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69

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# Numerical investigation of the spatial distribution of *Escherichia coli* in river deltas for different values of river discharge, temperature and irradiation of the water surface

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## Abstract

*Escherichia coli* and other enteric pathogens' presence indicate that the water has been contaminated with fecal matter. River deltas are population hotspots which are becoming increasingly urbanized and where poor sanitation has been frequently identified as a pressing issue. In this study, we have investigated the spatial distribution of *E. coli* in river deltas under varying river discharge, temperature and irradiation at the water surface. A hydrodynamic and water quality model has been used to reproduce an idealized river delta configuration and to investigate the spatial distribution of *E. coli* across the delta floodplain and channels. The concentration of *E. coli* rapidly declines downstream, following a tripartite trend with different decline rates on the delta front, pro-delta and shelf area. The highest differences in the spatial distribution of *E. coli* bacteria occur for low-river discharge values. Temperature and irradiation both influence the concentration of *E. coli* and mostly influence downstream areas and smaller channels.

**Key words:** Delft3D, *E. coli*, numerical model, river deltas

## INTRODUCTION

Around 50% of the world's population live in the proximity of the sea, and river deltas are among the most populated areas in the world (Leonardi *et al.* 2013; Fagherazzi *et al.* 2015; Edmonds *et al.* 2017). Large amounts of wastewater are discharged daily into coastal areas, including wastes from coastal communities without adequate sewage or wastewater depuration systems (Shuval 2003). Several health issues are associated with bathing/swimming in wastewater polluted water and with the consumption of seafood harvested in wastewater polluted coastal areas. Epidemiological studies analyzed by the WHO support the view that certain enteric and respiratory infections and diseases are associated with bathing in coastal waters contaminated with pathogenic microorganisms (Fattal *et al.* 1987). Seafood, especially bivalves which are frequently undercooked, can transmit serious infectious diseases. Infectious hepatitis A (HAV), a serious disease of the liver, is frequently transmitted by shellfish (e.g. Shuval 2003). Pathogenic bacteria can survive in the coastal environments for weeks, and viruses can survive for months. According to Gerba (1988), HAV can survive in the sea for over a year. Enterotoxigenic *Escherichia coli* has been identified as the most common cause

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of infectious diarrhea for young children in developing countries (Rao *et al.* 2003). As an example, in a cohort of 397 children from two villages located in the Nile Delta, 3,477 episodes of diarrhea were registered with an average of 5.5 episodes of diarrhea per child per year (Rao *et al.* 2003). In a study conducted on the Niger Delta, the bacteria count showed a clear exceedance of the international standard of drinking water with the presence of *E. coli* and other enteric pathogens such as Enterobacteria, indicating that the water was significantly polluted with fecal matter (Williams *et al.* 2018). In the Pearl River Delta and near the urban area of Shenzen, due to the high levels of organic pollution, the overall water quality was only marginally acceptable to the 2nd Class Standard of the State Surface Environmental Quality Standards (Ho *et al.* 2001). Globally, it has been estimated that diarrhea accounts for 25% of child deaths under 5 years old and is the second most common cause of child deaths from infectious diseases followed by pneumonia (Pneumonia & Diarrhea Progress Report 2017; Saha *et al.* 2019). India, Nigeria, Pakistan, Republic of Congo and Angola are among the most affected by early diarrheal deaths (Saha *et al.* 2019). A recent global analysis has suggested that the population on deltas is growing from 237 million in 2000 to projected 322 million in 2020, with population density also growing from an average of 322 people per km$^2$ in 2000 to projected 422 people per km$^2$ in 2020 (Edmonds *et al.* 2017). For deltaic regions, there is increasing concern about pollution because the coastline receives huge amounts of human and industrial waste, including organic pollutants from municipal and domestic sewage (Sojinu *et al.* 2012). For some low lying deltaic regions, which are currently under development, gastrointestinal disease outcomes are also more severe due to the malnutrition and lack of intervention strategies for the region (e.g. Ashbolt 2004).

The survival and dispersal of fecal bacteria depend on physiochemical conditions and on the physical dilution due to hydrodynamics. Among the various physiochemical conditions, temperature and irradiation play a crucially important role and these variables are expected to vary under future climate change scenarios (e.g. Mancini 1978; IPCC 2013). In spite of numerous insightful studies, more efforts are needed to understand the distribution and transport of potentially infectious microorganisms along the coastline and possible risks to human health.

In this work, we will focus on the transport patterns of *E. coli* along an idealized river delta network and for different temperature, solar radiation and river discharge values.

This article aims to unravel the impact of temperature and irradiation on the mortality rate and concentration of *E. coli* along channel networks and along different portions of the river delta. To achieve this, we focus on the mortality rate and concentration decay of *E. coli* with the distance from the river mouth with different discharge conditions on changes in *E. coli* concentration with the bifurcation order and changes in *E. coli* concentration with different radiation and temperatures.

## MATERIAL AND METHODS

This is an idealized numerical modeling study aimed at identifying transport and spatial distribution of *E. coli* in river deltas under different temperature, solar irradiation and river discharge conditions. The hydrodynamic model Delft3D and the water quality model Delft3D-WAQ were used for this investigation. Delft3D solves the unsteady shallow water equations in two (depth averaged) dimensions. The equations consist of the horizontal momentum equations, the continuity equations and a turbulence closure module. The vertical momentum equation is reduced to the hydrostatic pressure relation because vertical accelerations are assumed to be small compared to gravitational acceleration and are not taken into account (Lesser *et al.* 2004). Delft3D further includes a sediment transport and a morphology module which are used to reproduce an idealized river delta configuration. The dispersion of *E. coli* was calculated using Delft3D-WAQ which is an Eulerian transport model solving transport and physical, (bio)chemical and biological processes. The model takes into account the decay rate of fecal bacteria depending on ambient conditions of salinity, temperature and UV radiation. The decay rate is determined according to the following (Mancini 1978):

$$k(z) = (k_b + k_s S)\theta_T^{T-20} + k_I I \mathrm{e}^{-e_t z} \tag{1}$$

where $k_b$ is the basic decay rate ($\mathrm{d}^{-1}$), $k_s$ is the salinity dependent decay rate ($\mathrm{d}^{-1}$), $k_I$ is the solar irradiation dependent decay rate ($\mathrm{d}^{-1}$), $\theta_T$ is the temperature correction factor, $S$ is the salinity, $T$ is the water temperature (°C), $I$ is the solar irradiation ($\mathrm{W/m^2}$) and $e_t$ is the light extinction coefficient ($\mathrm{m}^{-1}$). Water salinity was set equal to 15‰, which is an average value chosen based on the physical properties of the Niger Delta (Abowei 2010). For the Delft3D-WAQ substance file describing *E. coli* properties, the following parameters have been used, which are the default values of the numerical model, as introduced by Mancini (1978): a first-order mortality rate of 0.8 1/d, an UV-specific irradiation coefficient of 0.05 $\mathrm{m^2/g}$ DM and a background extinction UV light of 0.08 1/m. An *E. coli* input concentration of $3{\cdot}10^8$ $\mathrm{MPN/m^3}$ was then used. The temperature ranged from 15 to 28 °C, and the irradiation of the water surface ranged from 100 to 350 $\mathrm{W/m^2}$. These values are intended to cover a wide range of physical conditions potentially indicative of daily, seasonal and geographic variations. From a physical geography point of view, the river delta is an accumulation of fluvially derived sediments that form at river mouths. A 2D simulation was first conducted to produce the river delta morphology starting from a flat bathymetry. The resulting morphology was then kept fixed for the simulations. The model domain has a rectangular grid of 4 km by 4 km. The grid resolution is 20 m in both $x$ and $y$ directions. A finer resolution of 10 m was adapted close to the channel area to improve accuracy. The morphology of river deltas is determined by several external agents including the ratio between fluvial and sea energy. Several river deltas are characterized by channels leveeing and bifurcation creating the crenulated shorelines whose plan-view morphology and networks can be classified based on the channel bifurcation order. The channel bifurcation order is a useful parameter that can be used to describe complex channel networks across riverine deltas of various sizes and shapes. A bifurcation point is defined as the upstream intersection of bifurcate channels centerlines, and the bifurcation order can be defined as the number of bifurcations upstream of the channel in question (e.g. Edmonds & Singerland 2007).

## RESULTS

The numerical model was used for the creation of the idealized river delta bathymetry used in this study. The idealized delta model presents a typical river-dominated configuration with several braches and bifurcation order up to 3 (Figure 1(a)). Channels width and depth decrease with the channel order as typically found in river-dominated river deltas (Figure 1(a)). The morphology of the system was kept constant throughout the simulations. The velocity field of the system for a river discharge of 100 $\mathrm{m^3/s}$ is also presented in Figure 1(b) where red colors indicate the highest velocity values and blue colors indicate no-velocity.

Figure 1(c) shows the spatial distribution of *E. coli* across the domain and for the 100 $\mathrm{m^3/s}$ discharge rate. For a discharge of 100 $\mathrm{m^3/s}$, the concentration of *E. coli* rapidly declines and there are large variations in *E. coli* concentration across the domain. As the river discharge increases (Figure 2), the plume spreads further away from the river mouth with lower concentration values covering a wider portion of the river delta. Furthermore, as the river discharge increases, the decline in *E. coli* follows an increasingly more pronounced tripartite trend with an initially gentler decline on the delta plain and main channels, a steeper decline on the pro-delta regions and another low rate decline on the seaward side of the domain (Figure 2).

Figure 3(a) illustrates changes in *E. coli* concentration with the stream order (being zero the main river channel), and for temperatures ranging from 15°C to 28°C. Highest concentrations are present

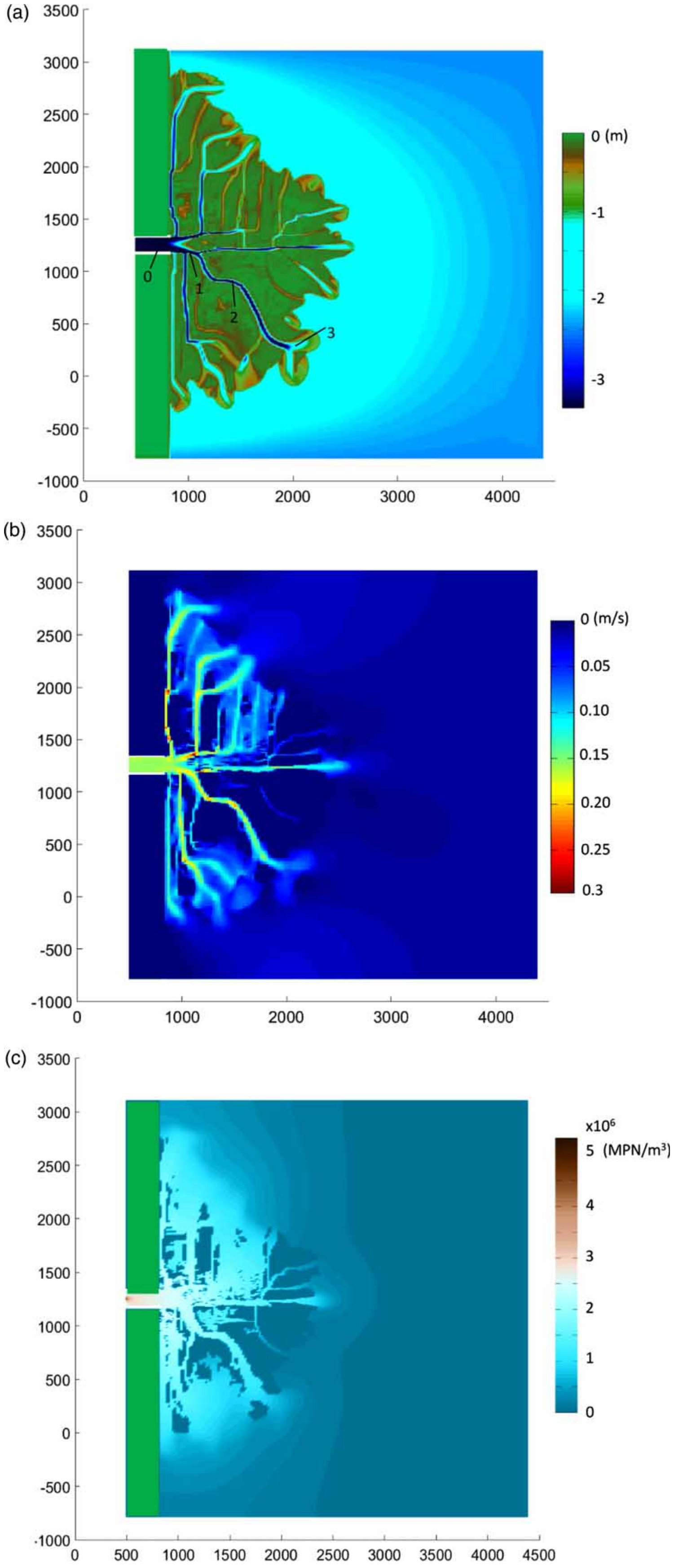

**Figure 1** | (a) Bathymetry of the river delta. (b) Depth averaged velocity across the river delta for a river discharge of 100 m$^3$/s. (c) *E. coli* concentration (MPN/m$^3$) for a discharge of 100 m$^3$/s.

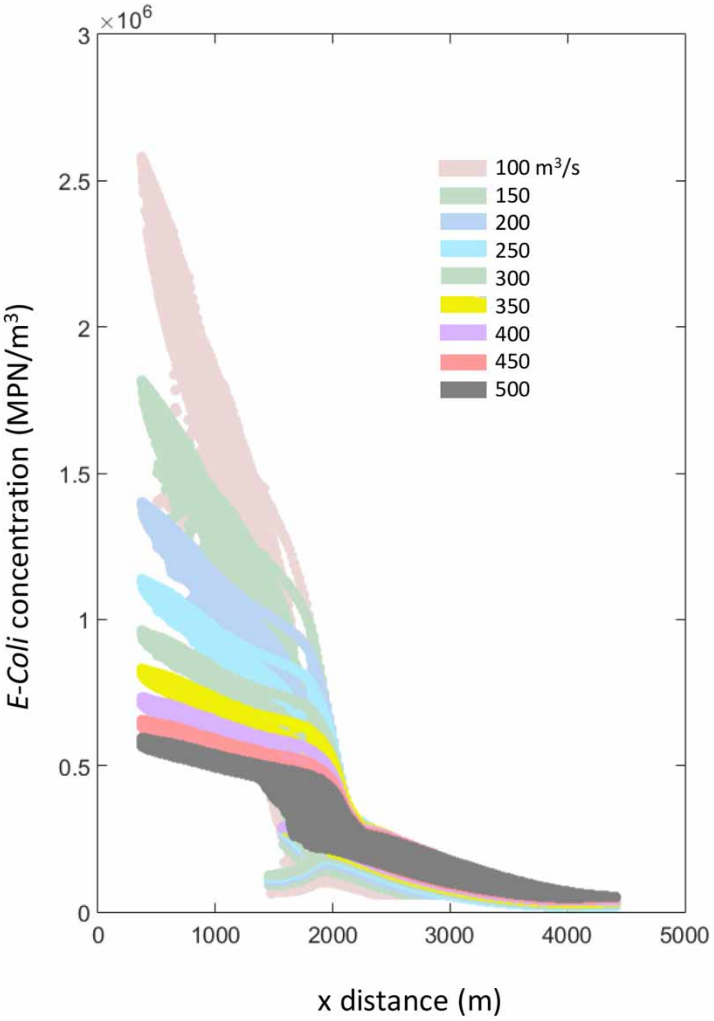

**Figure 2** | Spatially averaged *E. coli* concentration (MPN/$m^3$) over the river delta as a function of the distance from the river mouth.

when the temperature is the lowest; this is in agreement with Equation (1) which predicts an increase in the mortality rate with temperature. The *E. coli* concentration significantly declines as the stream order increases. Notably, the highest differences in *E. coli* concentration due to different temperatures are present for the lowest concentration and the highest bifurcation order (Figure 3(a)).

Figure 3(b) illustrates changes in *E. coli* concentration for different irradiation of the water surface, ranging from 100 to 350 W/$m^2$. Maximum concentrations are present for the lowest values of radiation. Radiation has a stronger effect for highest stream order values where the water depth is lower in agreement with Equation (1). For channels of stream order 3, the average values of *E. coli* concentration are only present for radiation values lower than 300 W/$m^2$. Similarly, than for the impact of temperature, the influence of irradiation is significantly more noticeable for higher bifurcation orders.

## DISCUSSION AND CONCLUSIONS

In this study, we have used an idealized river delta configuration to investigate the spatial distribution of *E. coli* bacteria over a river delta. We further investigated the influence of temperature and surface water radiation on the concentration of *E. coli*.

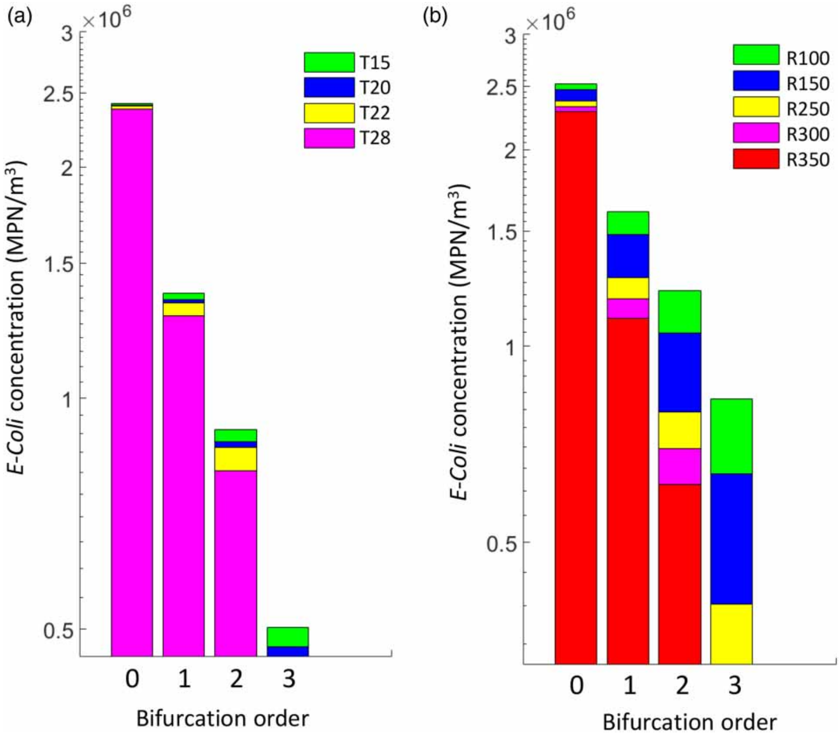

**Figure 3** | (a) Average value of *E. coli* concentration as a function of different bifurcation orders and temperature values. (b) Average value of *E. coli* concentration as a function of different bifurcation orders and irradiation at the water surface values.

We found the following:

- The concentration of *E. coli* bacteria inside the deltaic channels rapidly declines with the bifurcation order.
- Temperature and irradiation both influence the concentration of *E. coli* and mostly influence downstream areas and smaller channels.
- The highest differences in the spatial distribution of *E. coli* bacteria occur for low-river discharge values.

Adopting the bifurcation order as a synthetic descriptor of deltas' geometry supports the upscaling of our results to deltaic regions of different sizes and with different morphologies, as the bifurcation order is frequently used as a non-dimensional metric to describe channels networking independently from local morphological features. As the bifurcation order increases, channel depth and width decrease, and the influence of temperature and water surface irradiation also increases. Some limitations are associated with the use of our idealized modeling framework. For instance, the model does not include simulations for an entire catchment area which would be necessary to investigate the influence of different land uses as well as the dynamic interactions between land and ocean. Wang *et al.* (2019) provide an example of a catchment scale approach for the monitoring of water quality in Singapore's coastal areas. Specifically, they combined 1D-hydrological/hydraulic, transport models as well as 3D-hydrodynamic and water quality models. By incorporating catchment characteristics, the model of Wang *et al.* (2019) allowed incorporating point sources such as sewage treatments, industries as well as diffuse sources from agriculture. The latter are an important inclusion for the accurate monitoring of the spatial and temporal distribution of water quality parameters along the coastline. Field investigations should be also conducted in support of numerical modeling. For instance, in order to investigate water quality in the Singapore coastal water, Goh *et al.* (2017) measured *in situ* chemical contaminants and bacteria. Specifically, they used Colilert™ and Enterolert™ (IDEXX Laboratories, Inc., Westbrook, Maine) to quantify *E. coli* and *Enterococcus* concentrations. Goh *et al.* (2017) further combined field investigation with principal component analysis (PCA) and provided insight into the spatial variations in Singapore's water quality in support of health risk assessments. To accurately model water quality, Wang *et al.* (2016) further proposed a new framework combining modeling and data assimilation techniques. Their framework allowed information extracted from observations to feed into a data-driven local/modified local model and results from the data-driven model to be then fed into the original process-based model for the improvement of forecast abilities. The application of our modeling framework to a real case scenario and validation with real data is outside from the scope of this article but might be the object of future studies.

The influence of both temperature and irradiation on the average *E. coli* concentration is almost undetectable within the main river (stream order zero), but significantly increases further from the river mouth where different temperatures and irradiation values can determine the presence or absence of *E. coli* bacteria.

Our results suggest that daily or seasonal variations in temperature and radiation, as well as possible changes in climate extremes or mean values might potentially have a stronger impact, in terms of *E. coli* concentration, on those channels with a higher bifurcation order where temperature or irradiation-induced fluctuations are the highest.

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