Water Research 101 (2016) 114–126

Contents lists available at ScienceDirect

Water Research

journal homepage: www.elsevier.com/locate/watres

# Water quality permitting: From end-of-pipe to operational strategies

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ARTICLE INFO

*Article history:*
Received 18 February 2016
Received in revised form
16 May 2016
Accepted 24 May 2016
Available online 27 May 2016

*Keywords:*
Integrated modelling
Multi-objective optimisation
Stakeholder engagement
Urban wastewater system
Water quality permitting

ABSTRACT

End-of-pipe permitting is a widely practised approach to control effluent discharges from wastewater treatment plants. However, the effectiveness of the traditional regulation paradigm is being challenged by increasingly complex environmental issues, ever growing public expectations on water quality and pressures to reduce operational costs and greenhouse gas emissions. To minimise overall environmental impacts from urban wastewater treatment, an operational strategy-based permitting approach is proposed and a four-step decision framework is established: 1) define performance indicators to represent stakeholders' interests, 2) optimise operational strategies of urban wastewater systems in accordance to the indicators, 3) screen high performance solutions, and 4) derive permits of operational strategies of the wastewater treatment plant. Results from a case study show that operational cost, variability of wastewater treatment efficiency and environmental risk can be simultaneously reduced by at least 7%, 70% and 78% respectively using an optimal integrated operational strategy compared to the baseline scenario. However, trade-offs exist between the objectives thus highlighting the need of expansion of the prevailing wastewater management paradigm beyond the narrow focus on effluent water quality of wastewater treatment plants. Rather, systems thinking should be embraced by integrated control of all forms of urban wastewater discharges and coordinated regulation of environmental risk and treatment cost effectiveness. It is also demonstrated through the case study that permitting operational strategies could yield more environmentally protective solutions without entailing more cost than the conventional end-of-pipe permitting approach. The proposed four-step permitting framework builds on the latest computational techniques (e.g. integrated modelling, multi-objective optimisation, visual analytics) to efficiently optimise and interactively identify high performance solutions. It could facilitate transparent decision making on water quality management as stakeholders are involved in the entire process and their interests are explicitly evaluated using quantitative metrics and trade-offs considered in the decision making process. We conclude that the operational strategy-based permitting shows promising for regulators and water service providers alike.

## 1. Introduction

Permitting is a widely practised approach to control environmental risk imposed by activities with non-negligible (water, gas or solid) waste emissions. Urban wastewater discharges to the environment are strictly and routinely regulated by setting quality and/or quantity limits on the effluent from wastewater systems based on treatment technology and estimation of the impact to the environment (U.S. Environmental Protection Agency, 2010a; Environment Agency, 2011). As protection of the aquatic environment has become more highly valued and understood, permits to discharge have become more demanding, more comprehensive but also more costly. For example, the UK water industry expects to invest £27 billion ($46 billion) between 2010 and 2030 (Severn Trent Water Limited, 2013) to install additional treatment capacity (e.g. biological, adsorption or ultrafiltration processes for the removal of metals, pharmaceuticals, nutrients and ammonia etc.) (Georges et al., 2009) to meet the requirements of "good status" of the European Water Framework Directive (WFD) (European Parliament and Council of the European Union, 2000). In addition to the financial burden, enhanced treatment (e.g. increased aeration or carbon source addition, and treatment process extension) can increase Greenhouse Gas (GHG) emissions (Flores-Alsina et al., 2011; Georges et al., 2009; Sweetapple et al., 2014a, 2014b) thus contributing to climate change. The increased wastewater treatment under the WFD is estimated to increase $CO_2$ emissions by over

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http://dx.doi.org/10.1016/j.watres.2016.05.078

110,000 tonnes per year in the UK (Georges et al., 2009). As such, it is difficult to comply with a stricter effluent permit without raising GHG emissions (and cost) by the conventional strategy of enlarging capacity of the existing treatment processes.

In contrast to the strict regulation of effluent discharges from wastewater treatment plants (WWTPs), spills of untreated wastewater from Combined Sewer Overflows (CSOs) are separately controlled by simple measures such as spill frequency (U.S. Environmental Protection Agency, 1995; Environment Agency, 2011), even though the highly concentrated wastewater spills have an acute toxic effect and can be lethal to the aquatic community (Kay et al., 2008; Weyrauch et al., 2010; Phillips et al., 2012). Indeed, research has clearly shown the poor correlation between reducing CSO spill frequency or volume and improving receiving water quality (Lau et al., 2002). It was estimated that some 8000 of approximately 25,000 CSOs in England and Wales were causing water problems at the beginning of the 1990s (Clifforde et al., 2006) and many remain underperforming even today (Nardell, 2012). The investment needed to improve CSOs is considerable, e.g. £2.9 billion ($4.9 billion) was estimated for the UK (Clifforde et al., 2006) and £26.5 billion ($45 billion) for the USA (U.S. Environmental Protection Agency, 1999).

To address urban water pollution in a more sustainable manner, flexible permitting approaches have been introduced to encourage cost-effective, risk reduction solutions as compared with conventional end-of-pipe permitting approaches. Examples are integrated permitting of wet weather discharges from sewer systems (U.S. Environmental Protection Agency, 2007), and water quality trading between a WWTP effluent discharge and other pollution source(s) in the same catchment to attain cheaper and environmentally equivalent or superior pollutant reductions (U.S. Environmental Protection Agency, 2007; Selman et al., 2009). Despite the progress achieved so far in integrated wastewater governance, regulation of WWTP effluent discharges and CSOs is still fragmented which contributes to the poorly coordinated management of the sewer system and the WWTP. For example, operational strategies of the sewer system are often developed to minimise the volume of wastewater spill and retain for treatment with limited account of the capacity of the WWTP (U.S. Environmental Protection Agency, 1995). Likewise, technological measures targeted at the WWTP, such as resource recovery and recycling schemes (Guest et al., 2009; Mccarty et al., 2011; Jin et al., 2015), innovative wastewater treatment technologies (Strous et al., 1997; U.S. Environmental Protection Agency, 2013; Castro-Barros et al., 2015) and efficient operation and control techniques (Thornton et al., 2010; Sweetapple et al., 2014a), are developed with little consideration of the interactions between the WWTP and the sewer. This may lead to under-performing solutions as the overall impact of the urban wastewater system (UWWS), i.e. the sewer and WWTP, on the receiving water is not fully appraised (Lau et al., 2002).

Integrated modelling of the sewer system, WWTP and receiving water body is a valuable tool in providing a holistic view of system performance (Meirlaen, 2002; Butler and Schütze, 2005; Vanrolleghem et al., 2005; Bach et al., 2014). It has already been used to demonstrate the potential for significant improvements in river water quality by optimising an integrated operational strategy of an UWWS without the need for upgrade or redesign of the treatment system (Schütze et al., 2002; Fu et al., 2008). Apart from surface water quality analysis, multiple features of system performance (e.g. GHG emissions, cost) can also be evaluated using mathematical modelling (Fu et al., 2008; Sweetapple et al., 2014a) and be considered simultaneously in optimising system operation by multi-objective optimisation tools (Deb et al., 2002).

The aim of this study is to develop a new permitting framework for the comprehensive regulation of WWTP effluent and CSOs, which reduces overall environmental impacts and improves treatment cost effectiveness simultaneously. An operational strategy-based permitting approach based on integrated control of the whole urban wastewater system, rather than traditional end-of-pipe limits or CSO spill frequency, is introduced in this paper. It is developed based on the latest systems thinking using integrated UWWS modelling, multi-objective optimisation, and visual analytics. The proposed approach is applied to a case study site and in the regulation context of England and Wales, UK.

## 2. Proposed permitting framework

A four step decision-making framework (Fig. 1) is proposed for the development of operational strategy-based permitting.

**Step I:** Due to the wide environmental, economic and social impacts of permitting policy (Johnstone and Horan, 1996), a broad coalition of stakeholders (e.g. wastewater dischargers, regulators, farmers, Non-Governmental Organisations (NGOs), academic experts, local residents) should be engaged in the first step to ensure no important perspectives are neglected in the decision-making. Structured and facilitated discussion fora should be arranged (e.g. workshops, customer engagement panels) to give all stakeholders an equal opportunity to express their needs and views and to facilitate discussions and exchange of information. A quantitative analytical procedure based on a correlation test (Yurdakul and Tansel Iç, 2009) is then employed to identify key stakeholders' interests without requiring full knowledge on the participants. To achieve this, the different stakeholder interests are first described by performance indicators (with the help of analysts and facilitation specialists) that can be assessed by an integrated UWWS model. For example, a fish farmer's interests can be formulated in terms of the DO and ammonia concentrations in the river downstream of the wastewater discharge. An independent analysis supported by the integrated UWWS model is then conducted to provide a balanced overview of the correlations and trade-offs between the performance indicators by analysing results from various operational scenario simulations. If two or more performance indicators are strongly correlated, only one is needed for further steps of the decision-making process (Hurford et al., 2014). The identified representative indicators are used in Step II as objectives to optimise system operational strategies.

**Step II:** Evolutionary algorithms (EAs) are a class of stochastic optimisation methods that simulate the process of natural evolution (Nicklow et al., 2010; Reed et al., 2013). They are considered to be especially suited to multi-objective optimisation problems (Reed et al., 2013) and perform better than other blind search strategies (Valenzuela-Rendon and Uresti-Charre, 1997). Multi-objective evolutionary algorithms (MOEAs) are chosen for the optimisation of integrated UWWS operation in this research because a) the UWWS is a non-linear system with various physical, chemical and biological processes, so the search for 'best' operational strategy cannot be solved by analytical methods; b) there are many operational handles in the system and therefore numerous combinations of operational variable settings, which makes it impractical to use enumerative techniques; and c) different (even conflicting) aspects of the system performance can be considered simultaneously in a single optimisation run. Non-dominated Sorting Genetic Algorithm-II (NSGA-II) (Deb et al., 2002), an improved version of NSGA and popular for its computational efficiency and good performance (Coello, 2006), is employed in this study, though others can also be applied.

To start, an optimisation problem is formulated, which consists of: