Linking integrated water resources management and integrated coastal zone management

P.S. Rasch*, N. Ipsen, A. Malmgren-Hansen* and B. Mogensen***

*DHI Water & Environment, Approved Technological Service Institute, Agern Allé 5, DK-2970 Hørsholm, Denmark

**UCC-Water, UNEP Collaborating Centre on Water and Environment, Agern Allé 5, DK-2970 Hørsholm, Denmark

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Abstract Some of the world's most valuable aquatic ecosystems such as deltas, lagoons and estuaries are located in the coastal zone. However, the coastal zone and its aquatic ecosystems are in many places under environmental stress from human activities. About 50% of the human population lives within 200 km of the coastline, and the population density is increasing every day. In addition, the majority of urban centres are located in the coastal zone. It is commonly known that there are important linkages between the activities in the upstream river basins and the environment conditions in the downstream coastal zones. Changes in river flows, e.g. caused by irrigation, hydropower and water supply, have changed salinity in estuaries and lagoons. Land use changes, such as intensified agricultural activities and urban and industrial development, cause increasing loads of nutrients and a variety of chemicals resulting in considerable adverse impacts in the coastal zones. It is recognised that the solution to such problems calls for an integrated approach. Therefore, the terms Integrated Water Resources Management (IWRM) and Integrated Coastal Zone Management (ICZM) are increasingly in focus on the international agenda. Unfortunately, the concepts of IWRM and ICZM are mostly being developed independently from each other by separate management bodies using their own individual approaches and tools. The present paper describes how modelling tools can be used to link IWRM and ICZM. It draws a line from the traditional sectoral use of models for the Istanbul Master Planning and assessment of the water quality and ecological impact in the Bosphorus Strait and the Black Sea 10 years ago, to the most recent use of models in a Water Framework Directive (WFD) context for one of the selected Pilot River Basins in Denmark used for testing of the WFD Guidance Documents.
Keywords 3D; ecological modelling; ICZM; integrated management; IWRM; modelling; WFD

Introduction

The interface between freshwater and coastal zone management

The interfaces between the management of river basin issues and coastal zone issues will naturally be focused in the areas surrounding river mouths, estuaries and delta areas (Ipsen et al., 2002). Impacts will occur in the coastal waters from the river and have an impact area, the size of which will depend on the physical and biological characteristics. In the same way changes in coastal water levels and sediment deposition patterns will have an area of influence reaching upstream into the river. The following sections describe some typical examples of physical and biological links between a river basin and a downstream coastal zone.

River basin impacts on coastal zones

River discharge. The regime of river discharges has a profound effect on the salinity conditions in the river mouths, estuaries, delta areas, lagoons, mangroves and coastal wetlands. Persistent alterations in low flows and flood situations may bring about significant changes and impacts on ecosystems.

Decrease of river flow due to river basin development or land use changes will affect the lower reaches and cause increased tidal reach inland along with increased saltwater intrusions. If the salinity increase persists permanent damage can be done to agricultural land, specialised ecosystems and wildlife habitats (Bach et al., 1998). This again negatively affects the livelihoods of communities in the affected areas. Also, intakes for water supply to the coastal population can become invaded by saline water.

Water quality. The quality of the river water in the lower reaches is a result of the basin's soil quality, land cover, and, in particular, the human activities along the river. If river water is biologically or chemically contaminated it will have highly negative impacts on the health of coastal communities and ecosystems.

Sediment transport. Often, rivers carry heavy sediment loads, in particular if the basin is suffering from inappropriate land use and erosion. In the coastal zone the sediment will settle in the deltas and estuaries (Bach et al., 1991). Here, the deposited material is the basis for productive ecosystems (mangroves, mudflats, and seagrass beds). In many regions the finest silt, which is washed out to the sea, supports very productive pelagic ecosystems. But excessive sediment loads may also have detrimental effects through eutrophication and subsequent alteration of the coastal ecosystems.

In other areas, sedimentation in the coastal areas tends to block estuaries and river mouths and cause relocation of the main river channel. This creates serious problems for coastal communities in terms of town locations, navigation, etc. and destroys productive ecosystems.

Floods. The effect of river floods in coastal areas is normally damage to urban housing, roads, bridges and other infrastructure in towns. River floods can give rise to serious health problems when sewage systems and water supplies are interrupted and when stagnant pools of heavily polluted water are formed. Floods often destroy the low-lying agricultural land in coastal areas by topsoil erosion or depositing unfertile sediments. And they may cause significant shocks to the coastal ecosystems.

Coastal zone impacts on river basins

Increase in river water levels due to tides. The upstream effects of tides are related to flooding and saltwater intrusion in deltas. Saltwater penetrates into delta watercourses and may flood low-lying delta lands. The lower the upward gradient of the delta is, the more pronounced are these effects. The coastal ecosystems will have adjusted to this cyclical effect, but alterations of the coastal morphology may lead to saltwater intrusion further inland. Such situations will have adverse effects on the near inland ecosystems.

Storm surges. Under storm surge conditions seawater often floods vast land areas, not only those adjacent to deltas or riverbanks. Seawater penetrates far inshore and often destroys crops, livestock, infrastructure, and housing and may cause numerous casualties. The effects are often long-term, as damage is sometimes not overcome before the next storm surge event and agriculture land is salinised.

Material transport along coastlines. Transport of material (i.e. erosion, transport, sedimentation, re-suspension phenomena) along shorelines affects all coastal states. Enormous amounts of material take part in this process. Material that sediments in estuaries and blocks them can cause flooding upstream in rivers and prevent or disturb navigation into these.

Examples of integrated modelling and management. To exemplify the use of modelling as a tool to approach and resolve some of the issues described above, two distinct cases are described in the following. These two cases also illustrate the progress towards integration of models and management within the last decade.

Case study, 1994 Istanbul Master Plan

The metropolis of Istanbul was in 1994 in the process of establishing a master plan for the period up to the year 2030. At the time, the population was expected to increase from the then 8 million inhabitants of Istanbul, including suburbs, to a total of 20 million people in 2030. In fact today, 10 years after, the total is 9.6 million inhabitants.

As a part of the Istanbul Master Plan, a comprehensive environmental impact study was conducted by DHI in 1993–94. The Client was Ömerli and Elmali JV for Istanbul Water and Sewerage Administration (ISKI). It was a major modelling study, whose purpose was to determine the spreading of wastewater from existing and future outfalls in the Bosphorus region. The modelling was based on DHI's three-dimensional modelling system, MIKE 3, which is a general modelling system for baroclinic flow simulating unsteady currents, water levels, salinity and temperature fields. A model set-up was prepared covering the Black Sea–Bosphorus–Marmara Sea junction. The model was calibrated and validated by data from a dedicated field program as well as previous field data (Hansen *et al.*, 1995). The Middle East Technical University, Erdemli-Icel Turkey, conducted the dedicated field programme. The model was designed to describe the characteristic features of the flow in the junction area. The effects of variations in the water level differences between the Sea of Marmara and the Black Sea on the important two-layer structure in the strait and the flow fields generated by the upper layer jet in the Bosphorus–Marmara junction were evaluated.

Hydrodynamic conditions of the area

The Bosphorus area is oceanographically very complicated. A distinct two-layer system in the strait is present, where the dense Sea of Marmara water (about 37 psu) flows towards the north in the lower layer and the less dense Black Sea water (about 18 psu) flows towards the south in the upper layer. The Sea of Marmara is permanently and strongly stratified, with a top layer 10–30 m thick. The Black Sea is also stratified with a top layer more than 100 m thick. The lower layer is fed constantly from the Aegean Sea via the Dardanelles, and the water in the lower layer flows steadily towards the Bosphorus to pour northward into the Bosphorus lower layer and passes a sill at about a depth of 33 m, which acts as a hydraulic control. The seasonal variability is related to the changes in the adjacent basins, the seasonal heating and cooling cycle, whereas the variations on the time scale of days are related to changes in the atmospheric pressure and wind. These variations may dominate the flow and give rise to substantial modifications of the regional and local flow structure. The local layer can be completely blocked and strong surface jets and large scale eddies in the Bosphorus – Marmara junction can be generated due to changes in water level differences.

It is evident that these hydrodynamic conditions are critical for all marine and hydraulic work in the Bosphorus Strait. In order to predict such conditions, it is necessary to apply a high accuracy numerical model able to maintain fronts and describe the strong gradients without numerical errors.

Modelling

In the first part of the study, the description of the hydrodynamic conditions, the 3D Reynolds-averaged Navier–Stokes model MIKE 3 with the Advection–Dispersion (AD) module was set-up and validated (Vested *et al.*, 1992).

The second part of the study was aimed at describing the immediate environmental effects of the wastewater in the Bosphorus Strait and the junction areas, and also the long-term regional effects in the Sea of Marmara. One of the consequences of discharging sewage into the environment is the potentially resulting oxygen deficit caused by the oxygen consuming degradation of organic material in the sewage. To study these effects the Water Quality (WQ) BOD/DO module was used.

For the study of the long-term eutrophic effects of the additional loading of nutrients from the increased sewage, the eutrophication (EU) module of MIKE 3 was implemented (Bach *et al.*, 1995).

Results

In Figure 1 are a few examples of some of the results obtained in the models. With the Water Quality model a number of scenarios of various locations of sewage outfalls and preliminary treatment where simulated, and the accumulated effects in the year 2030 evaluated.

Conclusions of the study

Besides the establishment of the first comprehensive predictive model of the Bosphorus–Marmara junction area, it was also the first time that the discharge in the strait and the water level difference between the Black Sea and the Marmara were measured simultaneously. The results of the study were subject to a severe local scientific peer review by Professor Derin Orhon.

The comprehensive experience gained led to significant improvements in the scientific understanding of the oceanographic conditions in the junction area (Hansen *et al.*, 1995).

The general conclusions were that the subsea strategy for biologically treated waste water would result in conditions close to the present situation, a surface discharge on the other hand was predicted to worsen the conditions for the biological communities in the area. Tertiary treatment was predicted to improve surface conditions over the present day, and keep the nutrient export to the Black Sea at the present level (Bach *et al.*, 1995).

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Case Study, 2004 Odense Fjord

A recent case study from Denmark describes a more integrated approach to the management issues related to nutrient loading, especially from non-point sources (Jensen and Madsen, 2003).

Odense Fjord with a water area of 65 km^2 at the island of Funen is a shallow inlet with a narrow entrance to the open sea. Two major streams are discharging into the inner part of the Fjord where also the outlet from Odense wastewater treatment plant is situated. The catchment area is 1060 km^2 constituting 30% of the total area of Funen County. Approximately 70% of the catchment area is used for agricultural production.

The environmental problems are related to the urban and industrial point sources and especially non-point sources originating from the agricultural activities in the catchment area causing significant release of nutrients to surface and ground water, which are partly transported to the estuary. The heavy input of nutrients results in eutrophication and effects on the biological resources and occasionally oxygen deficiency in the water phase.

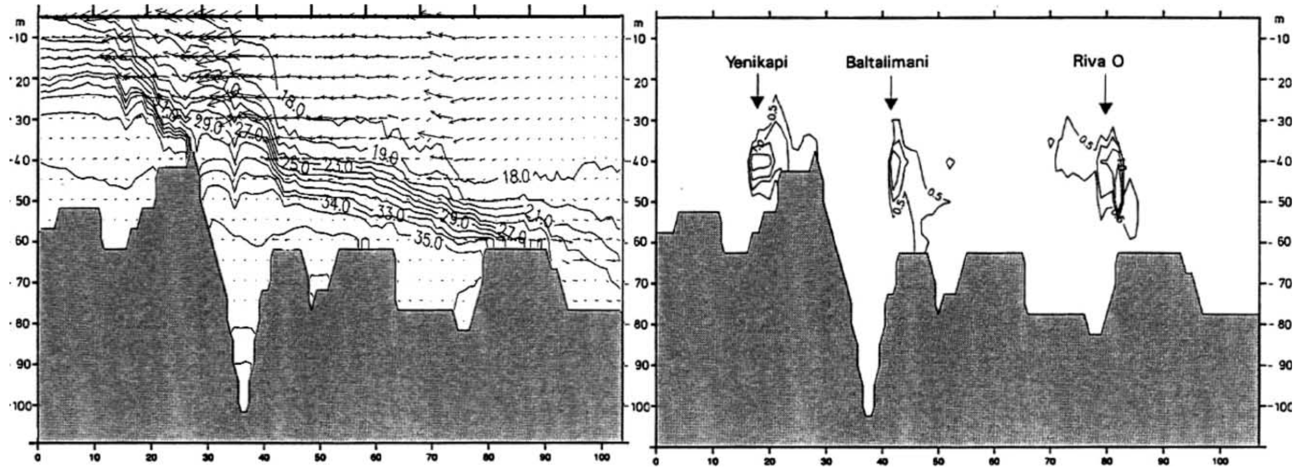

Figure 1 Vertical cross-sections along the Bosphorus Strait. Left: Example of the vertical currents and salinity distribution as simulated with MIKE 3. Right: example of calculated BOD concentration (mg/l) at three discharge points along the Bosphorus Strait (vertical transect). The names refer to sewage outfalls

The total Danish agricultural production has increased by about 20% in the period 1985–2000. Therefore, a conflict exists between environmental problems related to the agricultural sector and the preservation of the natural resources.

Modelling

With the introduction of faster PCs it has become more feasible not only to make three-dimensional (3D) simulations of water levels, currents, water quality and the transport of nutrients, but also longer simulation periods to include seasonal effects. In many systems, like stratified lakes and marine areas with haloclines or thermoclines, a (3D) resolution of the transport processes is needed to be able to make a sensible prediction of, for example, the water quality.

In connection with an application for an extension of the emission of cooling water from a coal-fired power plant, a 3D modelling system was set up of Odense Fjord with the purpose of assessing the effects on the environment.

The applied modelling system was DHI's three-dimensional model, MIKE 3, consisting of a hydrodynamic (HD) module simulating water level and currents, an advection/-dispersion (AD) module for the calculation of the salinity and an eutrophication module for the calculation of water quality (DHI, 1998).

In order to simulate the important ecological parameters in the fjord and the transport of nutrients in and out of the area, the eutrophication module has been extended with a description of the benthic macrovegetation and a description of nitrogen and phosphorus pools in the sediment (Rasmussen *et al.*, 2000).

Results

The different modules in the MIKE 3 model system have been calibrated and validated separately against measured data.

The hydrodynamic model is calibrated against water level data from two stations and for salinity data from three stations. Both the simulated salinity and the water levels match the measured data. A similar agreement between measured and simulated water levels and salinity has been achieved at the other stations and at other periods. Based on this information, it may be concluded that the hydrodynamic model, as well as the advection dispersion model, is well calibrated and the model is ready to be used for the next step: water quality modelling.

The modelled and measured total N & P and inorganic N &P from station 8 at Seden Strand are presented in Figure 2. There is a good agreement between measured and simulated values for all four parameters. The N pattern is partly due to a decrease in the N load and partly due to the fact that the denitrification of the inorganic N (NO_3-N) is high in the summer period. The opposite trend is seen for PO_4-P with the highest concentrations during the summer, despite the fact that the load from the land is at its lowest. The summer maximum of PO_4 has been explained by an internal load of P.

The oxidised sediment layer is dependent on the concentration of NO_3 in the water as well as on the nitrification and denitrification processes in the sediment. During the summer, when the NO_3 concentration in the water is low and denitrification in the sediment is at its highest, the oxidised layer is smallest, whereas it is highest during the winter. The simulated seasonal variation of PO_4-P chemosorbed to oxidised metals in the sediment (FESP) has a seasonal variation, which is the opposite of the variation of the oxidised layer. During the summer the oxidised metals in the sediment are reduced, and the PO_4-P is released into the pore water increasing the flux of PO_4-P from the sediment to the water, Figure 3.

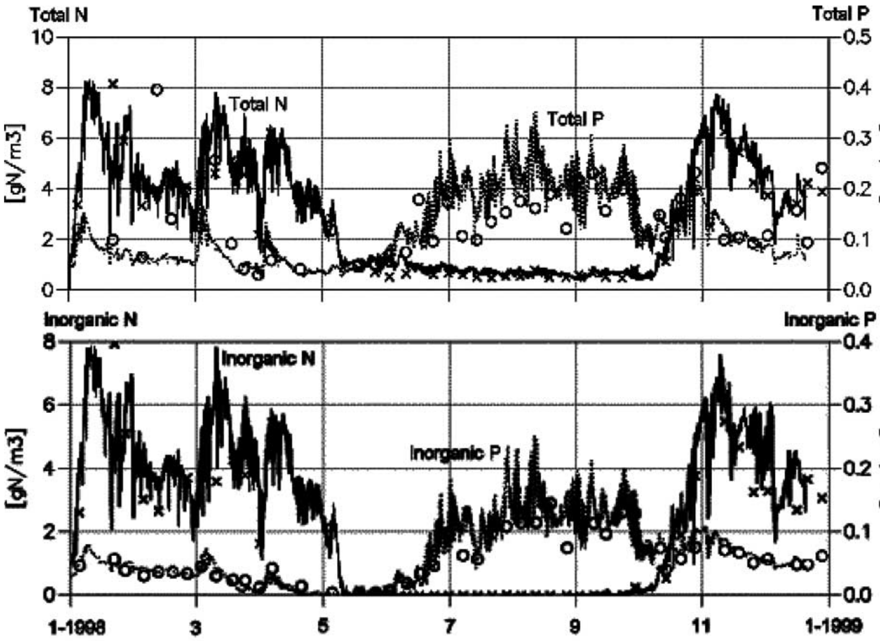

Figure 2 Simulated and measured total N & P (top) and inorganic N & P (bottom), St. 8 Odense Fjord

The model results confirm the idea of the internal load of P being responsible for the summer maximum of PO_4-P in the water.

In a shallow fjord, the biomass of the benthic vegetation may be important for the seasonal variation of dissolved nutrients as well as the overall N and P budget (Bach 1992, Bach *et al*., 1997). This model includes both rooted vegetation (*Zostera marina* and *Ruppia* sp.) and macroalgae (mainly *Ulva*).

Until the beginning of the 1990s, before chemical treatment of wastewater from the city of Odense, massive blooms of *Ulva* occurred at Seden Strand. After the reduction of the N and P loads the *Ulva* blooms were restricted and *Ruppia* vegetation increased. The differences in N and P loads between 1997 and 1998 resulted in a similar pattern, which was also reproduced with the model.

Nutrient budget

Using the model results, it is possible to calculate nutrient budgets for the entire fjord or for sections of the fjord. In Table 1 the nutrient budgets for total N and P for 1997 and 1998 are presented. In 1997, the N and P loads were only 37% and 43% of the loads in

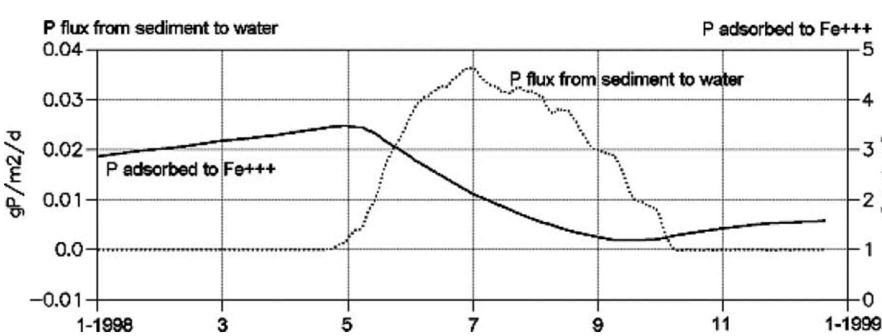

Figure 3 Simulated pools of PO_4-P chemosorbed to oxidised metals in sediment together with simulated fluxes of PO_4-P from sediment to water

Table 1 Nitrogen and phosphorus balance for Odense Fjord 1997–98

Year	Nutrient	Loading Tonnes/year	Retention Tonnes/year	Export Tonnes/year	Retention % pr. year
1997	N	1264	446	818	35
	P	30.4	−36.7	67.1	−121
1998	N	3408	502	2906	15
	P	70.0	−19.6	89.6	−28

1998. The significant lower loads in 1997 are due to lower precipitation resulting in lower non-point loads of N and P from the intensively farmed catchments. The budget for phosphorus shows a negative retention for both years. A breakdown of the P budgets (not shown) shows that this negative retention is caused by P released from the sediment. This finding is consistent with the implementation of N and P treatments of domestic sewage at the beginning of the 1990's, reducing the average P load with about 80%. The N budgets show a net retention of 15–35% of the load, mainly due to the burial of organic N in the sediment and denitrification.

Conclusion of the study

In addition to traditional water quality parameters, it is also possible to set up nutrient budgets for a user-defined area using a combined model system including modules for hydrodynamic, advection dispersion and eutrophication extended with a description of the N and P cycles in the sediment.

In the case of Odense Fjord, the model revealed a significant internal loading of P from the sediment after implementation of N and P treatments of domestic sewage years ago and a retention of nitrogen in the range of 15–35% of the load from land.

The very convincing results of the integrated models developed in this study have meant that the models today are an integral part of the continuous management and monitoring of the fjord.

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Conclusions

Both case studies above were and are state-of-the-art studies in their own time. They are both examples of how all available knowledge of an area has been used to make optimal use of both measurements and models. The value of models, which are not vigorously calibrated and validated against real world measurements, is questionable at best. Measurements by nature only give information about a specific point, and only of the past or at best the present conditions at that location. Combining the two, however, gives the best of both worlds, and the added benefit of being able to give a qualified estimate of the conditions in the future.

Comparing the studies and similar cases around the world clearly reveals the development of model studies to include more and more processes, and account not only for the freshwater system or the coastal zone, but both. In each case reliable results were only found when care was given to integrate and link Integrated Water Resources Management (IWRM) and Integrated Coastal Zone Management (ICZM).

This added focus on integration is seen not only on the management side, but also on the modelling side. Today the MIKE models span from sewers and rivers to floodplains, coastal regions and open seas, and all these models can be linked so that all aspects can be considered simultaneously. For ecological modelling the integration effect is perhaps most profound. In the 1994 study, separate models were used for water quality and eutrophication, and in Odense Fjord 2004, a sediment module was introduced. Today all these processes are covered in the ECOLAB module, which enables the integration of these processes and others that are found, or even considered to be important, in the integrated solution to a given problem (www.dhisoftware.com).

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