Integrated modelling of urban, rural and coastal domains for bathing water quality prediction – Smart Coasts and Acclimatize Projects

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Abstract
This paper presents the results of the Interreg funded SMARTCOASTS project in which an integrated catchment (MIKE11) and coastal (MIKE21 and MIKE3) modelling tool was developed for predicting the bathing water quality, at Bray, Co. Wicklow, on the east coast of Ireland. The Bray bathing waters had historically been prone to episodic short-term pollution, caused primarily by rainfall related catchment run-off. Accounting fully for the complexity of the pollution inputs for water quality prediction in the system required an integrated modelling approach. The approach for integrating the individual component models (NAM, MIKE 11, and MIKE 3 FM) was simple but efficient. The component models, interfaced to the core of the forecasting system, were run sequentially, i.e. in the form of a cascade with the forcing of each downstream model being the result of the model upstream of it. Rainfall (both forecasted and measured) drives the hydrological processes in the NAM model, which produces runoff that generates sub-catchment inflows into the river network. The output from NAM serves as the input to the MIKE 11 model which routes the flow and water quality variables in the river network and transports them to the coastal waters. Finally, the MIKE 3 FM coastal model uses flow and water quality outputs from MIKE 11, together with tidal and meteorological data, to simulate the current flow, transport and fate of water quality variables in the marine environment. Models were calibrated using measured data. Adjustment of the tidal constituents of the MIKE global model resulted in a markedly improved fit to measured water levels at five reference tidal gauges, used for calibration. Bottom friction was calibrated to produce good correlations of measured and simulated current speed and direction. When applied to water quality prediction, results of the transport model showed that the model adequately replicated measurements of *E.coli* and Intestinal Enterococci within the coastal domain. Computational simulations of bathing water quality are not without difficulty and a significant challenge in this work involved incorporating real-time meteorological data from a sensor network within the catchment into the model predictions. The work of Smart Coasts is currently being built on in the Interreg funded Acclimatize project. Acclimatize is focussing on the bathing waters of Dublin Bay and involves the development of a modelling platform that will facilitate a longer-term assessment of the likely pressures on bathing water quality in the context of a changed climate.

1. INTRODUCTION

Coastal waters throughout the world are valuable natural resources that support a variety of recreational and economic activities. Tourism in many countries is centred in coastal zones where the ability to bathe safely is a primary attraction. In Europe, the quality of these bathing waters is currently governed by the Revised Bathing Water Directive 2006/7/EC that superseded Directive 76/160/EC. The new directive places increased emphasis on the protection of public health and in this regard, defines bathing water quality over a four-year monitoring period in terms of two parameters, namely Intestinal Enterococci (I.E.) and Escherichia coli (*E.coli*). The Revised Directive also recognises that elevated levels of faecal coliform bacteria in bathing areas can derive from the overland transport of waste from livestock in the rural fraction of river catchments. On days therefore, that follow significant storm events in coastal agricultural catchments, exceedences of threshold bacteria levels may occur. Discarding of these elevated pollutions from the four-year record is permitted if exceedences in threshold bacteria levels are predicted in advance and mitigating actions to reduce the exposure of the public to polluted waters are taken. Implementation of the Revised Directive therefore requires a proactive approach to the management of bathing water quality and greater public participation.

This paper presents a real-time integrated catchment and 3-dimensional coastal modelling tool for predicting the bathing water quality, at Bray, Co. Wicklow. The linked model has been developed as a 'proof of concept' that will have the capacity to advise responsible Authorities of high faecal bacteria in bathing waters prior of their occurrence. The forcasting of exceedences in threshold pollution levels in this regard will facilitate application of the discarding mechanism in the Revised Directive and the adoption of such tools nationally, may assist in Ireland's compliance with the new legislation. The model has been calibrated and validated with extensive field measurements and the collection of this data is explained. The research was undertaken as part of the Interreg funded SMARTCOASTS project (www.smartcoasts.eu). More recently, the Interreg funded Acclimatize (www.acclimatize.eu) project has commenced. This project is assessing the pressures that are likely to influence bathing water quality in Dublin Bay in the context of predicted climate change. While the data presentation in this paper will be limited to the SMARTCOASTS project, Acclimatize merits mention in this paper in that the integrated modelling platform and methodologies being adopted in this project, are developing from those that were used and validated in SMARTCOASTS.

2. METHODS

2.1 Study Area

The Smart Coasts integrated model has been developed for the River Dargle catchment and its nearshore area in Bray, Co. Wicklow, which is situated on the east coast of Ireland (Figure 1). The Dargle catchment, with an area of 133 km^2, comprises an upland where the primary land use is bog and forestry. The remaining catchment with the exception of the urban fraction which is located downstream, supports arable, sheep, dry stock and dairy farming.

A study of the Dargle catchment (Bruen et al., 2001) showed that the microbial quality of Bray beach was vulnerable to rainfall-related combined sewer overflow discharges together with pollution runoff from the catchment. Until 2013, a further pressure on the bathing water quality at Bray beach derived from untreated sewage discharges through a sea outfall located approximately 1.5 km offshore. The pollution at Bray Beach from this outfall is particularly acute when easterly winds prevail. Furthermore, during extreme storm events, raw sewage is sometimes pumped through a shorter outfall pipe located a short distance from Bray Harbour. Based on evidence from historical pollution episodes (Allen et al., 2003), the bathing waters off Bray provided a suitable test-bed for study.

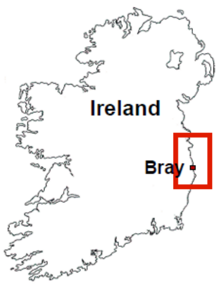
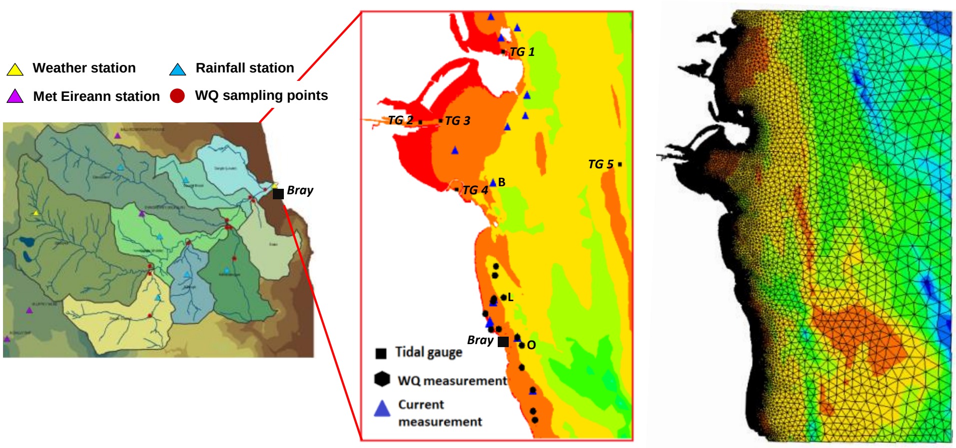


Fig. 1 Location of study area

2.2 Data Collection

An extensive dataset was required to facilitate calibration and validation of the integrated catchment and coastal model developed in this study. High frequency (15 minutes) data from within the catchment was obtained from a real-time network of 20 automatic sensors in weather (rainfall, air temperature, wind speed) rainfall, and river stations (Figure 2 (a)).



(a) (b) (c)

Fig. 2 Data collection stations in the River Dargle catchment (a) and in Bray coastal zone (b). The model mesh is shown in (c).

River stations comprised water level recorders and temperature sensors. Data from all sensors was transmitted remotely via a telemetric system developed for the project to a database where an interactive viewing facility facilitated the continuous monitoring of the time-series data. Met Eireann is the lead agency in Ireland for collection of meteorological data. Met Eireann currently maintain a number of rain gauges in the study area (Figure 2 (a)) and data from these was also utilised. *E.coli* and I.E. was determined from water samples collected in three sampling programmes. Baseline bacteria levels were determined from weekly sampling of a downstream point in the river prior to its discharge to the harbour, monthly data was recorded from water samples taken from the river at each of the 10 flow and water quality sampling locations in Figure 2 (a) and the profile of bacteria levels in the river during storms was determined from hourly sampling for the duration of a number of storm events in the catchment. Within the nearshore coastal zone that was included in the model domain, water current data was collected for full tidal cycles from 13 locations (Fig. 2 (b)) using a bed mounted Acoustic Doppler Current Profiler (ADCP). In addition, tide levels, referenced to ordnance datum from 5 tide gauges between Dublin and Bray were utilised. This data was augmented by *E.coli* and I.E. concentrations determined from water samples collected on an hourly basis at the water quality (WQ) locations shown in Fig. 2 (b) during a range of tidal cycles.

2.3 Development and Calibration of the Integrated Model

The study used the physically-based MIKE models developed by the Danish Hydraulic Institute (DHI). The catchment model was developed using the MIKE11 software that includes flow and water quality transport components. Model inputs include digital elevations (from a DEM) for catchment delineation, rainfall, water temperature, wind speed and direction, flow, and water quality data. The catchment model simulates diffuse and point source flow and concentrations of *E.coli* and I.E. This was linked (integrated) to a nested coastal model of the nearshore waters of Bray developed using the 3-dimensional hydrodynamic MIKE3 software such that river discharges from the Dargle catchment formed an inflow boundary to this coastal model. Using bathymetric data of the model domain to form a finite model mesh (Fig. 2 (c)) and with tidal elevations and wind inputs (obtained from Met Eireann) along the domain boundary, the model simulates the hydrodynamic patterns and transport of water quality parameters in the domain. The model domain covers an area of circa 3,500 km^2 extending to maximum distances of 64 km in the north south direction and 60 km in the east-west direction.

Tidal constituents for the model's boundary conditions were extracted from the MIKE global model and calibrated to tidal elevations at the five reference tidal gauges in the model domain (Fig. 2 (b)). Calibration of the tidal stream and of the water quality transport model was calibrated using field data collected during the 2012 bathing water season. This dataset was 'split' for calibration and validation purposes. Bottom friction was adjusted in the calibration process to provide a good correlation between observed and simulated tidal currents at the various locations in Fig. 2 (b). Following satisfactory correlation between the observed and simulated hydrodynamic characteristics of the model, the water quality transport model in MIKE3 was calibrated by adjusting the dispersion coefficient and the T90 decay rates in the model (12, 24 and 36 hours) until a good fit between observed and simulated *E.coli* and I.E. for the calibration period was achieved at the sampling points within the model domain.

3. RESULTS AND DISCUSSION

3.1 Calibration

3.1.1. Tidal Elevations and Tidal Streams

Root mean square errors between measured and simulated tidal elevations for the 33-day calibration period are shown in Table 1.

Table 1 Root mean square errors (RMSE) between observed and simulated tidal levels

	RMSE				
Scenario	**TG 1**	**TG 2**	**TG 3**	**TG 4**	**TG 5**
Pre-calibration	30.68	11.17	12.35	13.26	9.83
Post M2 calibration	19.08	8.29	7.00	6.09	9.11
Post S2 calibration	17.08	6.73	6.89	4.05	7.97

Table 1 indicates that calibration of the M2 tidal constituents produces a significant decrease in RMSE vales at the 5 tidal gauges in the model domain. Calibration of the S2 resulted in a further improvement to the fit, although this was not as pronounced as for the M2 calibration. Final calibration produced amplitudes of the M2 and S2 tides that were 5% greater than those in the MIKE global model. The calibration also resulted in phase lags that were 15% greater than in the global model.

Calibration of tidal streams indicated a good fit between measured and simulated values on flood stages (period before time of high water) where residual velocities (velocities of small values that occur close to the time of turn of the tide) are well replicated. A poorer fit is noted between measured and simulated current velocities on the ebb tide.

3.2 Water Quality Prediction

The calibrated hydrodynamic model was used to simulate the transport of *E.coli* and I.E in the model domain. Inputs of *E.coli* and I.E. originate from the Dargle catchment and sewage discharges from the Bray pumping station (long and short sea outfalls) and from two wastewater treatment plants located 4 km north and 7 km south of Bray.

Observed *E.coli* and I.E are compared to simulated values at location O on the 5th September 2012 and at location L on the 23rd August 2012 in Fig. 3. Data indicates a reasonable fit between these bacterial levels and provides support for an approach of this type for implementation of the 'discounting' mechanism in the new bathing water legislation.

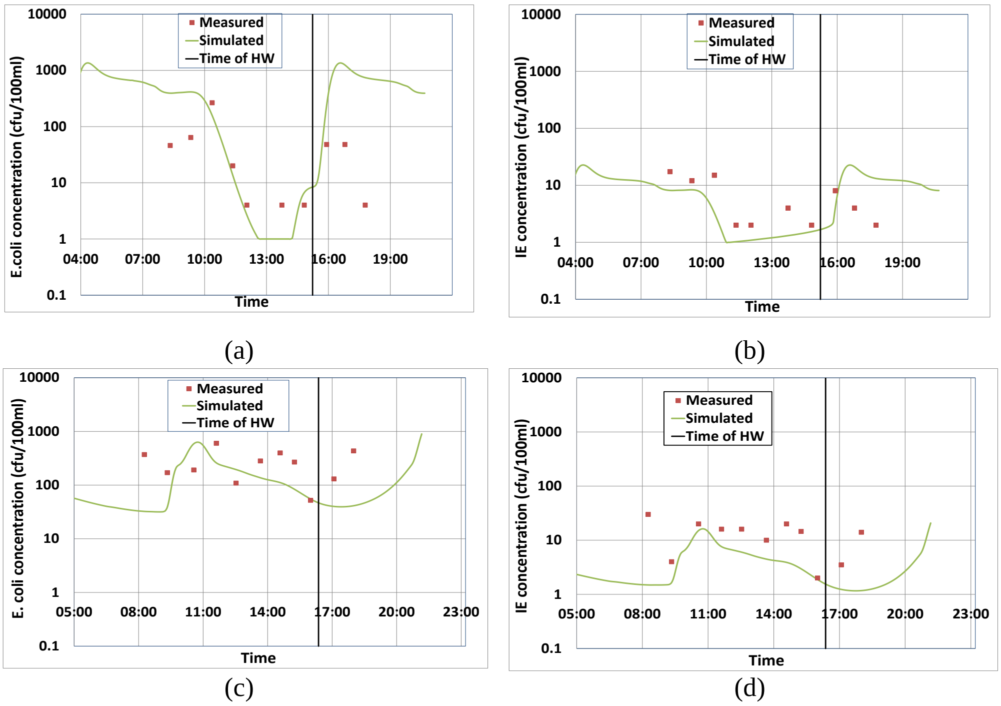


Fig. 3 Observed and simulated E.coli and I.E at Location O on the 5th September 2012 ((a) and (b)) and at location L on the 23rd August 2012 ((c) and (d))

4. CONCLUSIONS

This paper presents the findings of an on-going study to develop a real-time predictive model of bathing water quality using physically-based integrated catchment and coastal modelling tools. Such tools will ultimately be required by beach managers for warning the public of poor water quality as a result of short-term pollution incidents and to implement the 'discounting' mechanism in the Revised European Bathing Water Directive. The research is 'proof of concept' and Bray, Co. Wicklow was used as the test-bed. Results of the water quality transport model have shown that the model can adequately replicate measurements of *E.coli* and I.E. In this regard, the modelling approach presented is considered to have the potential to serve as a water quality forecasting tool and in this regard, will be useful to beach managers in satisfying the requirements of the new legislation.

Acknowledgements

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