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Integrated concentration statistics from river generated pollution in coastal zones

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Abstract:
River estuaries represent one of the most valuable and nevertheless most fragile ecosystems. By their own definition they act as an interactive border between river and sea, hence obtaining characteristics of both environments and yet unique ones such as brackish water or funnel shape. On the other hand, human impact is great at such coastal ecosystem due to multiple interests involved, ranging from agricultural via transportation to recreational activities. The river generated pollution is one of the most important threats to estuary ecosystem; hence this research investigates the potential of integrated concentration statistics as a measure of dilution and risk assessment. Previous work conducted includes the definition of pollution concentration moments and corresponding probability density functions. Hence, based on developed simple analytical solution for obtaining the moments, a more robust measure of dilution is introduced – expected mass fraction. The concept of expected mass fraction was previously used by several authors concerning the dilution processes in environmental flows. Being applied for an estuarine system for the first time, such measure is defined by spatial integration of point statistics over available volume. The result is an estimate of pollutant mass existing at some downstream distance which has the concentration above defined limit value. That kind of information gives potentially useful loading estimate when doing pollution risk assessment of the estuary ecosystem.

Keywords: Estuaries, River generated pollution, Pollution concentration moments, Probability density function (PDF), Expected mass fraction (EMF), Pollution loading estimate.

1. Introduction

Estuaries are complex ecosystems, however, they tend to be presented with some rather simple principles as described in research by previous authors (SAVENIJE 2005; CAI & SAVENIJE, 2013), which comes useful regarding the fact that most of estuaries are ungauged (SAVENIJE, 2015). Within lot of studies and research being conducted in estuaries and coastal zones (SARAIVA *et al*., 2007; PINTO *et al*., 2013; WANG *et al*.,

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2017; OGUNOLA *et al.*, 2017), we focus on the problem of nutrient loadings (e.g. nitrogen, phosphorous) and their transport process which may be considered as conservative one. Nutrient concentration statistics represent important data when analysing estuarine water body and it is also followed by European Commission directives (OJEC, 2000) and national regulations for water quality and bathing water quality (OJEU, 2006). When analysing the risk and the level of pollutant concentration dilution in environmental flows, due to its random nature, one is encouraged to use the stochastic approach and work with concentration statistics. Pollutant concentration data are statistical moments and probability density functions (PDF) which are defined in point. The above mentioned directives suggest the classical approach in defining the risk by using the point PDFs (SULLIVAN, 1997; GANOULIS 2009), which usually faces the challenge of dependency to a vast number of realizations or measurements. Such problem raises a necessity for a different measure of dilution. This research presents a follow up for the project and research described in (GALESIC *et al.*, 2016) where the analytical model for calculating pollution concentration statistics at an arbitrary point of an estuary was developed. The concept of expected mass fraction (EMF) is introduced into an estuarine system to meet the need for a more robust representation of dilution process. Such concept was previously engaged in research of atmospheric and groundwater transport processes (HEAGY & SULLIVAN, 1995; ANDRICEVIC *et al.*, 2012) and here it is applied by spatial integration of concentration statistics.

2. Methodology

The problem of mixing in the near field zone of a river dominated stratified estuary (depth integrated – 2D scheme) where steady and continuous river plume is entering coastal sea is observed. Such phenomenon is characterized by a combination of small scale turbulent diffusion and a larger scale variation of the advective mean velocities (FISCHER *et al.*, 1979). For conservative pollutant concentration, the fundamental advection diffusion equation is given:

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

where $c(\boldsymbol{x},t)$ is the scalar concentration, $v(\boldsymbol{x},t)$ is the flow velocity located by vector $\boldsymbol{x}$ at time t and e_m is the coefficient of molecular diffusion. After multiple averaging and an implementation of a near field zone approximation, a recursive solution for obtaining absolute statistic moments (m_{n+1}) is obtained:

$$m_{n+1}\left(x\right)=C_o^n\bar{c}\left(x\right)+\frac{k\alpha}{U}e^{-\frac{k\alpha}{U}x}\int_0^x\left[2m_n\left(\eta\right)\overline{c_t}-m_{n-1}\left(\eta\right)\overline{c_t}^2-C_o^n\bar{c}\left(\eta\right)\right]e^{\frac{k\alpha}{U}\eta}d\eta \qquad (2)$$

where C_0 is the source concentration, $k=n(n+1)$, $\alpha=e_m/\lambda$^2, and c_t is the background threshold concentration, and U is the mean velocity vector ($v(\mathbf{x},t)=U[U_x,0,0]$). The parameter λ defines the scale of concentration gradient, $\nabla c=(c - c_t)/\lambda$.

Furthermore, the PDFs can be reconstructed by moment inversion and one may obtain the probabilities of exceeding the limit concentration at a chosen point as shown in results section (Figure 2). But the crucial idea here is to upgrade this measure of dilution by applying the expected mass fraction:

$$f\left(c;t\right)=\frac{1}{M}\int_V cp\left(c;x;t\right)dv \qquad (3)$$

where V represents the available volume considered to have conserved and constant mass M due to continuous steady state being observed. This way EMF represents an integrated measure of concentration statistics and it is obtained by numerical integration of previously calculated PDFs (Figure 1):

$$f\left(i\right)=\frac{1}{M}\sum_c\ \sum_y cp\left(c,x_i,y\right)dc \qquad (4)$$

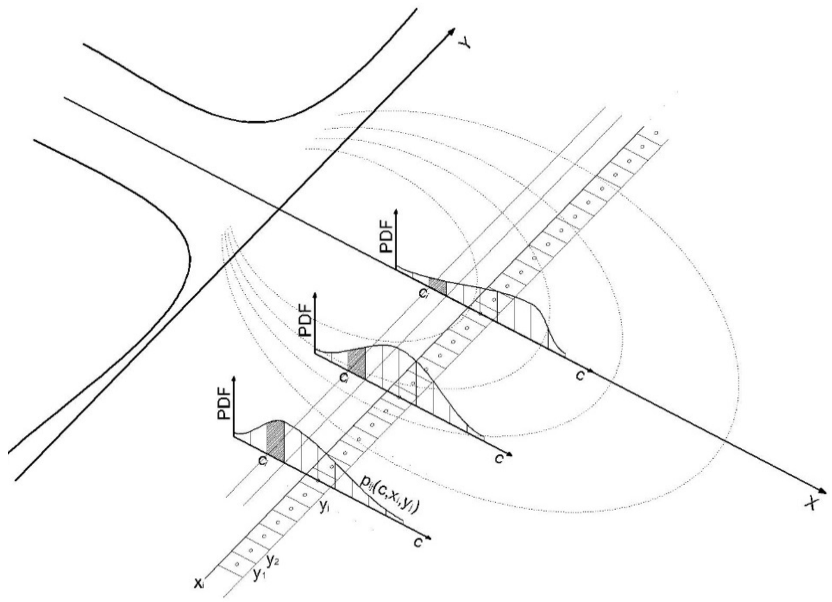

Figure 1 – Schematic representation of spatial integration of pollution concentration PDFs for chose downstream slice.

If one is to integrate the EMF for limit value of concentration – c^*:

$$F\left(c^*\right) = \int_{c^*}^{\infty} f\left(c;t\right) dc \tag{5}$$

The obtained cumulative distribution function – F(c*) represents direct, more intuitive application of an EMF by defining the fraction of mass consisting of concentrations equal or higher than chosen limit value.

3. Results

The developed analytical solution for obtaining the concentration moments and point PDFs is visualised on a pilot area of Žrnovnica estuary near the city of Split, where at given arbitrary points, the probabilities of exceeding the limit concentration (of total nitrogen in this case) are shown. The moment inversion was conducted by fitting the moments obtained by recursive expression (2) to a beta PDF which was previously tested as a good representation of dilution processes in environmental flows (CHATWIN *et al.*, 1995). By implementing the (4) continuously along the downstream slices the corresponding EMFs are obtained and shown in Figure 3. One may notice how initially there is the mass of pollutant with higher concentration, but it is systematically shifted to lower values of concentration in further sections.

Figure 2. Žrnovnica estuary map with mean concentration results and probabilities of exceeding the limit concentration at chosen points (background map is courtesy of Google Earth).

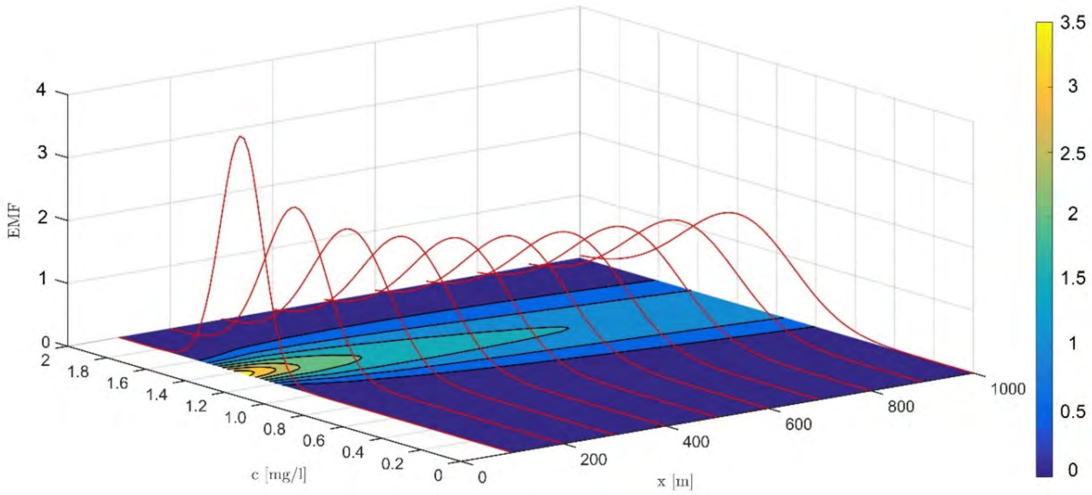

Figure 3. Obtained EMFs at different distances from the river mouth.

4. Conclusions

Such integration of point PDF overall available space (in this case the perpendicular slice of the downstream estuary) to obtain an EMF gives new measure of dilution – the fraction of mass that exceeds the limit concentration at chosen distance from the pollution source (i.e. river mouth). Observed mass reduction is certainly expected, however, the prediction of distance from the river mouth at which there is no more mass of some critical concentration shows worthy potential in risk assessment. It gives more robust assessment by defining the loading to the aquatic system as opposed to single point data which is hardly representative for a water body. The ongoing and future research include further development of integrated concentration statistics to make it less dependent of the choice of point pdf and an introduction of spatially integrated concentration moments.

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