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Modelling of Water Exchange in an Estuary

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A two-dimensional horizontal hydrodynamical model has been used to estimate the changes that a harbour road will cause in the water exchange of an estuary. The research area has been the Kokemäenjoki river estuary on the coast of the Gulf of Bothnia in western Finland.

The numerical model has been verified on the basis of a regression model describing the water exchange of the estuary at present with a multiple correlation squared of 0.9. The factors having an influence on the water exchange are the wind, the sea level fluctuation and the river discharge.

The changes in the water exchange have been considered during a dry spell, a flood period and an average year with three different cross-section areas of the road line. The accuracy and reliability of the estimation are found to be very satisfactory.

Introduction

At coastal areas covered with islands it is often appropriate to build roads over narrow straits and bays. When planning the road banks and the size of the bridge openings one has to take into account the possible changes in the water area that will be caused. The immediate consequences of the road banks are the decrease in water exchange and possibly high current velocities in the bridge openings.

The basis for the estimation of the consequences are the field measurements. In favourable cases the results of the field measurements can be expressed e.g. as a regression model, where the water exchange of the area is presented as a function of outer factors such as the wind, the sea level, and the river discharges flowing into the area.

The numerical models give a possibility to quantitatively estimate the effects of future measures, such as the reduction of the bridge openings, thus offering a reliable basis for planning. In recent years hundreds of models for different purposes have been developed all over the world (Hinwood and Wallis 1975). The limitations of the numerical models are also in general quite well known (e.g. Fisher 1976).

In this work the results of the field measurements and the regression model concerning the present situation give an excellent opportunity to test the numerical model and to determine the reliability of the estimation.

By means of the numerical models one has until now tried e.g. to understand the character of the phenomena, to separate the role of different factors and to generalize the field results to concern the whole research area or the lacking field conditions. Here we have applied a two-dimensional horizontal hydrodynamical model (Hansen type) for a comparison of design alternatives in order to give a proper basis for decisions of economical and environmental value.

The Research Area

The research area was the Kokemäenjoki river estuary outside the town of Pori in western Finland on the coast of the Gulf of Bothnia (Fig. 1.). There is a plan to build a new harbour road to the northern side of the Pihlavanlahti Bay from the mainland to the Reposaari Island.

The Kokemäenjoki river, which flows into the Pihlavanlahti Bay has a mean yearly discharge $MQ=206$ m^3/s (mean high discharge $MHQ=584$ m^3/s, mean low discharge $MNQ=53$ m^3/s). The water exchange between the bay and the sea occurs through the bridge opening of the existing harbour road (the Reposalmi strait) and through several straits to the north.

The planned road line goes over four straits on the northern side of the Pihlavanlahti Bay. The cross section areas of these straits counted from west to east at present and according to two design alternatives at mean water level are as follow

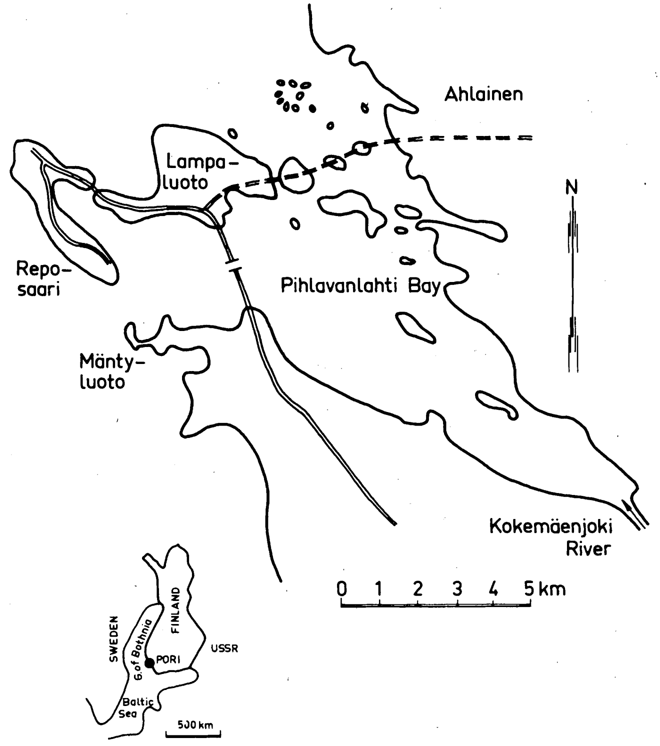

Fig. 1. The research area.

	at present	the alternatives 1.	 2.
strait 1	120 m²	51	51
strait 2	1310 m²	6	300
strait 3	750 m²	0	0
strait 4	940 m²	139	450
total	3120	196	801

The cross section area of the Reposalmi strait is 635 m^2.

The second alternative corresponds to the smallest integrated cross section area of the straits on the southern side of the planned road line.

The area of the Pihlavanlahti Bay is about 38 km^2 at mean water level and the mean depth about 3.5 m. Temperature and salinity stratification is not frequent because of the shallowness of the area.

46.3% of the winds blow from the southern sector (SE, S, SW) and 34.4% from the northern sector (NW, N, NE) according to a long term distribution (Venho

1963). The mean velocity of the wind is 4.1 m/s and 5.6% of the velocities are over 11 m/s. About 2/3 of observed sea levels deviate less than 20 cm and about 5% more than 40 cm from the mean sea level (Lisitzin 1959). 52.5% of the water level changes are less than 10 cm/day and only 4% more than 30 cm/day (Lisitzin 1952).

Observations

Current measurements were made in March-May 1974 and August-September 1975. Five recording meters (Aanderaa RCM4) were used. Two of them were placed in the Reposalimi strait and three in the northern straits. The dependence between the current velocity at the recording point and the corresponding discharge through the strait was determined by measuring the distribution of the current velocity in the cross section under different discharge conditions.

The sea level and the wind were observed at Mäntyluoto and the discharge of the Kokemäenjoki river at an upstream power-station about 30 km from the estuary.

The Regression Model

The statistical analysis was made on the basis of daily mean values of 75 days. The regression models for the discharges of the straits describing the present situation are as follows

$$Q_w = 13.7 + 0.672Q_I - 38.43e^{-0.00465Q_I} W_s - 2.48\Delta Z \qquad (1)$$

$$(R^2 = 0.982)$$

$$Q_N = -4.2 + 0.334Q_I + 33.52e^{-0.00465Q_I} W_s - 1.07\Delta Z \qquad (2)$$

$$(R^2 = 0.915)$$

where

Q_W = the discharge through the opening of the existing road bank (m^3/s)
Q_N = the discharge of the northern straits (=through the planned road line) (m^3/s)
Q_I = the discharge of the Kokemaenjoki river (m^3/s)
W_S = the wind component from the south (m/s)
ΔZ = the change of the sea level (cm/day)
R^2 = the multiple correlation squared

The positive direction of the discharges points to the sea.

The mean values and standard deviations of the observations were as follows

	March-May – 74		August-September – 75	
	mean	st.dev.	mean	st.dev.
Q_I (m^3/s)	388	95	80	27
W_S (m/s)	1.9	2.6	-2.5	3.0
ΔZ(cm/day)	0.0	7.4	0.8	7.7

The observation periods differ strongly from each other regarding the river discharge, which has allowed to form the dependence between the influence of the wind on the discharges of the straits and the river discharge Q_I. The factor k = -0.00465 included in the wind term (of form Ce^{-kQ_I}) is a result of optimating the multiple correlation squared of the models. The term gets a value C when $Q_I = 0$, and approaches zero when the discharge increases.

The models show, that about 1/3 of the river discharge flow to the sea through the northern straits when there is no wind. The dominating winds from the southern sector increase the share flowing to the north to be more than 1/3 on an average.

According to the analysis there is no significant correlation between the east component of the wind and the discharges in the straits.

The regression model can also be used when the Pihlavanlahti Bay is ice covered provided that the sea is open outside Mäntyluoto. According to an analysis made by the Institute of Marine Research in Finland, the average time for permanent ice cover 2 miles outside Mäntyluoto has been only about 1.5 months, occurring in February-March based on the years 1931-60.

The Numerical Model

The numerical model was a vertically integrated 2-dimensional one-layer model, which solves the Navier-Stokes equations of motion

$$\frac{\partial u}{\partial t} = -\frac{ru}{H} + fv - g\frac{\partial \zeta}{\partial x} + \frac{\lambda W W_x}{H} + \nu \cdot \nabla^2 u - u\frac{\partial u}{\partial x} - v\frac{\partial u}{\partial y} \qquad (3)$$

$$\frac{\partial v}{\partial t} = -\frac{rv}{H} - fu - g\frac{\partial \zeta}{\partial y} + \frac{\lambda W W_y}{H} + \nu \cdot \nabla^2 v - u\frac{\partial v}{\partial x} - v\frac{\partial v}{\partial y} \qquad (4)$$

and the continuity equation

$$\frac{\partial \zeta}{\partial t} = -\frac{\partial (Hu)}{\partial x} - \frac{\partial (Hv)}{\partial y} \qquad (5)$$

in a space-staggered mesh by the finite-difference method. The method was essentially the one used by Sündermann (1966) and Laevastu (1974). In the equations

u, v = depth-averaged velocity components (mm/s)
ζ = water level elevation (mm)
r = bottom friction (mm/s)
f = coriolisparameter (s^{-1})
g = gravity acceleration (ms^{-2})
λ = wind drag coefficient ( )
ν = horizontal eddy viscosity (m^2/s)
H = total depth of the water column (m)
W = wind velocity (m/s)
W_x, W_y = wind velocity components (m/s)
$\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}$ = the horizontal Laplace-operator
x, y = horizontal co-ordinates (m) and
t = time (s).

Because of the shallowness of the area the use of a 2-dimensional model is well justified.

Boundary Conditions

At closed boundaries the natural boundary condition is that no water is carried through the shore line, i.e. the perpendicular velocity components are zero.

At open boundaries, on the other hand, some additional conditions are needed. In the river mouth (I) the given river flow Q_I is fed to the bay through a cross-section of $H\Delta s$ perpendicularly to the boundary, so that the velocity components will be

$$v \equiv \frac{Q_I}{H\ s} \qquad u \equiv 0\,, \tag{6}$$

At the northern boundary (II) it is assumed that

$$\frac{\partial(Hv)}{\partial y} \equiv 0 \qquad u = 0 \tag{7}$$

which means that the volume transport through the boundary is the same as the one calculated in the previous grid row, and that the flow is directed perpendicular to the boundary, the latter condition being imposed by closed boundaries of the straits. At the western boundary (III) the water level is set equal to the measured sea level Z_W

$$\zeta \equiv Z_w , \tag{8}$$

which allows calculation also with changing water elevation.

Model Parameters and Grid Definition

The model parameters have been as follows:

time-step $\Delta t = 40$ s
mesh-size $\Delta s = 604.8$ m
wind drag coefficient $\lambda = 2 \cdot 10^{-6}$
bottom friction $r = 0{,}4$ mm/s and
eddy viscosity $\nu = 0$.

The time value satisfies the Courant-Friedrichs-Lewy stability restriction

$$\Delta t < \frac{\Delta s}{\sqrt{2gH}} \approx 50 \text{ s} :$$

The grid net of the area is shown in Fig. 2. Because of the finite mesh-size the strait contractions must be taken into account by decreasing the depth of the strait so that the area of the cross-section remains correct. This is why the depths at the grid points are given with an accuracy of 1 cm.

Principles of Calculation

Comparison of the Models with Observations

Verification of the numerical model has been carried out with the present bottom configuration ($A = 3000\text{m}^2$). A comparison of the computed results with the observed time series is shown in Fig. 3. The differences are greatly due to the smoothness of the input parameters, because for the river inflow Q_I and for the sea level fluctuations DZ_W the slowly varying daily averages were used. The wind data of the numerical model, based on the observations at Pori airport, were changed stepwise after each three hours. As a whole the numerical model properly explains the main features of the observed time series and thus offers a reasonable basis for the calculation of the daily averages.

When considering the daily mean discharges, the steady state solutions of the numerical model can be used, the steady state being obtained in 9 to 12 hours. An example of the computed flow field is given in Fig. 2. The regression model justifies the use of the daily averages, reduces the number of independent

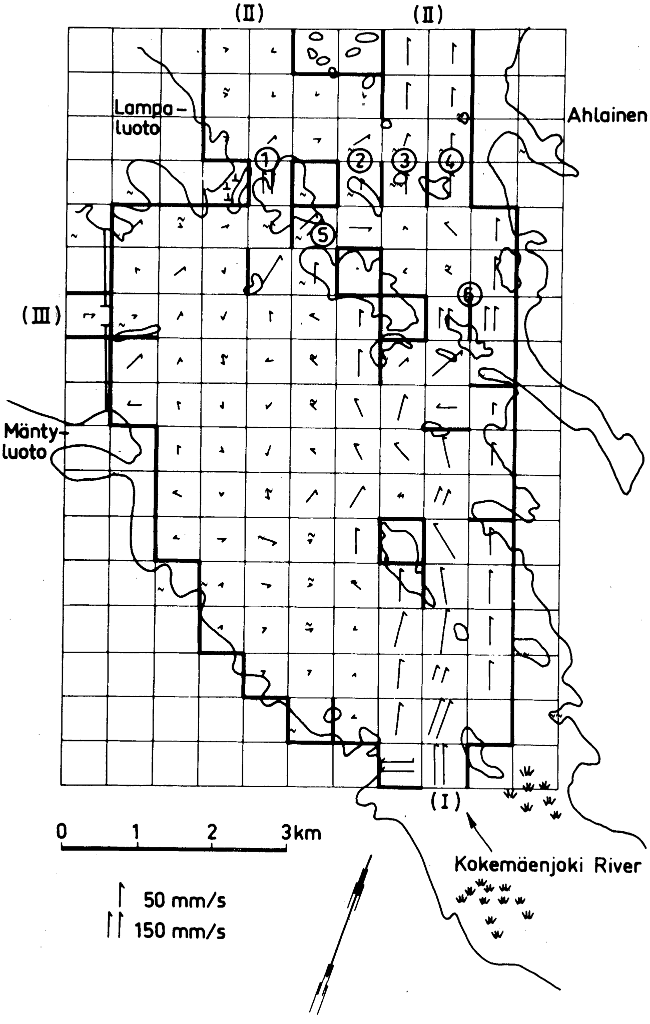

Fig. 2. The grid net with an example of the flow field (Q_I = 100 m³/s, W_S = 5 m/s, ΔZ = 0).

variables to three only, and can be used for comparison of the numerical model results.

A comparison between the models and the measurements is made in Fig. 4 where the flow through the northern straits. Q_N is presented as a function of southern wind component W_S. The observations have been transformed to correspond just to the computed situation (Q_I = 100 m³/s, ΔZ = 0) by means of the relevant terms of the regression model (2). The linear vs. quadratic form of the wind term in Eq. (2) compared with (4) and (5) comes clearly up in the figure. The

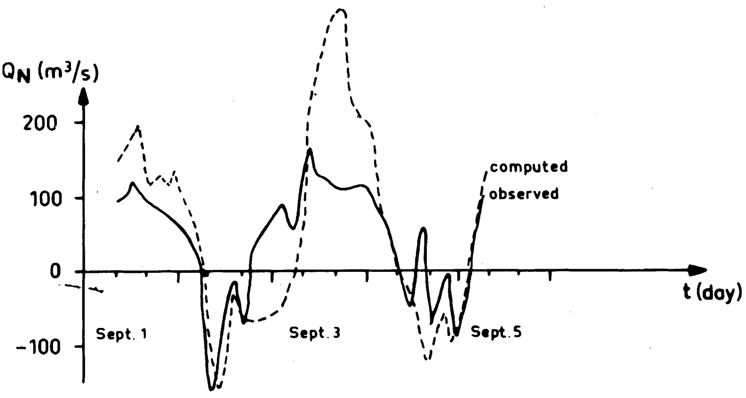

Fig. 3. Comparison of the computed time series with observations (Q_I = 50...80 m³/s, W_S = -6...+11 m/s, ΔZ = -5...+10 cm/day).

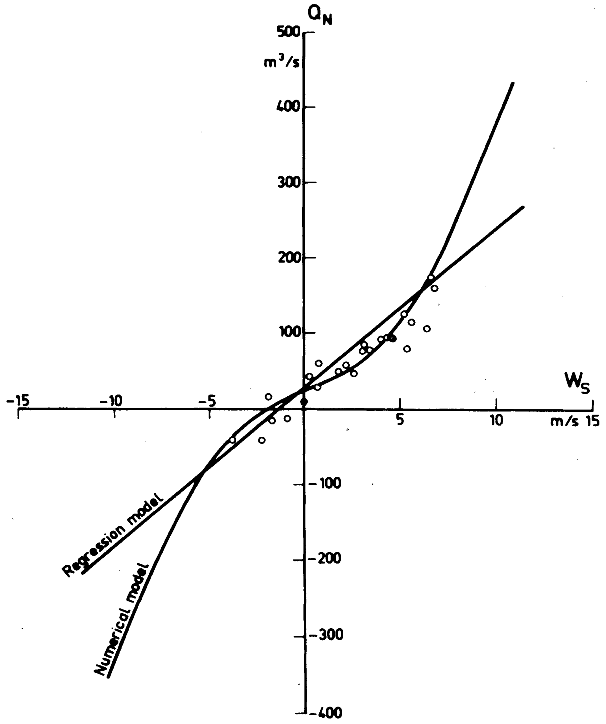

Fig. 4. Comparison between the models and the observations (Q_I = 100 m³/s, ΔZ = 0).

correlation coefficient squared due to the wind only is the same in both models, R^2 = 0,87. The total multiple correlation squared of the numerical model was R^2 = 0,84 without any special adjusting of the parameters r, λ and ν.

As an additional check of the numerical model results the distribution of the northern discharge Q_N between different straits (Fig. 2) may be considered. The mean proportions of the discharges through each route, obtained from measurements and the numerical model respectively, were

	observed	model
strait 1	23%	16%
strait 5	35%	35%
strait 6	42%	49%

The small overestimation of the discharge through the eastern strait 6 is caused mainly by the slight x-component of the southern wind in the grid net used.

Computed Situations

The changes in the water-exchange of the Pihlavanlahti Bay caused by the harbour road have been considered during the dry spell, the flood period, and the »average years«, with three different cross-section areas (A = 3000 m^2, 840 m^2 and 200 m^2) each. Different wind directions and velocities have been weighted in the proportions of their frequencies in the long distribution of the relevant season in Mäntyluoto from the years 1931-60 (Venho 1963). The distribution from Mäntyluoto was completed with more accurate velocity classification from Pori airport 1946-56 (Nurminen 1963). The steady state flow field was computed with each set of conditions, and the outflows Q_W and Q_N were then determined by means of the flow velocities in the straits.

For each inflow and cross-section 8 different wind directions and 8 velocity groups have been considered, i.e. 64 wind conditions in all.

For the dry spell a period was selected during which the flow of the Kokemäenjoki river is Q_I = 100 m^3/s. According to an analysis carried out by the Hydrological Office of the National Board of Waters in Finland the repetition times of such a period are

2.3 years (with a duration of 30 days) and
3.2 years (with a duration of 90 days).

As weighting factor for each wind condition the frequencies in the long term distribution from June to November were used. For the flood flow a value of Q_I = 400 m^3/s was chosen. The inflow exceeds 400 m^3/s annually during 3 weeks on the average (Hyvärinen and Gürer 1976). The wind distribution was that of the spring season (March-May).

The flows of the average year have been

in winter (Dec.-Febr.)	200 m^3/s
in spring (March-May)	300 m^3/s
in summer (June-Aug.)	160 m^3/s
in autumn (Sept.-Nov.)	200 m^3/s.

The average wind distribution of each season has been used.

Main Problems Considered and the Calculation Procedure

The most central problems concerning the water quality of the Pihlavanlahti Bay and neighbouring areas are

1) the discharge of the river water Q_R to the northern side of the road line
2) the amount of sea water Q_S flowing to the Pihlavanlahti Bay.

The former has an influence on the water quality on the northern side of the road line, the latter on the water quality and salinity of the Pihlavanlahti Bay.

The amounts Q_R and Q_S are determined by comparing the flows Q_N and Q_W with the inflow Q_I.

The present situation has been calculated both based on the regression equation and the numerical model. The estimation of the future situation has been possible only with the numerical model.

Estimation of the Influence of the Harbour Road

Summer Dry Spell of the Kokemäenjoki River

When the flow of the Kokemäenjoki river is small the wind causes in the present situation almost continous sea water inflow into the Pihlavanlahti Bay. During small river flows the wind also has a clear influence on the routes of the river discharge.

The high frequency of southern winds increases the average flow in the northern straits from that determined on the basis of geometrical relations only. In the present situation ($A = 3000\ m^2$) the average flows during the dry spell ($Q_I = 100\ m^3/s$) are as follows:

- river water to the north of the road line $Q_R = 43\ m^3/s$.
- sea water to the Pihlavanlahti Bay $Q_S = 35\ m^3/s$.

When the cross-section is reduced to 840 m^2 the corresponding flows are

- $Q_R = 38\ m^3/s$
- $Q_S = 29\ m^3/s$

and with a cross-section of 200 m^2
- Q_R = 20 m^3/s.
- Q_S = 10 m^3/s.

The dependence of Q_R and Q_S on cross-section A is graphically presented in Fig. 5. Both flows decrease sharply after the cross-section becomes smaller than 800 m^2, which is the area of the narrowest passage at present.

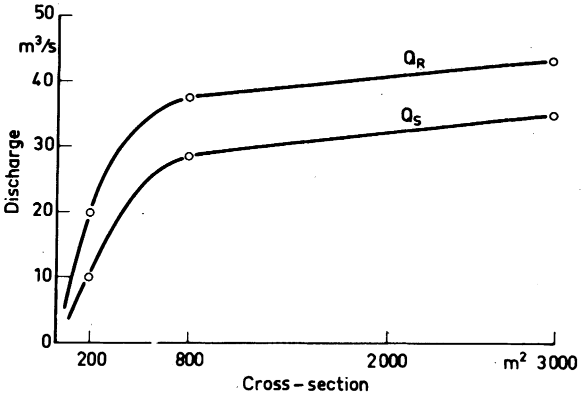

Fig. 5. The dependence of the discharges Q_R and Q_S on the cross-section area of the road line during the dry spell.

Flood Period

During the flood period no sea water flows to the Pihlavanlahti Bay. The discharge Q_R decreases from 135 to 25 m^3/s when the cross-section is reduced from the present 3000 m^2 to 200^2, the dependence being of the same shape as in Fig. 5.

The greatest flow velocities in the northern straits did not under any circumstances seem to exceed 1 m/s. In the western strait, Reposalmi, the greatest flow velocities increase from the present 2 m/s to about 2.2 m/s.

The Average Year

In an average year the influence of the road line on the sea water flow is important only during the summer season. The flow Q_S then decreases from 12 to 4 m^3/s as a consequence of reducing the cross-section area. During other seasons, when the river flow is greater, the sea water flow to the Bay is only 0...5 m^3/s regardless of the cross-section.

The flow of river water to the north of the road line Q_R is 25-30 m^3/s in the new situation ($A = 200 \text{ m}^2$), regardless of the season. In spring the flow to the north is evidently determined by the great inflow of the Kokemäenjoki river; during other seasons, by contrast, the dominating southern winds compensate for the decrease of the pressure caused by the river inflow. In the present situation ($A = 3000 \text{ m}^2$) Q_R varies between 64 m^3/s (in summer) and 105 m^3/s (in spring), the dependence on cross-section being again the same as in Fig. 5.

Discussion

Relatively long and varied time-series of observations and the regression equation explaining these (with $R^2 = 0.92$) have provided a favorable possibility to test the accuracy and reliability of the numerical model. In the present situation the multiple correlation coefficient squared between the numerical model and the observations $R^2 = 0.84$ shows that all main factors influencing the water exchange of the Bay are properly included in the numerical model. As the water exchange in the future bottom configuration is determined by the same factors as at present, it is to expected that the power of explanation in the estimation will be of the same order of magnitude as that in the verification.

Because of the permanence of the changes in the water exchange caused by the road line, the coupling of biological models with the flow field model is a very suitable subject for further investigation.

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