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Optimal sensor placement for detecting organophosphate intrusions into water distribution systems

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ABSTRACT

Placement of water quality sensors in a water distribution system is a common approach for minimizing contamination intrusion risks. This study incorporates detailed chemistry of organophosphate contaminations into the problem of sensor placement and links quantitative measures of the affected population as a result of such intrusions. The suggested methodology utilizes the stoichiometry and kinetics of the reactions between organophosphate contaminants and free chlorine for predicting the number of affected consumers. This is accomplished through linking a multi-species water quality model and a statistical dose—response model. Three organophosphates (chlorpyrifos, malathion, and parathion) are tested as possible contaminants. Their corresponding by-products were modeled and accounted for in the affected consumers impact calculations. The methodology incorporates a series of randomly generated intrusion events linked to a genetic algorithm for minimizing the contaminants impact through a sensors system. Three example applications are explored for demonstrating the model capabilities through base runs and sensitivity analyses.

1. Introduction

Water distribution systems (WDS) deliver water from water sources to water consumers via a large network of pipes, water treatment plants, pumping stations, storage devises and many other infrastructure components. Given their large size and numerous access points water distribution systems can be vulnerable to accidental or deliberate contamination events.

Detection by water quality sensors has the potential to mitigate the effects of contamination events and improve water security. This understanding had led to considerable amount of work conducted over the past decade on sensor network placement strategies and optimization in WDS, resulting in over 100 published papers (Hart and Murray, 2010).

A large number of contaminants can be introduced into a WDS. These can be further transported by the water to various locations in the network. Three members of the organophosphates group, chlorpyrifos (CP), parathion (PA) and malathion (MA), which are commonly used as pesticides, were examined here as possible contaminants. The objective of this study is to increase the reliability of water quality sensor locations in WDS methodologies by incorporating detailed reaction chemistry between possible contaminants, in this case organophosphates, and free chlorine containing water. The

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methodology developed herein consists of a multi-species water quality model based on the suggested reactions reported by Schwartz et al. (2014), and a genetic algorithm optimization process to find optimal sensor locations. The objective function is a modification of Ostfeld et al. (2008). Indexes were added to the original formulas in order to extend it for a multi-species framework. By doing so, the effect of the contaminants and their by-products on the consumers' could be quantified. Three example applications, with increasing complexity, were used to demonstrate the methodology performance and limitations through base runs and several sensitivity analyses.

2. Literature review

The work presented in this paper forms part of a field aimed at enhancing the security of water supply systems by using water quality sensors for early detection of contamination events. The general field includes studies on optimal sensor layout, contamination source identifying (Tryby et al., 2010; Kumar et al., 2012), response modeling and decision making following contaminant detection (Preis and Ostfeld. 2008a; Alfonso et al., 2010; Rasekh and Brumbelow. 2014) and event detection models (Murry et al., 2010; Oliker and Ostfeld. 2014), which are based on the statistical analysis of a data series in order to learn the behavior of water quality parameters and to identify deviation from normal behavior.

Over 100 studies have already been published in the field of optimal sensor placement. A review of the vast majority of these can be found in Hart and Murray (2010). In order to compare several algorithms a "battle of the water sensor networks" (BWSN) was conducted (Ostfeld et al., 2008) in which 15 different approaches were compared. The comparison consisted of four objective measures: (1) expected time of detection; (2) effected population prior to detection; (3) consumption of contaminated water prior to detection; and (4) maximization of detection likelihood. A winner was not declared due to the multi-objective nature of the above targets.

In most cases researchers tackle the problem of optimal sensor locations by assuming ideal sensors (Hart and Murray, 2010). In contrast, Preis and Ostfeld (2008b) formulated a methodology for contamination source identification using information from imperfect sensors. Ostfeld and Salomons (2004) generated a matrix of compromised nodes due to random contamination events; and a genetic algorithm was used to obtain the optimal coverage of the pollution matrix. Selection methods of the contamination events are additional sub-field of the sensors location problem. Perelman and Ostfeld (2010, 2012) and Rasekh and Brumbelow (2013) focused on finding extreme impact events, whereas Davis and Janke (2011) aimed at establishing pattern behavior of potential impact associated with contamination events. The above studies are engineering oriented, i.e. chemical aspects of the optional contaminants were not addressed.

Organophosphates are widely used pesticides, which makes them relatively accessible. Consumption of organophosphate can result in malfunction of the nervous system or even death, if consumed in large quantities. Chlorine, which is

Table 1 – Oragnophosphats pesticide and daughter compounds solubility and oral LD$_{50}$.

Organophosphats pesticide	Solubility (mg/l)	Oral LD$_{50}$ (mg kg^{-1})
Chlorpyrifos (CP)	2	[a]135
Chlorpyrifos oxon (CPO)	140	[b]2
3,5,6-trichloro-2-pyridinol (CPH)	36,000	NA
Malathion (MA)	148	[a]2100
Malaoxon (MAO)	38,000	[c]158
Parathion (PA)	12.4	[a]13
Paraoxon (PAO)	880	[d]1.8
p-nitrophenol (PAH)	3200	[e]202

[a] From WHO, 2009.
[b] From Lockridge et al., 2005.
[c] From Lewis 1996.
[d] From Tsang et al., 2004.
[e] From Isayev et al., 2006.

the most commonly used disinfectant for potable water, is known to oxidize organophosphates to form their corresponding oxon (Wu and Laird. 2003), which is typically much more toxic than the original contaminant. This property is shown in Table 1 which specifies the oral lethal reference doses (LD$_{50}$) of the organophosphate species modeled in this work and that of their oxidation by-products. Organophosphates have the potential to pose a significant threat to water consumers in a contamination event. No toxic cumulative relations were found in the literature between mother and daughter compounds, therefore in the incidents calculations described below, the maximal potential incidents between the two was used.

Durik et al. (2009) investigated the fate of several organophosphates in chlorinated water including chlorpyrifos (CP), parathion (PA) and malathion (MA). It was found that these organophosphates have similar degradation patterns when reacted with free chlorine. Organophosphates (OP) are rapidly oxidized by hypochlorous acid (HOCl) to form the corresponding oxon (OPO) which is more toxic than the parent pesticide. Both OP and OPO may undergo further hydrolysis to form OPH, a stable and less toxic group of end products. Hypochlorite ion (OCl^{-}) was found not to oxidize OP pesticides but rather to act as a nucleophile, accelerating hydrolysis at high pH values. This work is discussed further in the water quality model formulation section.
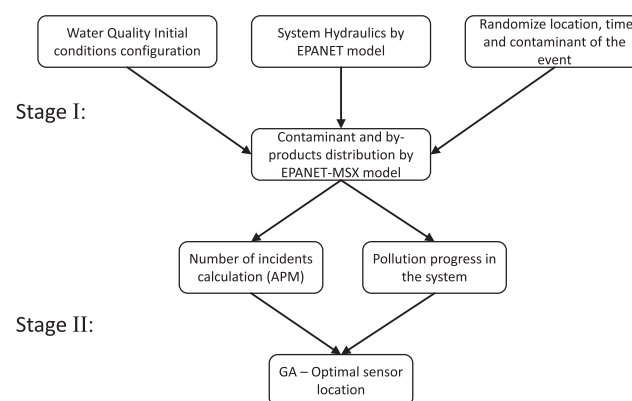

Fig. 1 – Solution scheme.