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# Integrated hydro-bacterial modelling for predicting bathing water quality

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A B S T R A C T

In recent years health risks associated with the non-compliance of bathing water quality have received increasing worldwide attention. However, it is particularly challenging to establish the source of any non-compliance, due to the complex nature of the source of faecal indicator organisms, and the fate and delivery processes and scarcity of field measured data in many catchments and estuaries. In the current study an integrated hydro-bacterial model, linking a catchment, 1-D model and 2-D model were integrated to simulate the adsorption-desorption processes of faecal bacteria to and from sediment particles in river, estuarine and coastal waters, respectively. The model was then validated using hydrodynamic, sediment and faecal bacteria concentration data, measured in 2012, in the Ribble river and estuary, and along the Fylde coast, UK. Particular emphasis has been placed on the mechanism of faecal bacteria transport and decay through the deposition and resuspension of suspended sediments. The results showed that by coupling the *E.coli* concentration with the sediment transport processes, the accuracy of the predicted *E.coli* levels was improved. A series of scenario runs were then carried out to investigate the impacts of different management scenarios on the *E.coli* concentration levels in the coastal bathing water sites around Liverpool Bay, UK. The model results show that the level of compliance with the new EU bathing water standards can be improved significantly by extending outfalls and/or reducing urban sources by typically 50%.



## 1. Introduction

Bathing water quality is of increasing international concern, and public awareness of the impacts of poor bathing water quality on health risk has increased in recent years. Beach closures now frequently occur due to the non-compliance of water quality to the required standards. It is therefore increasingly a challenge to balance wastewater disposal with other activities in estuarine and coastal waters (Bedri et al., 2016). In order to comply with the standards required by regulatory authorities world-wide, many bathing water quality improvement measures have been drawn up and many projects have been carried out worldwide to study non-compliance. For example: the TIMOTHY project in Belgium (de Brauwere et al., 2011; Ouattara et al., 2013), the Southern California Coastal Water Research Project (de Brauwere et al., 2014a; Field and Samadpour, 2007; Griffith et al., 2009) and Michigan Lake (Liu et al., 2013; Pramod et al., 2010; Safaie et al., 2016) in the USA, Hong Kong, China (Chan et al., 2013; Thoe et al., 2012) and the Cloud to Coast project (C2C) in the UK (http://www.shef.ac.uk/c2c/index), are all examples of studies undertaken to investigate bathing water quality. However, bathing water non-compliance is a complex problem, since it involves many aspects and processes (Huang et al., 2015b) including: catchment management (Byappanahalli et al., 2015), arrangements relating to the siting of sewage pipe networks and outfalls (Fan et al., 2015; Obiri-Danso and Jones, 1999), waste water treatment methods, weather conditions (Ackerman and Weisberg, 2003; Kashefipour et al., 2002), sediment suspension and transport (Gao et al., 2013), currents, waves, and sea birds and pets (Converse et al., 2012; Wither et al., 2005; Wright et al., 2009) etc. Moreover, it is still unfeasible to track the sources of Faecal Indicator Organisms (FIOs) and predict the fate and transport of FIO processes (Boehm et al., 2002), based only on case-specific measured data with a low spatio-temporal resolution (de Brauwere et al., 2014b).

Many hydrological models have been developed to predict the

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hydrological and FIO transport process in river catchments, e.g. the semi-distributed model Soil and Water Assessment Tool (SWAT) (Arnold and Fohrer, 2005; Cho et al., 2012), the Hydrological Simulation Program—FORTRAN (HSPF) (Benham et al., 2006; Liao et al., 2015) and the distributed model (Huang et al., 2015b; Niu and Phanikumar, 2015). Hydrodynamic and water quality models have been developed for bacteria process predictions in river networks (Yakirevich et al., 2013; Yang et al., 2002) and estuaries (Gao et al., 2013; Liao et al., 2015; Thupaki et al., 2013). Numerical model studies have also been undertaken for predicting FIO processes in both rivers and coastal waters (de Brauwere et al., 2014a; Huang et al., 2015a), and in some cases a catchment model is used to supply the upper boundary conditions (Bedri et al., 2014; Huang et al., 2015b). To summarize, these numerical models can be used (de Brauwere et al., 2014b) to: (i) identify the sources, processes and parameters controlling FIO dynamics; (ii) assess the impacts of natural events and human activity on bathing water quality; and (iii) support real-time decision making by providing short-term predictions of FIO distributions at bathing water and shellfish-harvesting sites.

Since the complex processes of the source, transport and fate of FIOs can occur in the catchments, sewage works, riverine and estuarine waters, and they are closely linked with environmental and sedimentary factors, it is difficult to use existing numerical models to reproduce the FIO processes for the whole study area, i.e from Cloud to Coast. At present, quantitative evaluation of bathing water improvements by various measures still involve significant uncertainties. Therefore, the main objective of this study has been to develop an integrated hydro-bacterial modelling system to quantify more accurately the effects of bathing water improvement measures on the water quality characteristics and particularly in terms of the FIO levels. The system comprises: two hydrological models, a 1-D river and sewage pipe network model and the 2-D/3-D Environmental Fluid Dynamics Code (EFDC) model. These models have been integrated to predict the fate and transport processes of FIOs from the upstream catchments, through pipe network and/or river systems to the estuarine and coastal waters. The FIO fluxes have been linked to the sediment transport processes, which are considered to be important in order to improve on the model predictive accuracy of FIO levels in river and estuarine waters. The model was first validated using hydrodynamic data and then further validated using sediment and faecal bacteria concentration data, measured in the river Ribble and its estuary in 1999 and 2012. In this study, *E.coli* has been used as the representative indicator for FIOs. A series of scenario runs have also been carried out to investigate the most efficient management strategy for reducing *E.coli* concentration levels along the bathing water beaches around the Ribble Estuary and Fylde Coast.

## 2. Materials and methods

### 2.1. Outline of the integrated model

The integrated modelling system is composed of 5 sub-models and a brief description of the system and the linkage between the sub-models is given below.

(1) HSPF model

The Hydrological Simulation Program – FORTRAN (HSPF) (Bicknell et al., 1997) is a sophisticated and comprehensive watershed model that simulates runoff and diffuse (or non-point) pollutant loads, for various land cover configurations and enables the fate and transport processes of solutes to be predicted in streams. HSPF comprises three main modules, including: PERLND, IMPLND, and RCHRES, and five auxiliary modules. In HSPF, the watershed is represented in terms of land segments and stream reaches. The PERLND module is used to simulate the hydrological and water quality processes over pervious areas, while IMPLND is used for impervious land, where infiltration is very small and can be omitted. Compared with distributed hydrological models with grid cells, HSPF has a high computational efficiency with reasonable accuracy.

(2) Infoworks model

The Infoworks model includes a distributed rainfall-runoff model and a pipe network model, built and simulated using the Infoworks CS software package. It can be used to solve the hydrological, hydrodynamic and water quality processes in urban catchments, rivers, drainage and sewerage networks and related devices. A more detailed description of the urban model is given in the Hydroworks/Infoworks CS menu (Wallingford Software Ltd, 1995) and various papers, such as (Rico-Ramirez et al., 2015) Rico-Ramirez et al. (2015).

(3) DMHSF model

A distributed catchment model (Huang et al., 2015b), which has been developed to simulate the hydrological, sediment transport and faecal indicator organism processes in river basin catchments, is based on the Xinanjiang (XAJ) flow yield mechanism (Zhao, 1992). In this model, the *E.coli* transport processes are associated with sediment transport fluxes, with the decay rate for *E.coli* being dependent upon temperature and irradiance, and with the *E.coli* being adsorbed or desorbed onto or from the sediment particles.

(4) One-dimensional river network model (RMN1D)

A one-dimensional river network model has been developed to predict the hydrodynamic and water quality processes in riverine basins. The model has been applied to the complex network of rivers associated with the Ribble basin. In this model, the implicit four point Pressimann finite difference scheme has been used for the hydrodynamic solution (Huang et al., 2016). Meanwhile, the finite volume method, with a staggered grid, has been used to improve on mass conservation for the sediment and water quality flux predictions. The model has proven to be highly accurate for simulating solute concentration levels in river networks, such as the Ribble, and particularly for *E.coli* concentration values which can vary from near zero to many millions.

(5) Modified EFDC 2D/3D model

The Environmental Fluid Dynamics Code (EFDC) is a general purpose modelling package developed at the Virginia Institute of Marine Science for simulating hydrodynamic, solute and biogeochemical processes in surface water systems (Hamrick, 1992). The model deploys a curvilinear-orthogonal co-ordinate system in the horizontal direction and a stretched sigma coordinate system in the vertical direction. It uses a finite volume-finite difference spatial discretization, with a staggered grid, to solve the governing equations representing the hydrodynamic, water-quality and sediment transport processes. A second moment turbulence closure model, developed by Mellor and Yamada (1982) and modified by Galperin et al. (1988), is used to provide the vertical turbulent viscosity and diffusivity. This turbulence closure model relates the vertical turbulent viscosity and diffusivity to the turbulence intensity and length scales. The EFDC model is second-order accurate in both space and time and is well documented and widely used.