) on 10 May—2 June 1994. The common periods for upper and lower current meters are marked.

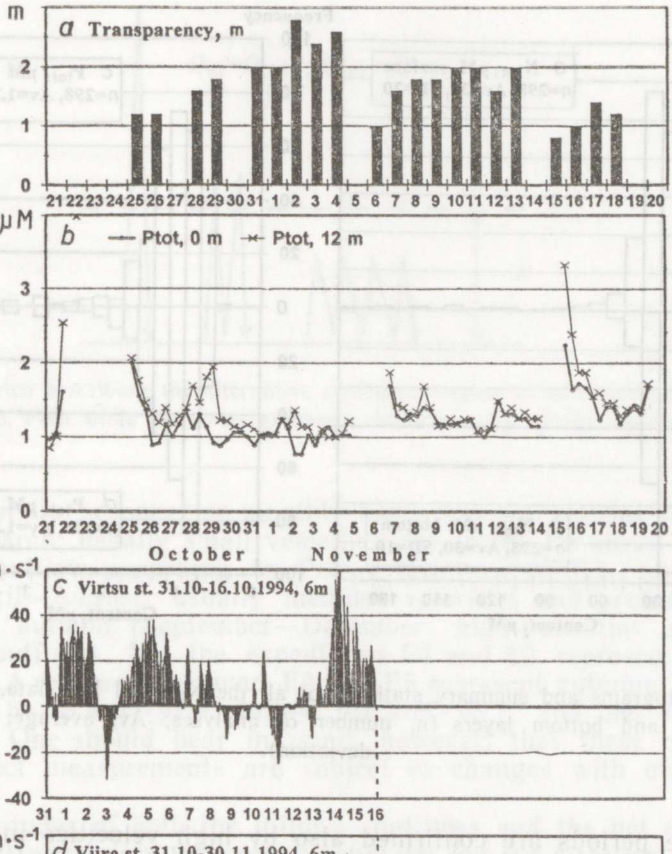

Fig. 8. Temporal variations in water transparency (*a*) and total phosphorus contents (*b*) on 21 Oct—20 Nov 1994; and temporal sequence of NNW—SSE components of velocity vectors in the Virtsu (*c*) and Viirelaid (*d*) stations. The common periods are marked. (Note the time-shift between *a*—*b* and *c*—*d*.)

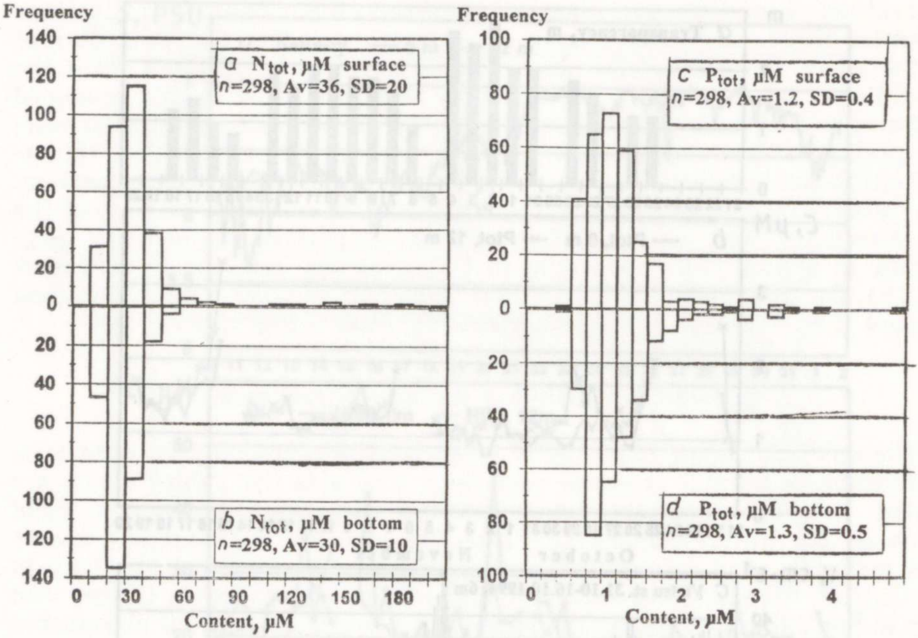

Fig. 9. Histograms and summary statistics of all the N_{tot} and P_{tot} data, separately for the surface and bottom layers (n, number of analyses; Av, average; SD, standard deviation).

The same periods are confirmed also by high velocities in the current measurements (Fig. 8*c*, *d*). The same feature was observed in November 1993 (see current records in Fig. 4*b*), when the total phosphorus content rose from about 1 µM to 2—3 µM. The contents of phosphorus are therefore somewhat higher in the near-bottom layers than in the surface layers, which is generalized also by the histograms in Fig. 9*c*, *d*. The nitrogen compounds, on the contrary, tend to concentrate in the upper layer (Fig. 9*a*, *b*), which shows a high trophic status of the Väinameri and the Gulf of Riga areas. Thus, the phosphorus regime in the study area is influenced by different factors in the following order: seasonality, storm events, and only then come hypothetically inflows—outflows, but only continuous ones. According to our preliminary estimations the dependence of the phosphorus contents on the currents is rather weak. The explanation could be that the gradients in the phosphorus contents between the Gulf of Riga and the Baltic Proper are not so strong as in the nitrogen contents.

3. Preliminary estimation of water and nutrient exchange and the future aims

Broadly, when calculating the total annual inflows (Q_{in}), outflows (Q_{out}), and net exchange ($Q_{net} = Q_{in} - Q_{out}$), there might be several levels of approximation. First, we can sum up the flows by direct measurements, and using the average daily characteristics just calculate the annual ones. This approach may lead to almost correct numbers if the number of direct measurements is very large. Doing so, we obtain the weighted average values of 91 km³ for outflows, 128 km³ for inflows, and the annual net exchange would be then 37 km³. Assuming that the mean value is a poor estimate for the parameter having a certain annual course, we can make

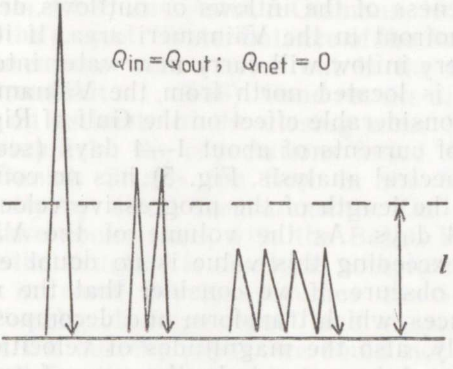

Fig. 10. The sketch describing the alternative ecological impact of currents with different durations, even while the water exchange characteristics remain the same.

averagings on the seasonal or monthly basis. Let the seasons be winter (January—March: usually small velocities due to the ice cover and predominating outflow according to Petrov (Петров, 1979)), spring and summer (April—August: usually medium velocities and predominating inflow), and autumn (September—December: high velocities and predominating outflow). Let the expeditions E3 and L3 represent winter; E1, E4, and L4 represent summer; E2 and E5 represent autumn. Then the outflow will be 78 $km^3 \cdot yr^{-1}$, inflow 107 $km^3 \cdot yr^{-1}$, and net exchange 29 $km^3 \cdot yr^{-1}$. One should bear in mind, however, that these estimates based on direct measurements are subject to changes with every new expedition.

The magnitudes of both the inflows—outflows and the net exchange (29 or 37 km^3) were close to previous estimates but the direction was just the opposite: according to Petrov (Петров, 1979) the net exchange via the Suur Strait is -38 $km^3 \cdot yr^{-1}$ and according to Mardiste (1976) about -50 km^3 (outflows!). These figures evidently show that the variability is really high and it is hard to find confirmation to calculated averages from the nature. However, our latest measurements for winter 1995 (which were being processed during the editing of this paper), will probably shift this balance towards the net outflow, again. Still, considering also the water exchange estimates in the Irben Strait (322 and 315 km^3 of inflows and outflows respectively according to Petrov) the role of the Suur Strait is about 23—26% of the total in- and outflows. This is doubtlessly a remarkable proportion.

Besides the large temporal variability of the currents some other complications should be noted: (1) Because of the strong alternate inflows and outflows the net exchange is to be calculated as a small difference between the large volumes of Q_{in} and Q_{out}: many factors therefore tend to damage the preciseness of the estimate; (2) Actually, in the ecological sense, Q_{net}, Q_{in}, and Q_{out} should not be overestimated, as these parameters describe to a large extent the oscillatory movements of the same water (see also Fig. 10). Alternatively, the inflow (outflow) can be declared to be ecologically effective, if the resultant length of the progressive velocity vector (*l*) exceeds, for example, 50 km (it is also roughly the meridional extension of the Väinameri), summing therefore only those continuous flows. In our example it means that the effective inflow just begins when the volume of the water pulse exceeds (without changes in direction) about 2 km^3. Very strong effective inflows occurred in spring and summer 1994 (about 30 km^3 during three months; see also Fig. 7). Actually estimations like that depend on the chosen criterion, the distance *l*. In practice the effectiveness of the inflows or outflows depends also on the position of the chemofront in the Väinameri area. If it is located in the Suur Strait area, every inflow will carry new water into the Gulf of Riga. However, usually it is located north from the Väinameri and only continuous flows have considerable effect on the Gulf of Riga. Quite a typical scale of variability of currents of about 1—4 days (see e.g. Fig. 4*a*, *c*, *d* and the results of spectral analysis, Fig. 5) has no considerable effect in such cases, because the length of the progressive velocity vector remains below 50 km in 3—4 days. As the volume of the Väinameri is about 10 km^3, the inflow exceeding this value is no doubt effective. The issue becomes even more obscure, if we consider that the nutrients are non-conservative substances, which transform and decompose along the whole "route". Consequently, also the magnitudes of velocities producing such flows should be taken into account. In the case of outflows one should bear in mind that a quasi-simultaneous inflow should occur in the Irben Strait and the "ventilation" of the western part of the Gulf of Riga would take place then.

Another possibility is to move on from the direct measurements and work out empirical models binding the wind characteristics and sea levels in some coastal stations with the currents. (And a third one could be budget calculations and numerical modelling of the whole Gulf of Riga.)

Using the empirical relationships it is possible to interpolate the periods between the direct measurements and to extrapolate the water exchange characteristics for any periods. As a pilot study the regression between the winds and currents in autumn 1993 was calculated (both data sets recorded by Aanderaa instruments with a 10-min interval). The correlation of corresponding N—S velocity components was quite strong at a high reliability level ($r=-0.85$), and it rose even up to -0.9 when both the winds and currents were averaged over the periods of up to 24 h. (Note that the negative r appears only because it has been agreed that the winds blow *from* and the currents flow *to*.) When the wind characteristics were just taken with an interval of 8 h (similarily to the meteorological stations) and only the current velocities were averaged over those periods, the coefficient r was still from -0.81 to -0.84. These relationships were especially good for strong winds, but in case of wind velocities less than 4 m $\cdot$ s^{-1} they were somewhat disturbed. The intercept was usually between -4 and -6 (cm $\cdot$ s^{-1}), i.e., in case of stillness the current was directed southwards (evidently due to the inclination in the sea level). On the basis of the regression model it could be found that the winds of 30—35 m $\cdot$ s^{-1} may produce current velocities up to 1.5 m $\cdot$ s^{-1} in this strait.

The regression between the currents measured with the current meter and wind data from the weather station of Virtsu was also investigated in May 1994. The correlation coefficient of N—S components was not so good (-0.57), partly due to the low wind velocities (less than 10 m $\cdot$ s^{-1}), but still quite reliable. Also the regression slope was somewhat lower than in autumn 1993 and the intercept was even -10 cm $\cdot$ s^{-1}). Therefore it must be concluded that (1) the relationships between the winds and the currents are not the same for all seasons, and (2) better results can be achieved when both the winds and sea levels are considered, which, however, are likely correlated also mutually.

There is a long experience of water balance studies in the whole Baltic Sea. For the estimation of the water exchange between the Baltic and the North Sea the relationships between the sea levels (in Hanko, the mean level of the Baltic, etc.) and direct measurements of currents in lightships in the Danish Straits and between the currents and flows can be found in e.g. Knudsen, 1899; Krümmel, 1904; Jakobsen, 1925; Hela, 1944;

Соскин, 1963; Wyrtki, 1954; and Astok & Otsmann, 1977. In the pilot study year (1975—76) of the project "Water balance of the Baltic Sea" very extensive current measurements were carried out in the Danish Straits (see: Baltic Marine Environment . . ., 1986). Good results of these measurements would have given an estimate of the closing error in all water balance calculations. Unfortunately, the expectations failed. Unlike the stratified and complicated Danish Straits the flow in the Suur Strait could be described successfully by direct measurements. On the other hand, the Gulf of Riga has two connections with the Baltic Proper including the Irben Strait, where the situation is nearly as complicated as in the Danish Straits. Therefore in some previous studies the Suur Strait has been declared to be of "negligible importance" and simply "closed" up. As it was also shown in the current paper, we could not do so. But we can close the Suur Strait for the balance studies of the Gulf of Riga by the good measurements in this strait.

Using the above-mentioned preliminary water exchange estimates for 1993—94 (from 29 to 37 $km^3 \cdot yr^{-1}$) and nutrient contents (Table) it is possible to find also the nutrient fluxes. As the inflows prevailed, they are roughly 1100—1400 t of phosphorus and 13 000—17 000 t of nitrogen per year. However, these values seem to be as variable as the water exchange characteristics and one should not overrate these very preliminary estimates. Moreover, it is not clear what these values actually represent: the transformation and sedimentation processes are taking place along the "route" of the flow. The nutrient pool of the Gulf does not really increase by those figures, if the predominant inflows carry relatively nutrient-poor water from the Baltic Proper. The nutrient exchange should be estimated by "ecologically effective" flows, rather than by net flows. Anyway, the nutrient exchange, as well as the real ecological effect of the Suur Strait, is not a simple multiplication of the volume flows and the nutrient contents. Paradoxically, it seems to be of no importance for the Gulf of Riga whether net inflows or outflows prevail in the Suur Strait. They both ventilate the Gulf, though from the different sides of the Gulf. Therefore, the approach where the Gulf is described by one "box" supplemented by single inputs via loading, outputs via sinks, and net outflows to the Baltic Proper seems to be quite deficient.

CONCLUSIONS

— The investigations of the velocity fields showed the water flow in the Suur Strait to be uniform enough for making water flow estimations based on direct measurements of currents in the strait.

— Spectral analysis proved that the temporal variability of the flow characteristics was remarkable, growing rapidly from the motions with periods of about 1—2 h towards the synoptical periods carrying the biggest share of the motion energy. The 12.5 h peak of semi-diurnal (M_2) tides is the only highly significant isolated peak featuring among the background spectra following the "$-5/3$ law". Less significant maxima were at 1.5, 4.5—4.8, 24, and 27—30 h, and 3—4 days. No special energy concentration was found at the inertial (14 h) period.

— Maximal velocities could be estimated as 1—1.5 $m \cdot s^{-1}$ (0.95 $m \cdot s^{-1}$ measured by our team so far), the average values being about 0.19 $m \cdot s^{-1}$. The analysis made on the basis of the field measurements in 1993 and 1994 gave the preliminary estimation of the water exchange in the Suur Strait as follows: inflows to the Gulf of Riga, 107—128 $km^3 \cdot yr^{-1}$; outflows, 78—91 $km^3 \cdot yr^{-1}$; and the net exchange from 29 to 37 $km^3 \cdot yr^{-1}$.

These estimates are not final, as expeditions, data processing, interpretation, and modelling will be continued. The estimates of the mean water exchange presented earlier (from -38 to -50 km^3 yr^{-1}) do not reflect the real situation in any year.

— The empirical regression models could be used for interpolating/extrapolating the flows between/beyond the expeditions. The correlation between the winds and currents was 0.85 in autumn 1993. Still, the regression seems to be different in different seasons and it is advisable to consider both the data of winds and sea levels in the future.

— The Gulf of Riga is characterized by excessively high contents of nutrients, especially nitrogen compounds. The continuous outflowing currents therefore carry nitrogen-rich water, and the inflows of saline and fresh water from the Baltic Proper reduce the nitrogen contents in the Suur Strait area. The rise in the phosphorus contents is most probably related to storm events, which turn up the suspended material from the bottom sediments.

— The nutrient amounts driven by the above-mentioned flow volumes were calculated to be of the order of 1000—1500 t of phosphorus and 12 000—18 000 t of nitrogen annually (net transport). However, these values evidently do not represent the real nutrient exchange. In the water exchange estimates between the Gulf of Riga and the Baltic Proper the share of the the Suur Strait is most likely about 25% and that of the Irben Strait about 75%. The role of the Suur Strait in the nutrient exchange could be even bigger, though very complicated to determine. The nutrient exchange mechanisms, especially the role of the Väinameri area, should be specified in the future.

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