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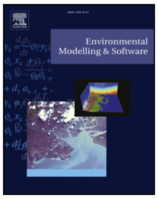

Evaluation of *E.coli* losses in a tidal river network using a refined 1-D numerical model

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ABSTRACT

Predicting the rate of *Escherischia coli (E.coli)* loss in a river network is one of the key conditions required in the management of bathing waters, with well verified numerical models being effective tools used to predict bathing water quality in regions with limited field data. In this study, a unique finite volume method (FVM) one-dimensional model is firstly developed to solve the mass transport process in river networks, with multiple moving stagnation points. The model is then applied to predict the concentration distribution of *E.coli* in the river Ribble network, UK, where the phenomena of multiple stagnation points and different flow directions appear extensively in a tidal sub-channel network. Validation of the model demonstrates that the proposed method gives reasonably accurate solution. The verification results show that the model predictions generally agree well with measured discharges, water levels and *E.coli* concentration values, with mass conservation of the solution reaching 99.0% within 12 days for the Ribble case. An analysis of 16 one-year scenario runs for the Ribble network shows that the main reduction in *E.coli* concentrations occurs in the riverine and estuarine regions due to the relatively large decay rate in the brackish riverine waters and the long retention time, due to the complex river discharge patterns and the tidal flows in the regions.

1. Introduction

Escherischia coli (E.coli) loss at the river-estuary transition zone is a complex process where decay and production through various sources coexist. The pattern of *E.coli* loss varies from case to case, and is governed by their biotic intrinsic parameters, abiotic environmental conditions and episodic sources. Field sampled data are important in the evaluation of the fate of *E.coli*, but they are usually limited. Therefore, numerical models are often used, together with limited field measurements and laboratory analysis to evaluate quantitatively the *E.coli* losses in riverine and coastal waters (Servais et al., 2007). However, the accuracy of the models used needs to be verified to ensure that the solutions are stable and mass conservative, as well as including appropriate values for key parameters such as: bed roughness, dispersion and decay rates (Steets and Holden, 2003).

A mass conserved, stable, accurate and computationally manageable model is therefore a prerequisite for *E.coli* concentration evaluation, since rainfall-runoff intensities enter river channels in pulses, often at minute scales, creating large gradients in pollutant concentrations (Sanders et al., 2001). This is especially important in complex river networks with relatively steep gradients and also where highly unsteady tidal currents exist in the estuarine and coastal zones. A small mass-conservation error in the hydrodynamic solution may cause a large error in the matter transport solution (Bousso et al., 2012). However, it is often difficult to obtain highly conservative solutions in a natural river system for a number of reasons, including: the use of non-consistent governing equations (Aral et al., 2000), partial or full linearization of the governing equations, different discretized formats between the hydrodynamic and mass transport model equations etc. In order to improve on the mass conservation properties of such solutions, the finite volume method (FVM) (Murillo and Navas-Montilla, 2016; Wu and Wang, 2008; Zhang et al., 2011) is increasingly used in water quality modelling studies, together with an unstructured grid. However, when an explicit FVM model is used, two key shortcomings remain, one being the smaller time step imposed by the Courant-Friedrichs-Lewy (CFL) limiting condition (Delis et al., 2000; Stelling, 2003), and the difficulty in maintaining robustness for complex looped and dendritic river networks (Jin et al., 2002). For long-term simulations, e.g. for up to 100 years, and for a series of scenario runs of the hydrodynamic, sediment and mass transport processes, 1D models are extensively used

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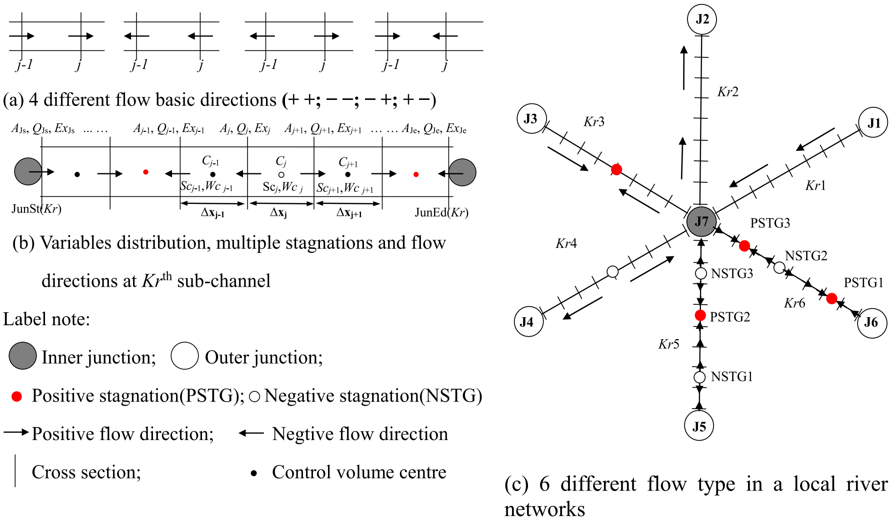

(a) 4 different flow basic directions (+ +; − −; − +; + −)

(b) Variables distribution, multiple stagnations and flow directions at Kr^{th} sub-channel

(c) 6 different flow type in a local river networks

Fig. 1. Four flow directions and multiple stagnation points and positions for key variables.

because of their higher efficiency and even higher accuracy than 2D and 3D models when dealing with large and complex river networks (Lauer et al., 2016; Wu et al., 2004; Zhou and Lin, 1998). Usually a 1-D model is used to link a catchment hydrological model (Merkhali et al., 2015; Paiva et al., 2011) and a 2D or 3D estuarine and/or coastal model (Bladé et al., 2012; Twigt et al., 2009). Therefore, 1D models are generally invaluable tools in an integrated modelling system for simulating hydrological, hydrodynamic and mass transport processes, from the catchment cells to river networks, and then to the receiving estuarine and coastal waters (Nanía et al., 2014; Salvadore et al., 2015).

In general different flow directions often exist in estuaries caused by the river flow and tidal waves and there four basic flow directions can exist in a sub-channel, including: (i) down flow, (ii) up flow, (iii) inward-flow, and (iv) outward-flow (Zhang et al., 2014). For the case of (iii), or (iv), a positive stagnation point, or a negative stagnation point, will occur (see Fig. 1c). However in a sub-channel there may be more than one stagnation point and the number of stagnation points and their locations can change continuously due to the interaction between the tides and river flows. Stagnation can also occur at more than a single point in an estuary and/or river reach. Therefore, an existing algorithm for dealing with only one stagnation, developed by Hu et al. (2010) and Zhang et al. (2014), has been refined in the current study to enable the physical processes of multiple stagnation zones to be predicted.

The main objective of this study is therefore to improve on the accuracy of numerical model predictions of *E.coli* losses in river networks and to reduce the error level in mass conservation. Details are given of the development of a FVM based model to simulate the mass transport processes in river and estuarine networks, particularly where multiple stagnation zones and different flow directions may occur. Firstly, in this model a new algorithm is developed to predict the formation of multiple stagnation zones and the mass transport processes in these zones. Secondly, a dynamic decay rate is formulated for different salinity and radiation levels, based on data obtained from laboratory studies and field investigation. Thirdly, field measured hydrodynamic and *E.coli* data, acquired for the river Ribble network and Fylde coast in 2012, are used to calibrate and validate the hydro-epidemiological model. Finally, the loss of *E.coli* in the river Ribble network is evaluated using the refined 1D model. A series of scenario simulations are also reported, using the refined 1D modelling system, and the *E.coli* losses in the middle and lower regions of the river Ribble, including different sources from 47 sub-catchments, are quantitatively predicted. The results show the importance of the need for model mass conservation, especially in the lower reaches of the river basin, where the reversing current and the multiple stagnation zones appear extensively, driven by tidal and river flow interactions.

2. Theory/model framework

2.1. Hydrodynamic model

The St Venant equations are widely used as the governing equations to predict the hydrodynamic processes in river networks, as given by:

$$B\frac{\partial Z}{\partial t} + \frac{\partial Q}{\partial x} = q \tag{1}$$

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}\left(\frac{Q^2}{A}\right) + gA\left(\frac{\partial Z}{\partial x} + s_f + s_e\right) + L = 0 \tag{2}$$

where B = wetted-cross sectional width (m), Z = elevation of water surface above datum (m), Q = river discharge (m^3/s), q = lateral discharge per unit channel width (m^2/s), x = curvilinear distance of river channel (m), t = time (s), A = wetted cross sectional area (m^2), g = gravitational acceleration (m/s^2), s_f = friction slope, expressed as $s_f = {n^2Q|Q|}/{A(A/B)^{4/3}}$, in which n = Manning's coefficient, s_e = local longitudinal slope of water surface due to localised head losses, and L = momentum of lateral discharge inputs.

2.2. Mass transport model

The mass transport equation given as:

$$\frac{\partial(AC)}{\partial t} + \frac{\partial(QC)}{\partial x} - \frac{\partial}{\partial x}\left(AE_x\frac{\partial C}{\partial x}\right) = S_C + W_C \tag{3}$$

where E_x = longitudinal dispersion coefficient, which is based on a formula derived by Fisher (Fischer, 1973), S_C = a source term due to bacterial decay ($S_C = Ins - K{\cdot}C$), K = decay rate (hr^{-1}), Ins = constant source term, for *E.coli* this term is zero. In engineering studies, the T_{90}, which is the time needed for 90% of the bacteria to die off ($T_{90} = \ln 10/K$, unit is hr), is usually used.The value of T_{90} is related to radiation, salinity and organic matter, etc(Yang et al., 2008). The limited measured data is given in Table 1(Huang et al., 2017) based on radiation and salinity condition then intepolated T_{90} is used in the model based on the given radiation and modelled salinity. W_C = external sources from point and diffuse source inputs, which is decided by the *E.coli* flux from lateral sub-catchments.

The FVM is used to improve on the mass conservation of Eq. (3). However, the consistency between Appendix S1: Eqs. (2)–(3) and Eq. (3) may not be entirely satisfactory, because of the additional errors