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EXCHANGE PROCESSES IN THE VÄIKE STRAIT (BALTIC SEA): PRESENT, PAST, FUTURE

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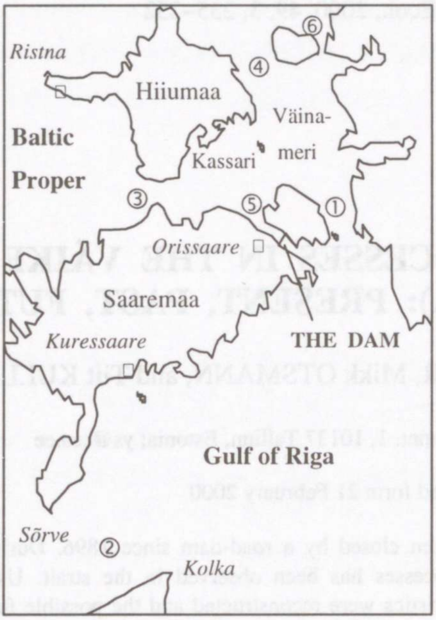
Abstract. The Väike Strait has been closed by a road-dam since 1896. During the last decade acceleration of eutrophication processes has been observed in the strait. Using hydrodynamic models the pre-dam flow characteristics were reconstructed and the possible future developments are discussed in relation to the plans to make openings into the dam. In the openings the flow with an average velocity of 50 cm/s will appear. The direction of the flow will change rapidly, but the resulting annual water flux of about 0.1 km^3 and 1000 tonnes of sediments will be directed from the Gulf of Riga to the Väinameri sub-basin. The desired positive ecological effect will remain modest and it will be limited to the vicinity of the openings. A slight improvement may occur in the southern part of the Väike Strait. To the north from the dam (near Orissaare), the temporal variability of hydrochemical parameters will increase, and the situation may even deteriorate.

Key words: currents, sea level, modelling, nutrients, resuspension, straits, Baltic Sea.

INTRODUCTION

The Väinameri Sea (also called the Archipelago Sea, the Moonsund) is a relatively shallow (maximum depth 21 m) and small (area 2243 km^2, volume 10.6 km^3) marine area between the western coast of Estonia and the West-Estonian Archipelago. The aquatic area together with the nearby islands and a narrow strip of mainland serve as the biosphere reserve of UNESCO's Man and Biosphere Program. Some other nature reserves are located in the region as well. Therefore assessing recent and future ecological developments in this vulnerable area is of considerable importance.

Five straits surround the Väinameri and connect it with the neighbouring sub-basins. Among the three major straits the Suur Strait is the southernmost, connecting the Väinameri with the Gulf of Riga (Fig. 1). The other two, the Soela Strait to the west and the Hari Strait to the north, connect the Väinameri with the Baltic Proper. An additional shallow and narrow Voosi Strait exists parallel to the



The straits:

1 - Suur Strait

2 - Irbe Strait

3 - Soela Strait

4 - Hari Strait
(Hari Kurk)

5 - Väike Strait

6 - Voosi Strait

Fig. 1. The study area: the Väinameri, the northern part of the Gulf of Riga, and the straits of the system.

Hari Strait. Since it is a nearly parallel strait, it carries no specific importance in this study and these two channels could be taken as one, the Hari Strait. There exists one more minor channel, the Väike Strait. It is parallel to the Suur Strait but it has been closed by a 3-km-long road-dam since 1896.

There are several papers that deal with the problems of water and nutrient exchange through the major straits of the Väinameri (Mardiste, 1975; Suursaar et al., 1995, 1996; Suursaar & Astok, 1998; Otsmann et al., 1999; Astok et al., 1999). However, as it might seem a local problem, little attention has been paid to the ecological situation in the Väike Strait area; one exception is Ecological Studies… (1994), based on the fieldwork in summer 1993. The present study deals mainly with the problems of matter fluxes in the Väike Strait. Using water exchange models we try to reconstruct the role of the strait before it was closed with the road-dam, and predict what will happen in the future in different scenarios.

STUDY AREA: PRESENT

The Väike Strait ("small strait" in Estonian, as opposed to the Suur Strait, the "big strait") is a marine area about 25 km long and on average 2.5 km wide, which is actually not a strait any more. There are two bays left, separated from each other by a road-dam. The preparatory work for the dam began in 1892, the construction started in 1894, and the opening of the road link between Saaremaa and Muhumaa islands (Fig. 1) took place on 27 July 1896.

The northern part (or the NW bay, to be more precise) has a length of about 11 km and an area of 28 km^2. Taking into account the average depth of the basin (1.5 m), the volume is about 42 000 000 m^3. The southern half, the SE bay, has the inner and the outer part. The inner (8 × 3 km) basin is very shallow (average depth 0.5 m), with a volume of about 12 000 000 m^3. The outer part (6 × 5 km) is deeper (about 4 m) and its volume is about 10 times as large as that of the inner part. In the NW bay fine sands and aleurites dominate as the bottom sediments. In the inner part of the SE bay coarse and medium sands prevail, these change to aleurites in the outer bay (Lutt, 1985). Muddy bottom can be found in the nearshore and near-dam sections of the study area. In recent years a sub-surface sandy bank has risen in the central part of the inner bay. In the case of low sea level it may emerge as a shoal, leaving free water near the coasts of either Saaremaa or Muhumaa.

The hydrophysical and -chemical regime of the study area is determined by the conditions of the Väinameri and the Gulf of Riga, respectively. The salinity is somewhat higher in the Väinameri (typically 6–6.7 PSU in Kassari Bay against 5.7–6.2 PSU in the northern part of the Gulf of Riga). The difference in nutrient concentrations is far greater. In the SE bay the relatively nutrient-rich Gulf of Riga waters prevail and in the NW bay the water of the Baltic Proper origin is common. Typical nutrient concentrations in the Väinameri are 0.2–0.3 μM $P\text{-}PO_4$, 0.3–0.4 μM P_{tot}, 0.1–0.6 μM $N\text{-}NO_3$, and 10–15 μM N_{tot} versus 0.3–0.5 μM $P\text{-}PO_4$, 0.4–0.7 μM P_{tot}, 0.5–1.3 μM $N\text{-}NO_3$, and 15–25 μM N_{tot} in the northern part of the Gulf of Riga in autumn in roughly similar conditions (Porgassaar, 1993; Suursaar et al., 1996; Suursaar & Astok, 1998). The dam represents the hydrochemical front, which under natural conditions pulsates somewhere between the Suur Strait and the Hari Strait depending on the prevailing winds and currents (Suursaar & Astok, 1998). In summer 1993 the average concentration of total phosphorus was 0.74 μM in the NW bay versus 1 μM in the SE bay. The respective values for the total nitrogen were 33 vs. 44 μM (Ecological Studies…, 1994). The difference could easily be up to 2–5-fold on different sides of the front (Astok et al., 1999). The wave-generated resuspension during storms and other local effects of the shallow sea could make their corrections in relation to average values in the Väike Strait.

Some evidence of local pollution (low oxygen, high nutrient values) was found near Orissaare in previous years. Since 1998 a new wastewater treating plant has operated at Orissaare and there should be no significant local pollution any more. According to investigations of phytoplankton, shore vegetation, benthic macrofauna, etc., eutrophication is more evident in the SE bay. Macrophytes and mud appear in the shallow parts of the sea and in the vicinity of the dam. The spawning grounds of several fish species, especially of whitefish, have been disturbed and fishery catches from this area have decreased (Ecological Studies…, 1994). These developments are in general of local character and the pelagic zone is not suffering more than the Gulf of Riga as a whole. Still, according to a widespread opinion, the ecological conditions are gradually deteriorating in the study area, as there is no water exchange in the strait. The original dam was quite loosely made of local building materials (gravel, ground, juniper timber). Considerable infiltration evidently took place through the dam. After the substantial reconstructions in 1990–96 the dam was made higher, twice as broad, and much more watertight. As a result, during the last decade eutrophication has been considerably accelerating in the study area (H. Kipper and V. Kaal, pers. comm.). The appearance of the shoal in the middle of the SE bay has also been associated mainly with the new solid dam. These developments could equally be related to the intensification of eutrophication processes around the whole marine coastal region of Estonia. Though during the last 5–10 years the overall pollution load has decreased in Estonia, the response of the marine environmental processes takes place with a time lag and in most cases it is difficult to point out a certain single reason.

In order to decelerate these undesirable ecological developments in the study area, it has been suggested that some openings should be made into the dam. Another reason was to protect the dam. Strong winds in limited direction bands (120°–150° and 300°–320°) could produce a pile-up effect in the narrow fjord-like channel of the strait causing considerable differences between the sea levels on both sides of the dam. Speculations on the necessity of the holes have been made for many years. Actually, the old dam had a culvert (since 1949) on its eastern side (near Muhu Island) and during the reconstructions the culvert was extended also for the new dam section (in 1996). As the cross-section area of this shallow and narrow opening is negligible, it has practically no effect. Then it was almost decided to design two major holes at places of sufficient depths on both sides of the dam, each 18 m wide. Presently curious "ears" for the traffic to bypass construction stand without function. The following questions arose: will such holes have the desired effect on the ecological state of the study area, or will they perhaps even evoke an environmental disaster?

PAST AND FUTURE: METHOD

The modified four-channel water exchange model

The main tool for both the reconstruction of the past flows and for calculating the future scenarios is the multi-channel forced oscillation water exchange model. Its different versions have been used for investigations of currents and water exchange processes in the Väinameri and the Gulf of Riga. The two-channel and four-channel versions were presented by Otsmann et al. (1997, and 1998, 1999, respectively). The modified four-channel version could be used for calculating the water and matter exchange in the planned openings. Basically the model consists of four motion equations (representing the Irbe, Suur, Hari, and Soela straits, see Fig. 1) and two balance equations (for the Gulf of Riga and the Väinameri). The generalized measures of the basins and channels, the directions of the channels, and the friction coefficient serve as model parameters. The model inputs with the time step of 3 h are (1) the wind stresses above the straits, calculated from the High Resolution Atmospheric Model (HIRLAM) winds, (2) the open sea level (measured by mareograph at the Ristna marine station or calculated by the HN-model of the Baltic Sea, and (3) the fresh-water input from rivers (constant flow from the Kasari River and mounted in one point the "Daugava + Pärnu" River).

The model outputs are the velocities (or flow volumes) in the channels and the space-averaged sea levels of the Gulf of Riga and the Väinameri sub-basins. The modelled dynamics of the water levels in these sub-basins serve as the sea levels on both sides of the dam of the Väike Strait on condition that there is no local wind generated pile-up effect. The situation is similar in the Suur Strait, where no dam exists and the water can flow freely towards the sea-level gradient. Because of the existence of the dam the four-channel model briefly described above should be modified by adding a term to the sea levels, which appears from the stationary motion equations and describes the local wind effect:

$$\xi = \pm\left(-\frac{h}{2}+\sqrt{\frac{h^2}{4}+\frac{|\tau_w|L}{g}}\right) \tag{1}$$

where h is the average depth of the strait, τ_w is the local wind stress, g is the acceleration of gravity, and L is the scale of the local wind. Using the Chezhy formula we can calculate the velocities and volume flows through the holes on the basis of modelled sea level differences.

Though we can investigate the behaviour of the system in different constructed forcings and idealistic conditions, the main simulations were done using realistic forcings of 1995. That year is the period most thoroughly investigated by us, both in terms of fieldwork and modelling efforts. The model has been successfully calibrated and verified for that period and extensive simulations were carried out (Suursaar & Astok, 1998). The maximum wind velocity measured by us in Viirelaid Island was 27 m/s (gusts up to 37 m/s) on 23 January. Simultaneous current measurements showed values up to 1 m/s in the deep part of the Suur Strait. As the wind direction was 150°–200° during that storm, it should have had the maximum effect on the Väike Strait sea levels as well. Thus, we can simulate the extreme conditions using realistic input and verification data.

The five-channel water exchange model

This model version was used to reconstruct the past flows through the Väike Strait and to calculate the time series of the flows in the Väike Strait as it would have been in 1995 without the dam. The model is similar to the four-channel version, but as the five-channel version has not been published so far, we present its short description below.

The basic equations consist of five motion equations (one for each channel), composed into the first equation in (2) using subscript *i*, and the two remaining equations are the volume conservation equations for the Gulf of Riga (subscript G) and the Väinameri (subscript V):

$$\begin{cases} \dfrac{\mathrm{d}u_i}{\mathrm{d}t} = \dfrac{g}{L_i}\Delta\xi_i + \dfrac{\tau_{wi}}{H_i} - \dfrac{r|u_i|u_i}{H_i} \\ A_G \dfrac{\mathrm{d}\xi_G}{\mathrm{d}t} = u_1 A_1 + u_2 A_2 + u_5 A_5 + Q_G \\ A_V \dfrac{\mathrm{d}\xi_V}{\mathrm{d}t} = -u_1 A_1 + u_3 A_3 + u_4 A_4 - u_5 A_5 + Q_V \end{cases} \tag{2}$$

where $i = 1, 2, 3, 4, 5$ denote the different straits (as in Fig. 1), t is time, A_G and A_V are the surface areas of the sub-basins and A_i is the cross-section area of the straits, L_i and H_i are the lengths and depths of the straits, respectively. The wind stresses τ_{wi} above the channels are calculated from the HIRLAM model winds and projected on the direction of the strait. $\Delta\xi_i$ denote the sea level differences, Q_G and Q_V are the river inflows to the sub-basins. Model outputs are space-averaged flows in the straits (u_i) and the sea levels inside both of the two sub-basins (ξ_G) and (ξ_V). The last term of the first equation in (2) describes the bottom friction. For parameter values and verification details of a similar four-channel version see Otsmann et al. (1998, 1999). The additional channel representing the Väike Strait (Fig. 1, No. 5) has the model length of 25 km, the average depth of 1 m, the width of 3 km, and the direction of 130°.

The Väinameri 2D hydrodynamic model

The model is based on the Baltic Sea hydrodynamic model. Here it is for the first time adapted for the Väinameri. The Baltic Sea model, using HN-approach (hydrodynamic-numerical; see also Hansen, 1956), was used by us for calculating the sea-level input data for the water exchange models described above. Its grid step is 2.5 miles. For the Väinameri a new 1 km-grid was adapted, also the coastal line and bathymetry were digitalized with better resolution. Broadly speaking, the two-dimensional HN models are based on hydrodynamic equations for shallow sea (vertically integrated barotrophic Reynolds equations). The model inputs are the HIRLAM winds and the Baltic Sea levels (or Kattegat levels at Göteborg for calculations of the Baltic Sea levels). The Väinameri 2D model outputs are the horizontal distribution of the sea levels in the Väinameri and the vertically integrated velocities in each grid step of the Väinameri.

Simulations of the Väinameri sea levels and currents were carried out for the entire year of 1995. For calculating matter exchange through the Väike Strait two points were chosen on both sides of the dam (4–5 km from each other) and velocity time series (N–S and W–E velocity components) were calculated for 1995. On the basis of the modelled velocities bottom stresses were calculated. This is the force that is responsible for resuspension, catching up some fractions of the bottom sediments, which could be further transported by the currents until they settle down in some other place. Using empirical relationships between the bottom stresses and the concentration of the suspended solids it is possible to calculate the fluxes of the suspended matter in the holes of the dam:

$$\begin{array}{ll} \dfrac{\partial C}{\partial t} = K_{\mathrm{e}}(\tau - \tau_{\mathrm{e}}), & \text{if } \tau \geq \tau_{\mathrm{e}}; \\[2ex] \dfrac{\partial C}{\partial t} = 0, & \text{if } \tau_{\mathrm{d}} < \tau \leq \tau_{\mathrm{e}}; \\[2ex] \dfrac{\partial C}{\partial t} = -\left(1 - \dfrac{\tau}{\tau_{\mathrm{d}}}\right)\dfrac{2W_{\mathrm{s}}}{h}C, & \text{if } \tau \leq \tau_{\mathrm{d}}; \end{array} \qquad (3)$$

where C is the concentration of the suspended matter and τ are bottom stresses. The relationships (3) and the values for constants τ_{d} (critical shear stress for deposition), τ_{e} (critical shear stress for erosion), K_{e} (coefficient of proportionality) and W_{s} (settling speed) were taken from Huttula (1994). It is also possible to calculate nutrient fluxes, but some additional investigations of the bottom sediments are needed for that.

RESULTS AND DISCUSSION

Reconstruction of the past water exchange patterns in the Väinameri

According to our field studies in the Väinameri (1993–96) the main water exchange goes north–southwards through the Suur Strait and the Hari Strait. The currents fluctuate strongly in both directions. In the Suur Strait the total sum of inflows (to the Gulf of Riga) was about 120–140 km^3/yr and outflows 150–170 km^3/yr (Suursaar et al., 1996), the whole system has due to river inflows a positive freshwater balance of about 30 km^3/yr. In our opinion, "water exchange" could be better described by the integral (cumulative) flow curves during a certain longer period (e.g. one year). Figure 2a shows the modelled integral curve (*IQ*) for the Suur Strait in 1995. Despite the conditions in occasional nontypical years, it appeared that in the Väinameri water flows generally northwards in the cold seasons (up to 50–60 km^3 during 2–4 months) and southwards in summer (up to 20–40 km^3). This seasonality is related to the seasonality in the wind conditions above West Estonia.

The simulations showed that both the average (0.2 m/s) and the maximum (about 1–1.3 m/s) velocities in the Väike Strait (without the dam) should be quite similar to those of the Suur Strait. The significant difference in the flow volume magnitudes is due to the (about 14-fold) difference in the cross-section areas. The sums of individual volume flows in the Väike Strait were 6.2 km^3 northwards and

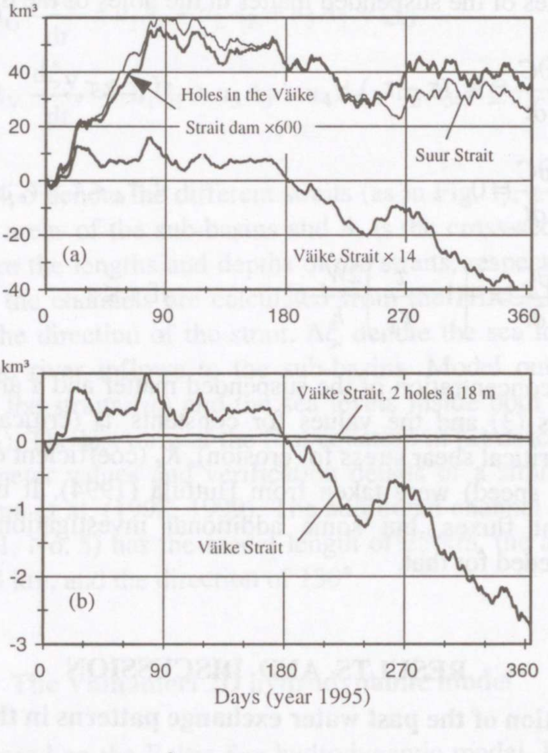


Fig. 2. Variations in integral flows (km^3) in the Suur Strait (thin line) compared to the flows in the Väike Strait and to the flows through the openings of the Väike Strait dam as modelled for 1995; for better comparison of the annual flow patterns similar magnitudes were obtained by multiplying the flows in the Väike Strait by 14 and the flows through the openings by 600 (a). Flows in the Väike Strait without the dam ("past" situation) compared with the flows through the openings in the dam (b) modelled for the same period.

9.0 km^3 southwards during the year. The corresponding integral curve can be seen in Fig. 2b, showing –2.8 km^3 for the annual resultant flow for the same period. The general appearance of the integral curve is quite similar to the one of the Suur Strait. However, the slight difference in the directions (130° and 155°, respectively) is enough for giving prevalence to different directions in annual summary. The currents enable good ventilation of the Väike Strait area. Though the influence of the Väike Strait is small for the neighbouring basins, the role of the flows for the Väike Strait area itself is important.

Figure 3a shows the velocities in the straits depending on the directions of stationary wind above the system. According to these simulations four main water exchange patterns exist in the Väinameri without considering the role of the Väike Strait (Fig. 4a). It appeared that though the Suur Strait and the Väike Strait function mainly in the same direction, there are two sectors of wind directions (45°–90° and 225°–270°) where they function in opposite directions, occasionally forming quite curious patterns (Fig. 4b). As the water masses at the ends of the Väike Strait would be of different origin, the pulsations of the frontal zone would produce substantial temporal variability of hydrochemical conditions in the whole Väike Strait area.

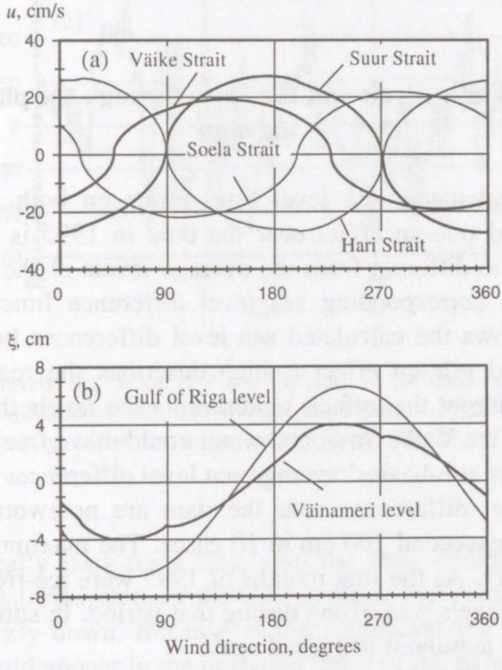


Fig. 3. Modelled velocities (u) in the straits of the Väinameri (a) and the sea levels (ξ) inside the sub-basins (b) depending on the direction of the stationary wind (module = 7 m/s, uniform wind over the whole study area).

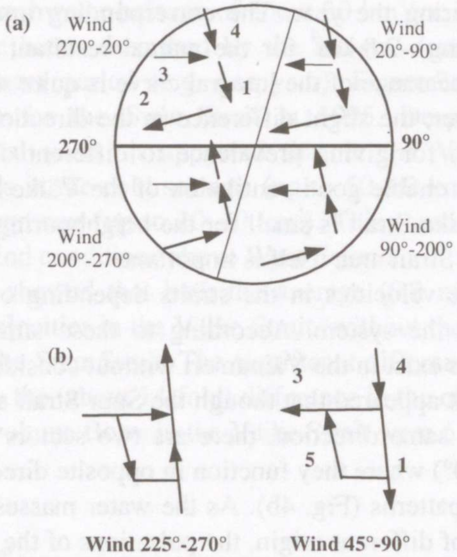


Fig. 4. Four basic stationary flow patterns in the straits of the Väinameri (a) depending on the direction of the stationary wind (the straits are numbered as in Fig. 1) and two additional flow patterns with the specific influence of the Väike Strait (b).

Sea levels in the Väike Strait and the flows through the planned openings in the dam

An excerpt of calculated sea level time series on both sides of the dam considering the local pile-up effect near the dam in 1995 is shown in Fig. 5a. These levels are quite different from the average levels of the Gulf of Riga and the Väinameri. The corresponding sea level difference functions in the Suur Strait. Figure 5b shows the calculated sea level differences both in the case of local wind-generated pile-up effect (which describes the real situation in the Väike Strait) and without that effect, representing the levels that would occur if there was no dam in the Väike Strait and water could move freely, similarly to the Suur Strait. While the sub-basins' average sea level differences rarely exceed 20–30 cm, the sea level differences near the dam are noteworthy. During 1995 the level difference exceeded 100 cm in 10 cases. The maximum difference was 190 cm on 23 January. As the first months of 1995 were ice-free and stormy, the variation of the sea levels was strong during that period. In summer the variation was lower and in the autumn it increased again.

Frequency distribution (histogram) of the sea level differences during 1995 shows that the level differences usually remain between ±10 and ±20 cm (Fig. 6a). The water level was statistically slightly higher (by 2.4 cm) in the SE part of the strait. The duration of the extreme sea level differences is very short,

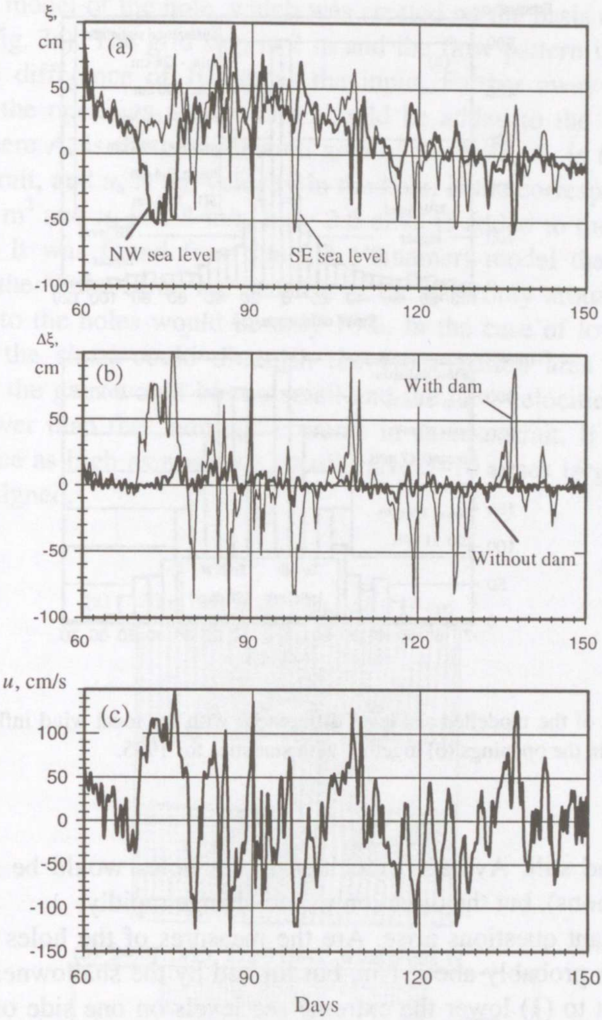


Fig. 5. Modelled sea levels (ξ) at the NW and SE sides of the dam with local wind-influenced pile-up (a), sea level differences with and without the influence of the dam (b), and calculated velocities (u) in the openings of the dam (c); an excerpt from 1995: days 60–150.

the "shock" typically lasts for a day, also the free-oscillation period of 24 h, found in the oscillatory system of the Gulf of Riga–the Väinameri, helps to bring the sea level quickly down. Because of the significant sea level differences the velocities that would appear in the designed holes of the dam could be substantial (Fig. 5c). Maximum velocities could be estimated as 1.5–2 m/s, higher velocities are hampered by the bottom friction. The histogram of the velocities (Fig. 6b) shows a bimodal appearance – water tends to move into one of the two directions

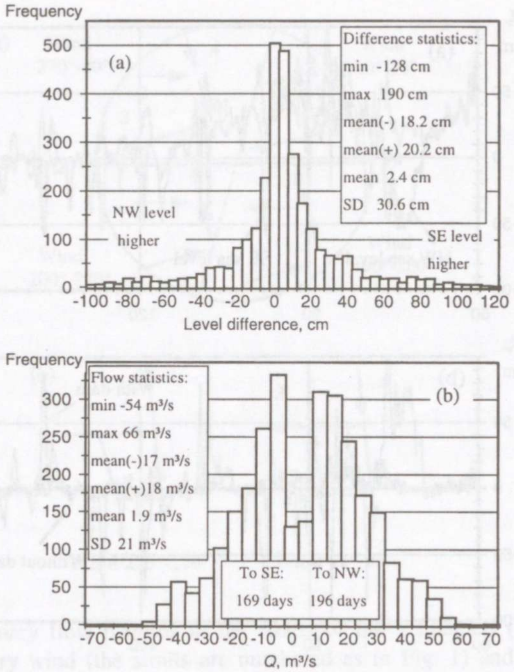


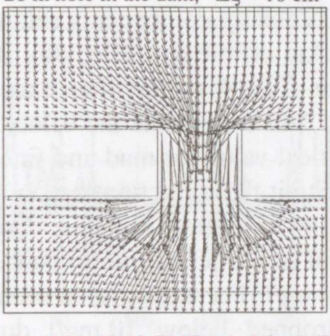
Fig. 6. Histograms of the modelled sea level differences with the local wind influence (a) and the flow volumes (*Q*) in the openings (b) together with statistics for 1995.

and not to stand still. Average velocities in the holes would be about 50 cm/s (for both directions), but the direction would change rapidly.

Two important questions arise. Are the measures of the holes (2 holes, each 18 wide; depth probably about 1 m, but limited by the shallowness and the sea-level) sufficient to (1) lower the extreme sea levels on one side of the dam, and (2) what is the influence of the flows in the holes on the velocity fields in the entire Väike Strait area? First, let us estimate the volume of the water "excess" in the case of maximum sea level difference of 2 m. As the sea level is inclined toward the open sea, the average height excess would be 1 m. In the case of the NW bay (area 28 km^2) the volume of the water excess is 28 000 000 m^3. A roughly similar volume could be estimated also for the SW bay. This volume would flow through the designed holes for about 5 days (average velocity 1.5 m/s). As such sea level differences could build up in the strait in about half a day, these holes are not large enough for quick equalization of the levels.

Second, we can predict velocities up to 1.9 m/s in the holes. However, farther away from the dam this influence diminishes quickly, roughly proportionally with the second power of the distance. The evident influence extends to the distance equal to a couple of widths of the holes. This could be illustrated by the idealistic 2D model of the hole, which was created on the basis of the Väinameri 2D model (Fig. 7a). The grid step is 2 m and the flow pattern is simulated with the sea level difference of 10 cm as the input. Farther away from the direct influence of the openings a new term should be added to the current velocity, $(A_a/A_v)u_a$, where A_a is the cross-section area of the hole, A_v is the cross-section area of the strait, and u_a is the velocity in the hole. If the corresponding areas are 36 and 2500 m^2 and u_a is 1.8 m/s, only 2.6 cm/s is added to the velocity of the Väike Strait. It was found from the 2D Väinameri model that the maximum velocities in the Väike Strait are because of the dam only around 30 cm/s. The increase due to the holes would be only 10%. In the case of low sea levels the existence of the shoal could diminish the cross-section area of the SE bay twofold. Still the gain would be too small and the new velocities would be still 3–4 times lower than the "normal" currents in such a strait. If we wish to get velocities twice as high as now, we should have 5–10 times larger cross-section areas than designed.

(a) 20 m hole in the dam, $\Delta\xi = 10$ cm



(b) 24.01.1995, 23.00 GMT, wind 6 m/s W

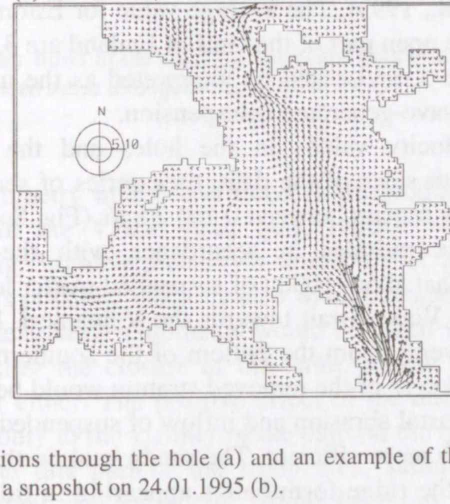


Fig. 7. 2D flow simulations through the hole (a) and an example of the modelled situation of the flows in the Väinameri, a snapshot on 24.01.1995 (b).

Possible ecological consequences

Flow volumes through the openings are proportional to the modelled velocities (Fig. 5c). Cumulative curves eliminate the to-and-fro oscillations and reveal ecologically important flows (Fig. 2). During the first month of 1995 about 0.1 km^3 (10^8 t) of water should have moved northwards through the holes. About half of that amount should have returned during the next 5 months and after that northwards motions should have slightly prevailed again. This pattern could somewhat vary in different years, depending especially on winter conditions (ice-free or not).

High velocities exist only in the holes. For calculating the resuspension of the bottom sediments velocities from the 2D model simulations were used. A snapshot for the whole Väinameri area can be seen in Fig. 7b. There seems to be a controversy: Fig. 7b shows flows in the Suur and Hari straits, while according to Fig. 3a W-winds should not generate flows in these straits. Actually, Fig. 3 illustrates the role of the wind stress as the only forcing, but simulation in Fig. 7b takes into account also the sea-level differences. In addition, realistic flows always have fluctuate and depend on the past, while the stationary situation (Fig. 3) is constant in time. Velocity components seldom reached 20 m/s in the two selected points, about 2 km off the dam (Fig. 8a). Bottom stresses calculated from the velocity simulations (Fig. 8b) quite often exceeded the critical value of 0.5 dyn/cm^2 (Huttula, 1994). This means that the velocities are sufficient to catch up sandy sediments. The critical value for mud and fine organic fractions is only 0.02 dyn/cm^2. In the Väike Strait these fractions are in a suspended state most of the time. Using the time series of bottom stresses, concentrations of suspended matter were calculated. Initial (realistic minimum) concentration needed for such calculations was taken as 5 mg/l. For example, in similarly shallow Pärnu Bay the concentration never dropped below 10 mg/l during the three days of investigations (Arst et al., 1993). The average value for Estonian rivers is 5 mg/l and typical values in the open part of the Gulf of Finland are 3.4–8.4 mg/l (Lutt & Kask, 1992). The value 5 mg/l could be interpreted as the average background value representing the wave-generated resuspension.

Multiplying the velocity values in the holes and the concentrations of suspended solids on both sides of the dam, time series of sediment fluxes were obtained. In general they remain between 0 and 2 kg/s (Fig. 8c), being on average 0.2 kg/s. Sediment flux pulsates in accordance with the velocity but the cumulative flux shows that about 1000 t of suspended matter left the Gulf of Riga and moved through the Väike Strait towards the Väinameri. If we removed this amount of sediments evenly from the bottom of the southern half of the Väike Strait (SE bay), the thickness of the removed stratum would be only 0.1 mm. The sedimentation due to coastal abrasion and inflow of suspended matter from rivers would probably be much more efficient. The sandy bank in the bottom of the SE bay is quite similar to the ridge-form banks appearing in tidal estuary mouths.

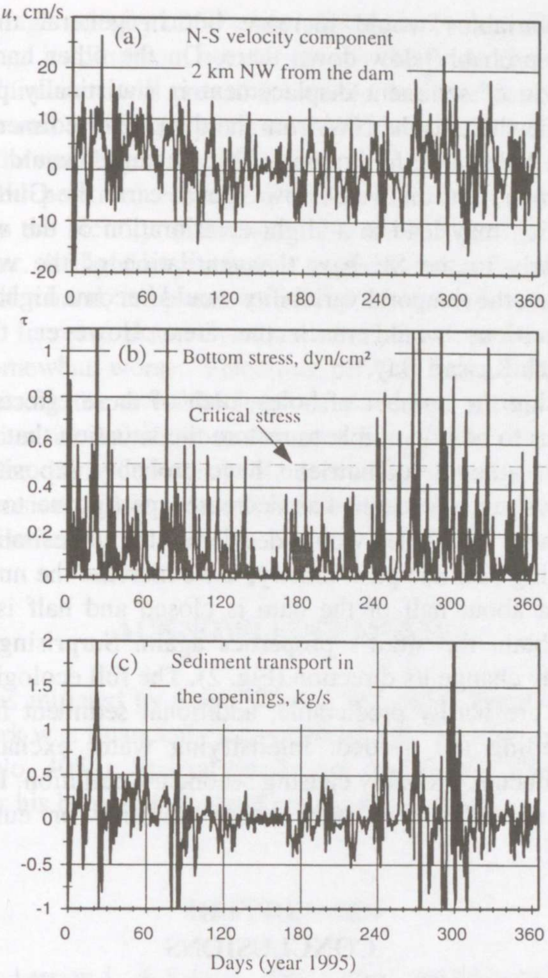


Fig. 8. Cumulative water flows in the holes (a), calculated bottom-stresses in the Väike Strait (b), and transport of suspended solids through the holes (c) in 1995.

Even a slight asymmetry in ebb and flood flows produces such banks (Dyer & Huntley, 1999). In the Väike Strait quite regular wind-generated sea level oscillations (see Fig. 5a) have probably a similar effect. Again, the dam has made such pile-up effects possible, blocking also water passages.

Evidently the desired developments would be much weaker than the opposite ones that began after the closure of the strait. Surely there would not be any ecological disaster either. The positive effect of the designed holes seems to be weak and limited only to the vicinity of the dam on the SE side. The holes would somewhat ventilate this part of the study area, salinity would fall for about 0.2–0.5 PSU, nutrient concentrations would decrease, temporal variability of hydrochemical variables would increase but in general the eutrophication processes would probably slow down there. On the other hand, as the above-described direction of sediment displacement is statistically prevalent, a shoal could appear somewhere to the NW from the dam. The sediment displacement is stronger near the holes and the bottom of the channels would be washed clean. The preferred direction of the water flows would carry the Gulf of Riga water to the NW bay, which may lead to a slight deterioration of the water quality near Orissaare. Similarly to the SE bay, the ventilation of the water mass would increase somewhat, the temporal variability would become higher, but also higher nutrient concentrations would reach the area. However, the effect would definitely not reach Kassari Bay.

When increasing the number of holes, both of these effects will increase as well. Still it seems to be impossible to restore the situation that existed 100 years ago. Considerable amounts of nutrients have probably deposited to the bottom sediments of the strait, the depth has decreased partly due to neotectonic land uplift of 2–3 mm/yr. The holes would decelerate the undesirable changes in the future, but not bring back the past. Finally, if we increase the number of the holes to the extent that about half of the dam is closed and half is open, the water exchange will obtain the strait's properties again. Surprisingly, the statistical resultant flow may change its direction (Fig. 2). The full ecological consequences of that situation are hardly predictable, additional sediment investigations and ecological modelling are needed. Intensifying water exchange will stir up accumulated sediments, probably causing secondary pollution. Due to continuous ventilation the situation may later either improve or eutrophication will regenerate itself.

CONCLUSIONS

1. The ecological situation is said to be deteriorating in the Väike Strait, which has been closed by a road-dam since 1896. After the reconstruction and consolidation of the dam 10 years ago practically no water exchange occurs through the strait. Velocities only up to 30 cm/s could be found, sedimentation and accumulation processes prevail.

2. Reconstructions with hydrodynamical models showed that before the closure the flow velocities were up to 1 m/s in the strait, the water exchange was about 14 times weaker than in the Suur Strait (roughly proportional to the corresponding cross-section areas). The resultant long-term flow directions were parallel, but in the case of wind directions of 45°–90° and 225°–270° the Suur and the Väike straits worked against each other.

3. The sea level differences can reach 2 m at present due to the local wind effect. Such situations are short-term, the difference usually levels within a day. If we make holes into the dam (provisionally designed 2 openings, 18 m each), the

flow with an average velocity of 50 cm/s (max up to 2 m/s) will appear. The flow will rapidly change its direction, but statistically the flows directed from the Gulf of Riga to the Väinameri will prevail (about 0.1 km^3 per year). Resuspension of the bottom sediments will slightly increase and about 1000 t of sediments will be carried through the openings to the NW section of the strait.

4. The (desired positive) ecological effect will remain modest and will be limited mainly to the vicinity of the holes. No environmental catastrophe should be expected either. A slight improvement might occur in the southern half of the strait. On the other hand, temporal variability of hydrochemical and -biological parameters will increase near Orissaare and the ecological situation could probably get somewhat worse. Velocities off the holes will be increased by 10–20%, for gaining the two-fold increase the holes should have 5–10 times larger cross-section areas than those designed now. If the extension of the holes reaches half of the dam, the statistically prevailing flow direction will probably reverse. Resuspension will increase, secondary pollution may cause a small-scale environmental disaster.

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REFERENCES

Arst, H., Kutser, T., Laesson, L. & Lukk, T. 1993. Optical measurements in Pärnu Bay. *Proc. Estonian Acad. Sci. Ecol.*, **3**, 27–37.

Astok, V., Otsmann, M. & Suursaar, Ü. 1999. Water exchange as the main physical process in semi-enclosed marine systems: The Gulf of Riga case. *Hydrobiologia*, **393**, 11–18.

Dyer, K. R. & Huntley, D. A. 1999. The origin, classification and modelling of sand banks and ridges. *Continental Shelf Res.*, **19**, 1285–1330.

Ecological Studies in the Aquatic Environment of Väike Väin Strait in West Estonia. 1994. Estonian–Finnish cowork during summer 1993. Report. Helsinki, Kuressaare.

Hansen, W. 1956. Theorie und Errechnung des Wasserstandes und der Strömungen in Randmeeren nebst Anwendung. *Tellus*, **8**, 287–300.

Huttula, T. 1994. *Modelling the Transport of Suspended Sediment in Shallow Lakes*. Academic dissertation. University of Helsinki.

Lutt, J. 1985. *Bottom Sediments of the Väinameri*. Valgus, Tallinn (in Russian).

Lutt, J. & Kask, J. 1992. Sources of sedimentation. In *Geology of the Gulf of Finland* (Raukas, A. & Hyvärinen, H., eds.), pp. 137–157. Estonian Acad. Sci., Tallinn (in Russian).

Mardiste, H. 1975. Volume transports in the Suur Strait, Väinameri. In *Dynamics of Water in the Baltic Sea*, pp. 88–94. Estonian Acad. Sci., Tallinn (in Russian).

Otsmann, M., Astok, V. & Suursaar, Ü. 1997. A model for water exchange between the Baltic Sea and the Gulf of Riga. *Nord. Hydrol.*, **28**, 351–364.

Otsmann, M., Suursaar, Ü., Kullas, T. & Astok, V. 1998. Helmholtz response to the system of two semi-enclosed basins and four straits. In *More Studies on the Water Exchange and the Nutrients of the Gulf of Riga* (Suursaar, Ü. & Astok, V., eds.), pp. 34–60. *EMI Report Ser.*, **9**.

Otsmann, M., Suursaar, Ü. & Kullas, T. 1999. Modelling currents along the western coast of Estonia as superposition of Helmholtz oscillators. In *Coastal Engineering and Marina Developments* (Brebbia, C. A. & Anagnostopoulos, P., eds.), pp. 99–108. WIT Press, Southampton, Boston.

Porgassaar, V. 1993. Content and distribution of phosphorus and nitrogen in the coastal waters of West Estonia. *Proc. Estonian Acad. Sci. Ecol.*, **3**, 166–180.

Suursaar, Ü. & Astok, V. (eds.) 1998. *More Studies on the Water Exchange and the Nutrients of the Gulf of Riga. EMI Report Ser.*, **9**.

Suursaar, Ü., Astok, V., Kullas, T., Nõmm, A. & Otsmann, M. 1995. Currents in the Suur Strait and their role in the nutrient exchange between the Gulf of Riga and the Baltic Proper. *Proc. Estonian Acad. Sci. Ecol.*, **5**, 103–123.

Suursaar, Ü., Astok, V., Kullas, T., Otsmann, M. & Nõmm, A. 1996. Väinameri – the buffer zone in the water and nutrient exchange between the Gulf of Riga and the Baltic Proper. In *Estonia. Geographical Studies* (Punning, J.-M., ed.), pp. 5–28. Estonian Acad. Publ., Tallinn.

VEE- JA AINEVAHETUSPROTSESSID VÄIKESES VÄINAS OLEVIKUS, MINEVIKUS JA TULEVIKUS

Ülo SUURSAAR, Mikk OTSMANN ja Tiit KULLAS

Väike väin on olnud maanteetammiga suletud alates 1896. aastast. Viimasel kümmekonnal aastal on Väikese väina piirkonnas täheldatud settimis- ja eutrofeerumisprotsesside kiirenemist. Kasutades hüdrodünaamilisi mudeleid on rekonstrueeritud veevahetuse iseloom enne väina tammiga sulgemist ning analüüsitud tammisse kavandatavate avade mõju ökosüsteemile. Leiti, et avades tekiks tihti suunda muutev voolamine kiirusega keskmiselt u. 50 cm/s (max 2 m/s). Aasta kokkuvõttes oleks eelistatud suund Liivi lahest Väinamere poole (summaarselt 0,1 km^3 vett ning u. 1000 tonni setteid). Eeldatav positiivne ökoloogiline efekt jääks siiski tagasihoidlikuks ning piirduks avade vahetu lähedusega. Hoovuse kiirus suureneks avadest eemal vaid 10–20% võrra. Väikese väina veekeskkonna ökoloogiline seisund võiks natuke paraneda tammist lõunas. Tammist põhja pool (Orissaare läheduses) suureneks hüdrokeemiliste näitajate ajaline muutlikkus ja olukord võiks mingil määral halveneda.