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# A novel model approach to bridge the gap between box models and classic 3D models in estuarine systems

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ABSTRACT

The multiple hydrodynamic and ecological processes characterizing estuarine systems make ecological modelling an essential tool for ecosystem-based management by increasing the understanding of the complex interactions and by quantifying the effects of various natural and anthropogenic pressures. The modelling technique used is dominated by computational simple box model approaches with a low spatial resolution and coupled 3D hydrodynamic-ecological models with high computational requirements. In this paper we present a novel concept (Flexsem) which combines the computational simplicity and condensed hydrodynamics from box models with a high spatial resolution characterizing coupled 3D models. The modelling framework Flexsem is a fast, flexible and user-friendly tool specifically targeted towards scientific and management challenges of the complex biogeochemical processes in coastal zone ecosystems. We use Flexsem to simulate the physical conditions in a typical Danish estuary, Horsens Fjord utilizing unstructured computational meshes to vary the complexity of grid geometry and resolution. The results showed that the model was able to reproduce the physical conditions in the estuary and provide reliable estimates for the tracer residence time.



## 1. Introduction

Estuaries play a critical role as physical and ecological gateways between terrestrial, riverine and oceanic systems. They also have an important societal function as fishing, transport and recreational areas for local communities. Estuarine ecosystems integrate contributions from various sources. They receive nutrients and sediments from terrestrial sources through rivers, karst and aquifer systems or direct land run-off and are therefore potentially susceptible to occasional or frequent eutrophication. The Danish coastline hosts a total of approximately 81 estuarine systems, consisting of bays, inlets and fjords. Only 50% of the Danish estuaries have catchment areas exceeding 100 $km^2$ (Conley et al., 2000). Eutrophication and oxygen depletion of bottom waters are common phenomenons in Danish coastal waters due to the high intensity of agriculture and animal production which cause nutrient loadings per unit area to be temporarily among the highest in Europe (Conley et al., 2002). However, coastal ecosystems worldwide experience eutrophication problems (Diaz, 2001) and in the coastal zone of the Baltic Sea hypoxia is increasing (Conley et al., 2011). According to the EU Water Framework Directive (2000/60/EG; WFD) all European coastal waters should achieve a good ecological status by 2015 and governmental action plans have been implemented in order to reduce nutrient loadings to satisfy the requirements outlined in the WFD. The general need for a better understanding of the link between terrestrial nutrient loadings and environmental effects in coastal and oceanic waters of the Baltic Sea is expressed in the need for developing and constantly improving marine ecosystem models and decision support tools. One particular challenge is the provision of realistic boundary conditions for freshwater input and associated nutrient loadings along coastal boundaries of climate and ecosystem models, as well as basin-scale decision support tools. A practical method to achieve this is the application and adaptation of box models to coastal areas where the parameter space of the governing processes is well-defined and does not require resource-intensive 3-D modelling approaches. Box models have a long tradition in ocean modelling and have been used to study processes in a variety of coastal systems from large estuaries to small fjords and inlets including water residence times (Dettmann, 2001; Sheldon and Alber, 2002), water exchange rates (Austin, 2002), nutrient and particle fluxes (Painchaud et al., 1987), freshwater discharge (Garvine and Whitney, 2006), wind and tidally induced dynamics (Hearn and Robson, 2002). Box models of different complexity employing formulations of processes linking oceanography and biogeochemistry have also been successfully applied to estuaries worldwide (e.g. Testa and Kemp, 2008). In contrast, box models are often restricted to reproduce processes not modulated by complicated coastlines and bathymetry. In the Baltic Sea, one of the most heavily used coastal and oceanic marine systems worldwide

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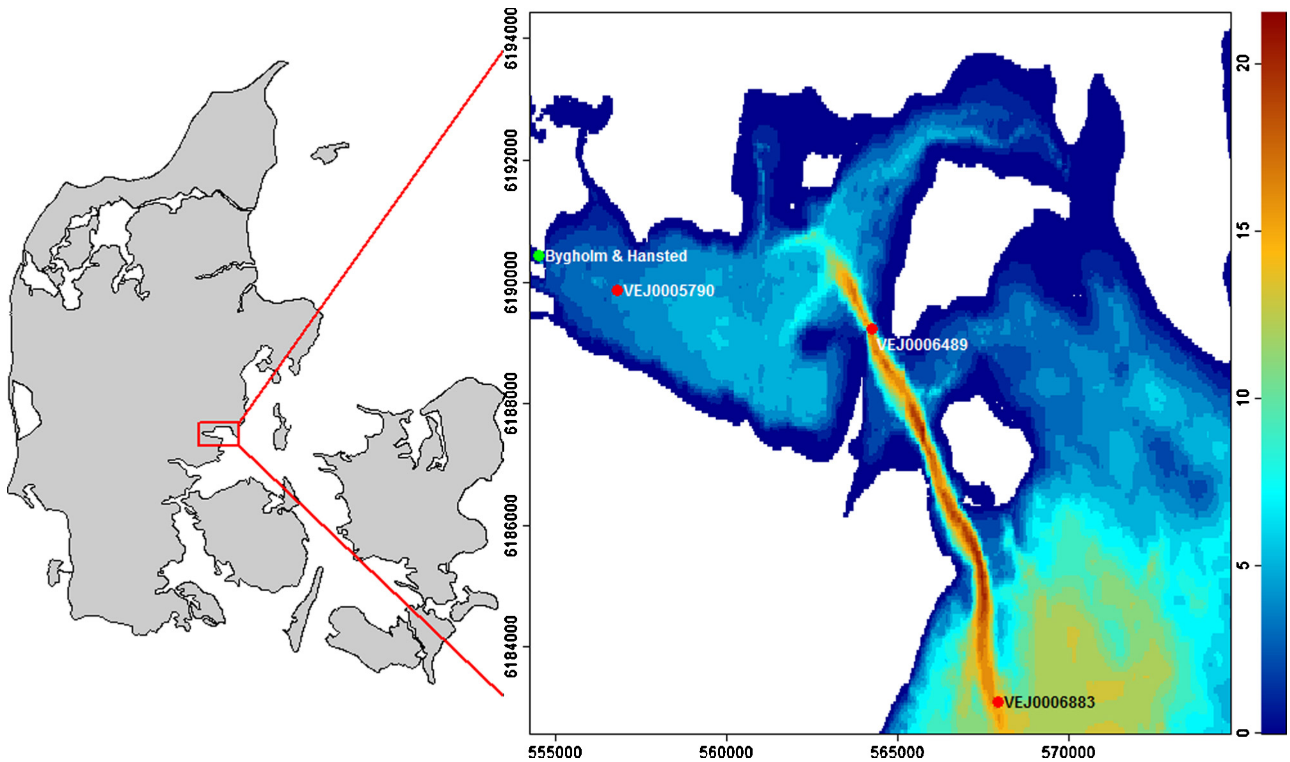


**Fig. 1.** Location and bathymetry of Horsens Fjord. Solid red circles indicate locations of selected monitoring stations and green solid circle is the location of the freshwater source (both Bygholm and Hansted). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

and dominated by terrestrial sources, an accurate evaluation of boundary conditions for freshwater input and nutrient loadings is vital to assess coastal biogeochemical processes and their implications on the large scale. This knowledge is particularly important as input to decision support tools to facilitate the implementation of measures to improve water quality and good environmental status, as identified in the Baltic Sea Action Plan (HELCOM, 2007).

In this article we present a flexible and user-friendly ecosystem modelling framework Flexsem in combination with a new hydrodynamic concept for shallow fjords and estuaries (HDLite).

Flexsem has been developed as part of the activities of the Baltic Nest Institute (BNI) linking processes acting on the local scales of individual estuaries with sub-basin and intra-basin scales. Flexsem is designed to fit the needs of both integrated coastal zone management and research with a focus on estuarine and fjord systems. It is aiming for an alternative approach to bridge the gap between simple box models and fully 3D hydrodynamic and ecosystem models by providing the user with full flexibility in grid design and process implementation without compromising ease of use and low computational effort. The simplified hydrodynamics of the HDLite module in Flexsem is targeted towards shallow fjords where physical processes are dominated by (1) stratification created by freshwater runoff and denser water penetrating from the open oceanic boundaries into the estuary and (2) erosion of this stratification through wind mixing. We demonstrate the concept by applying Flexsem to simulate oceanographic conditions and particle distribution patterns in Horsens Fjord using computational grids of different complexities. Model results are assessed and validated against observations from the Danish National Monitoring Programme. The paper is organized as follows: The model framework and hydrodynamic formulation are introduced in Section 2. The study site and model setup are described in Section 3. Model results of oceanographic conditions and particle residence times in the fjord based on simulations with model grids of different complexities are presented in Section 4. Results, benefits and limitations of this new model approach are discussed in Section 5 and conclusions outlined in Section 6.

## 2. Model concept and hydrodynamic formulation

### *2.1. General model framework*

The main design philosophy of Flexsem has been to provide managers and scientists with a fast and flexible tool, enabling modelling without the need of programming. The major steps of setting up and running the model include: (1) copying the model engine executable to a computer, (2) using any available text editor to create or modify mesh, bathymetry and setup file, and (3) running the engine from the command prompt/shell with the text setup file as input. Flexsem is a modular framework for marine modelling written in standard C++. It has been compiled on Windows with VC++ and on Linux with GCC. The model code is parallelized using OpenMP and can therefore be run on single-core and shared-memory multi-core processor architectures. The main components, also presented in Fig. 2, are:

- The core engine. It defines and handles the overall time stepping, the computational mesh, boundaries, sources, inputs and outputs.
- HDLite. This module contains simplified formulations of estuarine and fjord dynamics including advection, horizontal and vertical mixing. A detailed description of the processes implemented in HDLite is included below.
- Pelagic equation solver. This module allows the user to define a system of equations, which will be solved for all pelagic computational cells. Specifically this could be a system of temporally discretized ordinary differential equations, describing relevant pelagic biogeochemical state variables such as nutrient and chlorophyll a concentration as well as processes such as nutrient uptake and remineralisation. The equations are defined in the