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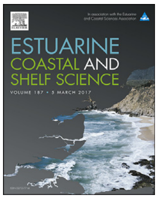

# Integrated hydro-bacterial modelling for predicting bathing water quality

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## ABSTRACT

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.

### 2.2. *Model verification*

#### 2.2.1. *Site description*

The model domain covered part of North West England, with about 9660 km$^2$ and 12,920 km$^2$ for the coastal region and catchments respectively (see Fig. 1a). The bed elevation ranged from −60 m to 866 m, and the minimum and maximum elevation regions were mainly located to the western edge of the sea boundary and the source regions of rivers Dee, Mersey and Lune, respectively. There were 11 main rivers included in the model, flowing into the coastal region along the East and North banks. In the extensively wide transitional lowland zones between the mountains and estuaries, major cities, such as Manchester, Preston, Liverpool, Blackpool, Chester are located at the lower and middle reaches of these rivers or around the main bay. Meanwhile, there are extensive arable and improved grass lands for crops and livestock breeding around these cities, which needed to be included in the catchment models. The well-known bathing water sites of Blackpool and Lytham St Annes are located between the deltas of rivers Wyre and Ribble, including the river Ribble network and its estuary. The domain was located along the North West region of England, with a total basin area of 1583 km$^2$. The river Ribble rises in the Yorkshire Pennines and has a length of around 75 miles in main channel length, with 3 key tributaries, including: the Hodder, Calder and Darwen.

The hydrological and hydrodynamic computational subdomains were extended to the other adjacent regions, especially considering the intense mixing due to the strong currents and related matter transport, partly associated with the bathymetry. In recent decades, non-compliance of bathing water quality has frequently occurred for the bathing beaches around the Ribble delta, although there has been a significant improvement in recent years due to the construction of a series of infrastructure assets, which have improved the water quality in the region.

#### 2.2.2. *Model set-up*

In modelling the Ribble catchment, the hydrological and *E.coli* simulation in the rural catchments were carried out by the c2c participants from Sheffield University (Phillips, 2014) using the HSPF model, where 52 sub-catchments with an average of 10 segments were used in the sub-catchments. If sewage pipe networks were also involved, then the Infoworks model which is built by Shepherd et al. (2015) was used to simulate the hydrodynamic and *E.coli* processes in these pipe networks and the related outputs were then included in the HSPF model as point sources. Meanwhile, the hydrological and *E.coli* processes in the catchments were calculated by a distributed hydrological model system (Huang et al., 2015b), except for the river Ribble and sediment concentrations in the catchment domain. The curvilinear grid was refined to give a higher resolution near the bathing water sites and the river delta regions (see Fig. 1b). The bathymetry, bed sediment size distribution, bed roughness values, and the initial and boundary conditions were setup using the EFDC model, including the coastal region and the river network inputs (Huang et al., 2015a).

The rivers Ribble, Wyre, Mersey and Lune were all modelled up to the tidal limits in the estuaries, using the EFDC 2D model, while the middle and upstream reaches of the river Ribble were modelled using RNM-1D. The main channels were included as they were located relatively close to the region of interest, i.e. the bathing water sites along the Fylde Coast and the Ribble Estuary. For the key focused coastal domain, the boundary conditions at the open seaward boundary were specified based on the tidal level data obtained using the EFDC-2D hydrodynamic model for the Irish Sea region (Zhou et al., 2014). A constant salinity level of 35 ppt, a

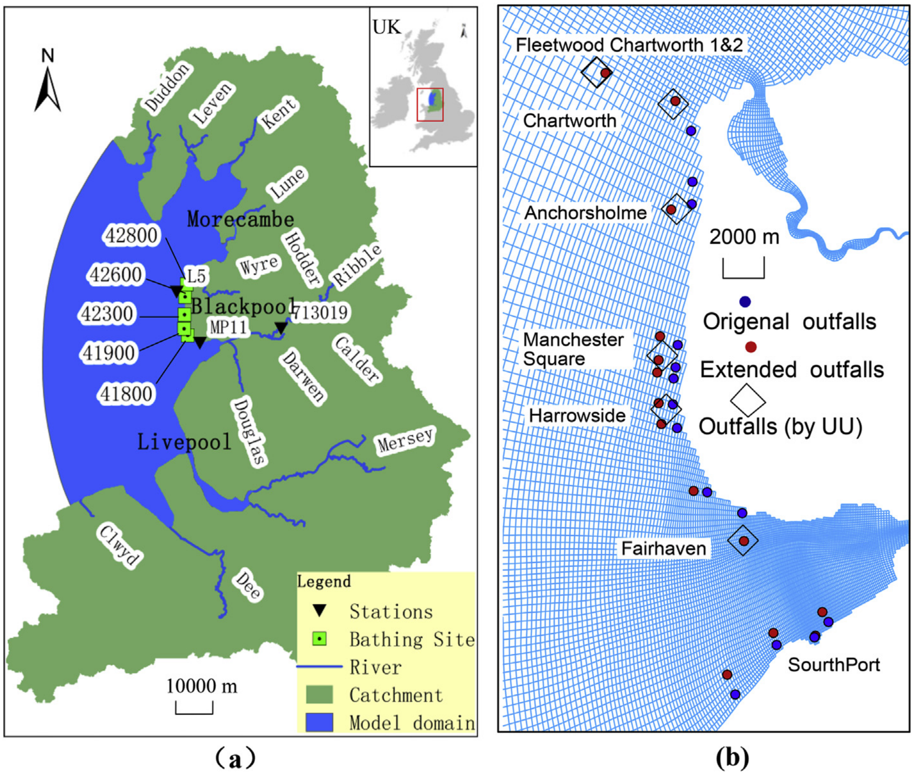


**Fig. 1.** (**a**) Map of the study area including: monitoring sites and bathing water compliance sites for the rivers and coastal region; and (**b**) view of the nearshore region around the Ribble estuary, showing the original outfall locations and extended locations, together with planned outfalls.

temperature value of 20.0 °C, a suspended sediment concentration of 5 mg/l and an *E.coli* concentration of 10 cfu/100 ml were all assumed at the seaward boundary. At the upper riverine boundaries the measured data acquired in 1999 (Kashefipour et al., 2002) and the modelling data acquired in 2012 from the 1-D and HSPF or distributed catchment models (Huang et al., 2015b) were specified respectively. The inputs included: discharges, suspended sediment and *E.coli* concentration data, and a water temperature time series, obtained from the UK Meteorological Office. Lateral point sources were also included using either measured data for 1999 or predicted using the catchment models for 2012.

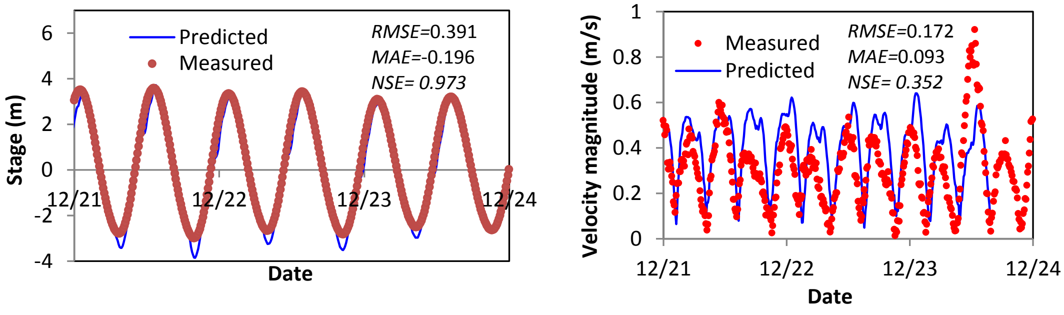
### 2.2.3. Linkage of different models and calculation efficiency

In considering the large differences in the time step, calculation speed, and model formats for the different types of land use considered, a simple data flow and model linkage procedure was used in the model system. For the river Ribble catchment the outflow results obtained from the HSPF and Infoworks models were used to provide the upper and lateral boundary conditions to the RNM1D model. For other catchments, where the sewage network data were unavailable, the DMHSF model was used to simulate the flow, sediment and *E.coli* processes, with the related processes in the sewage pipes being simplified to some degree. Finally, all of the output data from the 1D model and parts of the catchment model output data were inputted into the EFDC-2D model to predict the sediment and FIO concentrations in the estuarine and coastal waters. Because the upper boundaries of the 2D model were located in the region of the tidal limit, any calculation errors in the hydrodynamic and mass transport predictions would be relatively small.

A personal computer with a speed of 3.4 GHz was used throughout this study; it took about 100 h to undertake one month of simulations of the hydrodynamic, sediment and FIO processes for the whole study area. In the model system, the calculation efficiency was mainly governed by the EFDC 2D model due to its large model domain and the fine grid structure in the estuarine and coastal areas. The catchment and 1D models took much less computational time.

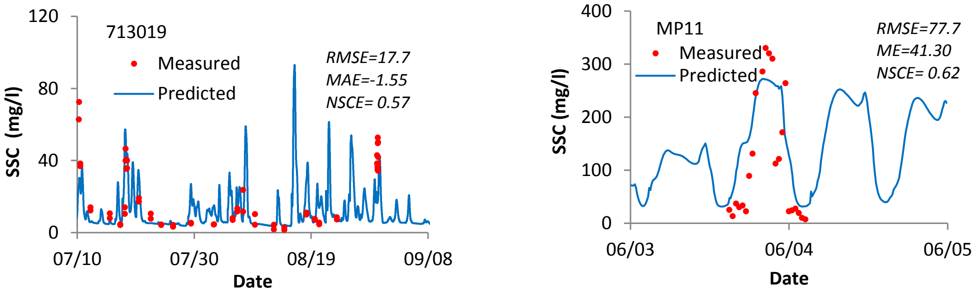
### 2.2.4. Hydrodynamic verification

Comparisons were made between the model predicted water level and velocity values and their corresponding field measurements, at selected sites in the Ribble Estuary, Morecambe Bay, Liverpool Bay and other key sites. The water levels predicted by the model generally agreed well with the field measurements, with an example prediction being shown in Fig. 2, at station L5 near Blackpool. For the comparisons between the field observed and model predicted velocities, some relatively large differences were found, with some predicted peak flow speeds being either greater or less than the field measured values. In particular, during the period between 12:00 and 18:00 on 23 December 2012 the observed velocity values were significantly greater than the model predictions, and also much greater than the measured velocities for the preceding tidal periods. However, the observed tidal level values were generally in line with those measured for the preceding periods. Such discrepancies were considered to be either caused by storms or by the relatively low resolution of the bathymetric data used in the model. Some deep and narrow channels were thought to have been smoothed out when the data were interpolated linearly to generate the model bathymetry. This would affect the accuracy in predicting the water elevations at low water, and the peak velocities values. The bathymetry will be refined further as improved bathymetric data becomes available from future field studies.



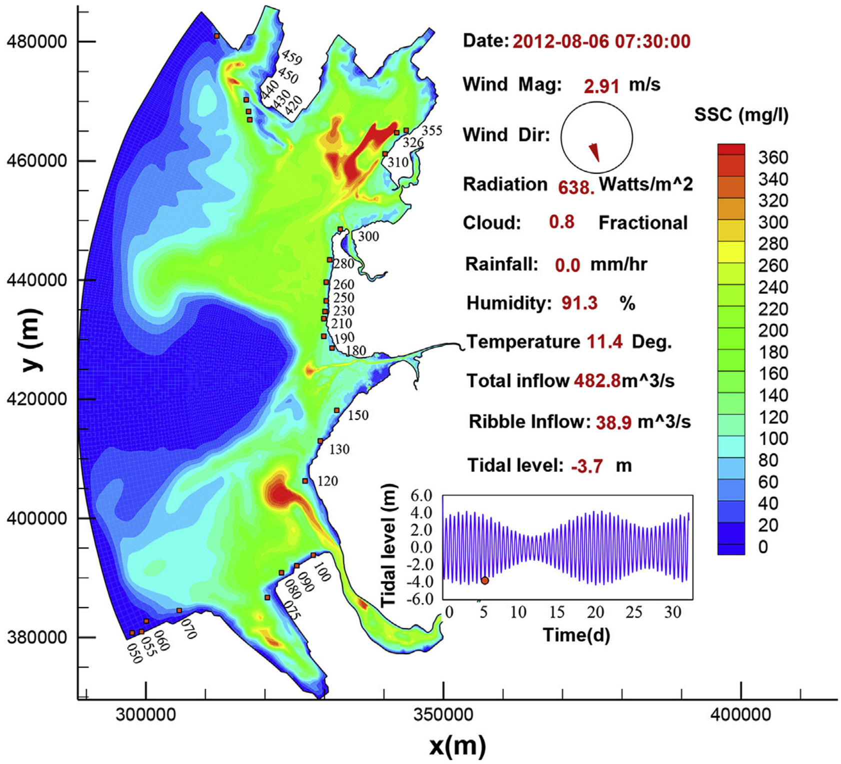
(a) Water level (b) Velocity

**Fig. 2.** Verification of water level and velocity predictions at a typical coastal monitoring site L5 in 2012, as shown in Fig. 1b.

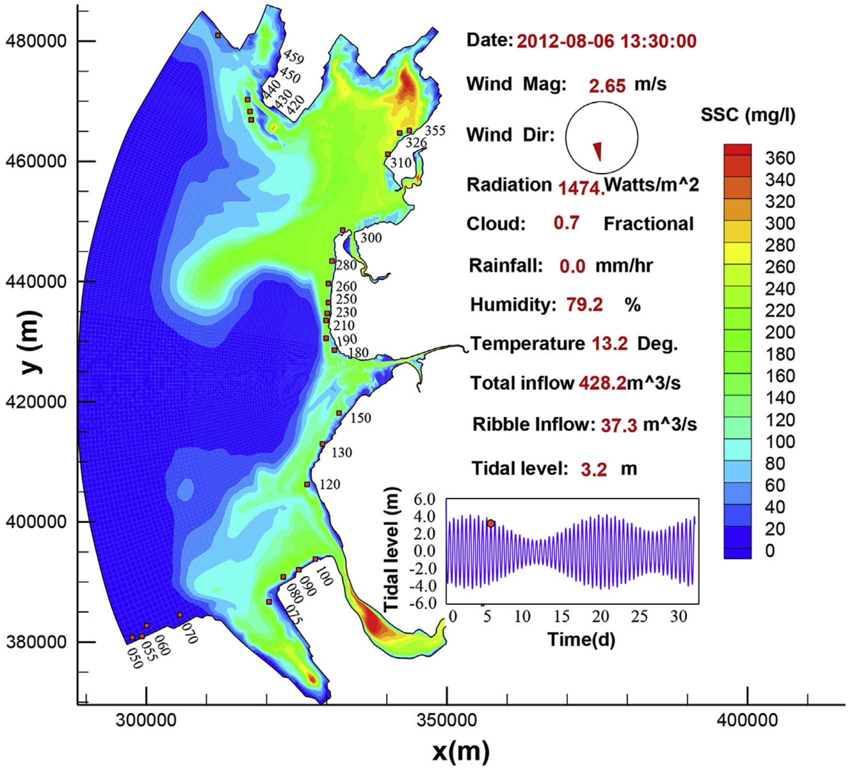


(a) No. 713019 in River Ribble (b) No. MP11 in Ribble Delta

**Fig. 3.** Suspended Sediment Concentration (SSC) verification at two typical monitoring sites.



(a) Low water



(b) High water

**Fig. 4.** Suspended sediment concentration distributions at: (a) low, and (b) high spring tide on 6th August 2012.

### 2.2.5. *Sediment verification*

The numerical model results showed that the relatively high suspended sediment concentrations (SSCs), ranging from 100 to 300 mg/l, appeared in the estuarine and shallow coastal regions. The sediments were predicted to have originated from the main feeding rivers, transported by the riverine flows and tidal currents from the rivers to the estuarine and coastal waters. Subsequently, the periodic SSC fluctuations were caused by regional erosion and resuspension, induced by the tidal currents. At the bathing sites, i.e. primarily at Blackpool and Lytham St Annes, the SSCs were found to be lower than the corresponding SSCs in the delta regions. The sediments were thought to be transported from Morecambe Bay, the Wyre and Ribble deltas through the complex sediment-laden currents. This was due to the relatively large proportion of coarse and fine sands along the beaches and the long distance from the river delta to the source. Meanwhile, the FIOs adsorbed on the sediments, have been transported with the sediments from the rivers Ribble and Wyre and have been deposited along the bathing beaches following certain specific hydrodynamic conditions. The predicted and measured comparisons for SSCs are shown for two typical sites, namely No. 713019 and MP11 in the Ribble main channel and estuary, respectively (see Fig. 3).

The numerical model predicted SSCs showed encouraging agreement with the corresponding measured data at all sites. For example, in the upper reaches of the river basin (i.e. Fig. 3a), the highly episodic variations in the SSCs were generally well reproduced using the distributed hydrological model. Likewise, in the estuary at Milepost 11 (i.e. Fig. 3b), the more slowly varying SSCs were also well predicted using by the EFDC-2D model. The SSC distributions around the whole Fylde Coast are also shown at low and high tide respectively in Fig. 4. The results show relatively high concentration levels across much of Morecambe Bay, to the north, and in the Ribble Estuary, with the levels in the latter being noticeably higher for low, vis-à-vis high, tides. It was found that the suspended sediment fluxes from Morecambe Bay, and the rivers Mersey, Ribble and Wyre governed the SSC distribution across the domain. Local erosion and deposition near Blackpool North may also have had some effect. The main sediment deposition area was identified as being around the river deltas of the Ribble and Wyre and with the relatively low tidal currents in the region of Blackpool therefore providing good conditions for safe bathing.

### 2.2.6. *Faecal indicator organism (FIO) calibration and tests*

(1) Model calibration

In order to predict the *E.coli* concentration distributions as accurately as possible, the decay rate was represented dynamically and expressed in the form of $T_{90}$ values, i.e. the time specified in hours for the concentration to reduce by 90%. Based on recent data acquired by the Centre for Research into Environment and Health (CREH), at Aberystwyth University (http://www.shef.ac.uk/c2c/dissemination/events), which are presented in Table 1, with the $T_{90}$ values in the modelling system being based on a simplified for day and night variation only. In addition, since *E.coli* in the river and marine bed material can survive up to 1–2 months (Davies et al., 1995; Garzio-Hadzick et al., 2010)-2, $T_{90}$ in the bed sediments was therefore et to 30d in the modelling system. The corresponding $T_{90}$ value was then converted to an equivalent decay rate $k_d$ (with units of $sec^{-1}$), and with this decay rate being corrected according to the local water temperature. The *E.coli* concentrations were then coupled to the suspended sediment concentrations, to take into account the effects of adsorption and desorption of the bacteria to and from the sediments. When the sediments were concentrated near the bed then the *E.coli* level did not reduce significantly, because of the high $T_{90}$ value (due to darkness) and the corresponding low decay rate in such conditions.

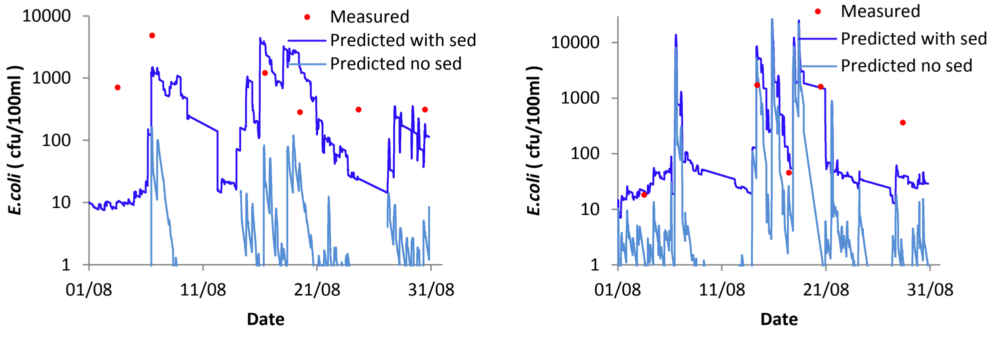
Fig. 5 shows the *E.coli* predictions using the original model without coupling to the sediments, with the predicted and measured *E.coli* concentrations being compared at two bathing water sites (No. 41900 and 42,800) near the north bank of Ribble estuary and the south bank of the Wyre estuary, respectively. Comparisons were made between the predictions and data acquired in August 2012. As can be seen from Fig. 5, the measured and predicted *E.coli* values agreed generally well, and the agreement improved when the interactions with the sediments were included. These results highlight that it is essential to model the interaction of *E.coli* with the sediments if accurate predictions of *E.coli* concentrations are to be obtained in sediment laden flows.

(2) Model results

The spatial distribution and temporal variation of *E.coli* concentrations in the riverine and coastal domains are affected by several factors, including: the inflow volume and *E.coli* concentrations, sediment particle size and concentrations, and environmental

**Table 1**
$T_{90}$ value measured by CREH and used in the RNM-1D and EFDC-2D model.

| *E.coli* | n | Mean $T_{90}$ irradiated (hr) | Mean T90 dark (hr) |
|---|---|---|---|
| Freshwater | 68 | 13.61 | 355.51 |
| Estuarine | 32 | 8.56 | 30.64 |
| Saline | 20 | 2.33 | 33.77 |

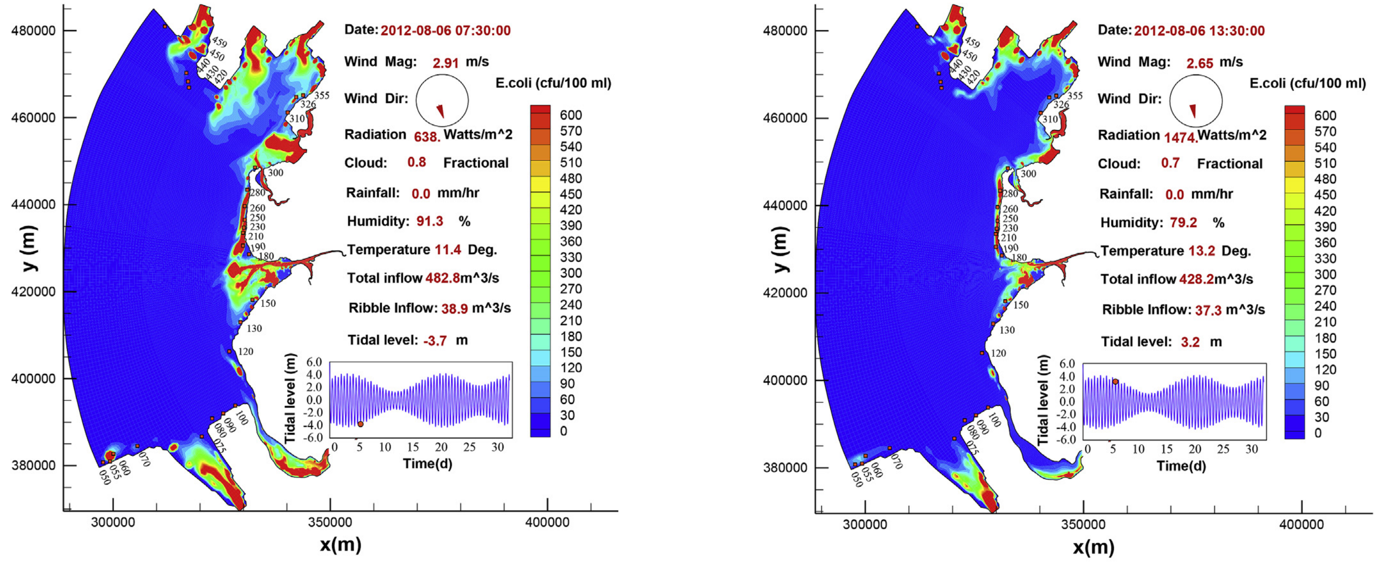


(a) No. 41900 (b) No. 42800

**Fig. 5.** Comparison between predicted and measured *E.coli* concentrations at 2 bathing sites, both with and without sediment interactions.

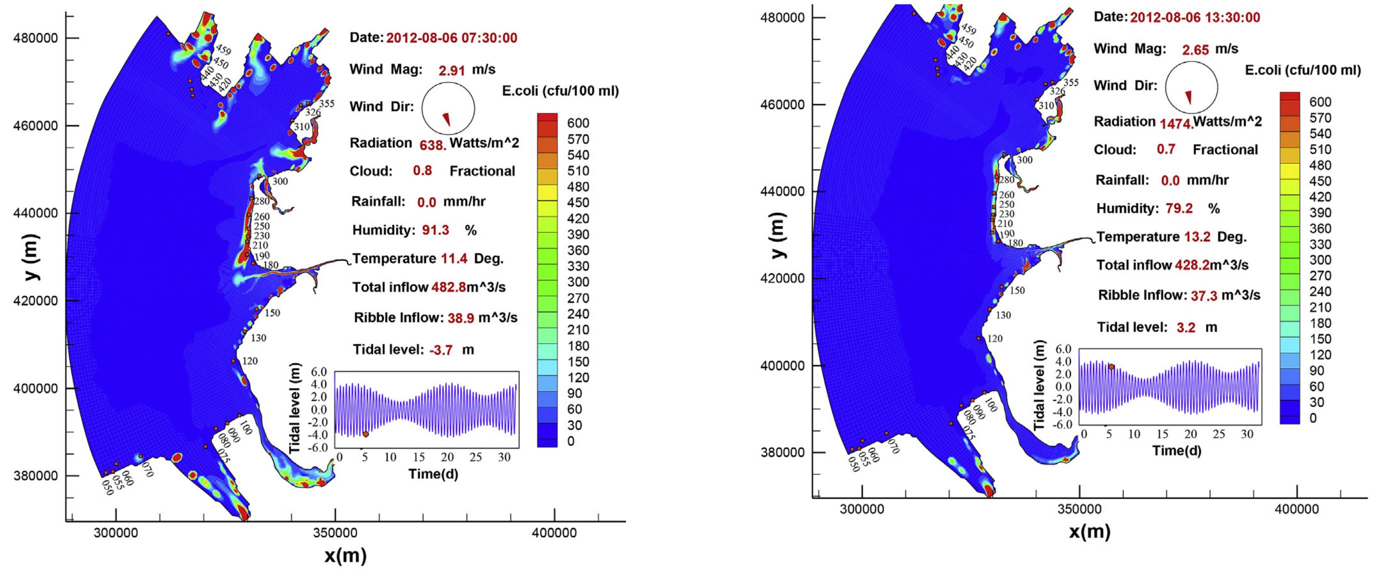
conditions, such as light intensity, wind speed etc. The spatial distributions of the modelled *E.coli* concentrations are shown for low and high tides in Fig. 6, both with sediment coupling (Fig. 6a, c) and without sediment coupling (Fig. 6b, d). The results show that the relative high *E.coli* concentration regions, with a concentration in the range exceeding 500 cfu/100 ml, are located mainly in the river deltas, salt marshes and a part of the beach. The high concentration regions may move to and fro along the river corridor and coastline, controlled by the river flow and tidal currents (Fig. 6a, c). The middle concentration region, where the *E.coli* concentration ranges from 200 to 800 cfu/100 ml, tends to move in a south-westerly direction, along the river corridor, controlled mainly by the river flow. The front of the middle concentration region may reach Southport, to the south of the estuary (Fig. 6 c). In addition, under some conditions, e.g. strong southerly winds and currents, the middle concentration region may also occasionally reach the Fylde Coast to the North. The low concentration region appears in the estuary, with these conditions primarily occurring at neap tides and for large river discharges. The local point sources near the bathing water sites may also have some impact on the *E.coli* concentrations locally.

From the model predicted *E.coli* concentration distributions, both with and without sediment coupling, it can be seen that the sediment transport processes may play an important role in the *E.coli* surviving rate by changing the sunlight radiation effects and by sediment: advection, deposition and erosion, and adsorption and desorption of the FIOs to/from the sediments. The *E.coli* bacteria attached to the surface of sediment particles can be



(a) With sediment coupling, at low water neap tide

(c) With sediment coupling, at high water spring tide



(b) Without sediment coupling, at low water neap tide

(d) Without sediment coupling, at high water spring tide

**Fig. 6.** Spatial distributions of predicted *E.coli*: with (a and c), and without (b and d) sediment coupling on 6th August 2012.

transported more readily to the offshore marine waters as an additional net source of *E.coli* (Zhongfu et al., 2010,) while the free swimming *E.coli* component is much more likely to stay within the coastal zone. This means that *E.coli* concentrations will generally be underestimated without including the coupling sediment processes of adsorption and desorption, especially in the offshore region. Furthermore, since the *E.coli* concentration is regularly predicted and measured to be relatively high in the intertidal region, more *E.coli* bacteria are likely to be attached to the sediment particles. The resuspension and subsequent movement with tidal currents then delivers the *E.coli* bacteria to the nearshore region, resulting in a likely further increase in the *E.coli* concentration levels in this region.

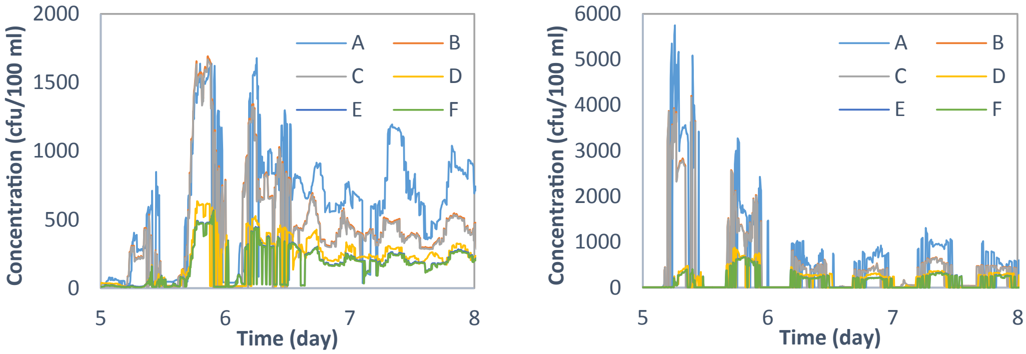
### *2.3. Evaluation of effectiveness of management plans*

In order to evaluate the effectiveness of the proposed management plans for *E.coli* concentration reductions in estuarine and coastal regions 6 scenario runs were carried out. The details of the 6 designed scenarios are listed as follows: (i) Scenario A: baseline plus FIO loads to the urban networks since summer 2012; (ii) Scenario B: all major urban areas improved to a level consistent with plans for Preston/Blackburn to 2020 (urban flux 50% reduction); (iii) Scenario C: rural improvement (rural flux: 50% reduction); (iv) Scenario D, E, F: up to 1000 m extension of 5 key main outfalls toward the open sea, according to the plans outlined by the local water company and the Environment Agency, while the *E.coli* inputs from the upstream catchments are kept the same as for Scenarios A, B, C respectively. The *E.coli* and sediment coupled model was used in the scenario runs based on the data acquired during August 2012. The predicted *E.coli* concentration values at the key bathing water sites, namely UK41800, UK42300 and UK42800, are presented in Fig. 8. The main results can be summarised as follows: (i) the scenarios leading to a 50% cutoff in the urban flux and outfall extension are effective in reducing the *E.coli* concentrations at the bathing water sites (see Fig. 8), with the *E.coli* concentrations being reduced to about 1/3rd of their original values and with the peak value being reduced to 500–1000 cfu/100 ml, which is close to the upper-limit of the new EU bathing water standard (500 cfu/100 ml); (ii) the extension of the outfalls is more effective than other measures in reducing the peak value of the *E.coli* concentration; and (iii) the 50% cutoff of the rural sources in the catchments near the Wyre delta to the Ribble delta is not effective at the bathing water sites near Blackpool, since the high urbanized intensity in this region, and the ratio of the rural source input, is an order of magnitude smaller when compared to the urban *E.coli* sources. Comparisons with the new EU bathing water quality standards, and the effectiveness of these various schemes, will be further analyzed in the next section using the accumulated probability calculation.

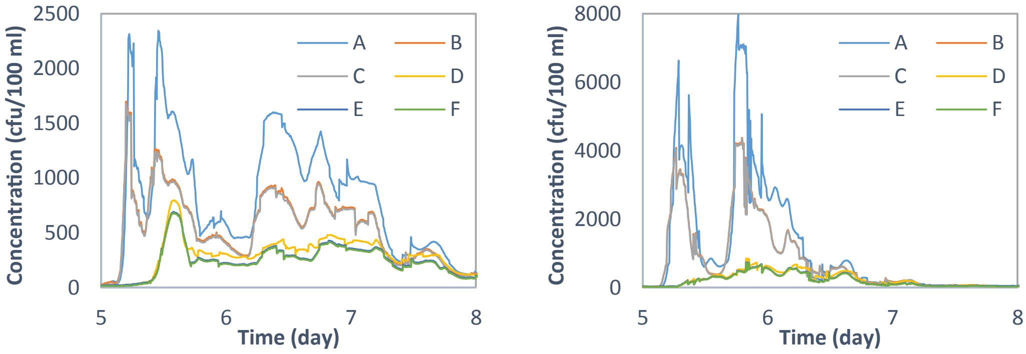
## 3. Results and discussions

### *3.1. Functions from sediment and sediment-E.coli coupling*

The model results indicate that with sediment-*E.coli* interaction the predictive accuracy at the bathing water sites is enhanced (see Fig. 6). The main differences between the sediment-*E.coli* interaction model and the clear water model are: (i) the decay rate in clear water is greater than that for water with sediments in suspension; (ii) the *E.coli* concentration reduction rate due to the net *E.coli* loss within the water column is an order of magnitude smaller than the reduction caused by dilution due to advection and diffusion (Pramod et al., 2010); and (iii) the time dependent transport and



(a) UK41800 (b) UK41900



(c) UK42300 (d) UK42600

**Fig. 7.** *E.coli* concentration variations for the 6 scenarios at 4 key bathing sites, namely UK41800, UK42300 and UK42800.

resuspension of sediment particles, which are associated with *E.coli* adsorption and desorption to the sediments, may further change the movement of *E.coli*. In comparison with the clear water model, the model results with sediment coupling are found to be closer in agreement with the measured *E.coli* concentrations and a smoother transformation occurs between the maximum and minimum values (see Fig. 5). Without sediment coupling, the minor peaks and low values due to the *E.coli* desorption and adsorption with the sediments may disappear.

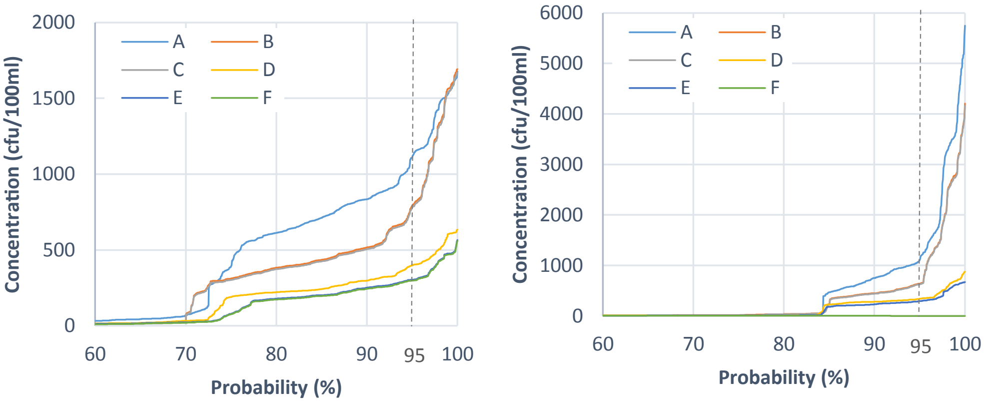
### 3.2. *Effectiveness of management plans*

Based on a probability analysis of the results shown in Fig. 8, the *E.coli* reductions for the various management and engineering scenarios maintain the same trends as shown in Fig. 7. Furthermore, any extension of the outfall is predicted to be more effective in reducing the peak *E.coli* value, which is sensitive to the distance between the bathing water beach and the outfall sites. After implementation of the combined sewage extension plan, the *E.coli* concentration value at the 95% probability level will be less than 500 cfu/100 ml, except at the bathing water site named UK42600, which, however, has shows a substantial reduction from 2300 cfu/100 ml to 550 cfu/100 ml for the worst case scenario. This means that the microbiological compliance with the new EU Bathing Water standard (maximum 500 cfu with 95% probability level for *E.coli* in estuarine bathing waters) can be improved significantly with outfall extensions. According to the model predictions, the outfall extensions taken further offshore are preferable for spring tide conditions in order to satisfy the new EU bathing water standards. Moreover, due to the large proportion of urban FIO sources in the catchments, the urban source cutoff will also play an important role in reducing *E.coli* inputs. However, a 50% cutoff in the urban source alone does not seem to be not sufficient to enable the bathing water quality along the Ribble estuary and coast to satisfy the new EU standard.

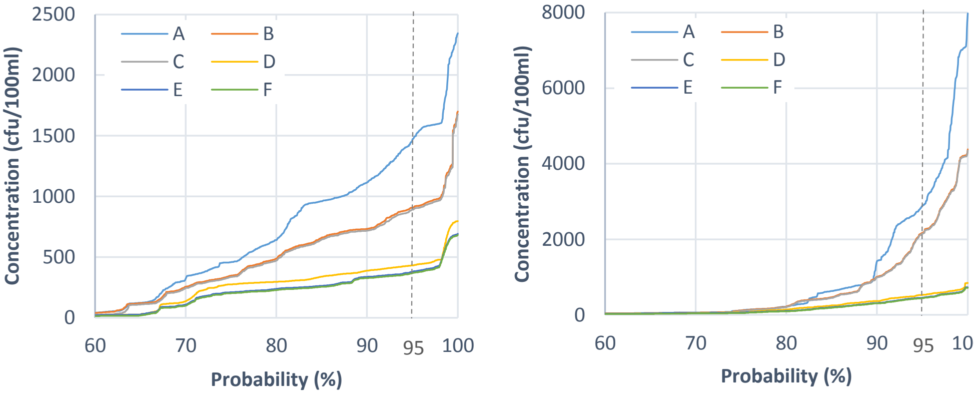
## 4. Conclusions

In natural marine and aquatic waters the fate and transport processes of FIOs are highly dynamic and complex and they can vary significantly from the upstream catchments to the coastal regions. In the current study an integrated numerical modelling system has been refined and applied to predict the spatial and temporal distribution of FIOs in riverine basins and, in particular, coastal bathing waters. The integrated model includes the river network (RNM1D) model and the open source 2D/3D EFDC model, in which the upper boundaries are specified from the results for two catchment models for rural regions and the Inforworks model for urban regions. The key refinement to the existing codes is the inclusion of FIO interactions between the water column and suspended sediments. The modelling system was applied to 11 catchments of the river Ribble basin and the coastal receiving water of the Liverpool Sea, UK, with model predictions being compared with field measurements taken along the Ribble river and estuary in 1999 and 2012. The level of agreement between the measured and predicted hydrodynamic, sediment transport and *E.coli* parameters were encouraging at most of the sites.

Because the integrated model covers all of the important sub-



(a) UK41800 (b) UK41900



(c) UK42300 (d) UK42600

**Fig. 8.** Accumulated probability analysis results for the 6 scenarios at 4 key bathing water sites, namely UK41800, UK41900, UK42300 and UK42600.

catchments and better represents the fate and transport processes of FIOs from the source region to the coastal receiving waters, it has the potential to provide more accurate solutions than non-integrated models, particularly for large and complex river basins. Due to the different coding formats and time steps in the sub-systems, a simple linkage approach using input and output data modes was used to link the different sub-systems. Since the 2D model domain was extended to the tidal current limits for the riverine inflows, and due to the relatively large spatial scales used in the current research study, the errors related to this aspect of the study were considered to be small. However, further research needs to be carried out to investigate the impact of stronger dynamic coupling problems.

The results confirm that sediment transport is a key process by which FIOs can be transported from river basins to coastal waters. The concentration distribution of FIOs in coastal and estuarine waters, and exclusion of the transport mechanism of FIOs through adsorption and desorption with the sediments, can lead to a marked under-prediction of the FIO levels along coastal waters, and particularly at regions near bathing water sites. The higher FIO levels near bathing water sites appears to be influenced by the resuspension of sediment particles and the subsequent movement with tidal currents in the offshore direction.

The analysis of 6 scenarios in the current study indicated that a significant reduction in the *E.coli* levels can be obtained by extending outfalls and/or significantly reducing the *E.coli* source inputs from urban regions. The cumulative analysis showed that the level of compliance with the new EU standard can be improved to a large degree by extending outfalls. Although the emphasis of the work reported herein has focused on the river Ribble Basin and Fylde Coast, the modelling developments are generic and can be applied to other river basin to coast studies, both elsewhere in the UK and internationally.

## Author contributions

Roger Falconer and Binliang Lin developed the original ideas and Guoxian Huang undertook the studies and further developed and improved on the original ideas as reported herein. Guoxian Huang and Roger Falconer drafted the manuscript, which was revised substantially by all authors.

## Conflicts of interest

The authors declare no conflict of interest.

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