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Bathing Water Quality Prediction Using an Integrated Catchment and 3-D Coastal Hydrodynamic Model

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Abstract
Under the new European Union Bathing Water Directive (2006/7/EC) which comes into force in 2014, more stringent bathing water quality standards, defined in terms of Escherichia coli (E.coli) and Intestinal Enterococci (I.E.), will apply in Irish bathing waters. Compliance with these standards is ensured through a structured water quality monitoring programme that is published by Authorities with responsibility for bathing water areas in advance of each bathing season. The directive 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. Given that these exceedences result from 'natural' rather than anthropogenic influences, a 'discounting' mechanism that allows for a temporary relaxation of these standards is allowed for short-term pollution incidents. In this regard, some high levels of faecal bacteria contamination can be excluded from the water quality record. However, this 'discounting' is only permitted if elevated bacterial levels are predicted in advance and mitigation actions to maintain public health protection are taken.

This paper presents an integrated catchment (MIKE11) and 3-dimensional coastal (MIKE3) modelling tool for predicting the bathing water quality at Bray, Co. Wicklow. Models were calibrated using flow and water quality data. Adjustment of the M2 and S2 tidal constituents of the MIKE global model has resulted in an improved fit to measured water levels at the five reference tidal gauges. Bottom friction was calibrated to produce good correlations of measured and simulated current speed and direction. Furthermore, results of the water quality transport model has shown that the model has adequately replicated measurements of E.coli and IE.

Keywords
Bathing water quality, prediction/ forecasting, catchment-coastal model, MIKE, Ireland

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 bath safely is a primary attraction. In Europe, the quality of these bathing waters is currently governed by the 1976 Bathing Water Directive (76/160/EC) (EC, 1976) which has as its goal the protection of public health and the environment from faecal pollution (CEC, 2002). This legislation set mandatory and guideline water quality (bacteriological, physical, and chemical) standards for all bathing waters within the member states. The introduction of Directive (76/160/EC) highlighted coastal sewage discharges as a major source of microbial pollution (Christoulas and Andreadakis, 1995; Martín et al., 2007; Kay et al., 2008) and while on-going investment in the sewage infrastructure of many countries has undoubtedly contributed to improved bathing water quality, coastal waters in many areas continue to be affected by diffuse faecal pollution from agricultural runoff subsequent to heavy rains (Vinten, et al., 2004; Hewett, 2007; Wyer et al., 2010).

In 2006, a revised Bathing Water Directive (Directive 2006/7/EC) (EC, 2006) came into force and will replace Directive (76/160/EC) in 2014. The new directive places stronger emphasis on the protection of public health and in this regard, defines bathing water quality in terms of two new, albeit more stringent parameters, namely Intestinal Enterococci (I.E.) and Escherichia coli (E.coli). The new directive also introduces a new classification system determined on the basis of a four-year water quality monitoring period instead of the monitoring results from a single bathing season. However, the directive 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. Given that these exceedences result from 'natural' rather than anthropogenic influences, a 'discounting' mechanism is included in the Directive where high levels of faecal bacteria contamination can be excluded from the water quality record. This discounting can apply to a maximum of 15% of water quality samples in the 4-year monitoring period and is only 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 new directive 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 'discounting' mechanism in the new bathing water 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).

2. METHODS

2.1 Study Area

The 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. The coastal zone off Bray is of recreational and heritage value and is a designated EU bathing site, serving the growing population of Bray town as well as nearby towns and villages.

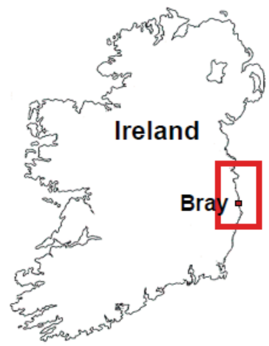


Fig. 1 Location of study area

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.

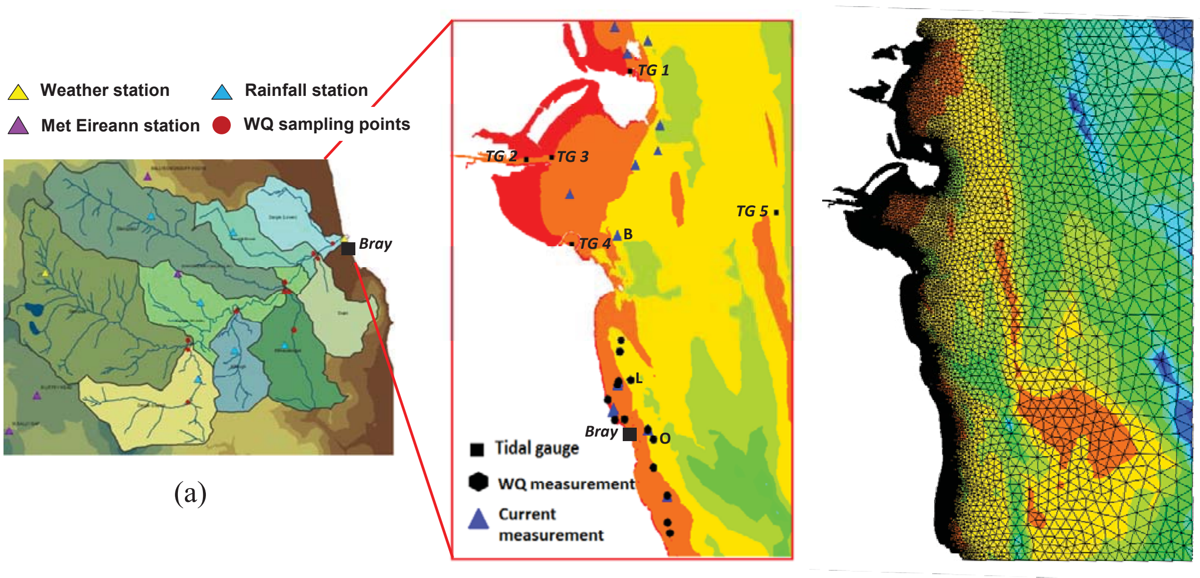
Bray beach had been subject to frequent episodic failures to comply with the standards of the 1976 Bathing Water Directive (Allen et al., 2003) and there is concern about the impact of the more stringent standards of the revised directive. Therefore, it is vital for the recreational value of Bray beach to avail of the discounting provision of the revised directive which can only be facilitated by the development of a real-time predictive tool for the bathing water quality.

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)). 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 and direction data was collected for full tidal cycles from 13 locations (Fig. 2 (b)) using a current meter and a surface and bed mounted Acoustic Doppler Current Profiler (ADCP). In addition, tide levels, referenced to ordnance datum from 5 tide gauges between Dublin and Bray was 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.

Water quality monitoring during the project was confined to the bathing season which continues from May to September each year. The data collection period was therefore consistent with the reporting period specified in the directive and in the course of which, results of bathing water monitoring are compiled and reported annually by member states to the European Commission. Detection of E.coli and I.E. in the water samples extracted from both the river and the coastal zone was performed according to the membrane filtration method described in ISO 9308-1 (ISO, 2000a) for E.coli and to ISO 7899-2 (ISO, 2000b) for I.E. This conforms to the requirements of the revised Bathing Water Directive (2006/7/EC).



(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).

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 64km in the north south direction and 60km in the east-west direction.

Tidal constituents for the model's boundary conditions were extracted from the MIKE global model. Only the eight largest tidal constituents (M2, S2, K1, O1, N2, K2, P1, and Q1) were used to run the model. Calibration of these constituents involved obtaining a good fit of between observed and simulated tidal elevations at the five reference tidal gauges in the model domain (Fig. 2 (b)). The calibration was undertaken for a 33 day period from 29th September to the 31st October 1989 during which all 5 tidal gauges were operational. To minimise the computational effort, only the largest M2 and S2 constituents were calibrated. These were adjusted sequentially for the 111 nodes that defined the sea boundary if the model in an extensive calibration routine.

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). The integrated model has as its objective the simulation of E.coli and I.E. transport from discharges at a number of sources in the study area (long and short-sea sewage outfalls at Bray, discharges from other sewage plants in the study area, the Dargle river outflow and direct discharges into the coastal waters). These point discharges were therefore included in the model.

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

Root mean square errors between measured and simulated tidal elevations for the 33 day calibration period are shown in Table 1 and the simulated Post S2 calibration tide is compared to the observed tidal record at TG4 in Fig. 3.

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

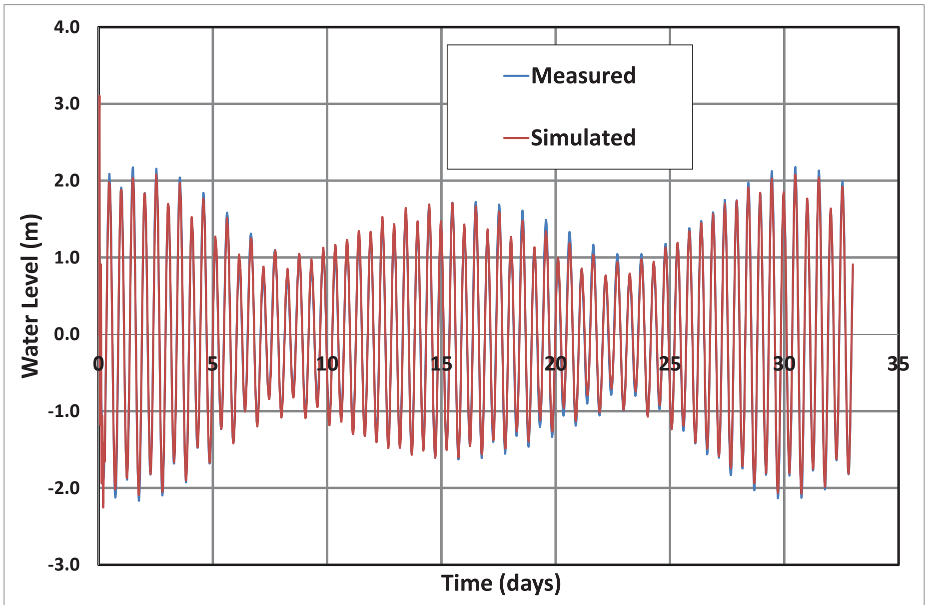
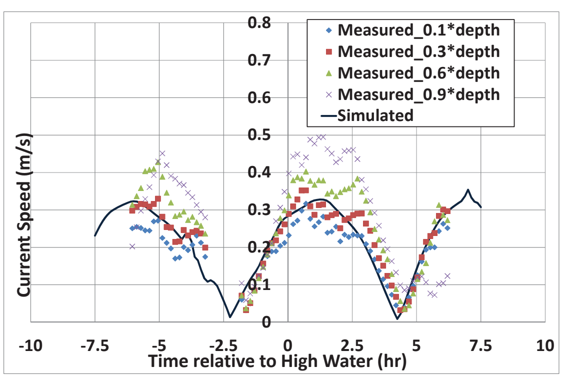


Fig. 3 Observed and simulated tide levels at TG 4 from 29th September to 31st October, 1989

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. Fig. 3 indicates that there is a good correlation with these calibrated constituents between the observed and simulated tidal record at TG4. 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.

3.1.2 Tidal Stream

Fig. 4 compares depth averaged simulated velocity magnitude and direction at location B (refer to Fig. 2 (b)) with measured values at between 10% and 90% of the water column depth. Data relates to a spring tide.



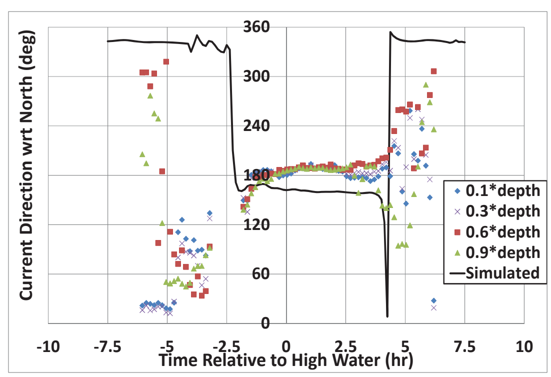


Fig. 4 Comparison of simulated depth averaged current velocity (a) and direction (b) with measured values at 10%, 30%, 60% and 90% depths in the water column at location B

Fig. 4 indicates that the model replicates current speed over the tidal cycle reasonably well. A particularly good fit between measured and simulated values is observed on the flood stage (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. The model is also shown to replicate reasonably well the gradual change in the general observed flow direction from a northwards flowing flooding current to a southward flowing current in the ebb stage. A good fit to measured direction of the flood stage is observed but measurements in the direction of the ebb tide indicate discrepancies.

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 4km 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. 5. 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.

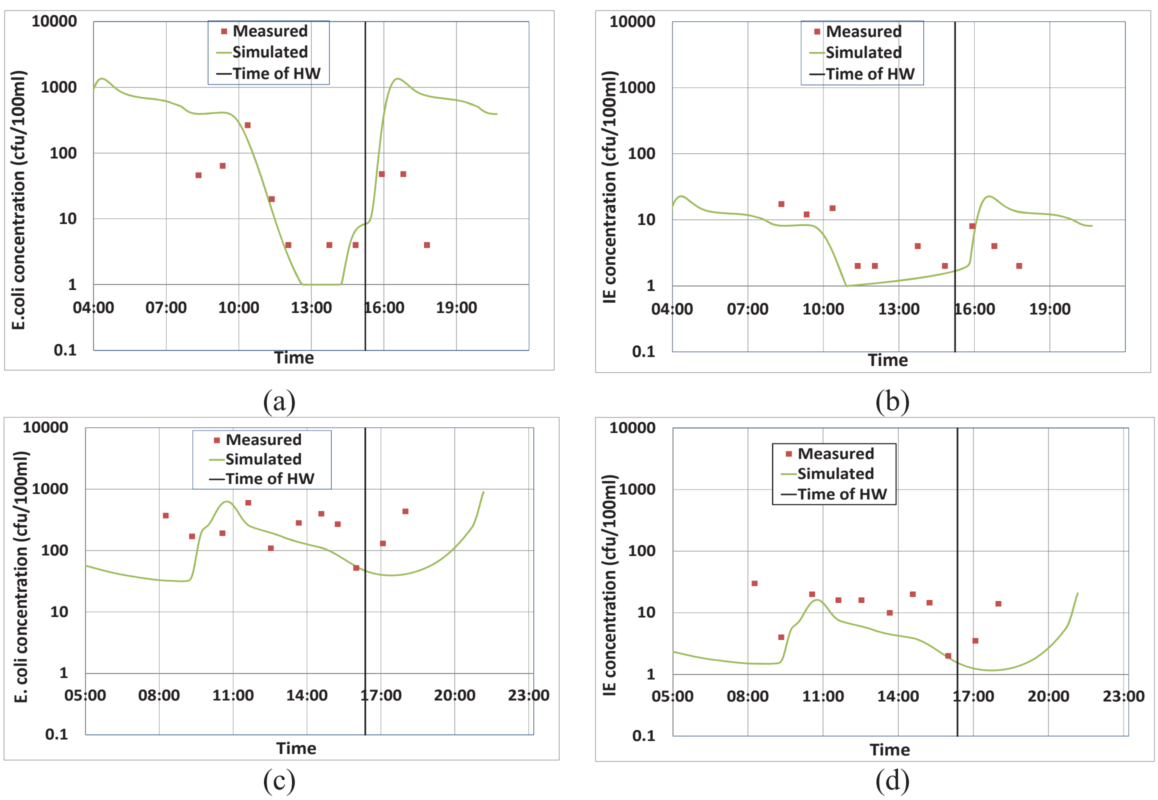


Fig. 5 Observed and simulated E.coli and I.E at Location O on the 5th September 2012 ((a) and (b)) and at location L on the 23rd August 2012 ((c) and (d))

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 new European Bathing Water Directive. The research is 'proof of concept' and Bray, Co. Wicklow has been 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.

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