Currents and transport of sewage water in the coastal area of Vaasa, Northern Baltic Sea - a study with current measurements and modelling

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Abstract

The sewage water of the city of Vaasa, located at the Gulf of Bothnia, pollutes the surrounding coastal areas and beaches near the city. The sewage outlet is planned to be moved to some other place in order to decrease the harmful effects in the most valuable areas close to the city. The currents and transport processes in the area were examined in order to find the most suitable outlet location, which would minimize the effects of wastewater.

An extensive set of current measurements gives an idea of typical current patterns in different conditions. The currents were calculated with a 3-dimensional nested hydrodynamic model, which was validated with the current measurements.

The calibrated transport model was used to describe the effects of sewage water, when the outlet is located in four different places. The main sewage water impact area varies to a great extent depending on the outlet location. Also the outlet depth affects strongly the wastewater mixing. Comparison between the present situation and one of the main alternative outlet locations are discussed in this paper.

Model simulations and analyzed current measurements describe the comparative effects of different sewage water outlet locations. The results are of great practical value when the location alternatives are examined.

Background

Municipal wastewaters are typically discharged in the vicinity of or just at the coastline, thus affecting strongly the quality of the coastal waters. One solution to improve the situation, in addition to reduce the wastewater load, is to remove the outlet location to an offshore position. The improved mixing conditions may lead to clear reduction of the negative effects in the coastal area.

This paper deals with a study on the impacts of the municipal wastewaters discharged from the town of Vaasa to the Gulf of Bothnia in the Baltic Sea. In the study, the impact of discharging the wastewaters in various, alternative locations was investigated. The alternative outlet locations were selected within a distance of a few kilometers from the coastline, still inside the Vaasa archipelago. The archipelago is composed of a great number of islands with complicated configuration. In this area the water depth is typically less than 10 metres.

Methods

Reliable information of the currents and mixing processes are of major importance when assessing the impacts and cost-benefit relation of relocating the wastewater outlet. This is why special attention was paid to measuring the flow pattern in the Vaasa archipelago. Nine measurement locations were selected (figure 1). Measurements were made close to the surface at each site and close to the bottom at the deepest sites. The deepest sites were located on the side of the shipping channel (sites 2, 4 and 8), considered also as potential area of the new outlet. Aanderaa recording devices were used for wind and current measurements with a sampling interval of 10 minutes. The measurement period lasted about two months. With the absence of tide, wind is the predominant current inducing factor in the Finnish coastal waters.

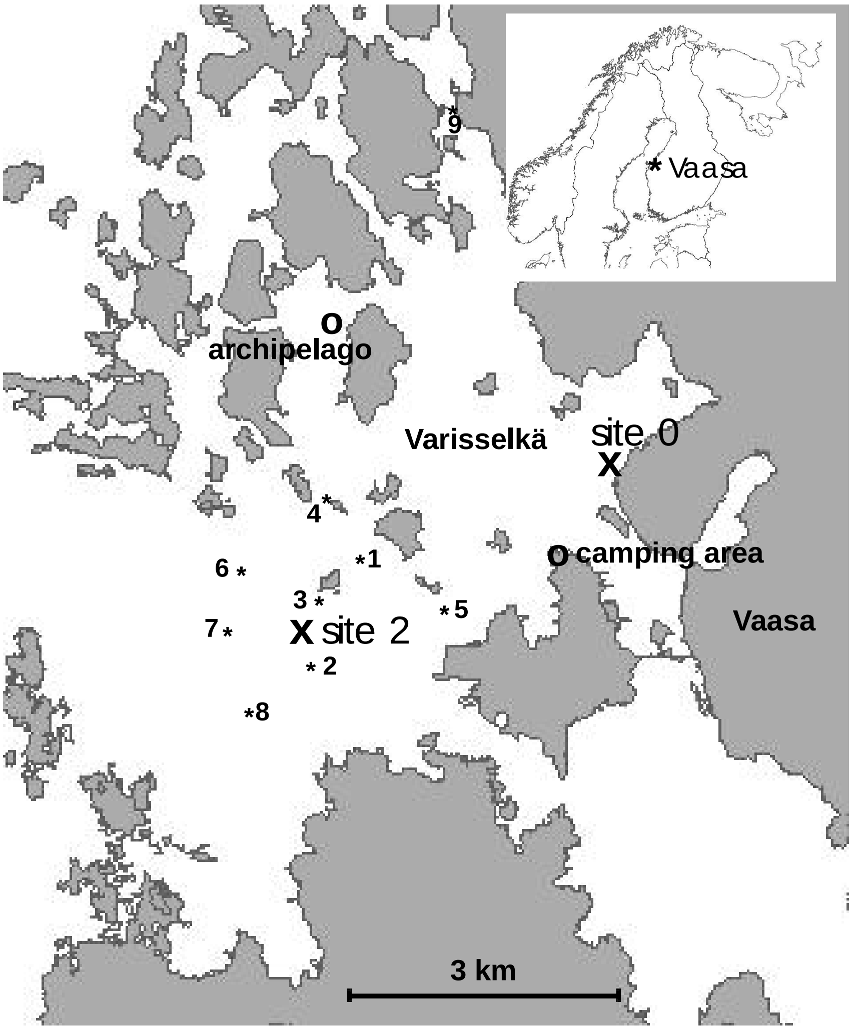

Figure 1. The study area.

Several outlet locations were considered. In this paper a comparison between two main alternatives is done. One of them is the present one and the other is sited 2 kilometers from the shore on the side of the main shipping channel from Vaasa to the sea (site 2, see figure 1).

The changes were calculated with a 3-dimensional hydrodynamic and water quality model (Koponen et al. 1992) which has been used in a great number of coastal applications in Finland. Currents are calculated with the 3-dimensional baroclinic multilayer model (Simons, 1980, Virtanen et al., 1986, Koponen et al., 1992). The water mass is treated as horizontal layers. Horizontally the model area is subdivided into rectangles with arbitrary mesh intervals in both directions. Explicit finite-difference schemes are used for the numerical solution of flow velocities and water level elevations. The currents in the model are determined by the following factors: wind force (or ice friction), atmospheric pressure at the surface, conservation and incompressibility of water, internal friction (viscosity), transport of velocity differences with water currents (advection), the Coriolis force, density differences and water level gradients (hydrostatic pressure) and bottom friction. The values of the principal model parameters in Vaasa application are shown in table 1.

Table 1. Principal hydrodynamic model parameters.

parameters and units used		value
A_v	vertical diffusion of momentum (m^2/s)	0.0045
A_h	horizontal diffusion of momentum (m^2/s)	1
C_d	quadratic wind friction coefficient	0.0007
C_b	quadratic bottom friction coefficient	0.0025

A nested grid was used with three nesting levels (6.5 kilometers resolution for the Gulf of Bothnia, 0.5 kilometers for the outer Vaasa archipelago and 100 metres for the inner archipelago. The innermost grid covers the area where the impacts of the outlet removal are expected to appear.

Water currents are calculated separately from material transport and water quality in order to save computer time. Short time-steps (often 10-30 s) needed in the calculation of flow velocities are unnecessary to repeat in the calibration runs of the water quality model. Either stationary or averaged flow fields are used for the water quality model.

In Vaasa application total phosphorus and nitrogen were calculated with a water quality model. Only transport and settling were modelled because the main emphasis was on comparing the mixing, transport and sedimentation from different outlet locations. Calculated results were compared with measured concentrations in order to ascertain that the calculated concentrations are not unrealistic. 3 cm/day settling velocity was used for total phosphorus.

Results

Measured flow patterns

Statistical analysis of the dependence between the winds and currents gave a good picture of the flow mechanism in the study area. This concerns both the large scale circulation through the archipelago and the currents in the vicinity of the optional outlet location at the shipping channel. As an example, the statistical relation is given at this location (in two depths at site 2) by the following equations

vn	= -0.14Wn+0.38We-0.03	R^2 = 0.60
ve	= -0.57We+0.17	R^2 = 0.62
Vn	= 0.18We+0.26	R^2 = 0.36
Ve	= 0.23Wn-0.24We-0.3	R^2 = 0.77

where

vn	= the velocity of the north component of flow at surface
ve	= the velocity of the east component of flow at surface
Vn	= the velocity of the north component of flow at depth 8 m
Ve	= the velocity of the east component of flow at depth 8 m
Wn	= the velocity of the north component of wind
We	= the velocity of the east component of wind

The general flow through the archipelago depends on the north-south component of wind. Southerly winds transport waters to the north and northerly winds to the south. This means that wastewater once brought in a pipeline to the sea on the western side of the town may be brought back to the town beaches by the current e.g. during SW wind, which is a frequent wind direction in this area. The measurements show, however, that the currents do not behave like this in the vicinity of the shipping channel. In the SW wind case they are directed to the west from site 2, i.e. opposite to the wind. The windward current, linked to the general anti clock-wise circulation occurs on the southern side of site 2. Actually, the currents along the shipping channel tend to move opposite direction relative to the east-west wind component. According to the measurements, this occurs at site 2 through the whole water column. This is an essential feature from the point of view of simulating the wastewater transport and the effect will be seen in the model calculations.

Water level rising accelerates flow to the north, falling level does the opposite. Water level changes seldom dominate the flow pattern because the amplitude is small.

Comparison between measurements and models

The results of the hydrodynamic model calculations over a two months period are shown from points 2 and 3 in figures 2 and 3. The fitting is very satisfactory at point 2 for both flow direction and speed. At point 3 the modelled current direction fits well with the measurements, whereas the model underestimates the speed. However, in general the calculated flow speeds are in agreement with the measured ones. At the point 5 (fig. 4) the calculated flow speed corresponds rather well with the measured values at the beginning and end of the measurement period. This location has special importance in relation to the transports between the outer and inner archipelago. The modelled direction deviates from the measured one especially in the beginning of the calculation period. Bathymetry is very complicated in this shallow area and the model resolution may not be enough to describe the currents in detail. Even the information on the bathymetry is rather limited. In case of northeast current in the beginning of September, the fitting is reasonable.

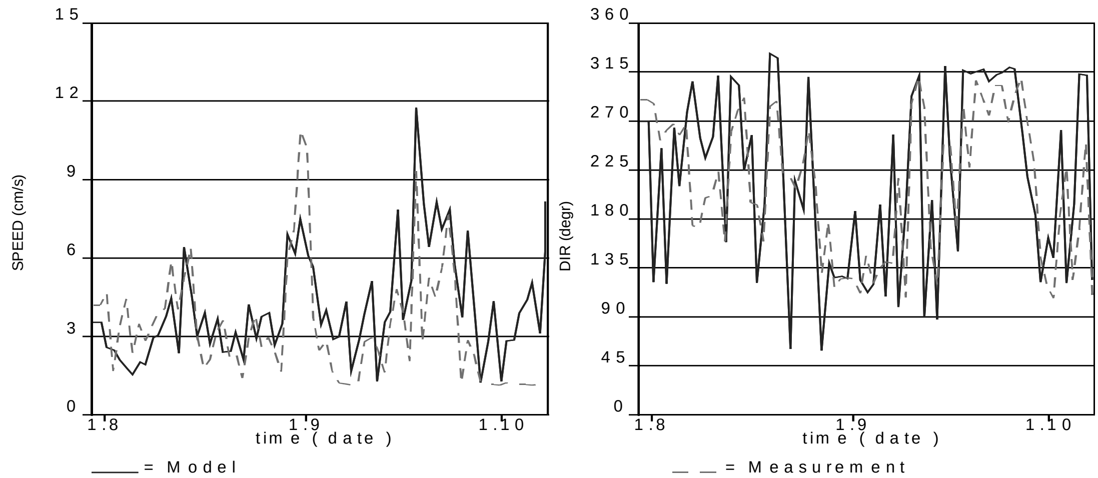

Figure 2. Measured and calculated flows from point v2.

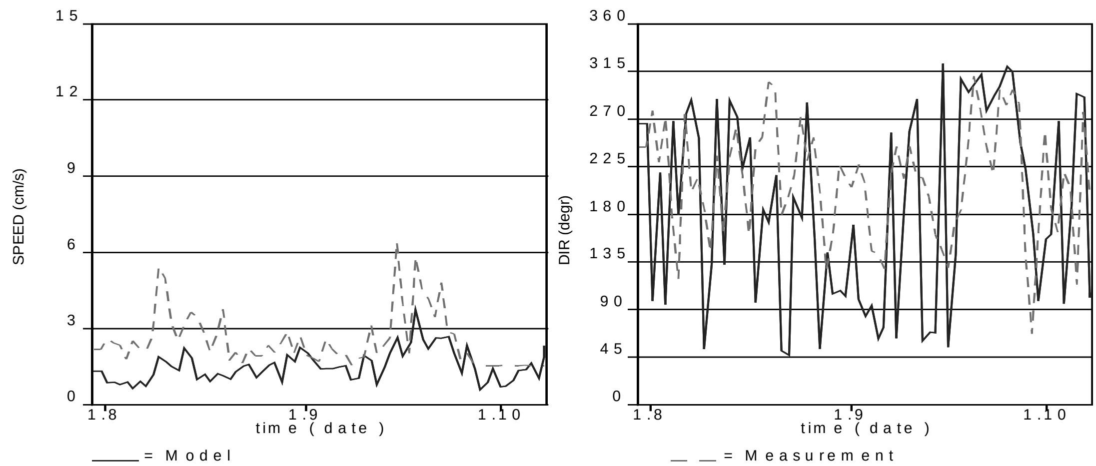

Figure 3. Measured and calculated flows from point v3.

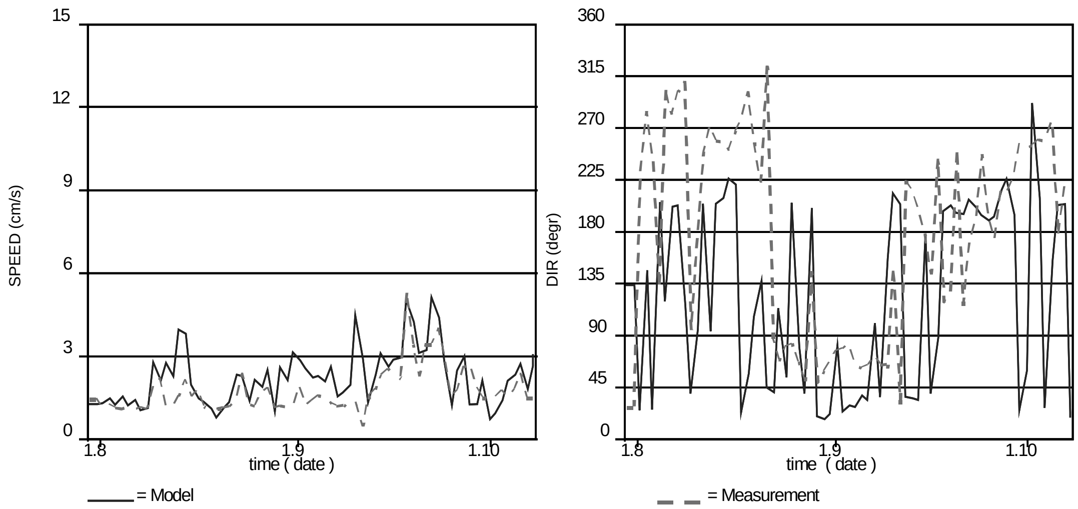

Figure 4. Measured and calculated flows from point v5.

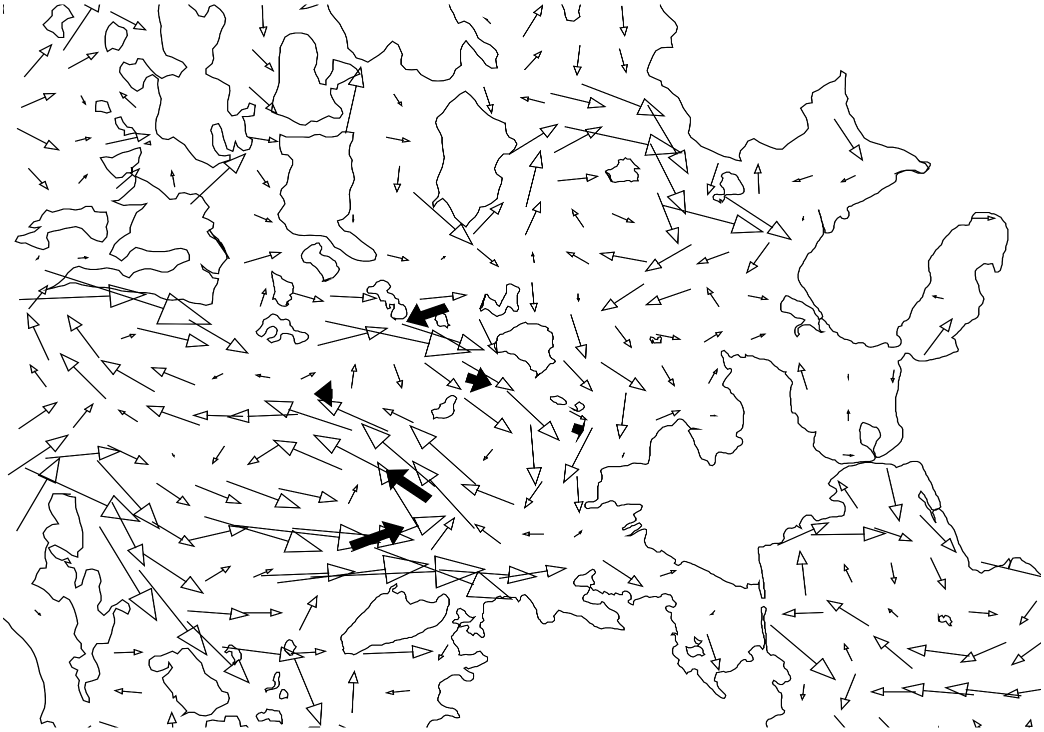

Figure 5. Flow field and calculated flows by regression equations from surface layer (0-2 m). Wind is 5 m/s from west.

Figure 5. Flow field and calculated flows by regression equations from depth 6-8 m. Wind is 5 m/s from west.

In figures 5 and 6 calculated flow fields are compared with the values obtained from the statistical analysis. Wind is from west 5 m/s. The statistical flows that correspond to this wind are shown with thick black arrows and the calculated values with thin ones. The directions agree generally very well except in the northern-most point near a small island. There the model resolution can not describe accurately the topography. The agreement between the measurements and the calculated results is rather remarkable taking into consideration the complicated flow pattern of the region.

Validation of the water quality model was fairly successful and proved the modelled concentrations of total P and total N to be on the right level. There was a large database available, originating from the regular monitoring of the wastewater impact as well as intensive sampling carried out for this specific project during the current measurements. In some points there were problems in fitting the model to the measurements. The reason seemed to be unknown nutrient loads from land and, occasionally, from the open sea. Also the fact that nutrient uptake by algae is not included in the model further complicates the comparison between modelled and measured nutrient concentrations.

Comparison of the alternative outlet locations

In the study, three new locations for the wastewater outlet locations were investigated. In this paper two of them are compared with each other i.e. the present one at the coastline (site 0) and one at the shipping channel 2 kilometers from the harbor (site 2). The impact assessment is made by

-comparing the differences in wastewater distributions in the surface water (filtering out the background concentrations)

-simulating the transport and mixing in stable wind conditions (SW and NE presented here) in order to assess the extreme extent of high wastewater concentrations

-simulating the transport and mixing when waste waters floated to the surface (maximum shore line impact) and in bottom waters (assuming an optimal mixing)

-simulating the transport and mixing in dynamic conditions in order to assess the appearance of concentration peaks in various parts of the shoreline and at the islands

The phosphorus discharge used in the model simulations was 12 kg/d. In the present situation (altenative 0) high wastewater concentrations appear during most wind directions at the shoreline of the town. The phosphorus concentration increase due to the wastewater may exceed 10 mg/m3. During northern winds the wastewaters are transported to the beach of the nearby camping area. Examples of stable wind conditions (NE and SW, 3m/s) are shown in figure 6. In the alternative 2 the concentration increase in the archipelago west of Varisselkä is typically 2-3 mg/m3 during southerly winds when the wastewaters are discharged to the surface. The impacts at the town beaches are small. In figure 5 the same situations are shown in case of discharging the wastewaters at the bottom and assuming an effecting mixing in the bottom layer. In this case the surface concentrations due to wastewater input remain clearly smaller in the alternative 2. Due to the shallowness of the site 0, the benefits of bottom release are much less. The distribution of the highest concentrations is somewhat changed as a result of the near bottom currents.

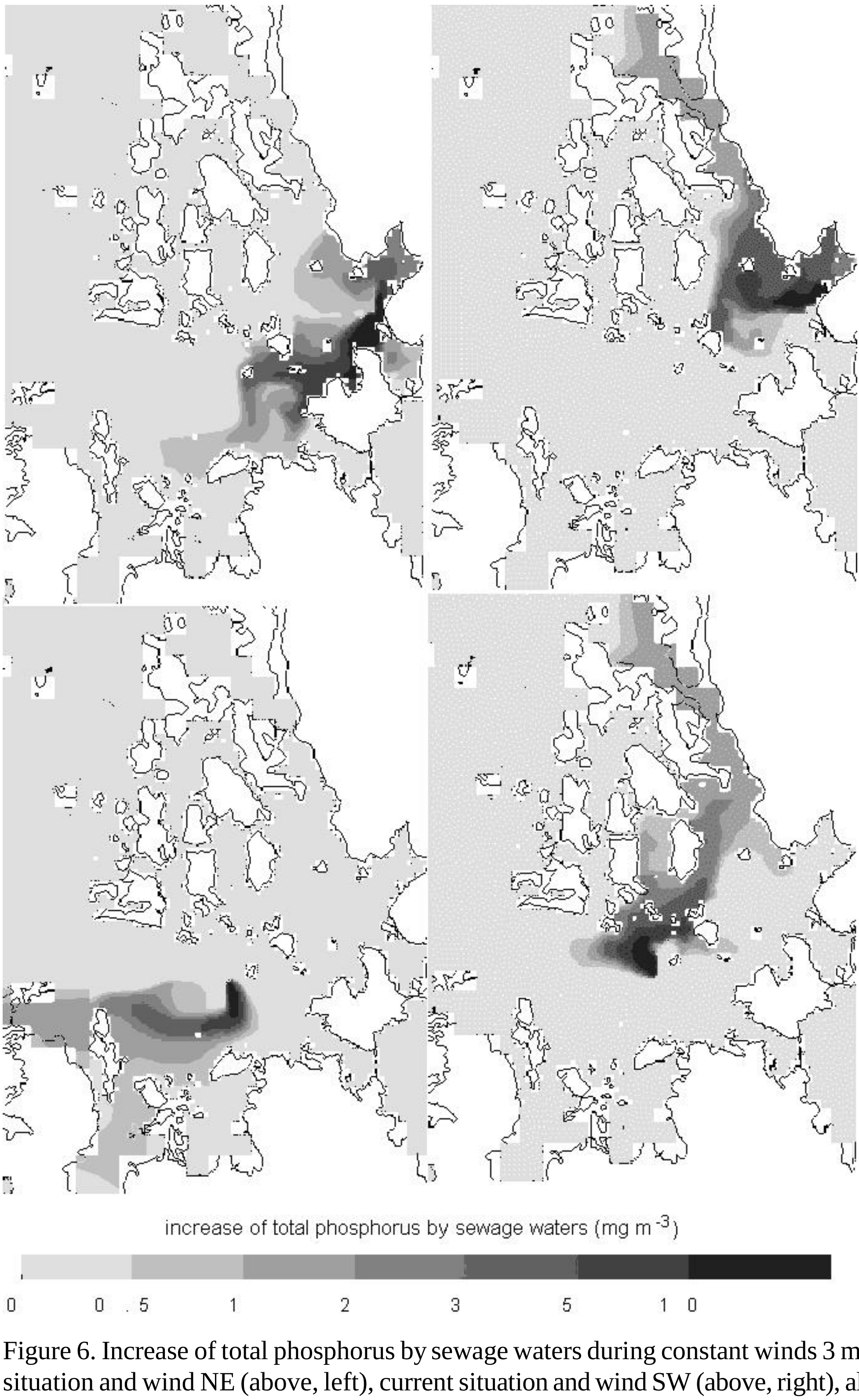

Figure 6. Increase of total phosphorus by sewage waters during constant winds 3 m/s. Current situation and wind NE (above, left), current situation and wind SW (above, right), alternative 2 and wind NE (down, left), scenario 2 and wind SW (down, right). Sewage waters are discharged to the surface.

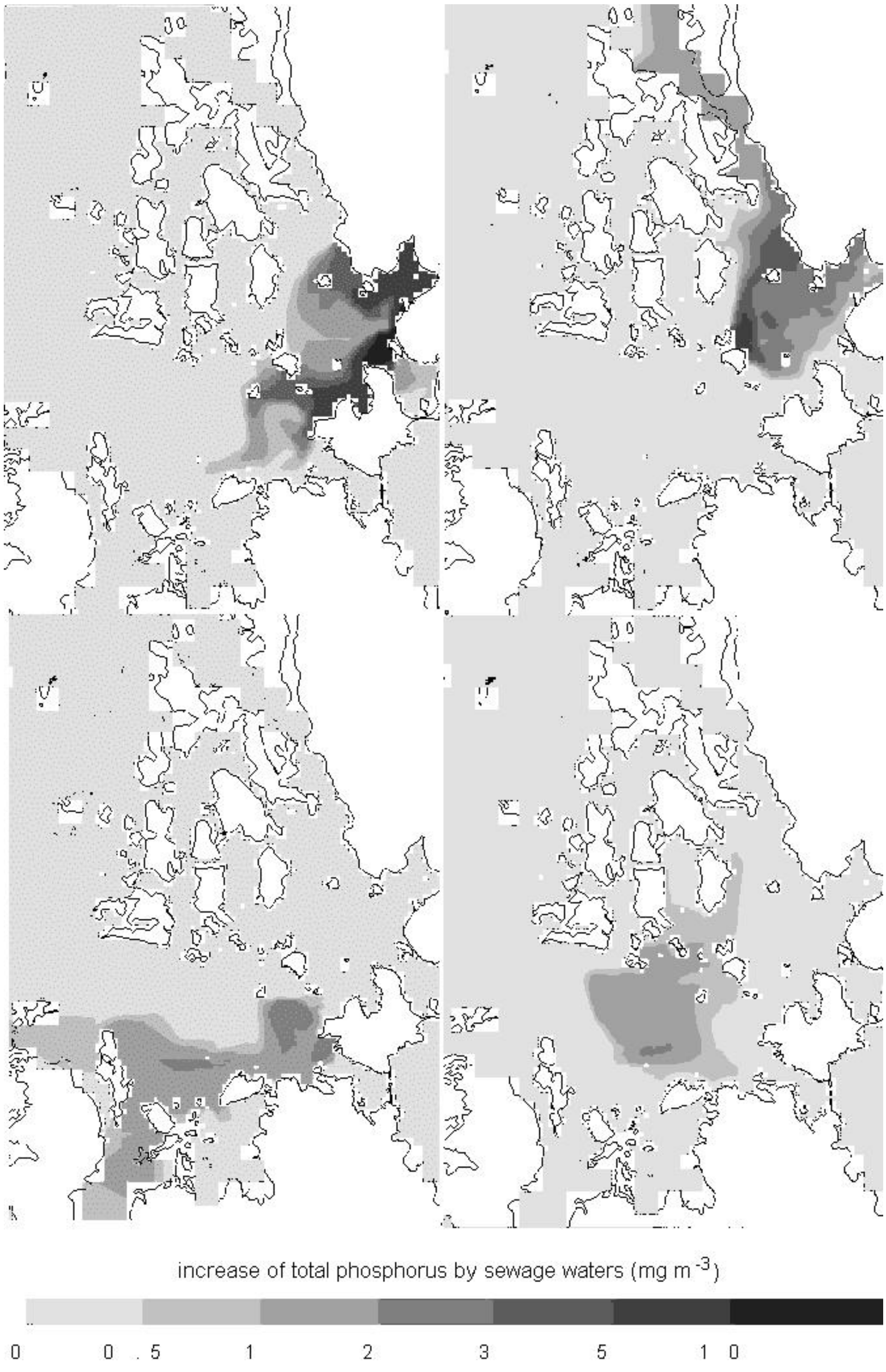

Figure 7. Increase of total phosphorus by sewage waters during constant winds 3 m/s. Current situation and wind NE (above, left), current situation and wind SW (above, right), alternative 2 and wind NE (down, left), scenario 2 and wind SW (down, right). Sewage waters are discharged to the bottom.

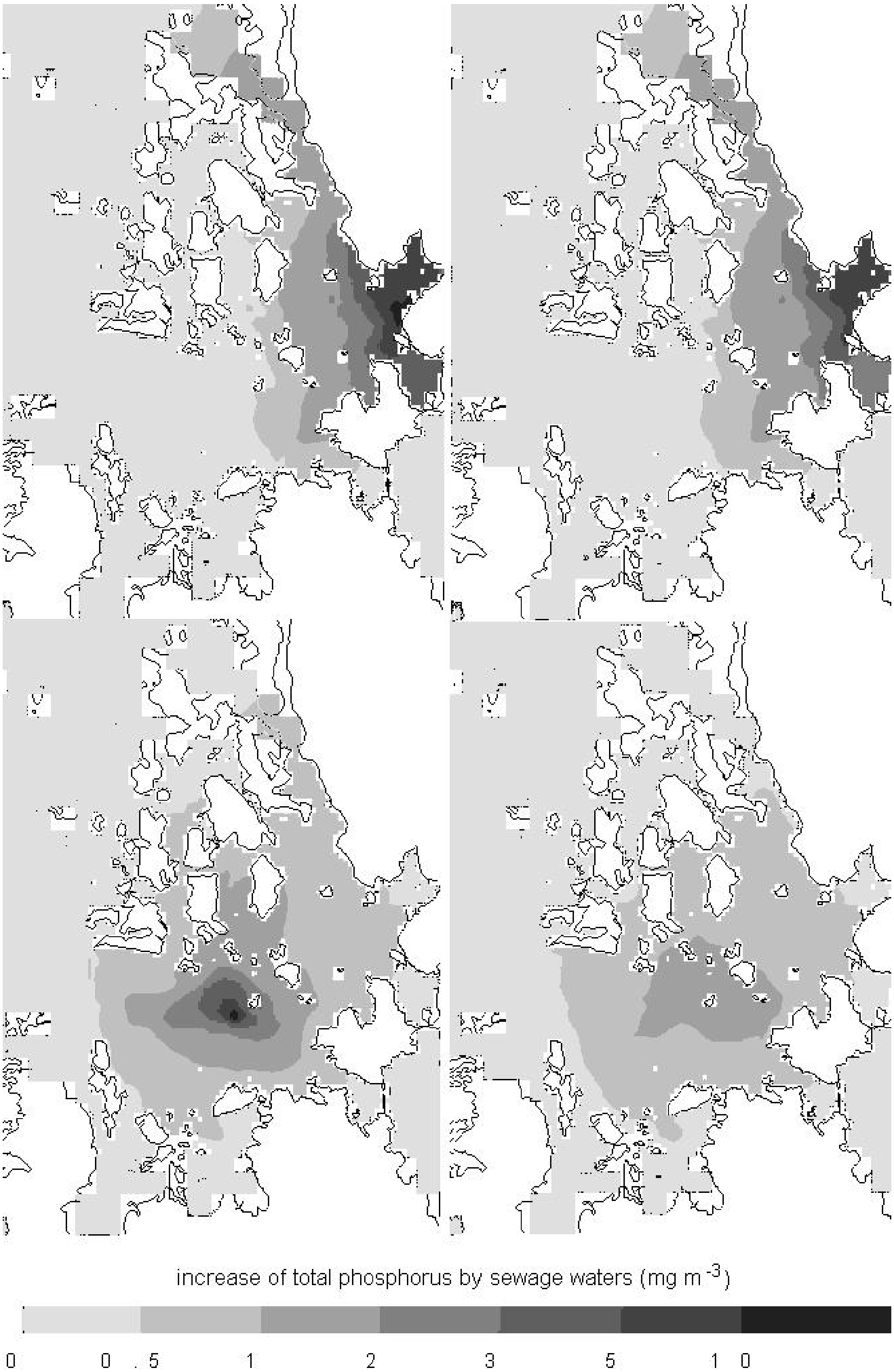

Figure 8. Avegrage increase of total phosphorus concentration during simulation period 1.8.-9.10.1998. The concentration maps are site 0 surface release (above left), site 0 bottom release (above right), site 2 surface release (down left) and site 2 bottom release (down right).

The average concentration increase during a dynamic simulation period are shown in figure 8. The biggest concentration increase (more than 10 mg/m3) is seen in the vicinity of the release when discharged to the surface. In the present situation concentration increase more than 5 mg/m3 covers the entire Bay on the northern side of the town. In the alternative 2 the concentration increase in the archipelago remains below 3 mg/m3. In case of bottom release the situation is clearly improved in alternative 2, because of the greater depth (8-9 m) and strong bottom currents. The surface concentration increase is in the order of 1 mg/m3. In this case (altenative 2) the relative change of surface concentrations, when compared to the present situation, would be approximately a 30 % decrease in the vicinity of the town and a 10 % increase in the vicinity of the new outlet location 2. (fig. 9)

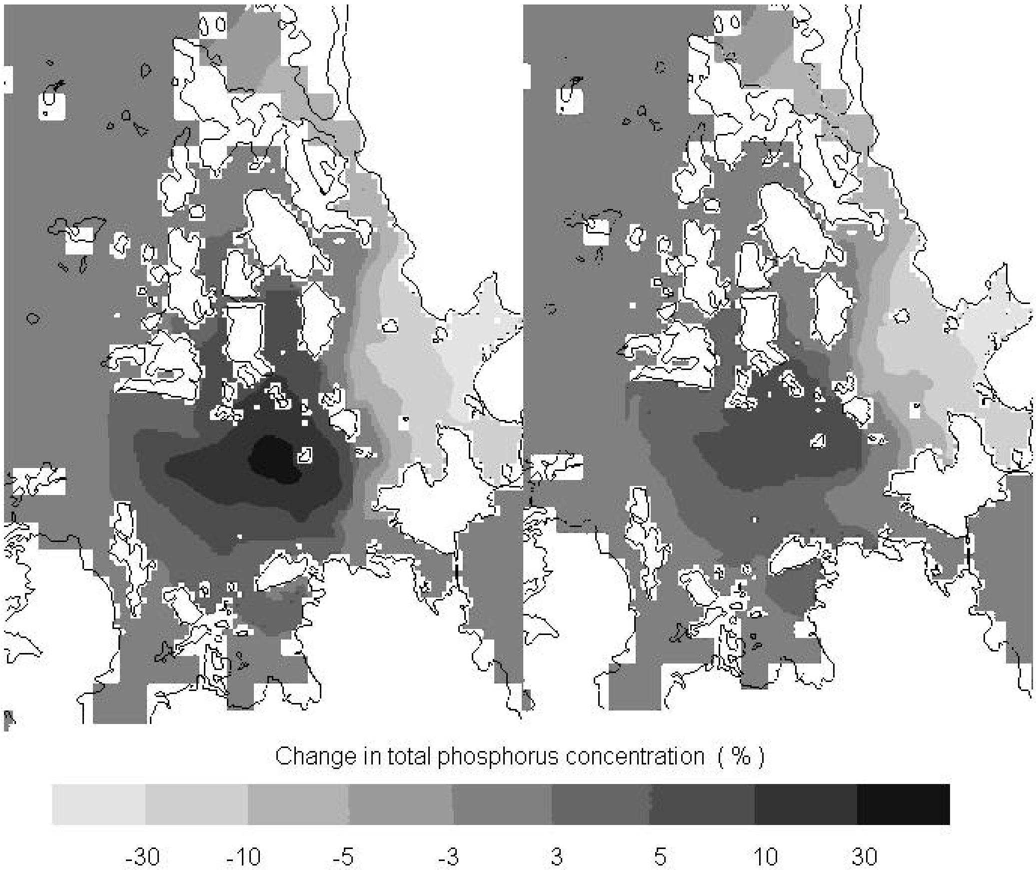

Figure 9. Percentual changes compared to current situation left surface release and right bottom one.

Time series from two sites near the camping area and inside the archipelago were are presented in figure 10. Three time series with alternative outlet locations are shown in the figures. Peak wastewater phosphorus concentrations near the camping area reach about 10 ug/l, once even 15 ug/l. When the outlet location is removed the maximum concentrations are diminished below 2 ug/l. Within the archipelago peak values are about the same (3 ug/l) with different outlet locations, but the mean concentrations are higher with the planned outlet. The bottom discharge in the new location diminishes the concentrations about 30 % compared to the surface discharge or wastewater floating to the surface.

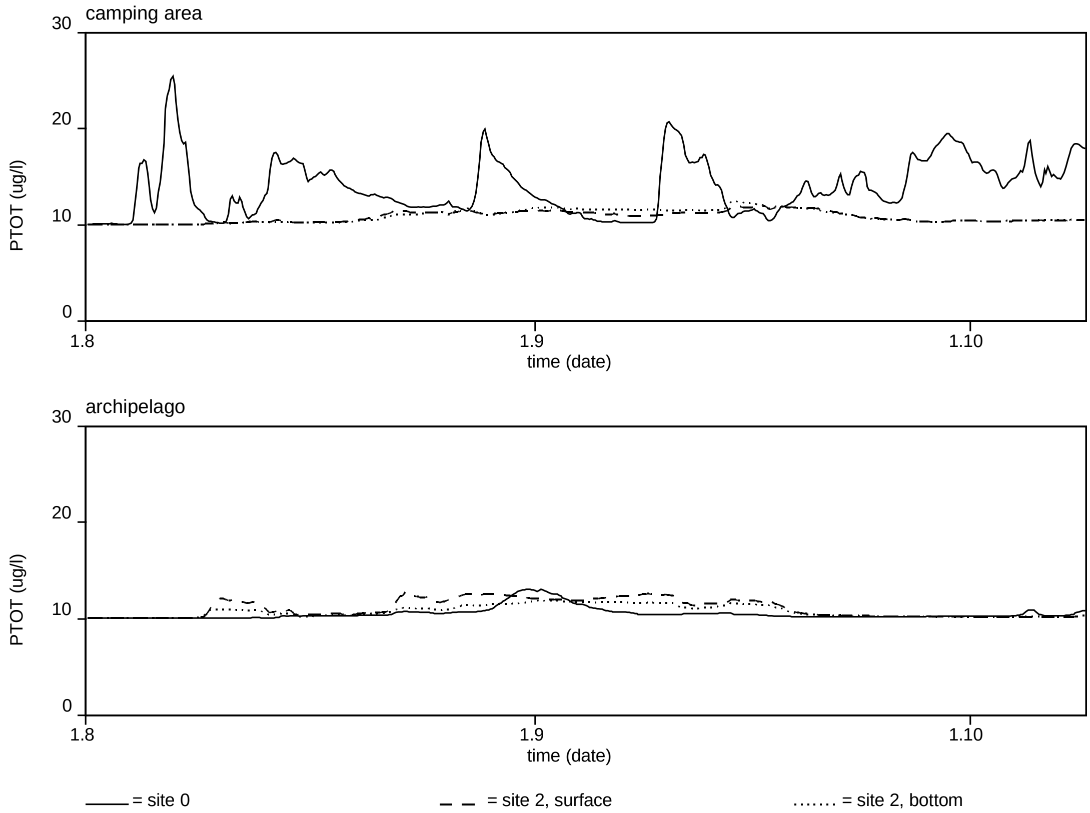

Figure 10. The timeseries of total phosphorus concentrations from two areas and two alternatives with current situation (site 0).

Conclusions

Discharging the wastewaters in the vicinity of the shipping channel about 2 kilometers out of the harbour would decrease the area of highest surface concentrations and their extension to the archipelago and the beaches. This phenomenon is evident in most cases, although in some wind situations the concentrations may rise inside the islands. The wastewater impacts decrease significantly in the innermost archipelago and the bays of the town. Especially great improvement in the surface concentrations is achieved when the wastewater is discharged in the bottom and guaranteeing an effective mixing in the bottom layer at the shipping channel. In this case the surface concentrations will rise only about 1 mg/m3 in the vicinity of the discharge site. Sufficient depth and favorable currents further the mixing and dilution of the wastewaters.

When considering the decision on the wastewater outlet location one has to bear in mind that the positive effects of removing the outlet would be less than calculated in the first years after the change. This is due to the internal load impacts of nutrient rich sediments in the vicinity of the present discharge location and the innermost archipelago. The internal load has not been estimated in the model calculations.

References

Koponen J., Alasaarela E., Vepsä H., Virtanen M., Lehtinen K., Sarkkula J., Simbierowics P. 1993, Modelling the dynamics of a large sea area, Bothnia Bay research project 1988-1990, 133 s.

Sarkkula J., Inkala A., Kuusisto M., Koponen J. 1999, Vaasan kaupungin jätevesien purkupaikan siirron vaikutukset Vaasan edustan merialueen tilaan, Loppuraportti, (In Finnish), 61 pp.

Simons T.J., 1980. Circulation Models of Lakes and Inland Seas, Can. Bull. Fish. Aquat. Sci., No. 203, 145 pp.

Virtanen M., Koponen J., Dahlbo K., Sarkkula J., 1986. Three-dimensional water-quality-transport model compared with field observations, Ecological Modelling 31:185-199.