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Process Engineering Tools to Reduce River In-stream Pollution

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This paper is focused on new possibilities for in-stream pollution control, such as automated systems for real time pollution counteraction based on advection-dispersion models for pollutant transport in rivers. Important related issues are addressed: steps to undertake for in-stream pollution control; the use of process engineering (PE) tools to fulfil these steps; and development of models for pollutant transport to be further used in control. The paper presents a case study involving a Scottish stream.

1. Introduction

1.1 Problem statement

Nowadays human pressure along flowing waters is constantly increasing: on one side there are pollution sources, lowering water quality; and on the other side there are consumers, requiring everyday larger water quantities with different water quality, depending on its destination (e.g. industrial use, irrigations, or livestock farms). These needs have to be fulfilled especially in areas with low availability of clean water, where rivers are crucial water sources for households including. Consequently pollution prevention and control have to be carried out. Pollution control is being approached interdisciplinary but in our opinion it is not benefiting enough from the knowledge and experience of engineering fields. This paper presents process engineering tools and methods applicable to pollution control.

1.2 Pollution control approaches

River pollution control literature has been focusing mainly on out-stream control techniques, concerning the reduction of effluent loads from potential pollution sources in order to avoid pollutants discharge in rivers (e.g. Hutchins et al., 2009). However, such techniques are prevention measures and do not solve entirely the problem of already polluted rivers (e.g. during accidental discharge), which should be approached trough in-stream pollution control (termed also counteraction, remediation or mitigation), in terms of reducing in river pollutant load. Lower amount of investigation has been carried out in this direction, even if instruments are vital, especially for rivers with multiple pollution sources or for those with accidental pollution hazard. The majority of studies are focused on insoluble pollutants, such as oil spills, counteracted trough methods like dispersion, herding, gelling, etc. (e.g. Adamovich et al., 2008); while soluble pollutants are not as popular. Two methods to decrease their in-stream concentration were employed in previous studies: (1) dilution and (2) neutralization.

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Pollutant dilution involves controlled discharge of clear water from sources (e.g. lakes, tanks) located beside river banks (e.g. Beck, 2005; Alvarez-Vázquez et al., 2010 and 2009); while neutralization involves controlled release of neutralizing agents aimed to transform pollutants in other compounds trough bio-chemical or chemical processes (e.g. Cristea et al., 2010). Another option to improve in-stream water quality would be to implement specific equipments for optimum re-aeration (e.g. weirs-like devices), designed using specific PE software. The limitation of this option is related to its applicability to only a limited number of water quality indices (e.g. dissolved oxygen).

1.3 The context of this paper

Among the very little amount of studies on remediation of in-stream pollution caused by soluble pollutants the most representative are Alvarez-Vázquez et al. (2010), on dilution, and Cristea et al. (2010), on neutralization. The first one implements optimal control (termed also model predictive control – MPC) along a short river reach, but in our opinion the underlying mathematical model for pollutant transport simplifies too much phenomena description (see Socolofsky and Jirka, 2005), since a key component of the transport (pollutant dispersion) is not taken into account. Cristea et al. (2010) employ a more suitable model (k-e turbulence model), but they only investigate the effects of a neutralizing agent released at a set point along a river without referring to the selection of a proper neutralizing agent or to the control of quantity to be released.

This paper presents a more comprehensive approach on new possibilities for in-stream pollution counteraction: support tools and methods for the application of MPC to dilution and neutralization. Following paragraphs point key problems related to in-stream pollution counteraction; show means to solve them; present a methodology for the development of pollution control systems; and describe an appropriate modelling approach.

2. Key issues and methodology for pollution reduction

Probably one of the most important problems related to in-stream pollution control is selecting the appropriate method (dilution or neutralization) to facilitate efficient water quality improvement in the shortest time. Regardless the method it is important to know where to discharge and what quantity in order not to produce more damage on the river and to be cost effective. From the point of view of implementing the control solution the key issue is the mathematical model formulation.

The methodology for the development of pollution reduction systems includes the following steps (described in detail in the next section): (1) identification of critical pollutants and critical reaches; (2) method selection: dilution vs. neutralization; (3) development of mathematical model for pollutant transport; (4) development of MPC units; (5) optimum location of releasing units. Usually the mathematical model development is the most consistent step, including: (1) parameter calculation using experimental data; (2) development of model for concentration prediction; (3) development of models for parameter estimation independent of detailed field data; (4) model calibration; (5) model validation (Ani et al., 2009). In this research there is an additional step at the end including the model further development to cater for other release types and not just the one considered during experiments (see Ani et al., 2010).

3. Development of in-stream pollution reduction automated system

3.1 Identification of critical pollutants and critical river reaches

A study on river pollution has to be carried out in order to identify the critical river reach/reaches in need for water quality remediation, as a function of: (1) pollution pressure along the river (given, among others, by population density, pollutants, pollution sources and accidents hazard); and (2) water needs at abstraction points. A PE tool useful in this purpose is the graphical mining method previously employed by Ani et al. (2010b) for the identification of pollution sources from long term monitoring data.

3.2 Method selection: dilution vs. neutralization

Discharge of clean water from storage tanks or lakes may be the most environmental friendly option, but not always applicable due to either shortage of clean water, the high costs to transport it or even the impossibility to do so. Controlled release of neutralizing agents is more suitable in such situations because neutralization needs lower volumes of substance (compared to clean water needed for dilution) and is not dependent on clean water availability. In case of neutralization there is a need for careful selection of the optimum neutralizing agent in order to obtain fast and effective pollutant neutralization resulting in environmental-friendly compounds. Neutralization agents can be chosen from a wide-ranging data basis of compounds with the help of a case based reasoning (CBR) tool. CBR tool will chose the most suitable neutralization agents based on compatibility calculation. Employed variables include: processes involving the pollutant to neutralize and each chemical in the data basis; compounds resulting in those processes; the nature of these compounds and their effect on river environment; conditions for transformation processes; transformation rates or other significant details.

3.3 Development of mathematical model for pollutant transport

The modelling approach is based on the advective-dispersive-reactive pollutant transport in rivers (Socolofsky and Jirka, 2005), a more appropriate approach compared to approaches in above cited studies, because it proved to be successful for a wide range of cases (see Ani et al., 2009).

Model development, calibration and validation relies on field data collected on Murray Burn stream during experiments organized at Heriot-Watt University, to mimic bulk releases, over a large range of flows (14 L/s to 2931 L/s), as described by Wallis (2005). Bulk pollutant releases are simulated using the Matlab model developed by Ani et al. (2009), while other release types (e.g. point continuous) are simulated with the help of additional modules (catering for those specific releases) added to previously validated Matlab model using the methodology of Ani et al. (2010). This methodology is an illustrative example on how existing knowledge, PE experience and tools can be employed in any modelling task in order to reduce experimental workload while model prediction accuracy is preserved at high values.

3.4 Development of MPC units

Rivers are complex systems with multiple influences and non-linear dynamics. MPC is the most appropriate option for concentration control along rivers, because it includes the mathematical model (of any complexity) and compensates efficiently delays and perturbations. So, the success of MPC relies on the concentration prediction given by the model. The decision on the quantity of water/neutralizing agent to be released is taken considering this prediction along with the concentration measured in the river, and the set point for the desired concentration in the river (e.g. threshold from legislation); in order to ensure that after water/neutralizing agent release the concentration in the river will be lower than the set point. Our intention is to develop MPC control unit with the help of Matlab MPC Toolbox.

3.5 Identification of optimum location of monitoring and releasing units

Optimum location of monitoring (measurement of pollutant concentration in the river) and releasing units (discharge of water/neutralizing agent) is vital for the success of any pollution remediation system. The formulation of an optimization problem depends on the dynamics of multiple variables: river hydrodynamics; pollutant transport phenomena; pollution sources; desired water quality level in the river; water abstractions. Objective functions have been formulated before for pollution remediation problems (e.g. Alvarez-Vázquez et al., 2009 and 2010) and also for the identification of optimum monitoring networks along rivers (e.g. Hu et al., 2009).

4. Case study simulation results

The efficiency of dilution and neutralization has been tested on Murray Burn using above mentioned experimental data and our mathematical model. The pollution source location is preserved for all experiments and simulations, while additional release unit (for fresh water or neutralizing agent, respectively) is located at an optimum distance downstream pollution source, in the middle of the stream. Three types of concentration series (in time and space) have been used in our comparison: original (relying on measurements at four sites downstream source); dilution (simulated when dilution is considered); and neutralization (simulated when neutralization is considered).

Figures 1 and 2 show results for the counteraction of a bulk (0.1 g) and a continuous (0.1 g/s) pollutant release with the stream at medium flow (261 l/s). Dilution and neutralization (additional release at 10 m downstream source) have been conducted to decrease concentration at the first monitoring site with 20% compared to measurements.

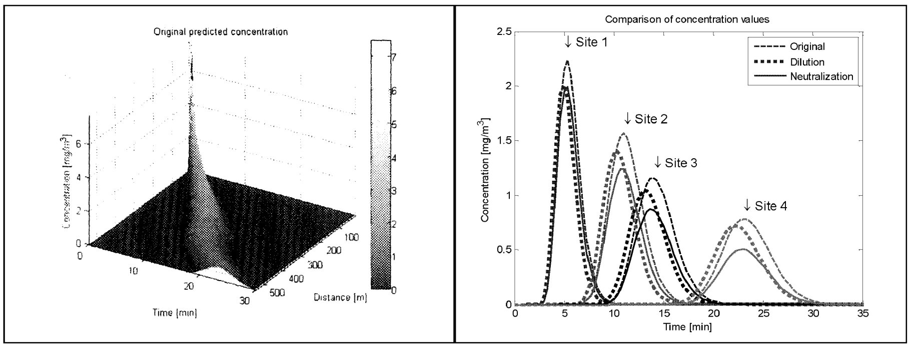

Figure 1: Results for point bulk release: no counteraction (left), counteracted (right).

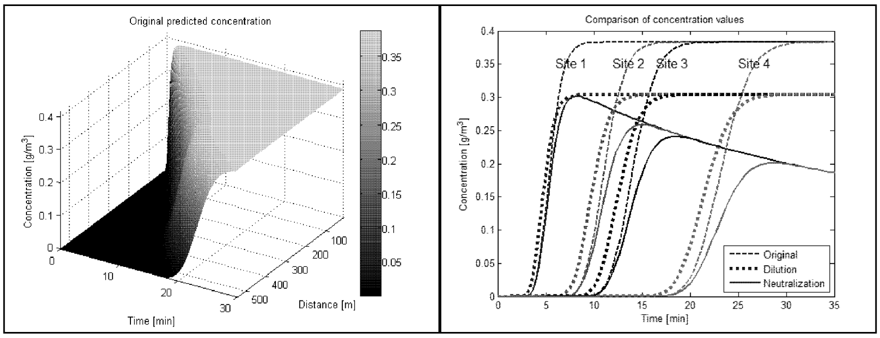

Figure 2: Results for continuous release: no counteraction (left), counteracted (right).

Results show that both dilution and neutralization are successful in reducing concentration, with difference of timing, affected river length and additional discharge.
Adding clean water to the river causes water flow increase, which results on one side on pollutant dilution (Figure 1 and 2) and on the other side on velocity and dispersion coefficient increase. This means shorter travel times at sites (Figure 1): a longer river length affected in shorter time by pollutant at lower concentration compared to the original situation (no counteraction). As pollutant will be transported faster dilution can help reducing environmental damages because sometimes flora and fauna can handle short exposure to large concentration, but die because long exposure to medium and low concentration (Ani et al., 2009). The main drawback of this method is the high amount of clean water required: 60 l/s for the bulk release and 68 l/s for continuous release.
Adding neutralization agent requires less additional discharge: 4 g for the bulk release and 2.5 g/s for continuous release; which can be dissolved in low amount of water. Furthermore concentration decrease along the river will be more effective compared to dilution (see sites 2 to 4 in Figures 1 and 2). Travel times at sites (for peak, centroid and trails) will be preserved as in the original situation, because hydrodynamic parameters are not modified. Only the magnitude of peak, centroid and trails will change due to concentration decrease. The drawback of this method is the availability of optimum neutralization agent for a pollutant and generation of additional substances in the river.
The comparison of bulk and continuous releases shows that a bulk is not easier to counteract even if less pollutant enters the river. Neutralization proved to be more efficient for bulks compared to dilution (see Figure 1), due to lower additional discharge involved and larger concentration increase.

5. Conclusions

Even if pollution control is carried out intensively now days there still are damaged rivers where management of pollutant overload is needed. This paper presents means to reduce in-stream pollution: automated systems for controlled release of (1) clean water to dilute pollutants; and (2) compounds acting as pollutant neutralization agents. Such systems are based on mathematical models for pollutant transport in rivers which are also discussed in the paper. Automated systems for in-stream pollution control are applicable, among other cases, for accidents, or in areas with water shortage, where river water is abstracted to be used in households or to be treated for drinking.

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