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An integrated catchment-coastal modelling system for real-time water quality forecasts☆

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ABSTRACT

This paper presents a new marine water quality forecasting system for real-time and short-term predictions. The forecasting system comprises an integrated catchment-coastal model and a database management system. The integrated model is validated in an Irish catchment-coastal system using hydrodynamic and water quality data. The forecasting system was then used to provide short-term and real-time forecasts of *Escherichia coli* (*E. coli*) and Intestinal Enterococci concentrations (IE) in the nearshore coastal waters of Bray, Ireland. Two hind-cast scenarios were simulated: 5F in which predictions were based on rainfall forecasts only; and I-5F where forecasts of 5F were improved by incorporating real-time data. Results indicate that predictions of *E. coli* of scenario I-5F are improved. Also predicted IE concentrations by Scenario 5F were comparably higher than the I-5F predications, but due to the wide scatter of observed IE concentrations, the superiority of one scenario over the second could not be definitively determined.

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1. Introduction

Achieving and maintaining high marine water quality standards at all times is an essential requirement for supporting the various activities and demands in coastal zones. Such a requirement has been enforced by growing and more stringent EU environmental legislations (e.g. Bathing Water Directive 2006/7/EC (EC, 2006a), Shellfish Waters Directive 2006/113/EC (EC, 2006b) and Water Framework Directive 2000/60/EC (EC, 2000)). To ensure the effective and efficient implementation of these directives, water resources managers need immediate knowledge of the water quality in order to take appropriate mitigating actions for social and ecological benefits in the event of pollution. Thus, the provision of a real-time water quality forecasting model in such circumstances is an essential tool for the support of decision makers.

Numerous and diverse real-time and long-term predictive models of marine water quality are reported in scientific literature. For example, Kashefipour et al. (2005), He and He (2008) and Zhang et al. (2012) developed real-time and long-term prediction models of faecal indicator bacteria (FIB) in recreational waters using Artificial Neural Networks (ANN). Other approaches, such as regression modelling of FIB are also popular (see Hou et al., 2006; Frick et al., 2008; Heberger et al., 2008). Moreover, Chan et al. (2013) presented a hybrid real-time model that combines an ANN model to quantify the export of FIB from a catchment and a deterministic model (EDFC) to simulate its transport in the adjoining coastal waters. The spreading of harmful algal blooms in coastal waters has been predicted using a range of approaches e.g. genetic programming (Muttil and Lee, 2005; Sivapragasam et al., 2010), a vector autoregressive model with exogenous variables (Lui et al., 2007) and ANN (Lee et al., 2003). An ANN approach has also been used by Palani et al. (2008) to predict temperature, salinity, Dissolved Oxygen and Chlorophyll-a in coastal waters off Singapore. It is apparent that most of the above-mentioned predictive models are based on data-driven approaches that employ various techniques in their attempts to describe the complex patterns involved in the real-time

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forecasting process using only available historical data. Although reasonable results are reported using these models, their performance will continue to be questionable if they are utilised to extrapolate patterns outside the range of data that was used in their development and training. Therefore, data-driven models can be of limited use in catchment-coastal systems subjected to systemic changes in background pollution levels.

The use of deterministic models is thus essential to fully capture the changing dynamics that describe the complex interactions between catchment and coastal waters. These changing dynamics, driven mainly by climatic forces, land-use activities, changing performance of wastewater treatment systems and hydro-geological behaviour, can severely impact on the marine water quality (Lloret et al., 2008; Brito et al., 2012; Rollo and Robin, 2010; Nikolaidis et al., 2009). This in turn has serious implications on the sustainability of aquaculture (see for example Riou et al., 2007; Almeida and Soares, 2012; Paterson et al., 2003), siltation in estuaries and harbours (Webster and Ford, 2010; Gleizon et al., 2003) and the recreational use of coastal waters (Kay et al., 2007; Vinten et al., 2004). The strong complex interactions between catchment and coastal zones requires the adoption of an integrated catchment-coastal approach for the numerical modelling of such environments in which the parameters that drive water and pollutant fluxes out of a catchment into a coastal area are represented. However, numerical modelling of such catchment-coastal systems as a single entity is often inadequate as the physics driving the processes in the components of these systems often differ. Therefore, numerical models of such systems are developed by coupling existing catchment and coastal models. As an example, Inoue et al. (2008) integrated a hydrological catchment model with a depth-averaged hydrodynamic model to study the salinity variations in the Barataria Basin which receives highly variable freshwater inputs. In a study investigating the impact of *Escherichia coli (E. coli)* loadings from the Mignonne River catchment, France, on the coastal water and shellfish quality, Bougeard et al. (2011) integrated the catchment model SWAT with the hydrodynamic model MARS 2D. Depth averaged coastal models may be adequate for well-mixed marine environments, but where vertical mixing is limited or absent due to stratified flow fields which dominate the vicinity of discharge outfalls, a three-dimensional (3D) model, as highlighted by Bedri et al. (2011), is essential for improving the representation of the coastal hydrodynamics. Of the few studies of integrated catchment- 3D coastal models, Nobre et al. (2010) assessed the impact of multiple land uses within a catchment on the shellfish production in a coastal area. The assessment involved a multi-layered ecosystem model that integrates the catchment model SWAT with the three-dimensional coastal model DELFT3D.

The challenges of integrating catchment and coastal models are many and depend to a great extent on the level of integration (discussed in Brandmeyer and Karimi, 2000; Nobre et al., 2010). An obvious problem arising from the different timescales of these models is the synchronisation of their modelling components while optimising the run-time. Some performance enhancing solutions include varying the number of timesteps performed between the coupled models as in Malleron et al. (2011) and Lieber and Wolke (2008). Branger et al. (2010) used a discrete event simulator "Scheduler" to synchronise the sequential execution of the components of the coupled models in a timely manner. Nevertheless, a major challenge that remains is the merging of real-time data for improved predictions or forecasts of marine water quality without compromising computational efficiency, accuracy, and robustness of the model predictions.

In this paper, a new marine water quality forecasting system is presented. The proposed system comprises an integrated, deterministic catchment-coastal model for both the real-time and short-term predictions of coastal water quality. The paper explores the technical challenges encountered during model development and testing (e.g. optimisation of runtime and merging of real-time data) and presents solutions to these challenges. The integrated catchment-coastal model is validated in an Irish catchment-coastal system using extensive hydrodynamic and water quality data. The coastal waters of the study area are exposed to episodic short-term pollution incidents that are primarily associated with catchment runoff. The direct response of water quality patterns in these coastal waters to rainfall-related catchment runoff makes this study area a suitable test-bed for the integrated modelling approach. Although the simulated water quality parameters in the current study are *E. coli* and Intestinal Enterococci (IE), the structure of the coastal model used would facilitate the inclusion of other water quality parameters (e.g. heavy metals, sediments and nutrients).

The paper is divided into five sections. Section 2 describes the structure and components of the proposed system. The design of the integration interface as well as the operation of the real-time component of the forecasting system is also explained. In Section 3, the application of the developed integrated model to the Irish test-bed is presented. The study area is initially described and following this, an outline of model set-up and testing scenarios is presented. The results of the model validation and testing scenarios together with a discussion of these results are presented in Section 4. The main findings of the current study and the conclusions drawn from the work are summarised in Section 5.

2. Structure and components of the water quality forecasting system

2.1. Overview

Two main components constitute the marine water quality forecasting system: (i) an integrated catchment-coastal model to simulate flow and contaminant transport from a catchment to marine waters; and (ii) a database for the access and management of the large amounts of input and output data required and generated by the system.

The MIKE modelling suite, developed by DHI (formerly the Danish Hydraulic Institute) is a leading environmental modelling software applicable to a range of water bodies including rivers, lakes, estuaries and coastal waters. Three DHI software; namely NAM (DHI, 2013a), MIKE11 (DHI, 2013a) and MIKE3 FM (DHI, 2013b) were selected for the purpose of the integrated catchment-coastal model for a number of reasons: (i) they offer a robust representation of the catchment hydrological processes and hydrodynamics of coastal waters; (ii) the coastal model, MIKE3 FM uses a flexible (unstructured) grid that enables the discretisation of a model domain using a highly variable-size mesh – an advantageous feature in optimising computation time of the integrated model; (iii) being of the same modelling suite, the models share the same metadata structures and programming language, enhancing model integration and communication between the modelling components; and (iv) the models' Application Programming Interface (API) and libraries are based on the .NET environment which serves as a powerful platform for model integration (Argent, 2004; Rahman et al., 2004).

The main forcing function driving the processes in the integrated model is rainfall. To enable the model to provide predictions of flow and contaminant transport, the forecasting system imports and processes forecasted precipitation obtained from meteorological sources to serve as inputs for the hydrological model, the modelling component first utilised in the integrated model. The

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