New screening tool for obtaining concentration statistics of pollution generated by rivers in estuaries

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Abstract

Rivers present one of the crucial pathways for the waterborne transport and therefore estuaries are critical coastal areas for a pollution hazard that might lead to eutrophication and general water quality deterioration. When addressing these problems, the decision makers and coastal area managers often need additional skills and expert knowledge, so they engage consultants to develop models and provide potential solutions. The actual implementation of a solution in practice is hampered with different stakeholders' interest and objectives. However, if the relevant institutions were provided with a screening tool, enabling them with a certain level of solution ownership, potentially more involvement would occur. This research utilizes analytical model based on ensemble averaging and near field approximations of the fundamental advective-diffusion equation for the case of continuous, steady, conservative substance transport where stream flow mean velocity is dominant. Such approach significantly reduces the costs and time needed to obtain enough measured data needed for common statistics analysis or more complex numerical model. Developed methodology is built into a simple software named CPoRT (Coastal Pollution Risk Tool) within recently conducted research project funded by European Social Fund. CPoRT is a free application which may be used by any stakeholder interested in an estuary pollution problem.

Keywords: estuaries, concentration statistics, screening tool, stakeholders' involvement

1. Introduction and problem formulation

Estuaries and coastal waters present complex ecosystems characterised by interdependence of hydrodynamic and ecological processes (Savenije 2005; Saraiva *et al*. 2007). The excessive nutrient loading generated by rivers collecting the products of agriculture, industry and population in the upstream area (Rabalais *et al*. 2009), often causes water quality deterioration. Water body that is exposed to nutrient loading is susceptible to the process of eutrophication which causes undesirable changes in ecosystem structure and function (Smith *et al*. 1999). Hence, the nutrient concentration statistics are crucial data when analysing and making decisions for a coastal water body near an estuary. European Commission uses limit concentrations as indicators of the health of water body (Decision 2000; Piroddi *et al*. 2015). Management of coastal systems is an everlasting competition of the overlapping economic interests for the same resources, which makes decision making a challenging job. Among numerous integrated coastal zone management focus areas (e.g. transportation, leisure), decision makers and stakeholders are under pressure to address and solve the water quality problems at different levels starting from one estuary to larger areas of coastal zone (Pinto *et al*. 2013). However, as these problems are inherently intertwined and require holistic approach for finding a solution; the common practice is to engage consultants and engineers to suggest potential solutions. Such practice generates several alternative approaches which are then presented to decision and policy makers who are not necessarily experts in the area, which can possibly lead to the lack of solution ownership. The aim of this conference paper is to describe an existing tool and showcase how stakeholders of interest informed its' further development. Presented tool is based on the analytical model developed in Galešić *et al*. (2016) and it was tested by a group of students and a group of coastal management stakeholders. The former occurred within the project *Risk Assessment of the pollution caused by rivers and discharges in coastal area*, or Coastal Pollution Risk Tool (CPoRT) based in Split, Croatia. Illustrative example is given for local estuary to show the potential use for developed application. Finally, we discuss the response by tested group of stakeholders who were given the CPoRT to check its applicability, usefulness, and more requirements to be met in the future development.

2. Three- steps strategy

Implementation of Water Framework Directive (WFD) guidelines establishes the Drivers – Pressures – Status – Impacts – Responses (DPSIR) approach (OECD 1993) as a common practice when addressing the issues of an estuarine complex system. Detailed holistic approach demands a vast amount of measurements and monitoring systems along with complex numerical modelling to predict scenarios and assess the potential solutions. We propose the methodology which would enable key stakeholders to get not detailed, but quick screening insight into pressure-status-impact relations in an estuary. The model predicts the concentration statistics for conservative pollutant entering via river by using few input data.

2.1 *Theoretical background*

The analytical setup for the calculation and prediction of concentration statistics in environmental flow was already introduced by several authors in different media (Sawford & Sullivan 1995; Sullivan 2004; Andricevic 2008). In Galešić *et al*. (2016) the similar methodology is used but implemented in surface water systems, more precisely in an estuary as presented in Figure 1.

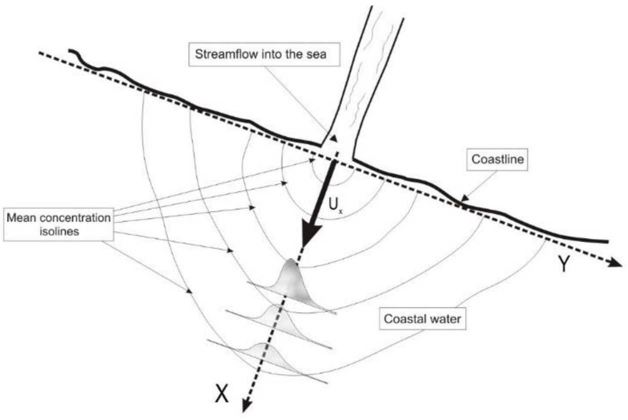

Figure 1. Problem description (adapted from Galešić *et al*. 2016)

We consider the problem of mixing in the *near field* zone of an estuary where steady and continuous river plume is entering coastal sea. For a conservative pollutant concentration, the fundamental advection diffusion equation is given:

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

where $c(\boldsymbol{x},t)$ is the scalar concentration in units of mass per unit volume, $v(\boldsymbol{x},t)$ is the flow velocity located by vector $\boldsymbol{x}$ at time t and e_m is the molecular diffusion. Furthermore, as described in previous research (Galešić *et al*. 2016), (1) is transformed into

$$\frac{\partial m_{n+1}}{\partial t} + \nabla \cdot \overline{vc^{n+1}} = -n(n+1)e_m \overline{c^{n+1}(\nabla c)^2} \qquad (2)$$

where, now, new variable to be solved is the absolute concentration moment (m_{n+1}) of $n+1$ order. Absolute concentration moments in general are defined by $m_n(x,t) = \int_0^\infty c^n p(c;x,t)dc$, where $p(c;x,t)$ is the pollutant concentration point probability density function (PDF), and PDF can be obtained by moment inversion (Sullivan & Ye 1996). In other words, if we are to solve the equation (2) for different orders and obtain an arbitrary number of concentration moments, we can reconstruct the PDF at the chosen point of certain pollution plume. The focus of this work is a 2D near field area of an estuary with the steady river plume and conservative pollutant entering the sea, for which the general recursive solution of concentration moments is:

$$m_{n+1}(x) = C_o^n \bar{c}(x) + \frac{k\alpha}{U_0} e^{-\frac{k\alpha}{U_0 \nu}(e^{\nu x}-1)} \int_0^x (2m_n(\eta)\bar{c_t} - m_{n-1}(\eta)\bar{c_t}^2 - C_o^n \bar{c}(\eta))\, e^{[\frac{k\alpha}{U_0 \nu}(e^{\nu\eta}-1)+\nu\eta]} d\eta \qquad (3)$$

where C_0 is the source concentration, $k=n(n+1)$, $\alpha = e_m/\lambda^2$, and c_t is background threshold concentration. The parameter λ defines the scale at which the concentration gradient, $\nabla c = \frac{c-c_t}{\lambda}$, occurs. To simplify this approach, the mean velocity field of the plume is considered to be steady and defined by $U(x) = U_0 e^{-\nu \cdot x}$, where U_0 is the riverine velocity at the source and $\nu[m^{-1}]$ is the robust attenuation coefficient representing all influences acting at the location to progressively reduce the initial velocity. Finally, the application for such concentration moments evaluation is retrieval of the PDF at an arbitrary point. In this work, simple moment matching method is applied to obtain the PDF. Following the previous research (Chatwin *et al*. 1995; Schwede *et al*. 2008) for other environmental flows, a beta distribution is used, and both PDF and CDF (cumulative distribution function) were calculated.

2.2 *The model – CpoRT*

Within the project, *Risk assessment of the pollution caused by rivers and discharges in coastal areas*, the methodology described in the previous chapter was further tested and implemented in a simple tool – the CPoRT. CPoRT aims to raise awareness of the importance of preserving water resources, with a thematic emphasis on coastal waters that are under burden of pollution from rivers and coastal discharges. One of the main outcomes of the projects was a development of tool for a quick assessment of probability of limit concentration exceedance. The coding and the application was developed in MATLAB 2012a (Mathworks 2012) interface. In Figure 2 the main working interface is presented. The application has a fully graphical interface, implemented as a single main tab and series of secondary tabs for the calculation and visualization of data. To get better spatial reference, there is an option to upload the map which may respectively be a screenshot of Google Earth or any other freely available open spatial data interface. However, the scaling and rotation factors within the working interface need to be adjusted in order to to assure the good spatial fitting.

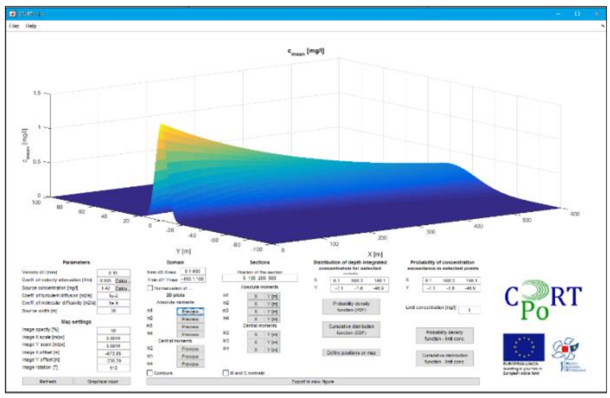

Figure 2. CPoRT application working interface

In the next step, a very few input data are required; making CPoRT quick and practical. Those data are organized into two blocks: parameters and domain. An arbitrary rectangular domain may be set in according to user's interest when analysing area, and it is defined by the initial and final value of X or Y, and an increment. Parameters block requires more data, some of which are measured data, but at the scenarios playing phase, the user may test the outcomes for different values. It is necessary to have the initial riverine velocity [m/s] at the source, contaminant source concentration [g/m^3] and the source width [m] representing the effective part of the river mouth width. The source concentration may be calculated in additional dialog box if the information about the contaminant max flux is known, $\dot{m}[kg/day]$. Molecular diffusion coefficient (e_m) is set to 10^{-9} $[m^2/s]$ by default, which is the regular value for surface waters (Rutherford 1994), but it is editable. The other coefficient, $e_t[m^2/s]$, is turbulent diffusion and it represents the scale of eddies that occur in the estuary when river plume is interacting with inertial mass of coastal sea. This value should be assessed for the estuarine system. However, if no data is available, different values can be tested in order to assess its potential effect on the pollution plume spreading; especially for the worst-case scenario. Velocity attenuation may be set to a measured value or calculated within dialog box if downstream centreline velocity data is known.

2.3 Stakeholders' involvement

In order to inform further development of CPoRT screening tool and incorporate end-user perspectives, two workshops were organised during different phases of the tool development process. In the early development stage (late spring of 2016), its use was tested with the group of 30 graduate civil engineering students at University of Split. The initial assumption was that participants have no significant knowledge of the river generated pollution in coastal seas. Nevertheless, the workshop was organised with the aim of gathering an initial feedback and feed into the further app development. Second and more highlighted testing was the workshop (September 2016) as the part of the project dissemination where relevant stakeholders (i.e. end-users of the screening tool) were invited. The group consisted of 44 participants from NGOs, academy (departments of science and technology, naval technology, institute for oceanography), SMEs, local water and sewerage utility, banking sector, local government and consulting agencies. The feedback from the participants was obtained both by the written survey and simultaneous discussion during the workshop. The survey questions were covering the themes of participants' background knowledge on the matter, their effective daily usage of computers, the functionality and the design of the CPoRT app, and finally the effect of CPoRT on their understanding and potential decision making in estuary and coastal waters.

3. Results

3.1 Illustrative example

The case study of Žrnovnica river, used in Galešić *et al*. (2016) is presented with the results obtained from developed CPoRT application. Žrnovnica is a small river next to the city of Split which has already been reported with increased nutrient values in the spring water (Loborec *et al*. 2015) and considering the golf courses near the river mouth, local population and agriculture there is a certain possibility of reaching limit concentration exceedance in the estuary. Such land use generated an assessed value of source concentration (c_0) for total nitrogen of 1.42 [mg/l] (using the guidelines from (Grizzetti & Bouraoui 2006)). The observed initial velocity for summer is 0.15 m/s and the effective river mouth width is 14 m. The limit value of nitrogen for the best water quality in Croatian regulation based on WFD is 1.0 [mgN/l], and such is used in the further calculation. Nevertheless, one may set the arbitrary value of limit concentration in the CPoRT workspace. In Figure 3 we present the map (courtesy of Google Earth) of Žrnovnica estuary which was imported into the CPoRT.

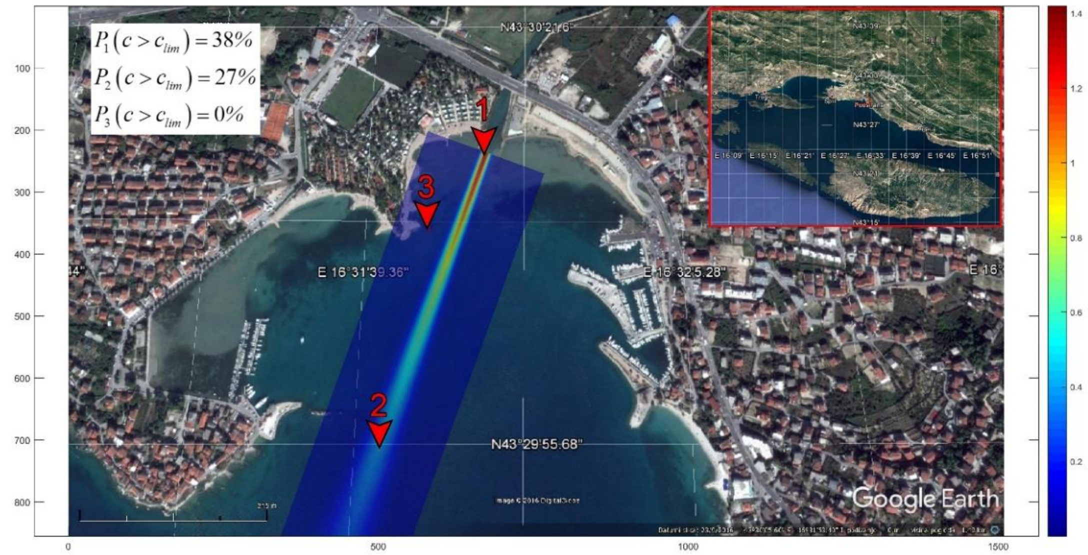

Figure 3. Žrnovnica estuary map with mean concentration results and chosen points (Courtesy of Google Earth)

The plot is modified to emphasize the location of the case study and the positions of three arbitrary chosen points where CDFs were calculated. The developed methodology is based on calculation of the conservative pollution concentration moments, hence we present the evolution of the mean value and variance along the downstream sections in Figure 4 a) and b). Finally, CPoRT may calculate and visualize both PDFs and CDFs, but for the purposes of this manuscript only the probabilities of limit concentration (1 mgN/l) exceedance at the chosen points are given (Figure 3). Three points are chosen at substantially different locations to see the extents of the solution. The first and the second point represent the longitudinal evolution of expected concentration, while the third is set outside of the expected plume transversal spread. The value of the probability at the location of the third point is important when considering the water quality at the beach of local auto camp. Since the probability at the beach location is near zero, the area may be considered out of the threat for the water quality reduction. Such result is the consequence of the river plume domination in the near field area where the beach is located and the lateral spreading of the plume is not so intense, which is visible in Figure 3.

3.2User's feedback

The workshops organised with students and later with stakeholders resulted in gathering invaluable feedback regarding the application functionality and its potential usefulness. For students, this was first interaction with a problem of a pollution in coastal zones.

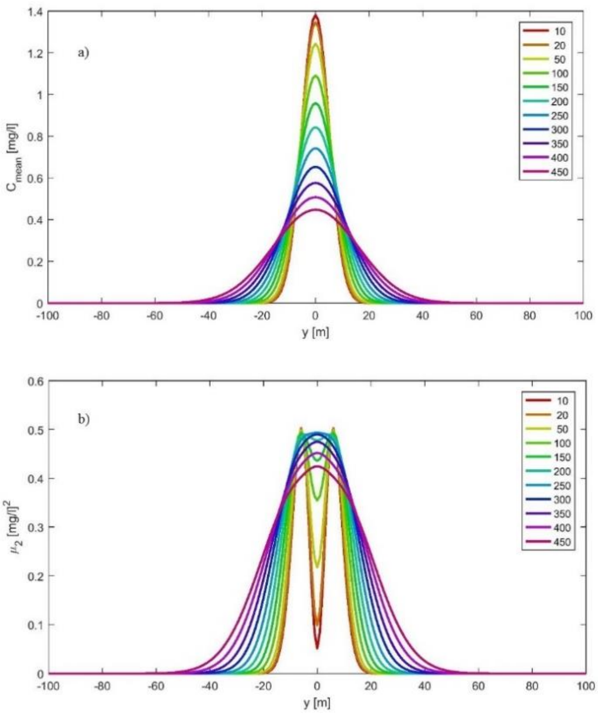

Figure 4. a) mean concentration; b) concentration variance, of total nitrogen at downstream cross sections

However, survey results indicate that they happened to grasp the basic principles of the physical processes happening at the river-coastal sea interface in less than 2 hours. Students provided feedback regarding software functionality by detecting the bugs and need for better explanation of the input parameters. In the stakeholders' workshop, most of the participants (30 out of 44) have reported to get better understanding of the problem and to feel more ownership of it. More than 50% (25 out of 44) said that the application would be more user friendly if it was web-based and GIS integrated. Furthermore, all of them agreed that CPoRT may be fully or partially helpful at decision making as a quick screening tool.

4. Conclusions and future work

CPoRT implements previously developed methodology for evaluation of concentration statistics for conservative pollutant transported by the river into an estuary. Such application represents a simplified screening tool which can serve as a platform for awareness raising through grasping the idea of an estuarine ecosystem's resilience. Furthermore, a tool can be uses for getting better inferences for relevant water resources management at the location. The 2D solution is based on few approximations: near field zone, steady and continuous river plume and conservative pollutant, and it lacks the details and calculation possibilities of common hydrodynamic numerical model. However, due to its simplicity it generates the results within seconds and the pre-processing can be done in few minutes when possessing the few required data. This simplicity provides an advantage when compared to more complex models. CPoRT has its place as the tool for educational purposes, raising awareness and helping stakeholders and decision makers to grasp the more general overview while detailed analysis and integrated complex scenarios are still do be done by more sophisticated numerical models. An interesting idea is built on the users' feedbacks and inputs by opening the doors to a collaborative modelling with the stakeholders for future CPoRT versions. Such approach, previously described (e.g. Basco-Carrera *et al*. 2017), would facilitate a learning process through which stakeholders would inform the development and be a part of the app co-production, while having continuous interdependent communication and collaborating in a joint effort to develop sustainable estuarine and coastal management.

Acknowledgment

We acknowledge the support of a student research grant co-funded by European Union from European Social Fund for the Project HR.3.2.01-0262, Risk assessment of the Pollution caused by rivers and discharges in coastal area (project CPoRT- Coastal Pollution Risk Tool)

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