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COMPARATIVE CALCULATION OF FLOWS IN THE STRAITS OF THE GULF OF RIGA AND THE VÄINAMERI

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Abstract. Two hydrodynamic models are applied for flow calculations in the Gulf of Riga and the Väinameri subbasins. The correlation between the measured and modelled time series and between the time series obtained with both models is high. The analysis of the modelled flows within the regions of the straits proved that in the straits of the Väinameri the flows are spatially unidirectional. In the wider Irbe Strait the velocity vectors in the strait are not so uniformly directed. However, a horizontal two-directional flow regime is quite rare and probably it is possible to get representative water exchange estimates at one point even in that strait.

Key words: currents, channels, hydrodynamic modelling, 2D models, measurements, Baltic Sea.

1. INTRODUCTION

In order to describe the water flows and to estimate the substance exchange through the straits of the Gulf of Riga and the Väinameri Sea, an extensive set of current measurements has been carried out in 1993–96 in the framework of the Gulf of Riga project. It appeared that the temporal and spatial variability of flows is substantial, requiring a simultaneous exploitation of many current meters in all the major straits during at least one annual cycle. In reality, only the measurements in the Suur Strait were representative enough for flow quantification. In addition, some results explaining the water exchange processes in the Irbe Strait and the Hari Strait were obtained, but as a whole the project failed in closing the system merely by field measurements. Probably there is no hope to find finances for similar measurements in the nearest future. But it is possible to calculate the flows using hydrodynamic models.

Using empirical data and knowledge obtained from the field measurements, two-channel [1] and four-channel [2,3] versions of the forced oscillation model (FOM) for water exchange have been worked out. Using open sea level, wind, and riverine inflow data time series, the flows in the straits and the mean sea levels inside the subbasins could be calculated. The model has been successfully verified using the data obtained during six months in the Suur Strait and used already in some applications, including evaluation of ecological risks of some hydrotechnical buildings (bridges, dams) in the straits [4,5]. Despite some sets of special measurements [6], certain doubts remained about the spatial homogeneity of the flows: are the flows in the straits of the Väinameri really unidirectional so that the horizontally averaged flows are representative for the entire cross-section? The flows in the wider Irbe Strait, for example, are not considered homogeneous [7]. FOM gives temporal variations of the resultant flows over the cross-section of the Irbe Strait, but the division into simultaneous in- and outflowing components still remains open.

In order to obtain the description of spatial variations of the currents in the study area, two- and three-dimensional hydrodynamic models are needed. A quite complex 3D hydrodynamic ecosystem model FinEst [8] already exists for the entire Baltic Sea as well as for its parts (Gulf of Finland, Gulf of Riga). Our task was to develop a simpler two-dimensional model (2DM), describing some of the hydrodynamic aspects in a smaller study area (the Gulf of Riga) with better spatial resolution. The pilot applications covered only the Väinameri area [5] and for now the model can be applied to the whole Väinameri–Gulf of Riga system. Parallel existence of the two working models gives an opportunity for mutual verification of the models bearing in mind that the FOM is already verified against the measurements. On the other hand, the 2DM gives additional information about the spatial distribution of the flows in the straits and within the subbasins.

Thus the main aims of the current paper are the following: 1) to introduce the 2D hydrodynamic model for the Gulf of Riga–Väinameri and to present some preliminary results; 2) by comparing the outputs of both models to test whether the flows in the straits of the Väinameri could be considered as spatially unidirectional (and thus, describable by the measurements obtained at one point of the cross-section or calculated as an average over the cross-section); 3) to investigate the spatial structure of the flows in the Irbe Strait.

2. THE MODELS

2.1. The forced oscillation model

Due to the suitable size and configuration of the semi-enclosed subbasins and straits under discussion, it is possible to model the system as a combination of five individual Helmholtz oscillators [9]. In our case the system is composed of two oscillators for the Gulf of Riga and three for the Väinameri. As a result of superposition of these individual oscillators, a system with two free oscillation periods (about 24 and 12 hours) is obtained. The straits are modelled as rectangular channels where movements only along the channels occur. Within the basins only vertical movements are present. The basic equations consist of four motion equations and the volume conservation equations for the Gulf of Riga (subscript G) an the Väinameri (subscript V):

$$\frac{\mathrm{d}u_i}{\mathrm{d}t} = \frac{g}{L_i}\Delta\xi_i + \frac{\tau_i}{H_i} - \frac{k|u_i|u_i}{H_i},$$

$$A_{\mathrm{G}}\frac{\mathrm{d}\xi_{\mathrm{G}}}{\mathrm{d}t} = u_1 A_1 + u_2 A_2 + Q_{\mathrm{G}}, \qquad (1)$$

$$A_{\mathrm{V}}\frac{\mathrm{d}\xi_{\mathrm{V}}}{\mathrm{d}t} = -u_1 A_1 + u_3 A_3 + u_4 A_4 + Q_{\mathrm{V}},$$

$$\Delta\xi_1 = \xi_{\mathrm{V}} - \xi_{\mathrm{G}}, \quad \Delta\xi_2 = \xi_2 - \xi_{\mathrm{G}}, \quad \Delta\xi_3 = \xi_3 - \xi_{\mathrm{V}}, \quad \Delta\xi_4 = \xi_4 - \xi_{\mathrm{V}},$$

where ξ_2, ξ_3, ξ_4 and $\xi_{\mathrm{G}}, \xi_{\mathrm{V}}$ are elevations of the sea level in the open sea and inside the subbasins, respectively, u_i are space-averaged flows in the straits, $i = 1, 2, 3, 4$ denote different straits (1 – Suur, 2 – Irbe, 3 – Soela, 4 – Hari, Fig. 1), k is nondimensional friction coefficient, g is acceleration of gravity, t is time, L_i and H_i are the lengths and depths of the straits, respectively, τ_i are the wind stresses above these channels, Q_{G} and Q_{V} are the river inflows into the subbasins, A_{G} and A_{V} are the surface areas of the subbasins, and A_i are the cross-section areas of the straits.

The driving forces are the wind stresses τ_i calculated with HIRLAM (High Resolution Atmospheric Model), the sea level differences between the ends of the straits ($\Delta\xi_i$), and the river inflows to the subbasins. Rivers input is excluded from the present comparison of the two models since the rivers influence on velocities is negligible; rivers become important only by considering long-term water balance in the subbasins. Model outputs are the space-averaged flows in the straits and the sea levels inside both of the two subbasins. The last term of the first equation in (1) describes the bottom friction of the straits ($k = 2.5 \times 10^{-3}$).

To solve the system of differential equations (1) relative to u_i, ξ_{G}, and ξ_{V}, the fourth order Runge–Kutta method with one minute time step was used. For parameter values, verification, and a more detailed description of the model behaviour, see [1–3].

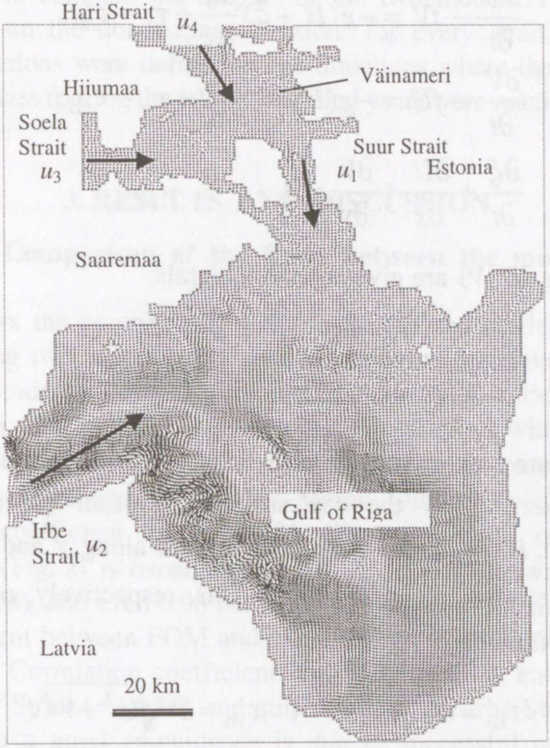


Fig. 1. The study area: the background presents a snapshot (26 January 1995 at 00:00 local time) of the velocity fields in the Gulf of Riga and the Väinameri, calculated using the 2D hydrodynamic model; arrows mark flow directions in the straits (u_i) according to the forced oscillation model.

2.2. Two-dimensional model

The 2DM is based on the Baltic Sea hydrodynamic model, using hydrodynamic–numerical (HN) approach [10]. The same model is used for calculating the sea level input data for the above described FOM. The grid step for the Baltic Sea was 2.5 miles. First for the Väinameri a new 1 km grid has been built and the coastal line and bathymetry have been digitized with corresponding resolution. Then, for the Gulf of Riga, 1 km grid was adopted on the basis of the Latvian bathymetric database [11]. The model domain is 150×241 points, including 16 405 marine points in the Gulf of Riga and 2510 marine points in the Väinameri subbasin.

The 2D HN model is based on hydrodynamic equations for a shallow sea (vertically integrated barotropic Reynolds equations)

$$\frac{\partial U}{\partial t} - fV = -g(H+\xi)\frac{\partial \xi}{\partial x} + \tau_x - \tau_{xB},$$
$$\frac{\partial V}{\partial t} + fU = -g(H+\xi)\frac{\partial \xi}{\partial y} + \tau_y - \tau_{yB}, \qquad (2)$$
$$\frac{\partial \xi}{\partial t} + \frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} = 0.$$

The volume flows (U, V) are given by the integrals:

$$U = \int_{\xi}^{H} u\,\mathrm{d}z; \quad V = \int_{\xi}^{H} v\,\mathrm{d}z,$$

where u and v are current velocities in x and y direction respectively, f is Coriolis parameter, ξ is the sea surface elevation (deviation from the equilibrium depth, H), τ_x and τ_y are wind stresses along x and y axis, τ_{xB} and τ_{yB} are bottom stresses along x and y axis, respectively, depending on the bottom stress coefficient k:

$$\tau_{xB} = kU\sqrt{U^2+V^2}, \quad \tau_{yB} = kV\sqrt{U^2+V^2}.$$

The model inputs, similarly to FOM, are the HIRLAM winds and the sea level oscillations at the straits entrance into the open sea. The outputs are the horizontal distributions of the sea levels in the study area and the depth averaged velocities at each grid point of the Väinameri and the Gulf of Riga.

2.3. The simulations

The simulations were carried out in parallel with both models, FOM and 2DM, using realistic input data for the year 1995. Year 1995 is the most thoroughly investigated period, reasonably well covered by field measurements and simulations with FOM [4,12]. The current velocities (and therefore the volume flows) are presented in all the straits with the time step of three hours during the whole year.

The output of the 2DM is far more extensive, including the time series of velocities and sea levels at every grid point. A velocity output is presented in Fig. 1, giving an example of the grid density as well as a snapshot velocity field under particular conditions. Further we analysed the data obtained in 8 different cross-sections of the four straits. Cross-sections contain 22 and 24 grid points in the Irbe Strait, 5, 7, and 9 points in the Suur Strait, 9 and 10 in the Hari Strait, and 7 points in the Soela Strait. Average flow characteristics over the cross-sections were calculated to compare the outputs of the two models. Projections of the velocity vectors on the dominating directions for every strait were calculated. Dominating directions were defined as the directions where the variances of the projected time series (during the whole modelled year) were maximal.

3. RESULTS AND DISCUSSION

3.1. Comparison of the flows between the models

Figure 2 shows the comparison of the measured and modelled flows in the Suur Strait during two months. The measurements were made using recording current meter (Aanderaa RCM-7), providing data on the directions and velocities of the currents as well as water temperatures and salinities with 30 min interval (on measurements see also [13]). The comparison of the results of FOM and corresponding measurements in January–March 1995 are described in [2]; then the correlation coefficient reached 0.96. The correlation of the results in June–July 1995 (Fig. 2) is excellent as well, being 0.94 between the measurements and the FOM, and even 0.98 between the outputs of the models.

Good agreement between FOM and 2DM for the four straits is demonstrated in Figs. 3 and 4. Correlation coefficient (calculated for the entire year) is very high for the Suur Strait ($r = 0.99$) and quite high for the Irbe Strait ($r = 0.97$). In our opinion such a good coincidence is due to successful calibration of the models. It also proves capability of the Helmholtz mode to describe the system as a prime mode of motions.

However, the time series of the differences between the respective values of the models show a relatively high variability (Figs. 3 and 4). Standard deviations of the differences reach 15–25% of the corresponding values for the original series and variability ranges are quite high as well (Table 1). That controversy may be explained by different nature of the models. Some notable deviations are

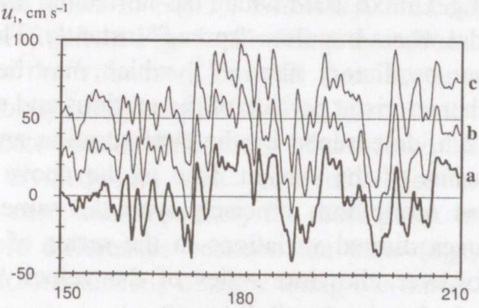
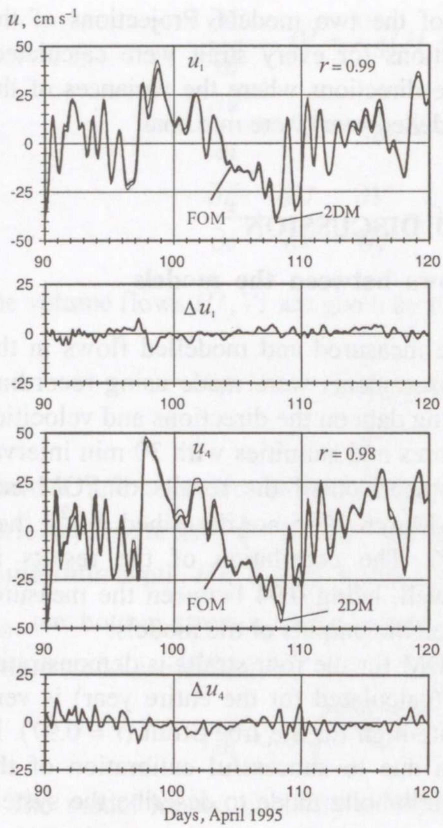


Fig. 2. Comparison of time series of u_1 (Suur Strait): a – field measurements, b – FOM, c – 2DM (respectively 30 and 60 cm s^{-1} are added to the modelled values for better distinguishing of the curves).



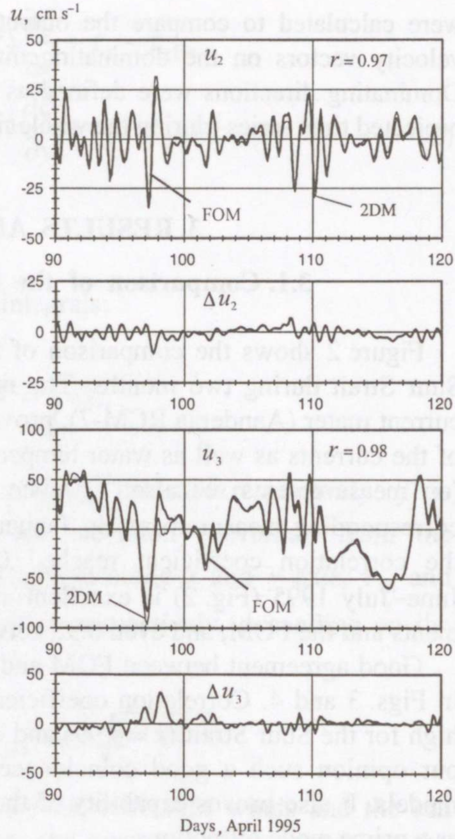


Fig. 3. Comparison of calculated velocities u_1 and u_4 using FOM and 2DM; r is given for the entire year of 1995.

Fig. 4. Comparison of calculated velocities u_2 and u_3 using FOM and 2DM; r is given for the entire year of 1995.

very short-term ones which appear due to a different temporal adjustment to the changes in the forcing. Unlike 2DM which has horizontal dimension, the FOM is actually a point model where impulses "spread" instantly. The flow in the system of the straits has an oscillatory nature [2] which may be described by both models. The most characteristic periods of the motions and sea level fluctuations are about 24 and 12 h, determined by the configuration and dimensions of the channels and subbasins of the system. Due to the above reasons, it is quite difficult to get these oscillations precisely with the same phases in different models. That produces diurnal variations in the series of velocity differences (Figs. 3 and 4). However, the time series of the velocity differences are not correlated to the original series ($r = 0$–0.1).

Thus the models show good agreement and probably describe successfully the water exchange processes with the time scale exceeding a few hours, whereas good short-term agreement is not to be expected.

Table 1. Comparison of some statistics of the 2DM and FOM–2DM in 1995

Statistic, cm s^{-1}	Strait							
	Hari		Soela		Suur		Irbe	
	2DM	FOM–2DM	2DM	FOM–2DM	2DM	FOM–2DM	2DM	FOM–2DM
Standard deviation	20	4	31	6	17	2	9	2
Variability range	114	44	213	55	109	28	82	22

3.2. Analysis of flows within the straits according to 2DM

Empirical distribution functions of current directions, calculated for every grid point in the straits, show that the flows fall indeed into narrow bands, at least in the case of the straits of the Väinameri (Fig. 5). Thus, measurement of the velocity at one point of the strait cross-section (and correcting the measurements with certain empirical coefficients depending on the location for obtaining realistic flow volumes through the whole cross-section) seems to be justified. The correlation coefficients between the time series of the individual grid points and the cross-section average were 0.87–0.98 in Suur Strait. Excluding the outer points of the cross-sections, the correlation coefficients become 0.95–0.98 and are high (0.84–0.97) for other straits of the Väinameri as well. Due to the large number of data pairs (2920), the reliability of the results is very high. Practically, it is possible to carry out measurements at any point of the strait with good or reasonably good results.

In the Irbe Strait, however, scattering of the individual distribution functions of the flow directions is much larger, deserving a special analysis. The functions are grouped for the two sides of the strait (Fig. 5d–e), showing relatively narrow direction bands for both of them (around 230° and 190–200°) and more uniform distributions in the central part of the strait (these functions somewhat contaminate the clear peaks in Fig. 5). Similarily, the correlation coefficients, depicted for the Irbe Strait in Fig. 6, show that the values are generally lower than in the straits of the Väinameri, but still there are areas where correlation with the average velocity is high (up to 0.84–0.87).

In order to estimate spatial differences of the flows in the Irbe Strait, the cross-section was divided into two parts of equal areas and the flow characteristics were computed separately for these parts. It appeared that there were no considerable differences between the parts (e.g., continuous inflow along one coast and simultaneous outflow along the other). Both parts showed nearly coherent fluctuations; the flow magnitude was about 1.6 times higher in the southern than in the northern part. Small residual differences (about 0.5 cm s^{-1} in average) between the flows in the two parts do not allow to speak about a major horizontally displaced two-directional flow regime.

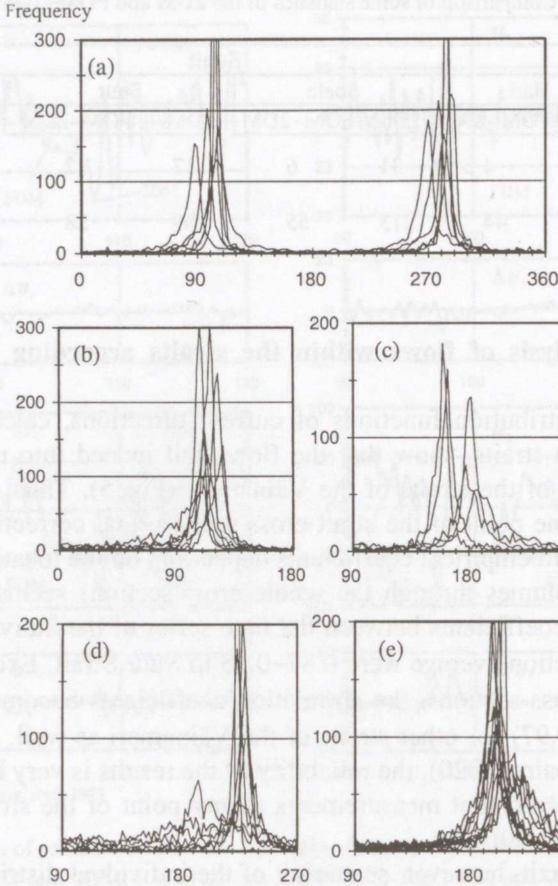


Fig. 5. Empirical distribution functions of current directions (degrees, counted anticlockwise from East) in the grid points of different straits: a – Suur Strait, full range of directions; b, c – Hari and Soela straits, half range; Irbe Strait, d – points near the Estonian coast, e – points near the Latvian coast.

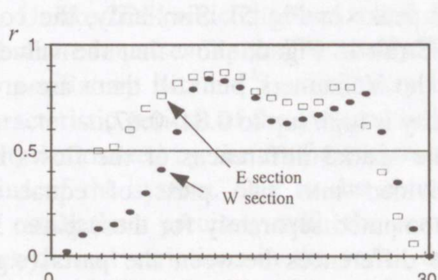


Fig. 6. Horizontal distribution of correlation coefficients between the annual time series at individual points along the E and W coast to coast sections of the Irbe Strait and the corresponding cross-section average series.

Thus, while earlier it was considered that the Irbe Strait needs two or even three current meters [14], our simulations show that for obtaining some of the most consistent water exchange characteristics it is sufficient to make measurements at one point. However, as 2DM is vertically integrated, we cannot say anything definite about the (hypothetical) vertically displaced two-layer flow regime. We also admit, as our findings are based merely on the modelling results and perhaps the models cannot reproduce all the physical processes in the straits, that even the absence of a frequent horizontal two-directional flow regime is not fully proved here. Nevertheless, it seems to us that such a flow regime is not prevalent in the Irbe Strait.

4. CONCLUSIONS

The correlation between the measured and modelled time series of the current, as well as between the time series calculated using both models, is high (*r* equals 0.97 in the case of the Irbe Strait and is around 0.98 in other straits). Though the two models are not particularly well in accordance by predicting short-time processes (within few hours) due to the difficulty of getting outputs with the same phase of oscillations, they can successfully describe the water exchange processes with the time scale starting roughly from the semi-diurnal period.

The analysis of the modelled flows within the regions of the straits proved that the flows are spatially unidirectional in the straits of the Väinameri. In the wider Irbe Strait the velocity vectors in the strait are not so uniformly directed. However, our preliminary results show that a horizontal two-layer flow regime is quite rare and probably it is possible to get representative measurements at one point even in that strait.

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LIIVI LAHE JA VÄINAMERE VÄINADE HOOVUSTE KIIRUSTE VÕRDLEVAD ARVUTUSED

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On kirjeldatud kahte eri tüüpi hüdrodünaamilist mudelit ning võrreldud nende abil simuleeritud hoovuste kiirusi Liivi lahe ja Väinamere väinades. Kooskõla kahe mudeli tulemuste ning modelleeritud ja mõõdetud hoovuste kiiruste vahel on hea ($r = 0,94–0,99$). Arvutustest selgub, et Väinamere väinade ristlõikes domineerib ühesuunaline voolamine. Laiemas, Irbeni väinas on kiiruste horisontaalne jaotumine mõnevõrra heterogeensem. Siiski tundub, et erisuunaline voolamisrežiim väina kallastel on seniarvatust harvem ning ka Irbeni väinas on põhiliste veevahetuskarakteristikute saamiseks võimalik hoovusi representatiivselt mõõta ainult ühes punktis.