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Concentration statistics of solute transport for the near field zone of an estuary

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ABSTRACT

Rivers are considered as one of the most influential hydrological pathways for the waterborne transport and therefore estuaries are critical areas for a pollution hazard that might lead to eutrophication and general water quality deterioration. This paper is investigating the near field mixing in the estuary as the result of a combination of small scale turbulent diffusion and a larger scale variation of the advective mean velocities. In this work concentration moments were developed directly from the fundamental advection–diffusion equation for the case of continuous, steady, conservative solute transport with the dominant stream flow mean velocity. The concentration statistics were developed considering depth integrated velocity field with mean velocity attenuation due to the wind induced currents and sea tides. In order to perform further studies of developed concentration moments, a set of velocity measurements in the local river Žrnovnica estuary near Split, Croatia, was conducted and numerical random walk particle tracking model was used to run the transport simulations based on measured velocity fields. The numerical model has confirmed quantitatively first two concentration moments, which are utilized to calculate the point concentration probability density function (pdf) often needed to assess the risk of exceeding the allowed concentration values in the estuary.

1. Introduction

Coastal areas worldwide are important and sensitive ecosystems. They are characterized by rich natural biodiversity, which is threatened by the intensive land use and pollution of coastal waters generated by high and still growing population density. Growing population, near coastline settlements, and their activities generate large environmental impact on the surface water in general. According to an estimate by Cohen et al. (1997) about 44% of the worlds population lives within 150 kilometres of the coast.

Many studies, especially in Baltic Sea area (Darracq et al., 2009; Destouni et al., 2008), had been conducted in order to determine all possible pathways of inland pollution entering the coastal waters. Rivers are considered as one of the most influential hydrological pathways for the waterborne pollution transport carrying nutrients, bacteria, heavy metals or any other kind of contaminants. An estuarine-coast ecosystem has extremely complex behaviour in many different aspects. Water circulation, in most general sense is driven by freshwater inflow, tides, wind stresses and internal density variations, which results in the turbulent mixing (Garel and Ferreira, 2012). Each estuary has unique characteristics from the geological aspect to the land use and there is no easy way of classifying them in order to establish some general principles. In their core phenomenon estuaries are intersections of different natural and even social gradients, e.g. salt water intrusion and tidal force from the sea, wind stresses in all effective directions, river flow gradients, and finally the human impact through their coast aiming vectors whether they represent urban, agro-industrial or recreational activities.

Among various topics the most relevant to this manuscript are those covering hydrodynamics and modelling of transport processes in estuaries. Some authors were focused on flow and transport dynamics mostly under the tidal force (Burchard et al., 2004; Chanson et al., 2012; Punt et al., 2003). The Lagrangian numerical model had been used to describe hydrodynamics and pollution behaviour in coastal zones (Campbell et al., 2014). Comprehensive research on pollutant dispersion in near-shore region had been conducted at the Mediterranean Spanish coast (Rodriguez et al., 1995), and similar research was also presented in Alexandria coast Mohamed et al. (2007), both showing dominant effects of long-shore currents on the transport. The majority of conducted research, found in the literature, is site specific and closely related

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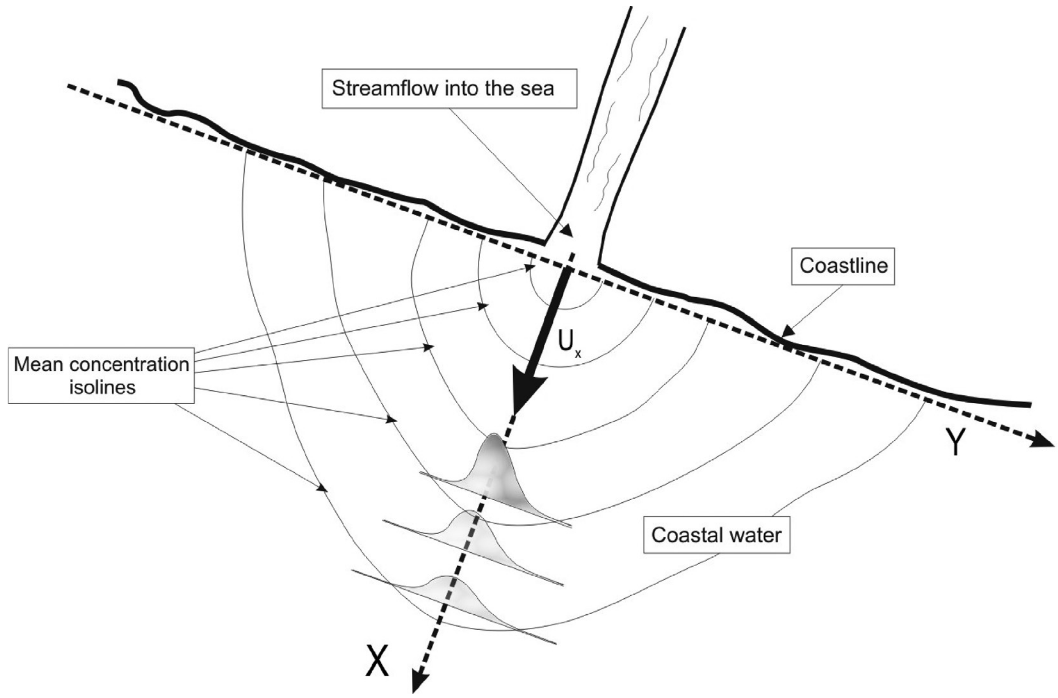

Fig. 1. Schematic view showing how the mean concentration is transported to coastal water from the river mouth and expanded in longitudinal and transverse direction.

to their geographic situation including their unique pollution generators like agriculture (Lindgren et al., 2007), plastic debris (Ivar do Sul and Costa, 2013) or print factory (Kumar et al., 2011).

The focus of this manuscript is on introducing a prediction tool for a concentration distribution estimate in the river dominated stratified estuaries as classified by Savenije (2005). The presented methodology provides a potentially useful tool for the screening assessment, enabling one to estimate the concentration statistics of any conservative substances continuously discharged in the sea by the river's surface water. The developed concept follows the similar methodology already applied in other environmental flows, such as in the atmosphere (Chatwin and Sullivan, 1990a; Sawford and Sullivan, 1995; Sullivan, 2004), and in the groundwater (Andricevic, 1998; 2008; Gotovac et al., 2009).

In the Section 2 we present the general problem formulation and Section 3 describes the proposed methodology for deriving concentration moments. The concentration moments follow directly from the fundamental advection–diffusion equation for the case of continuous, steady, conservative transport where stream flow mean velocity is dominant, which is typical situation for the near field conditions. We introduced the exponential attenuation model for mean velocity field and its applicability was verified within the Section 4. Two sets of field velocity measurements were conducted at the local river Žrnovnica estuary, near the city of Split, Croatia, and numerical random walk particle tracking model has been developed to run the transport simulations based on the measured velocity field. Concentration moments obtained by proposed methodology are further used to investigate the effect that mean velocity attenuation and molecular diffusion have on the transport process itself and the results are presented in Section 4. In the discussion of the results we interpret some key findings along with the limitations of the performed study. The point concentration probability density function (pdf), which is calculated using the developed moments and two parameter beta distribution, is presented as an example for potential application. The pdf can be used to estimate the probability of exceeding the threshold concentration value for a certain substance.

2. Problem formulation

In this work we investigate the situation of near field mixing zone nearby the estuary mouth, hypothetically shown in Fig. 1, where concentration field of conservative substance is being transported from the river mouth to the estuary and coastal water in the advection dominated process. The river discharge is considered as continuous steady source where the dominant stream flow mean velocity direction is aligned with the x-axis of the coordinate system. This concept is based on the fact that in the near field zone the interactions between tidal and residual flow with a weak tidal force are rather limited or absent (Chawla et al., 2008).

Mixing in the near field zone of an estuary results from a combination of small scale turbulent diffusion and a larger scale variation of the advective mean velocities (Fischer et al., 1979). The advection and turbulent diffusion between streamlines cause an equilibrium process of mixing exchange.

For a considered incompressible and steady flow of conservative substance the mass conservation is described by the fundamental advection–diffusion equation

$$\frac{\partial c(\mathbf{x},t)}{\partial t} + \nabla \cdot [v(\mathbf{x},t)c(\mathbf{x},t)] = e_m \nabla^2 c(\mathbf{x},t) \tag{1}$$

where $c(\mathbf{x}, t)$ is the scalar concentration in units of mass per unit volume, $v(\mathbf{x}, t)$ is the instantaneous flow velocity at point $\mathbf{x}$ and time t, and e_m is the molecular diffusion coefficient. In turbulent flows the scalar concentration can be treated as a random variable due to the high irregularity of the turbulent velocity fluctuations, as well as of initial and boundary conditions. Such intrinsic randomness of the physical quantities prevents one from using deterministic theory in predicting the concentration field behaviour. Thus, the various mean values of random functions and the probabilities of random variables are of practical interest and will be the focus in this work. To characterize the reduction of concentration, due to the mixing processes, we consider the pdf

$$p(c;\mathbf{x},t)dc = prob\{c \le c(\mathbf{x},t) \le c + dc\} \tag{2}$$