

# **Integrated Water Modelling and Management for Bathing Water Compliance**

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## **ABSTRACT**

Due to the increasing cultural and economic benefits of bathing waters and the shellfish industry in the UK, water quality in estuarine and coastal waters has attracted considerable public attention in recent years. However, some bathing beaches have had to be closed on various occasions because the Faecal Indicator Organism (FIO) levels exceeded the minimum mandatory standard. The relationships between faecal bacteria sources in the upstream catchment and the bathing water quality are complex, since multiple processes and driving factors affect the transport and fate of FIOs through the basin. To obtain accurate FIO predictions and better management of bathing water compliance, for a changing environment and more stringent standards, it is necessary to build an integrated modelling system which includes comprehensive dynamic faecal processes from catchments, gullies, pipes, tanks, river networks etc., through to the estuarine and coastal waters. In the paper, details are given of the development of such an integrated numerical model for simulating the transport and dynamic decay processes of FIOs from a catchment region to the coast. The model is used to predict the distribution of FIO concentrations in the bathing waters near Blackpool, which is one of the most popular bathing resorts in the UK. Furthermore, its bathing water quality is governed by multiple faecal sources in the catchments, with different land uses and some highly urbanised regions. In addition, the FIO transformation processes in the riverine and estuarine waters are driven by: tidal currents, wind induced waves, inflow and faecal discharges, unsteady sediment transport etc., and are included in the integrated model by linking a number of processes within a modified EFDC 2-D model. The extensive measured and statistical data from the catchments, river networks, CSOs, WwTWs discharges and estuaries have been collected for determining various model parameters, and for calibration and validation of the integrated model. Model predictions are used to assess the impact of different concentrations and locations of FIOs on the bathing water quality, with the aim being to provide information for deriving more effective management strategies to meet the new EU standards, to be implemented in 2105.

## **1. INTRODUCTION**

### **1.1 Background**

An elevated concentration of FIOs may indicate the presence of pollution, which usually originates from sewage or livestock waste etc. Due to the increasing cultural and economic value placed on bathing waters and the shellfish industry in the UK, together with the high health risks associated with faecal micro-organisms, coastal water quality has attracted increasing public attention over the past two decades or so. A series of infrastructure improvements have been undertaken over the past 20 years, such as building water storage tanks, and measurements post 2000 have shown that bathing water quality has generally improved significantly across the UK, especially for wet weather and storm surge conditions. In order to find a reasonably accurate

solution, the understanding of the continuous faecal bacteria transport processes from source regions, passing through brooks, streams, pipelines, CSOs, WWTWs, river networks, and finally entering into the coastal waters, is important. Therefore, an integrated deterministic modelling system has been developed and applied to a UK river basin, with details of the model being briefly presented herein. Different cell systems or hydrological response units (HRUs) have been used in a distributed hydrological model, to distinguish between natural HRUs, rural arable land and pastures and city regions. Vector polygon cells are used in some urban hydrological models, in which the spatial shapes and their connections in different HRUs are closer to reality [1]. However, if there are different, crossing or even changing boundaries which exist between the different sets of HRU boundaries during the solution of multiple variables, such as surface water, ground water, sediment yield, faecal bacteria and nutrition processes, then this method may be of limited accuracy. Hence in the current study a rigid uniform rectangular grid system has generally been used, with some triangular cells being used near irregular boundaries to fit the catchment boundary.

### 1.2 Key physical, chemical and ecological processes

The transport and dynamic transformation processes of FIOs from catchment regions to the coastal region mainly involve the following aspects: (1) source apportionment processes in the rural and urban catchments, including both the land surface and soil layer; for example, livestock and wild animal populations, age structure, manure collection, storage and spreading, grazing activity and river basin management; (2) faecal bacteria die-off and releasing, driven by intrinsic life process and environmental factors such as: rainfall, radiation, temperature, suspended sediment concentrations (SSCs), substrate, predator population, moisture and nutrition conditions; (3) delivery, driven by natural and anthropogenic forcing; with parts of any released faecal bacteria being transported from hills, via gullies, brooks, streams, rivers and then to the estuary and coastal waters, while anthropogenic activities may change the bacteria levels due to farmland, pasture, arable, ponds, sewage pipes, tanks, CSOs, WWTWs, rivers and estuaries; during transportation, the SSCs and the bed sediment particles may cause some faecal bacteria concentration variations by absorption, desorption, attenuation of radiation etc.; (4) coupling, integration, evolution and accumulative impact by the conjunction of natural and man-made river systems, and episodic concentration variations of the faecal bacteria driven by extreme events.

### 1.3 Brief review of methods and models.

In recent decades a series of investigations of daily faecal bacteria production has been undertaken [2], with faecal bacteria production estimation methods being reviewed in references [3, 4]. Related tools, such as the Bacteria Indicator Tool (BIT) [5] and the Bacteria Source Load Calculator (BSLC) [6], have been developed to estimate the faecal sources and fluxes from catchments into rivers. However, the uncertainty level is often still high because of the daily, monthly and seasonal changing in grazing activities [7], manure age [8], distribution of land-use and soil distribution etc. Moreover, the variation of the livestock population and communities are not fully considered in these tools. When faecal bacteria is left on the land-surface and buried into a shallow soil layer with manure, the rainfall will cause additional losses, which may be expressed using linear and exponential relationships between the shallow groundwater depth and the rainfall intensity [3]. For the surface loss, the releasing parameter needs to be adjusted according to the grid size, or using other double parameter models, based on concepts outlined in Vadas, Kleinman [9]. At same time, the faecal bacteria die-off in the catchment is a key reason for decreasing faecal bacteria counts in catchment cells. Chick [10] exponential model is used extensively for this purpose, wherein the model parameters are adjusted according to the bacteria types and environmental conditions; for example, radiation [11, 12], moisture [13], soil PH value [14] and vegetation, etc. When washed or detached faecal bacteria in a HRU enter into a brook, stream, pipe, river and estuary, there will be a complex change of FIO concentrations in the surface water column, and potentially via the adsorbed levels on the SSCs and on the channel bed for different flow discharges. The channel bed can be considered as a transient reservoir [15]. Nagels, Davies-Colley [16]. From these studies it was found that about 30% of the bacteria were re-suspended from the bed sediments. Similar results [17] showed that under the effects of an artificial flood, the *E. coli* concentration in the water column increased by two orders of magnitude, from a background level of  $10^2$  cfu per 100 ml to over  $10^4$  cfu per 100 ml. The number of total in-channel storage levels

was approximately  $10^8$  cfu/m<sup>2</sup> of the streambed. Wheeler Alm, Burke [18] undertook field investigations which showed that the abundance of faecal indicator bacteria, in the form of enterococci and Escherichia coli, was 3–38 times higher in the top 20 cm of wetland cores than in the water column, with measurements taken at six freshwater bathing beaches. Passerat, Ouattara [19] produced results that showed that 77% of the E. coli levels in CSOs were due to high levels attached to the suspended particulate matter (SPM). The re-suspension of sewer sediments contributed to 75% of the SPM levels, with the corresponding levels being 10-70% for E. coli and 40-80% for intestinal enterococci. Even, Mouchel [20] undertook numerical tests and found that water quality models should take into account CSO inputs in order to be reliable. The linear isotherm is usually used to calculate partitioning and attachment of faecal bacteria onto the SPM; Chapra [21] assumed an instantaneous equilibrium of the absorbing and desorbing processes. However, there is a large variation for the partitioning coefficient in the literature, primarily because of the different clay content levels governing the particle size [22] and the model domain spatial scale.

A comparison between SWAT and HSPF has demonstrated that the calculated result from SWAT have a higher level of accuracy than HSPF, because of consideration of the absorbed bacteria [23]. Meanwhile, the minimal temporal scale of the SWAT and HSPF models is one day and an hour, respectively, which is relatively large because field investigation show that the faecal concentration may have a large variation within one hour. Many faecal bacteria budgets in the middle [24] and high [25] urbanised catchment regions show that the FIO flux from sewage networks may occupy large parts of the total flux, especially during intense rainfall events. Moreover, sewage pipe flows may have higher variations than channel flows because of their smaller storage volume and strong human intervention, thus the simple channel flow routing calculation using the output function in HSPF and variable storage coefficient method in SWAT [26] seem to be too crude to be used to calculate the highly unsteady flow and FIO transport processes, in spite of their high calculated efficiency and solution stability. In contrast, some high-precision numerical methods are used to solve the high unsteady flow and related mass transport in mountain streams, pipelines and rivers with steep slopes [27-30]. However, the smaller time step needed for explicit methods may limit the use for complex river and pipe networks. The Priessmann method and slot technique are adopted for flows in open channel and closed conduits under different flow conditions [31-33]. In estuarine and coastal regions, extensive interaction occurs between the FIO transport processes and the river inflows, tides, wind waves, sediment transport etc. Therefore, 2D and 3D models are usually used to calculate faecal processes in such water bodies [34-38]. Over the past 20 years, many numerical models have been developed to calculate the FIO transport processes separately in upstream catchments, sewage pipes, rivers, estuarine and coastal waters. However, it is desirable to integrate different types of models to achieve a better solution, from the source regions of a catchment and the sewage networks, to rivers, estuaries and coasts. Although some commercial software packages, such as MIKE, Infoworks, SWMM and ISIS, have been developed and coupled numerical models have been developed using various linking techniques [39, 40], truly integrated models for predicting the FIO transport processes and the fate of FIOs from upstream catchments to the sea are rare.

In the current study an integrated model has been developed based on the concept of C2C (cloud to coast) to predict the transport and fate of faecal indicator organisms throughout the river basin. A distributed catchment, river and pipe network model has been developed to simulate the hydrological and sediment and FIO transport processes. This model is then linked to a refined EFDC 2D model. The integrated model is used to calculate the FIO transport processes for the Ribble catchment and river and the downstream estuary and coastal waters. The model has been verified using field observed data. Finally, model predictions of faecal bacteria distributions on the catchment surfaces and in soil layers, river and channel flows, SSC and estuarine and coastal waters have been undertaken for a range of different boundary conditions. The numerical model results are important to gain a reasonably accurate estimate of the parameters governing the bathing water concentrations, particularly for better management of the bathing waters to meet the compliance requirements in the future.

## 3.2 MODEL DETAILS

### 3.1 Model grid system

The model domain is represented by the following three main components.

(1) In a sub-catchment of area ranging from 0.3 to 20 km<sup>2</sup>, a series of rectangular and some triangular grid cells with a spatial scale of 250×250 m are included. A sub-channel is used to link the sub-catchments. Between the sub-channels, a series of junctions are used to link the sub-channels;

(2) In the middle and lower region (MLR), a hybrid river network model is used, and the results from the distributed model are used as point and non-point sources to the river networks model. If pipelines are included, they may be linked to urban cells, or rural sub-catchments, or sub-channels, and then to the main river in the MLR. The unsteady hydrodynamic and suspended particulate matter transport processes in the networks and pipelines are solved;

(3) In the river, estuary and coastal regions, a two-dimensional model based on the EFDC-2D model is used, in which an orthogonal curvilinear grid is used for fitting irregular boundaries. In addition, other natural and man-made parameters, such as: reservoirs, lakes, CSOs, Tanks and WwTWs, can be included. All of the fundamental units are organised and linked with each other according to some topological rules, which give a reasonable connectivity among sub-catchments and grid cells, sewer pipelines, junctions etc. In total, there are 2.07×10<sup>5</sup> cells, 6,607 sub-catchments, 5,112 sub-channels, 5,288 junctions and 4.06×10<sup>4</sup> cross-sections.

### 3.2 Catchment hydrological model

#### 2.2.1 Hydrological model in catchment cells

The distributed hydrological model used in the current study is based on the Xinanjiang (XAJ) conceptual model [41], which is the most popular rainfall-runoff model in China, and widely used worldwide [42], while the Shabei (SB) model is used for the drought region, where the infiltrate rate and soil moisture level is low. The water conservation equation is expressed as:

$$P - E - R = W_1 - W_0 \quad (1)$$

where  $P$  = precipitation (mm);  $E$  = evapotranspiration (mm);  $R$  = total runoff (mm), which is equal to the sum of surface flow ( $R_s$ ), the shallow soil flow ( $R_i$ ) and the groundwater flow ( $R_g$ ); and  $W_1$  and  $W_0$  = soil moisture at the beginning and end of a time step. The Muskingum method is used to route the surface flow component ( $R_s$ ) in a sub-catchment, following the path generated by a D8 algorithm [43], while the soil and groundwater flow is calculated using the linear reservoir method.

The sediment transport equation is given by:

$$\frac{\partial (hS_k)}{\partial t} + \frac{\partial (qS_k)}{\partial x} = S_e(i, k, t) \quad (2)$$

where  $t$  = time,  $x$  = distance along the flow direction,  $h$  = water depth,  $q$  = unit width discharge and  $S_k$  = sediment concentration of  $k^{\text{th}}$  fraction. The upper boundary condition is  $S_k(0, k, t) = 0$ , and the initial condition is  $S_k(x, k, 0) = 0$ , or an equilibrium concentration is used for a hot start.

Following Alam and Dutta [44]'s method, soil erosion estimates consist of the calculation of soil detachment due to rainfall and overland flow. The total potential detachment value at the  $i^{\text{th}}$  cell and  $t^{\text{th}}$  time step  $S_e(i, k, t)$  is expressed as follows:

$$S_e(i, k, t) = DR(i, k, t) + DF(i, k, t) \quad (3)$$

in which the soil detachment due to rainfall is given as:

$$DR(i, k, t) = (1 - C_g) P_b(i, k) \frac{k}{\rho_s} (KE)^{-zh} \quad (4)$$

where  $k$  = soil detachability index ( $m^2 J^{-1}$ ),  $\rho_s$  = density of sediment ( $kg/m^3$ ),  $C_g$  = fraction of ground cover (paved area),  $P_b(i, k)$  = ratio of  $k^{th}$  size fraction of bed sediment,  $KE$  = total kinetic energy due to rainfall and leaf drip impact ( $J/m^2/mm$ ),  $z$  = correction factor for water depth  $h(m)$ , and the soil detachment due to overland flow is:

$$DF(i, k, t) = \alpha_{LU} P_b(i, k) \beta_k \omega_{s,k} (TC_k - C_{s,k}) \quad (5)$$

where  $C_{s,k}$  = sediment concentration of  $k^{th}$  size fraction ( $kg/m^3$ );  $\alpha_{LU}$  = erosion modification coefficient by land use type in a cell,  $\beta_k$  = erosion coefficient of water flow for  $k^{th}$  particle size fraction;  $TC_k$  = sediment carrying capacity for  $k^{th}$  particle size fraction ( $kg/m^3$ ),  $\omega_{s,k}$  = sinking velocity for  $k^{th}$  group sediment ( $m/s$ ).

The sediment yield and transport capacity are given by:

$$Y_{Sed} = \begin{cases} S_{inflow}(i, k, t) + S_e(i, k, t), & TC_k > S_{inflow}(i, k, t) + S_e(i, k, t) \\ TC_k, & TC_k < S_{inflow}(i, k, t) + S_e(i, k, t) \end{cases} \quad (6)$$

$$TC_k = \frac{1}{q} \frac{6.42}{\left(\frac{\gamma_s - \gamma}{\gamma}\right)^{0.5}} (\Theta - \Theta_c) \cdot \gamma_s \cdot D_k \cdot V \cdot S_0^{0.6} \quad (7)$$

where  $S_{inflow}(i, k, t)$  = sediment concentration from upper grid cells,  $\Theta$  = Shields number,  $\Theta_c$  = critical shields number,  $\gamma_s$  = specific gravity of sediment particles,  $\gamma$  = specific gravity of water,  $D_k$  = sediment diameter ( $m$ ),  $V$  = flow velocity in the grid cell,  $S_0$  = cell slope,  $S$  = flow slope at cell, in the model it is equal to  $S_0$ .

### 2.2.2 Sediment processes in streams and river channels

The total-load sediment transport is considered in the current study. The sediment transport and bed change equations in the streams are given as (Wu, 2007):

$$\frac{\partial (AS_k)}{\partial t} + \frac{\partial Q_k}{\partial x} + \frac{1}{L_s} (Q_k - Q_{*k}) = 0 \quad (8)$$

$$(1 - p') \frac{\partial (A_{bk})}{\partial t} = \frac{1}{L_s} (Q_k - Q_{*k}) = 0 \quad (9)$$

Equation (8) can be rewritten as:

$$\frac{\partial Q_k^{n+1}}{\partial x} + p Q_k^{n+1} = q \quad (10)$$

where

$$p = \left( \frac{1}{U_k^{n+1} \Delta t} + \frac{1}{L_s} \right), \quad q = q_k + \frac{Q_k^n}{U_k^n \Delta t} + \frac{1}{L_s} Q_k$$

$$Q_k^{n+1} = e^{\bar{p}x} \left( \frac{\bar{q}}{\bar{p}} e^{\bar{p}x} + C \right) \quad (11)$$

where  $L_s$  = nonequilibrium adaptation length of sediment transport,  $Q_k$  =  $k^{\text{th}}$  size fraction of sediment transport rate in river channel (kg/s),  $Q_{t,k}$  = sediment transport capacity (with bed load) in river channel,  $C$  = integration constant.

### 2.2.3 Distributed bathing water quality model

The key processes involved in modelling bathing water quality are to [45]: (a) determine the production and distribution of waste water and the associated concentration of micro-organisms, (b) simulate the transport of micro-organisms from the land surface to the receiving streams along the hill slope, based on a governing equation similar to Eq.(2) and (c) route the micro-organisms through the stream networks.

#### (1) Production of faecal bacteria

The production and distribution of waste water and the associated concentrations of micro-organisms are calculated according to the method from the BIT tools (USEPA, 2001). The main processes and related input data are: (i) livestock density per grid cell, (ii) livestock confinement and grazing schedule, (iii) access of livestock to streams, (iv) manure application rate and timing, (v) locations of feedlots, and (vi) manure production estimates and waste characteristics. Herein we have assumed that:

$$M_{Surf} = \sum_{i=1}^N (\alpha_{LMN} M_{MN}^i + \alpha_{LGZ} M_{GZ}^i) \quad (12)$$

$$M_{Soil} = \sum_{i=1}^N [(1 - \alpha_{LMN}) M_{MN}^i + (1 - \alpha_{LGZ}) M_{GZ}^i] \quad (13)$$

where  $M_{Surf}$ ,  $M_{Soil}$  = counts of bacteria on the land surface and shallow soil at the beginning of time interval  $t$  (cfu),  $N$  = total number of domestic and wild animals on the land, grazing activity is considered only for wild animals and sheep, while both manure and grazing are included for other domestic animals for the arable and pasture land and habitat regions, respectively.  $M_{MN}^i$  and  $M_{GZ}^i$  = amount of bacteria in the shallow soil layer and land surface, respectively,  $\alpha_{LMN}$ ,  $\alpha_{LGZ}$  = coefficients for manure and grazing, with their values being 0.1 and 0.8, respectively.

#### (2) Wash-off faecal bacteria from surface manure

This is given by the following equation:

$$M_R = M_{Surf} \left[ 1 - (1 + k_3 \beta R_s)^\beta \right] \quad (14)$$

where  $k_3$  and  $\beta$  = dimensionless fitting parameters,  $M_{Surf}$  = amount of bacteria in surface (cfu), and  $R_s$  = runoff depth (cm). The amount of bacteria released from the soil is calculated using:

$$\Delta M_{Soil} = M_{Soil} k_1 \Delta R_i \quad (15)$$

where  $M_{Soil}$  = amount of bacteria in the soil at the beginning of time interval  $\Delta t$  (cfu).

#### (3) Wash-off of the absorbed faecal micro-organisms due to soil loss

The faecal bacteria absorbed in shallow soil will be transported with the detached soil, and the loads are calculated using:

$$\Delta M_{Eros} = Se(i, t) \cdot B \cdot \Delta t \cdot C_p \quad (16)$$

where  $C_p$  = faecal bacteria concentration in the soil or sediment (cfu/g),  $B$  = cell width (250m).

(4) Solar radiation-associated die-off [12] can be represented as:

$$K = K_n + I_{(t)} K_s \quad (17)$$

where  $K_n$  = natural die-off rate [ $d^{-1}$ ],  $I_{(t)}$  = solar radiation [ $MJm^{-2}d^{-1}$ ]; and  $K_s$  = solar radiation coefficient [ $m^2 MJ^{-1}$ ].

(5) In the soil, the direct radiation is weakened to zero. Nevertheless, the soil moisture level, driven by the rainfall and evaporation will impact the die-off rate. Therefore, the following die-off rate related to soil moisture is used:

$$K = K_n \left[ \alpha_m + 2(1 - \alpha_m) \frac{Um - Wu}{Um} \right] \quad (18)$$

Where  $Um$  = upper soil water storage maximum thickness, and  $Wu$  = upper soil water storage thickness at  $n+1$  time step, which is calculated by the distributed hydrological model. Here we assume that the upper soil water storage is half saturated (i.e.  $Wu = 0.5Um$ ), then  $K = Kn$ , in the model, and  $\alpha_m = 0.4\sim 0.6$ . When the radiation is strong enough in dry weather the soil soon becomes dry and the radiation will impact indirectly on the die-off rate.

(6) Die-off rate considering the temperature adjustment factor is as follows:

$$C_T = C_0 e^{Kt\theta(T-20)} \quad (19)$$

where  $C_T$  = concentration at time  $t$ ;  $C_0$  = initial concentration;  $t$  = time [d];  $\theta$  = temperature adjustment factor; and  $T$  = temperature [ $^{\circ}C$ ].

### 3.3 River networks and pipes model

The 1-D Saint-Venant equations and the Priessmann scheme are used for predicting the flows in the open-channels and closed conduits, meanwhile the slot technique is adopted for dealing with the drying and wetting problem. The 1-D equation used to describe the total bacteria transport processes is written as:

$$\frac{\partial}{\partial t}(AC) + \frac{\partial}{\partial x}(Q_R C) - \frac{\partial}{\partial x} \left[ AK_x \frac{\partial Q_R C}{\partial x} \right] = C_o^d + C_o^p + C_b^p - kCA \quad (20)$$

where  $C_b^p$  = a source term defining the attached bacteria from, or to, the bed sediments. Assuming that the sediments deposited from the water column to the bed are well mixed, then the exchange rate of the bed bacteria concentration,  $P_b$ , is expressed in the following form:

$$\frac{dP_b}{dt} = \frac{q_{dep}}{M_b} (P - P_b) + (k_{g,b} - k_b) P_b \quad (21)$$

where  $M_b$  = mass of bed sediments  $kg/m$  (or  $kg/m^2$  for the two dimensional model), and  $k_{g,b}, k_b$  = faecal bacteria growth and decay rates, respectively, in the bed sediments. The mass of bed sediments per unit area/length,  $M_b$ , also varies temporarily as given by the following equation:

$$\frac{dM_b}{dt} = q_{dep} - q_{ero} \quad (22)$$

### 3.4 Estuary model and integration of the models

The governing equations and related algorithms for ambient environmental flows and related solute transport are given in the EFDC help documents [46]. The main aspects of the code modification are listed as follows:

$$\frac{\partial C}{\partial t} = (K_B + K_I + K_{Sal}) \theta_W^{T-20} \left[ C + \frac{W_c}{V} \right] \quad (23)$$

where  $C$  = concentration of a water quality state variable,  $K_c^{New} = (K_B + K_I + K_{Sal})$  is the effective total decay rate (per day),  $K_B$  = base mortality rate in fresh water at 20°C under dark conditions without any settling loss;  $K_{Sal}$  = mortality rate due to salinity,  $\theta_W$  = an empirical coefficient for water temperature effects, and  $T$  = water temperature. The decay rate due for solar irradiation is given as:

$$K_I = \alpha_I I_0(t) \frac{1 - e^{-K_e H}}{K_e H} \frac{D}{D_w} \quad (24)$$

where  $\alpha_I$  = coefficient of irradiation, which is dependent on the type of bacteria,  $I_0(t)$  = intensity of solar irradiation;  $K_e$  = extinction coefficient of light; and  $D$  and  $D_w$  = average distribution coefficients in sediment laden and distilled water, respectively. The ratio  $D/D_w$  represents light intensity attenuation due to sediment suspension. At present, the distributed hydrological model, 1-D river network model and the EFDC-2D model are linked by data input and output as boundary conditions or point sources inputs. Further development is currently being undertaken to link dynamically the hydrodynamic and faecal bacteria transport models with the hydrological model.

## 3. MODEL APPLICATION

### 3.1 Model domain

The study domain includes 11 main rivers, namely the Clwy, Dee, Mersey, Ribble, Darwen, Douglas, Wyre, Lune, Kent, Leven and Duddon, that flow into the Liverpool Sea. Also included are the Morecambe and Duddon estuaries, where intense mixing takes place because of the irregular boundaries and bathymetry, the large tidal range, the strong currents and wind waves. In considering the strong coupling between the hydrological, hydrodynamic, sediment and faecal bacteria transport processes, all of the 11 catchments and the associated estuarine and coastal waters are included in the integrated model (Fig.1). The catchment and estuary areas are 12924 km<sup>2</sup> and 9664 km<sup>2</sup>, respectively. Moreover, there are 29 national bathing beaches and some shellfish habits located in this region, with both required to meet the standards set out in the European Water Framework Directives.

A large data set has been acquired from a variety of sources. This includes the Edina OS data, the BADC meteorological data, land and estuary bed soil and sediment data, land use data, population of communities, livestock, pipelines and waste water treatment device data and the hydrological, hydrodynamic, sediment, water quality data in the upstream catchments, river networks and bathing regions. The data are processed and interpolated onto a 25.0 m set of grid points, then assembled to obtain a cell averaged value for each 250 m by 250 m grid. According to the soil classification method of SYMBOL90 of the Harmonized World Soil Database (HWSD), there are 20 types of soil over the catchments, with different properties in soil diameter, drainage, soil thickness, etc. The main soil types in the model region are *Cambic Arenosols*, *Umbric Gleysols*, *Haplic Podzols*, *Stagnic Luvisol* and *Terric Histosols*. Three land cover maps of 25 m resolution obtained in 1990, 2000 and 2007 are collected from CEH. In considering the simplicity and comparability of the data for different years, different land use classifications of these data are unified from about 24 groups to 10 groups, with the same class being defined using the self-correlation analysis method. The 10 land use groups include: Broad leaf woodland, Coniferous woodland, Improved grassland, Semi-natural grassland, Mountain heath bog, Arable, Saltwater, Freshwater, Coastal, Built-up areas and gardens. In considering the accuracy and spatial

heterogeneity of the model parameters, the basic parameters are decided according to the soil parameters and then modified according to the land use and plant type and distributions. The D8 algorithm of O'Callaghan and Mark (1984) is used to generate the flow direction and topological structures for different cells in a sub-catchment originated from cross-section.

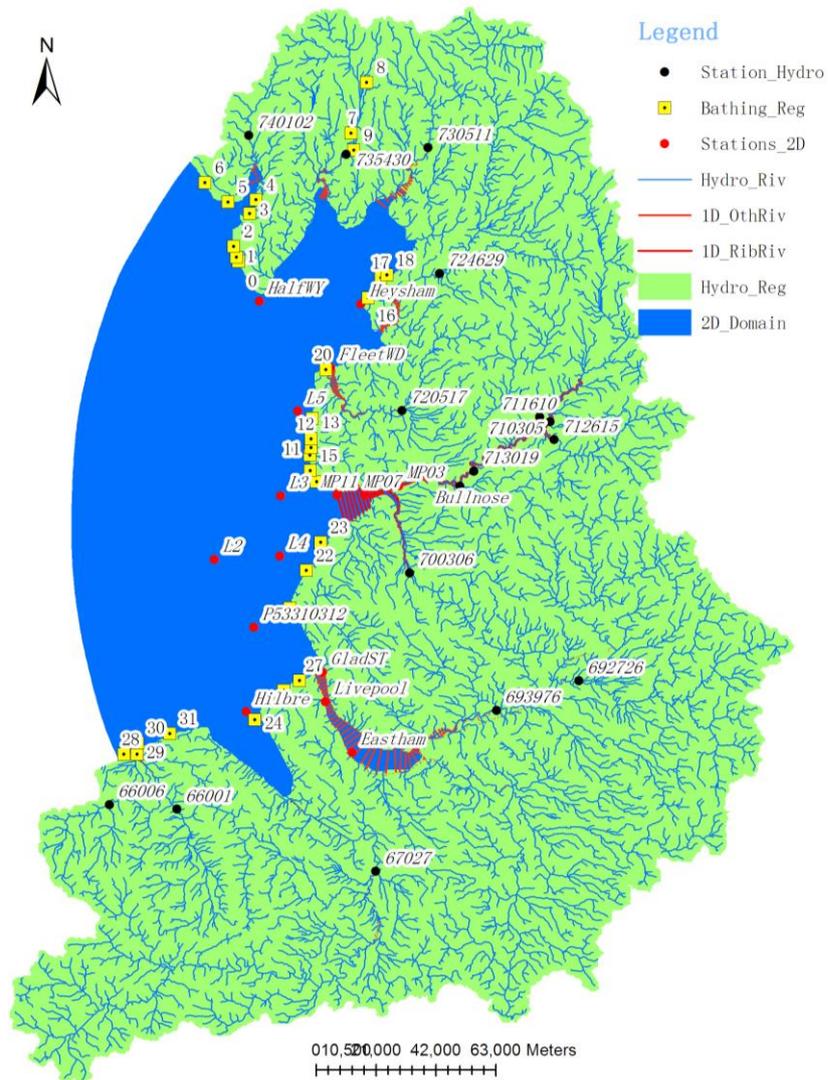


Fig1a. Sketch of the physical domains and hydrological and tidal control stations

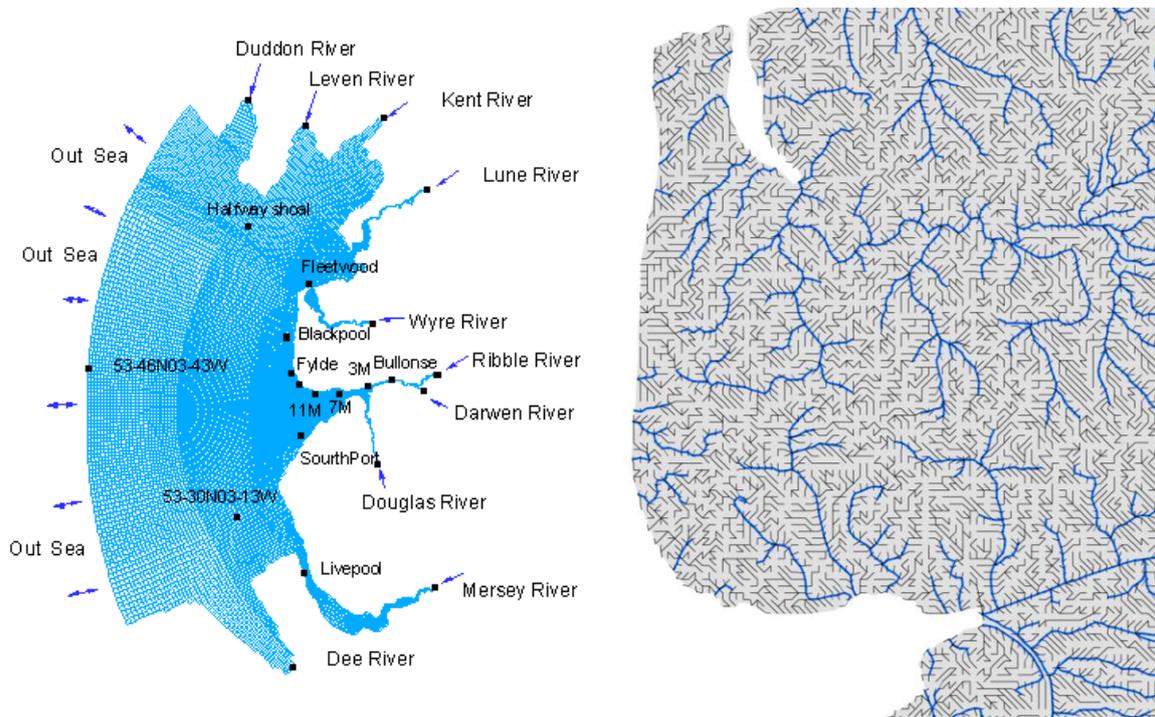


Fig1b. Estuarine model grid and local zoom map of grid-based hydrological model

### 3.2 Temporal and spatial variation in land use, livestock, population, pipes and water treatment distributions 1990-2014

The processed land use and livestock density maps for the years of 1990, 2000, 2010 were based on a 250m×250m grid model, originally supplied by the UK Government, and are shown in Figs. 2 and 3. It can be seen from these figures that during the period from 1990 to 2010, the number of observations of land use variations in the 11 catchments can be made. (1) There is a shift in land use. More land was used for arable purposes in the northern regions than in the southern regions of the study domain. An increase in arable land use appeared in the upper Douglas catchment, and the middle and lower Mersey and Dee catchments, close to cities of Preston and Manchester. (2) Improved grass land had expanded and intensified in the rural areas, whilst some traditional zones between the forest and grass regions were substituted by improved grassland for cattle and sheep pasture. In the meantime, the expansion and intensification of improved grassland may have induced the semi-grassland area to retreat along towards the mountain direction and even to disappear. (3) The improved grass land had a close relationship with cattle and sheep numbers around large cities. From the cattle and sheep density distribution maps it can be seen that compared to sheep the cattle density has rapidly reduced. (4) To reduce and control raw FIO fluxes into the rivers, some cleaning actions in these regions were carried out over the past 10 years. As a result, an obvious increase in sewage pipes, water tanks and other additional devices in the urban regions since 1997 can be observed. For example, the storm water storage tunnel, with 3.5km in length and approximately 40,500 m<sup>3</sup> in storage, has been built in the Preston and Penwortham areas. It will bring significant environmental improvements to the Fylde coast bathing waters and the designated shellfish beds located within the Ribble Estuary. The arrangement of the sewage system will reduce the frequency of the overland flows and prevent waste water entering into the rivers directly in the urban regions.

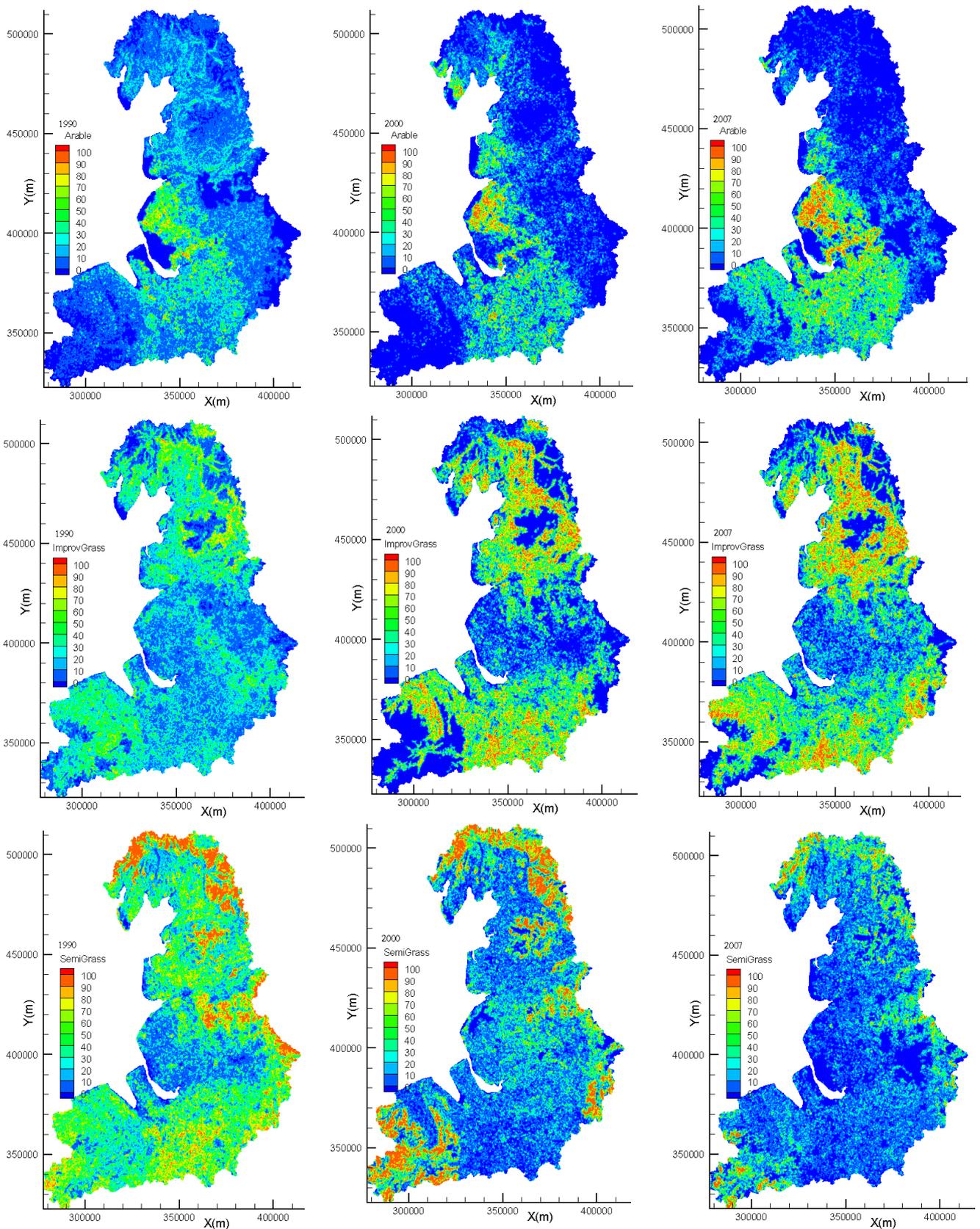


Fig.2 Land use related and its variations in 1990, 2000 and 2007

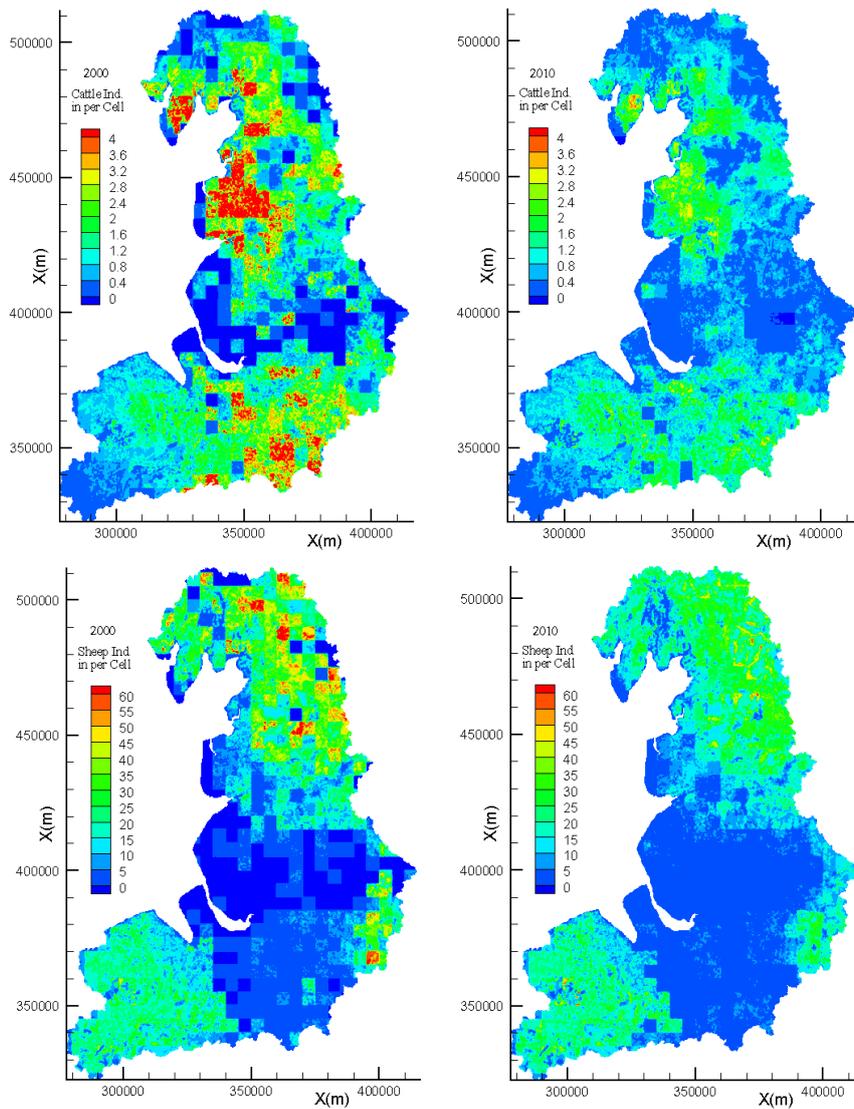


Fig.3 Population and livestock and its variation in 2000 and 2010

### 3.3 Key parameters related to hydrological, hydrodynamic and FIO transport processes

In the present model, there are some key parameters that are sensitive to the hydrological processes, sediment yield and transportation, faecal bacteria sources, and the fate and delivery. These parameters are listed in table 1. In the catchment and coastal models a fractional method is used to simulate the transport of non-uniform sediment, in which the sediment was divided into 7 grain size groups (50, 100, 200, 300, 500, 800, 1000  $\mu\text{m}$ ), with the first 5 groups being suspended sediment load and the last 2 groups being bed sediment load. The bed load component in the coastal and estuarine environments are interpolated based on the data collected from more than 2000 sampling points, while in the catchment and river channel bed layers, the soil data is resampled to decide the sediment particle component, by omitting the influence of historical fluvial processes on the sediment size distribution in the channel bed. In addition, different partitioning coefficient for the 7 groups of sediments are estimated based on the work undertaken by [47] and with different absorbing capacities for the FIOs being considered.

Tab. 1 Main parameter and related illustration

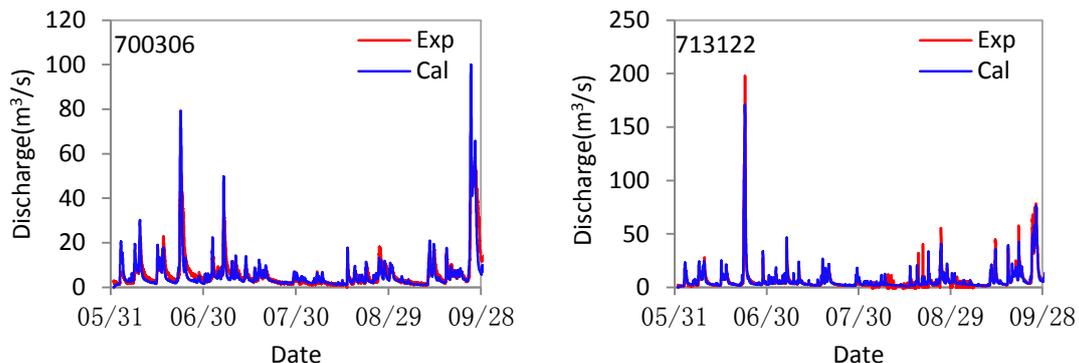
Parameter	Label	value	Note
Time step in catchment, 1D river and 2D coastal model	$\Delta t$	300, 30, 2	Time steps for different model (s)
Infiltration rate	IHoton	0.02-0.13	Soil type and land use (m/s)
Impervious area ratio	Alfalm	0.0-1.0	Land use

Top Soil layer thickness	Um	5-20	HWSD and land use (cm)
Mid soil layer	Lm	20-40	HWSD and land use (cm)
Bottom soil layer	Dm	30-50	HWSD and land use (cm)
Soil particle diameter	Dsed(i)	0.05-1.0	HWSD (mm)
Surface roughness	n	0.03-0.06	HWSD and land use (cm)
Transport time at surface	Ls	0.1-1.0	DEM, HWSD, land use (Hour)
Time in mid soil layer	Li	0.5-10.0	DEM, HWSD, land use (Hour)
Time in bottom soil layer	Lg	3-24.0	DEM, HWSD, land use (Hour)
Time in sub-channel	Lr	0.08-1.0	DEM, HWSD, land use (Hour)
River Bed thickness	ThkBed	0.1, 0.5	Estimation value
Bed sediment composition	Dsed Bed	50, 100, 200, 300,500,1000	Same with closest grid cell(um)
Manure ratio in surface	$\alpha_{LMN}$	0.1-0.3	Empirical value varied with manure mode
Grazing feces ratio in surface	$\alpha_{LGZ}$	0.8-0.9	Empirical value varied with land use
Washing coefficient for soil water	$k_1$	0.1-0.5	Empirical value with different soil
dimensionless fitting parameters	$k_3$	0.2	Washing coefficient in the surface
dimensionless fitting parameters	$\beta$	0.5~2.0	Washing coefficient in the surface
Natural die-off rate	$K_n$	0.5~10	Variation for different habitat
radiation coefficient	$K_s$	1.5	Constant
Moisture coefficient	$\alpha_m$	0.4-0.8	Variation with land use above
Temperature coefficient	$\theta$	1.047	Constant
Sediment partition coefficient	$K_d$	10~70	Variation with diameter, clay ratio and temperature (ml/g)

### 3.4 Model calibration and verification

#### 3.4.1 Discharge verification at the control gauging stations

The model predicted discharges by grid based distributed model (GBDM) at 10 main gauging stations are compared with the measured data for 15 min time intervals. From these comparisons it can be seen that the model predicted flood peaks and phases agreed well with the measured data. The main errors come from: (1) the tidal influence when the gauging station is located in the riverine region and the error being reduced by integration of the 1D unsteady model in the middle and lower reaches of the river; (2) the effects of reservoirs and wetlands in adjusting the hydrological parameters at the upper reaches of the control station and the flood adjustment can be simulated by coupling the wetland and reservoir regulation models; (3) The higher flood peak at Station No. 724629 of the Lune River and the corresponding error is caused by the large bed slope, especially in the source region; and (4) the man-made navigation and diversion of the water flow.



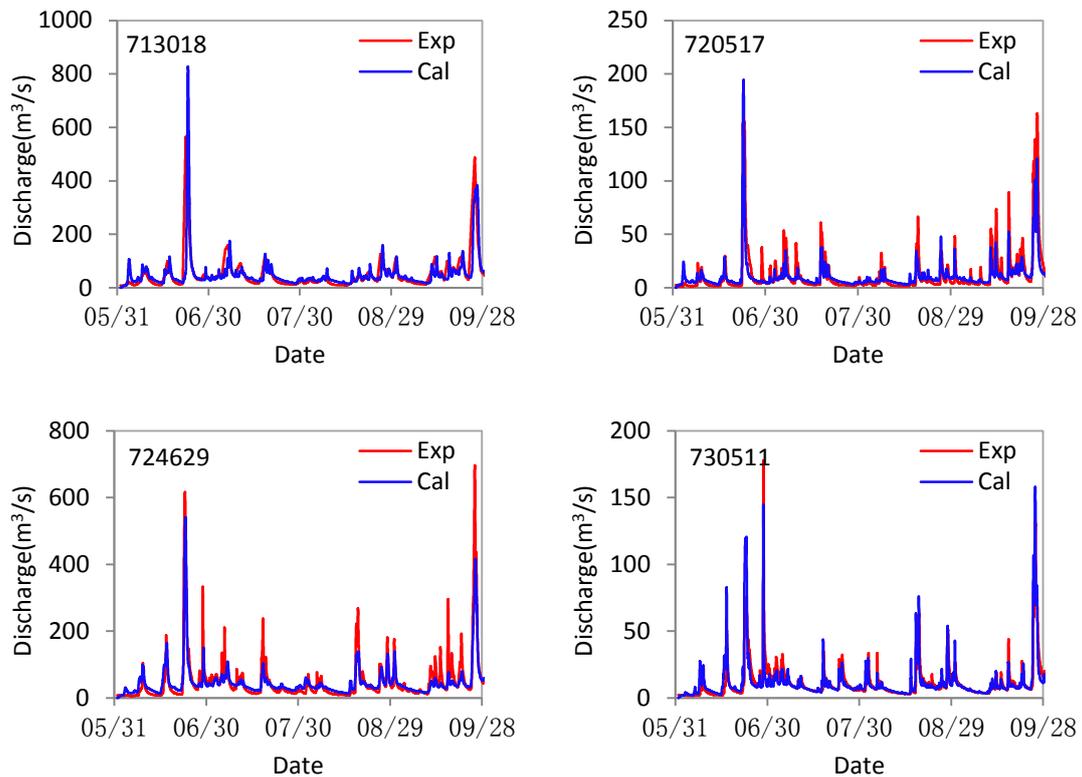


Fig. 4 Hydrological verification at controlled stations during 1<sup>st</sup> Jun and 30<sup>th</sup> Sep in 2012

### 3.4.2 Verification of sediment concentration at River Ribble

Figure 5 shows comparisons between the model predicted and field measured suspended sediment concentrations at 6 sampling points along the Ribble River, including the stations at the upper and middle reaches of the Ribble (No.710305), Calder (No.712615), Darwen (No. 713122), Douglas (No. 700306) and the lower reach of the Ribble at Milepost (MP) 3 and MP 11 (see Fig1.a, b). It can be seen that both the measured and model predicted SSCs are highly variable in the upper reaches of the Ribble, Calder and Darwen rivers, which may be driven by intensive rainfall, spatial heterogeneity in the soil particle size and properties, and the bed slope and land use. The deviation may be caused by the different sediment yield methods used for different land use types. The sediment production may be higher in arable land than in grass land and forest. For example, there is a higher ratio of arable land in the Douglas sub-catchments than in the Ribble sub-catchments. However, the SSC in the Douglas River has reached the same level as in other rivers, but its concentration profile is more stable. The model predicted SSC values generally agreed well with the measured data at the lower part of the estuary (i.e. at 11MP), while the model predictions overestimated the measured values at 3MP, which is mainly driven by the discharge processes upstream. The over prediction at 3MP may be caused by the relative coarse sediment input from upper reaches of the rivers Ribble and Darwen, with more coarse particles in the channel bed from 7MP to Bullnose, than in the estuaries. The sediment particles from the upper boundary are predicted to deposit on the middle reach of the Ribble main channel, i.e. from Bullnose to 3MP, because of the small channel longitudinal bed slope, the wide wetlands and the low flow velocity arising from the action of the tide. While in the Ribble estuary, the high sediment concentration is mainly caused by the re-suspension of the fine sediment particles and the transport caused by the river flow and the tide. The model predicts the concentration variations in the estuary region reasonably accurately. However, the model cannot predict the spatial distribution of the sediment concentrations in the riverine reach, because of the shortage in quantitative sampling data at these regions. The model needs further refinement in the future, using more comprehensive measured topographic and sediment data in the region. The sensitivity analysis results show that the fine sediment concentration in the estuary is mainly controlled by the sediment supply from the coast,

with the sediment flux from the rivers being of secondary importance, especially for middle and low inflows.

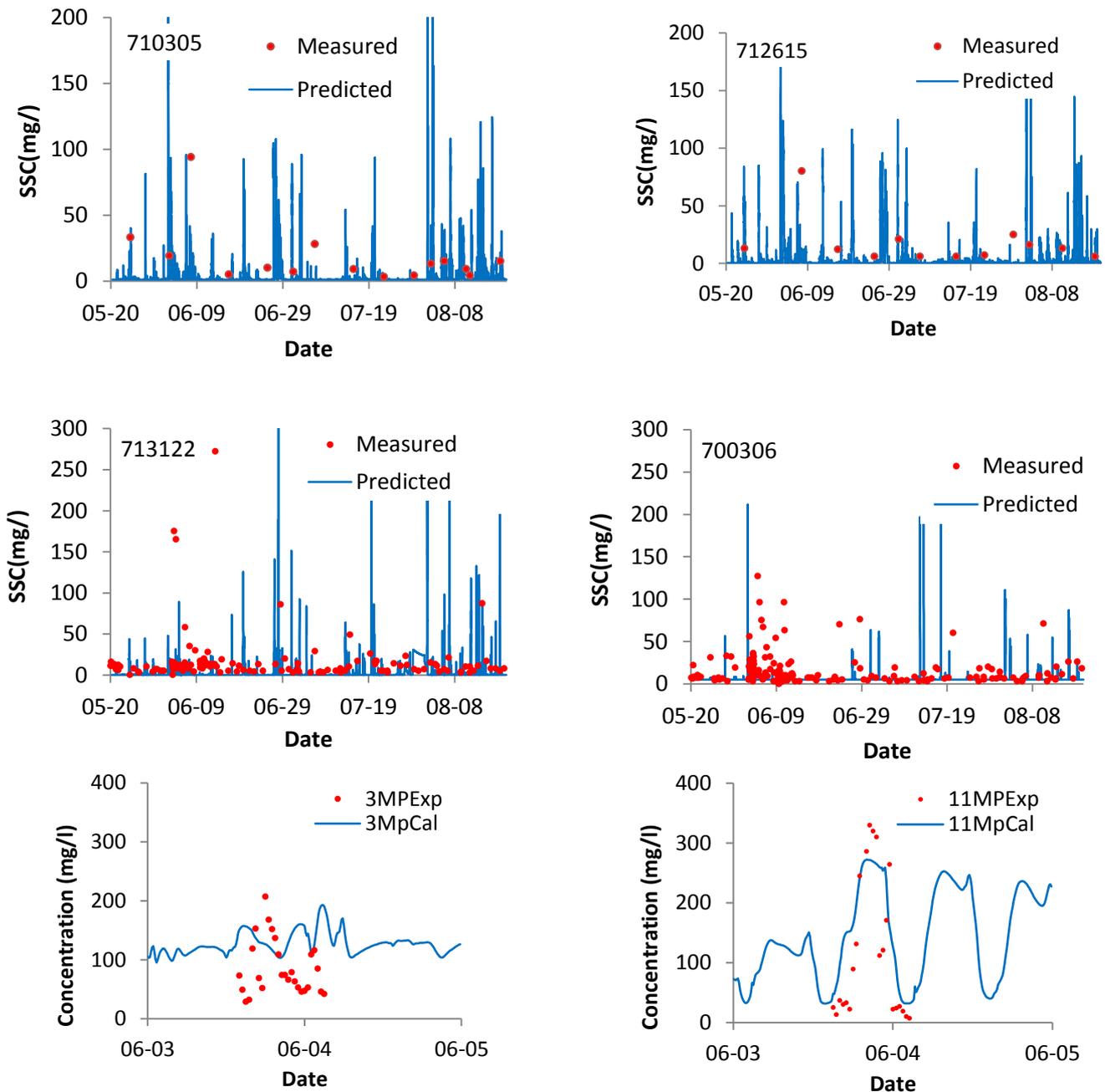
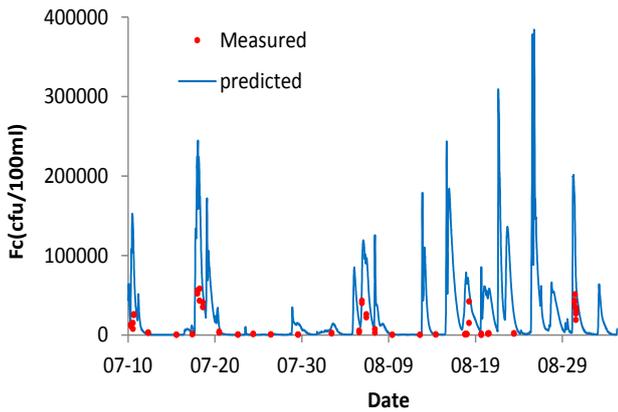


Fig. 5 Suspended sediment verification at 6 measuring sites in 1999

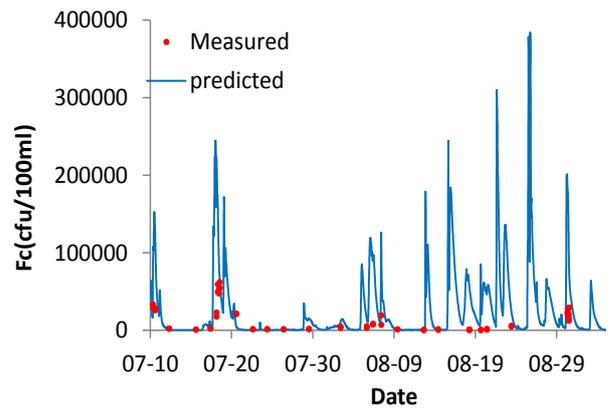
### 3.4.3 Faecal bacteria verification for the River Ribble

At present, the model predicted FIO travel speed fits generally well with the limited measured data. However, the predicted FIO concentrations are higher than the measured values. The over-prediction is thought to be mainly caused by the omission of numerous purification devices, such as water tanks, WWTWs and CSOs in the catchment model. In addition, some key parameters, such as manure volume and faecal bacteria decay rate at the land surface and in the soil layer, need further refinement based on more extensive measured data. Based on some preliminary numerical experiments, the errors in the estuarine and coastal model are considered to be caused by the following reasons: (I) the quality of the topography data is relatively low and the interpolations made using the 1D cross-sections may not be very accurate due to a shortage of measured data, (II) the distances between the point source outlets and the receiving main channels may be inaccurate for some deep and narrow river channels in the wetland and saltmarsh regions, (III) the rapid variation in the FC concentrations at the small temporal scales,

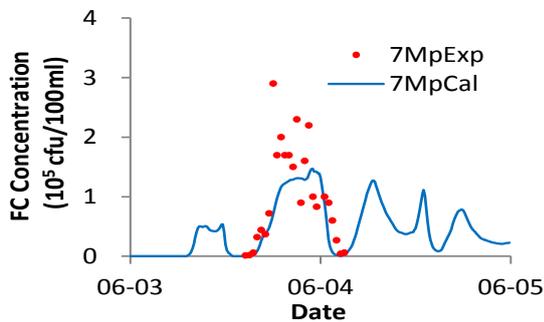
caused by episodic and intense point source outputs arising from small CSOs, WwTWs, storage tanks under storm conditions, are not fully reflected in the model.



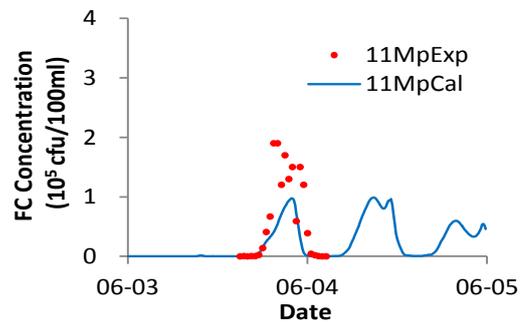
(a) Sawley Bridge(No. 710305) of Ribble in 2012



(b) Samlesbury(No. 713019) of Ribble in 2012



(c) 7MP of Ribble estuary in 1999



(d) 11 MP of Ribble estuary in 1999

Fig.6 Faecal bacteria verification in the catchment, river and estuarine system

Because the integrated model is capable of simulating the sediment and faecal bacteria transport and decay processes from the upstream catchments, to the streams, river channels and estuaries, the spatial and temporal variations in faecal bacteria concentration distributions can be predicted in the water column, the suspended sediments (i.e. through adsorption), and the channel bed of the catchment cells, streams, rivers and the estuary, see Fig.7. For the given wild and domestic animal densities and manure methods, the accumulated FIO counts are mainly controlled by the rainfall-runoff processes and the daily radiation variation. The catchment FIO counts may reach very large values, up to  $1.2 \times 10^{17}$ , under some unfavorable environmental conditions, while the value may decrease in a short period to  $1.0 \times 10^{16}$  under intense radiation and direct rainfall wash-off. The short period variation is mainly driven by the radiation process, while the long term variation is mainly impacted by the rainfall. The FIO counts attached to the sediments could be as much as about 10% of the accumulated FIO counts in the river catchment. This is equivalent to 80% of FIO die off in the catchment. In addition, the bed sediments provide a stable environment for FIOs to survive, because of the moisture and low radiation intensity environment. Therefore, the magnitude of the variation in the FIOs is smaller on the river bed than in the water column and the upstream catchment. The average FIO counts in the channel bed may be twice as high as the total FIO counts in the water column and SSC. The relationship between them is decided by the FIO inflow, the hydrodynamics, the sediment transport rate, and the sediment partition adsorption coefficient and the substrate conditions, etc. The present model can not only simulate the FIO dynamic transport processes in the water column, but it can also simulate the FIO levels in the non-uniform sediment particles from the upstream catchments to the estuaries.

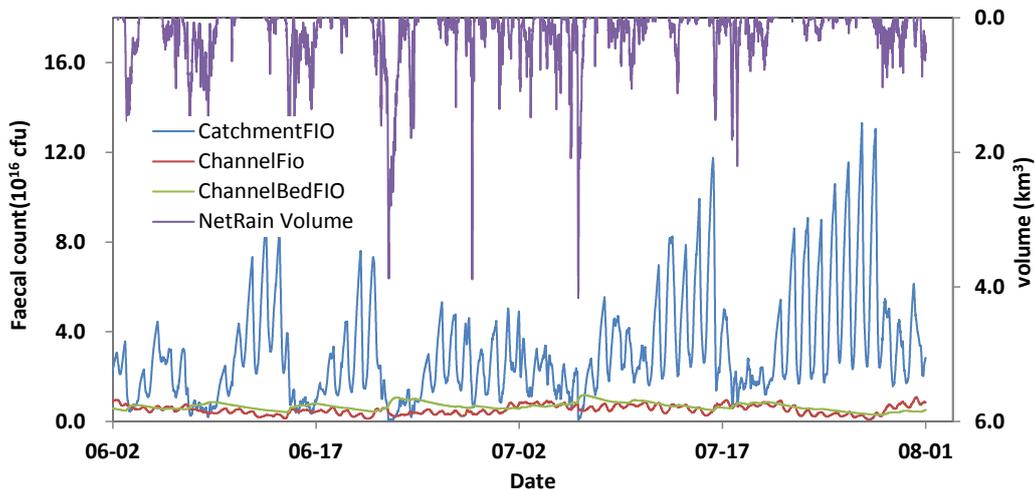


Fig. 7 FIO storage variation in catchment and river, including in SPM and on channel bed

#### 4. IMPACTED FACTORS RECOGNITION AND ANALYSIS FOR HIGH FIO CONCENTRATION EVENTS AT BATHING REGIONS IN 2012

Firstly, faecal bacteria concentration data were collected, from May to September in 2012, at 29 bathing water regions (BWR) from the Environmental agency, UK, in the model domain (Fig.1), together with integrated model predicted water flow, SSC, FIO flux results and the associated rainfall, radiation, wind magnitude, tidal level at 176 rivers catchments with a 15 min time step. Secondly, output data from the four rivers for every BWR, which may have certain relationships with high E.coli concentration levels in the BWR, were compared with the measured E.coli concentration levels. Finally, by integrating different measured and calculated variables with the two EU bathing water standards, namely SD1976/EC and SD2006/EC, the bathing water quality situation in the model domain and the impact factors for high E.coli concentration levels and possible management methods responsible for certain BWRs fail to meet the minimum mandatory standards were established and tabulated. Based on the measurements in 2012, there are 6 and 19 BWRs out of 29 (in total) where the BWRs could not meet the minimum mandatory EC 1976 and 2006 standards, respectively. Therefore further catchment clean operations and an integrated river and beach management are prerequisite in order to achieve a satisfactory bathing water status in the future. The brief high FIO concentration events are analysed and summarized as follows.

(I) **Intense rainfall linked events.** Among the 19 high FIO concentration events, about 9~12 events are caused by large storms with intense rainfall runoff rates, especially for small catchments, the overflow of CSOs and failure of sewage water storage in the storm conditions may strength the FIO concentration.

(II) **Accumulated and first wash-off Events:** If the weather condition is moderate and suitable for bacteria organisms to survive in the catchments and rivers, for example, with slight rainfall, enough moisture, lower radiation and continuous sediment deposition for many days, the accumulated bacteria organisms in the catchments and rivers will arrive a high level. For such a condition, even a moderate rainfall appears, then the outfall FIO concentration will arrive a high level; among the 19 events, there are about 3 events belong to this kind.

(III) **Delivery and resuspension caused events.** This is usually caused by the FIO inflow of large rivers, and then delivered to the BWRs by the convection or re-suspended of fine sediments several days under the action of currents and strong winds induced waves. For example, FIOs from the Ribble, Mercey, Leven rivers may arrived the BWRs far away from the river to estuarine waters than small rivers and they have an more permanent influence on the bathing water quality.

(IV) **Mixture events.** More than two kinds of events mentioned above mixed together to form a comprehensive pollution events for a BWR.

Although decreasing the input FIO counts flux for every river using series of approaches, for example, additional devices or constructions and controlled management approach for the rural

and urban regions are key to reduce these high FIO concentration events in BWRs, different relationships or coupling between concentrations exist at riverine and BWR sites because of the marine dynamic, wind and other environmental conditions. The complex relationship is obvious in the II, III and IV event types. Different river management measures developed to reduce the faecal sources in the catchments and related concentration variations in the BWRs will be evaluated using the integrated modelling system in the near future.

## 5. CONCLUSIONS

An integrated model system for predicting the hydrological, hydrodynamic, sediment and faecal bacteria transport and decay processes from the source regions in the catchments to coastal waters has been developed by linking a grid based distributed hydrological model (GBDHM), a one-dimensional river and pipe networks model (RPNM1D) and a modified EFDC-2D model. The model is capable of predicting quantitatively the faecal bacteria concentration distribution in the source regions and their impact on the receiving bathing waters. The model has been applied to a large and complex water system, which includes 11 river catchments and the associated estuaries and the Liverpool Sea. An extensive data set, including meteorological, hydrological and hydrodynamic data, and information concerning soil and sediment, land use as well as livestock waste control measures, have been considered in supporting the modelling and bathing water management plans. These parameters were first processed and then used in the model. The model has been calibrated and validated against the data and the model results generally fit well with the measured data, although further refinement of the sediment and faecal parameters is needed to improve the model accuracy. It has been established that the model predicted sediment yield, transport, erosion and deposition vary significantly for different types of catchments. More research is needed to investigate the mechanisms of sediment yield and transport in these catchments. The integrated model is currently used to identify the main factors and event types for the high FIO concentration events in 29 BWRs. The goal is to evaluate quantitatively the response of bathing water quality of different types of BWRs to a variety of clean management options under specific meteorological, hydrological and tidal conditions.

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