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Flow regimes and long-term water exchange of the Himmerfjärden estuary

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ABSTRACT

A numerical model of processes determining the water exchange encountered in Baltic coastal archipelagos is calibrated and validated against salinity and temperature field data spanning two decades with approximately bi-weekly resolution assessed in the Himmerfjärden estuary. This area is resolved into 17 basins interconnected by 38 individual straits of varying geometrical properties using GIS-based methods. All formulations of the strait exchange flows are free from parameters that need calibration and permit computations of the flow through a strait contraction with or without a coincident sill under a flow classification scheme, of which the first one (a) consists of two groups of multiple layers including aspirated layers from levels beneath the sill crest. The other regimes are as follows. (b) Pure barotropic flow; (c) rotationally controlled flow and (d) plug-flow, which serves as resort solution for flow situations that cannot be solved with (a) and also for computation of the barotropic part of the total flow. For long canals where friction effects act to reduce the flow, a fifth exchange regime is used. The vertical mixing formulation is based on energy balances between supplied wind energy and its work against buoyancy forces. The values of semi-empirical parameters involved in the mixing scheme have been established by calibration against measured data of the first decade period. A statistical evaluation is performed comparing the model results with the measurements of the second decade.

It is found that the accuracy of the model is yet limited by the poor temporal resolution in the boundary and the thermal forcing. The overall accuracy of this approach is found to be comparable to earlier model studies in the same area. Since the exchange flows are now based on first principles and are applied to four times more basins, it seems that this more articulated model approach can confidently be applied to more complex archipelago areas.

1. Introduction

The estimation of water exchange of the coastal zone is motivated from an ecological point of view since water-borne material – transported by advection – contributes significantly to the balance of material budgets. Methods to solve stationary or quasi-steady flow regimes have been known since Knudsen (1900) who combined simultaneous conservation of water and salt of the Baltic. Starting from the control concept formulated by Stommel and Farmer (1952), analytical solutions for maintained estuarine circulation can be formulated (e.g. Stigebrandt, 1981). A study area may under certain conditions be appropriately considered as horizontally well-mixed basins interconnected by straits. On time-scales allowing for transient water exchanges, most studies have been restricted to areas with a very limited number of interconnected basins, in most cases only one (Engqvist, 1993; Aure et al., 1996; Stipa, 1999). Only a few exceptional attempts can be found in the literature of more complex areas being subjected to detailed studies of the water exchange (Björk et al., 2000; Engqvist and Andrejev, 2003). The latter two contributions rely on a formulation of strait exchange derived by Stigebrandt (1990).

For the morphologically moderately complex Himmerfjärden estuary (Fig. 1), sufficiently long validation time series of data in the form of about 3000 salinity and temperature profiles sampled over the period 1981–2001 exist, providing an opportunity to improve and validate model formulations of material exchange. Based on experiences from earlier studies of the same area (Engqvist and Omstedt, 1992; Engqvist, 1996a), such improvements may be sought in many directions. As a first improvement, one would like to abandon the plug-flow description at least for straits that are hydraulically controlled and for which the contra-flowing layers obviously reduce their thickness when passing through the contraction in accordance with two-layer theory (e.g. Farmer and Armi, 1986; Armi and Farmer, 1986). As a second improvement, the

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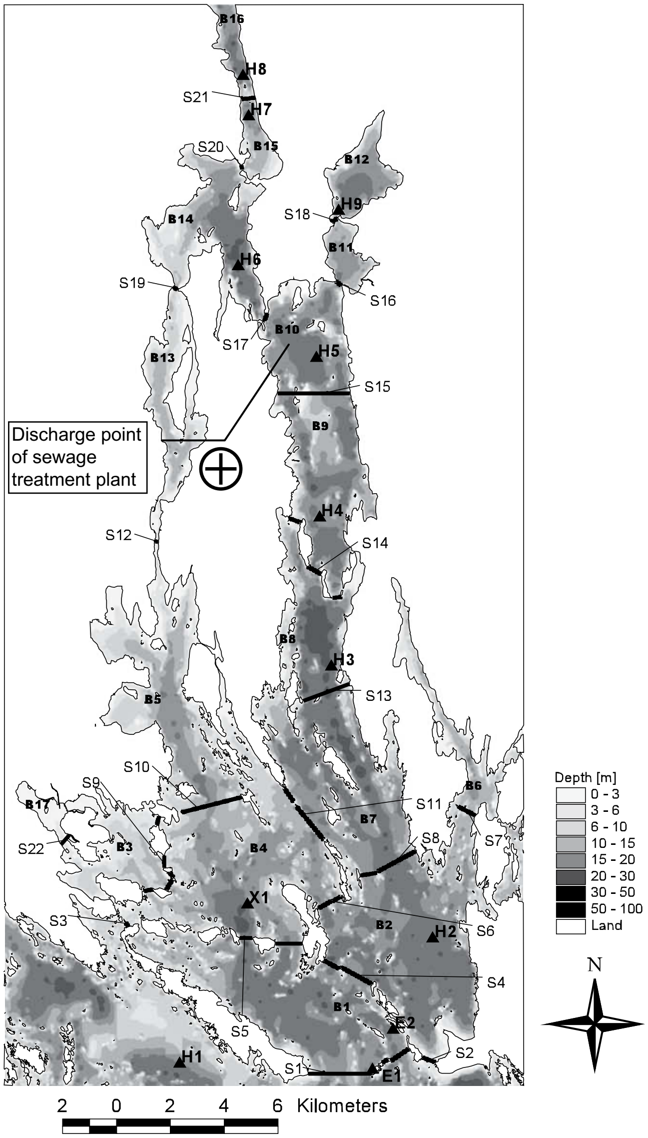

Fig. 1. Bathymetric map of the Himmerfjärden area together with the actual partition into sub-basins and straits. The position of the 12 measurement stations (H1–H9 and E1, E2 and X1) is indicated with triangular symbols. The ⊕ symbol marks the position 59°00′N, 17°40′E. Discharge from Lake Mälaren enters into the northern-most basin.

number of sub-basins should be increased to better resolve the estuarine axis gradients and the concomitant increase of the number of straits. This in turn leads to introduction of wider straits when some basins are split into two or more sub-basins. A third improvement concerns sufficiently wide straits for which rotational effects may come into play, limiting the exchange (e.g. Gustafsson, 2000).

The present model represents an intermediary complexity level between box models (e.g. Pilson, 1985) and 3D-models (e.g. Andrejev et al., 2004). A box model approach to compute the water exchange from conserved measured tracer concentration (e.g. salinity) allows together with volume conservation two flow variables per box. For a pair of vertically stacked boxes and with influxes determined by an upstream pair of boxes, these variables could represent four variables: e.g. horizontal outflow of each of the two boxes, vertical flux and vertical turbulent exchange (e.g. Hagy et al., 2000). For a simplified geometrical layout, with such basin pairs connected in series and with a sufficient salinity contrast between adjacent assumingly well-mixed boxes, it would be possible to reconstruct the flow from salinity measurement by such an inverse-method scheme. The inherent numerical sensitivity due to each flow component being computed by dividing a transport expression by a small salinity difference acts to discourage such an effort, however. An error in one section will propagate and affects all other subsequently computed sections as well.

On the other hand it would be possible to employ 3D-models. One major advantage with 3D-models is that the somewhat arbitrary subdivision into sub-basins is no longer a consideration; in principle almost any bottom and strait topography can be managed. If the aspect ratio permits the hydrostatic approximation to be applied, the computational effort would perhaps be reasonable. However, when trying to resolve small-scale strait features together with larger-scale basin features, the hydrostatic approximation tends to become questionable and non-hydrostatic models – e.g. MITgcm (Marshall et al., 1997) – are needed, thereby considerably increasing the computational cost.

The present approach is thus an attempt to systematically apply the scheme concerning strait exchange processes presented in Engqvist and Stenström (2004) and to validate the results with the field data. In order to do this, the strait exchange is derived from the functional-based theory (Dalziel, 1991) and then all basins are modeled with a free water surface that is used to allocate flows through parallel straits. For stratified flow this involves aspiration processes (Bryden and Stommel, 1984). Since different flow regimes may occur due to frictional and rotational effects, a classification scheme of these regimes is made an integral part of the numerical procedure.

An outline of the present paper is that first the hydrography and the hypsography of the Himmerfjärden estuary are presented in Section 2. This entails partitioning of the area into sub-basins, increasing the number from the previous four (Engqvist, 1996a) to 17. The straits have been adapted to fit the cross-section geometries described by the β-parameter (Dalziel, 1992). In Section 3 the proposed strait exchange processes are formulated including response of the basins to the exchanged flows. The results of the proposed method is presented in Section 4 in comparison to a long-term data series of salinity measured in various sub-basins of the Himmerfjärd estuary and the outcome is discussed in Section 5, followed by a summary and conclusions. Mathematical formulations are deferred to an Appendix and referenced in the text with a letter indicating the appropriate section and a number specifying the actual equation in that section.

2. Material and methods

2.1. Partitioning into basins and straits and assessing their geometrical features

A map over the study area is shown in Fig. 1, where the partitioning recommended by an inventory of the Swedish coast, Swedish Water Archives (SWAR, 2003) can be seen. This subdivision has been performed with regard to both the occurrence of straits and the presence of sills or underwater ridges. The complicated coastal bathymetry leaves some room for subjective interpretations, and the finally chosen partitioning mainly coincides with the one cited above; the major difference is that in order to avoid overly elongated basins, a few of those have been split into two or more sub-basins. The result is a partitioning into 17 basins (B1–B17) and 22 straits (S1–S22) that are either singular or consist of two or more conjoined parallel straits connecting the same two basins. The hypsographic data of the basins are given in Engqvist (1996a) and have since been refined using GIS-based methods. To