Science of the Total Environment 601–602 (2017) 571–579

Contents lists available at ScienceDirect

Science of the Total Environment

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

Measuring adaptive capacity of urban wastewater infrastructure – Change impact and change propagation

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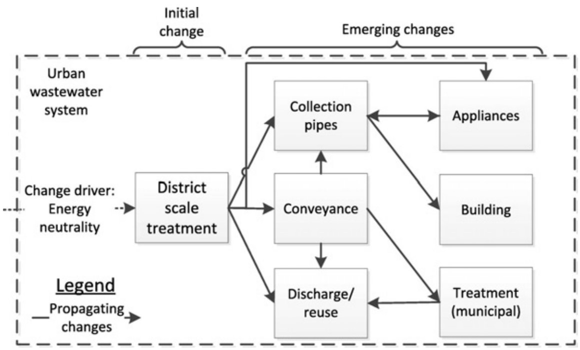
HIGHLIGHTS

- Evaluation of interdependency of (waste)water system components
- Quantification of system wide emerging changes as a result of innovation
- Identification of system components most affected by innovation
- Identification of the actors causing and receiving emerging changes
- Indication about a wastewater system's capacity to be adapted

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 7 March 2016
Received in revised form 24 April 2017
Accepted 17 May 2017
Available online 31 May 2017

Editor: D. Barcelo

Keywords:
Change propagation
Change impact
System
Transformation
Wastewater
Indicator

ABSTRACT

The ability of urban wastewater systems to adapt and transform as a response to change is an integral part of sustainable development. This requires technology and infrastructure that can be adapted to new operational challenges. In this study the adaptive capacity of urban wastewater systems is evaluated by assessing the interdependencies between system components. In interdependent and therefore tightly coupled systems, changes to one systems component will require alteration elsewhere in the system, therefore impairing the capacity of these systems to be changed. The aim of this paper is to develop a methodology to evaluate the adaptive capacity of urban wastewater systems by assessing how change drivers and innovation affect existing wastewater technology and infrastructure. The methodology comprises 7 steps and applies a change impact table and a design structure matrix that are completed by experts during workshops. Change impact tables quantify where change drivers, such as energy neutrality and resource recovery, require innovation in a system. The design structure matrix is a tool to quantify "emerging changes" that are a result of the innovation. The method is applied for the change driver of energy neutrality and shown for two innovations: a decentralised upflow anaerobic sludge blanket reactor followed by an anammox process and a conventional activated sludge treatment with enhanced chemical precipitation and high temperature-high pressure hydrolysis. The results show that the energy neutrality of wastewater systems can be address by either innovation in the decentralised or centralised treatment. The quantification of the emerging changes for both innovations indicates that the decentralised treatment is more disruptive, or in other words, the system needs to undergo more adaptation. It is concluded that the change impact and change propagation method can be used to characterise and quantify the technological or infrastructural transformations. In addition, it provides insight into the stakeholders affected by change.

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http://dx.doi.org/10.1016/j.scitotenv.2017.05.161

1. Introduction

Adaptive capacity or “the ability of systems to adapt to stress and changes by transforming into another more desirable state” (Folke, 2006) is proposed to be a key property for sustainable systems, whether natural or socio-technical (Holling and Gunderson, 2002). Specifically, for the field of urban water and wastewater, it has been argued that a sustainable urban water system is one that can cope with and adapt to changing circumstances (Daigger, 2012; Hering et al., 2013; Vairavamoorthy, 2009; Wilderer and Schreff, 2000). This requires adaptive management (Pahl-Wostl et al., 2007) and technological systems that are adaptive and flexible (Daigger, 2017; Jeffrey et al., 1997; Spiller et al., 2015). A study by Marques et al. (2015) shows that practitioners rank the indicators flexibility and adaptability 4th and 6th out of 29 sustainability indicators of relevance for urban water management. However, in this and other studies the methods for evaluation of adaptive capacity are not well defined. Spiller (2016) reviewed 38 studies that made used of sustainability indicators in urban water systems. Of eight studies that proposed the use of adaptive capacity indicators, only two studies provided a method to assessed adaptive capacity of technology and infrastructure. Kalbar et al. (2012) used expert judgement to allocate scores between 0 and 100 to indicate the flexibility of different wastewater technologies; and Milman and Short (2008) used questionnaires to detect which indicators of adaptive capacity are met in the water supply systems in three different cities. Furthermore, Spiller (2016) indicated that what is meant by adaptive capacity is often not well defined. Overall it appears that there is a shortage of approaches to measure adaptive capacity. Existing approaches are based on expert judgement and are not transparent about the reasoning behind an evaluation. Therefore, rending the assessments difficult to interpret and not easily defendable in decision making processes. Furthermore, the existing studies approach the concept of adaptive capacity by, if at all, providing rather broad definitions of what is meant by the term. Therefore, leaving much room for interpretation and inexplicit judgement of the experts consulted.

In this research the definition of adaptive capacity in engineered systems is narrowed by understanding it as a function of interconnectedness and coupling of system components. The importance of interconnectivity or coupling in engineered systems is that it makes them difficult to change, therefore impairing the system's adaptive capacity. Indeed, change in one part of the system rarely occurs in isolation, but rather affects other parts of the system (Ulrich, 1995). This interdependency makes change in engineering systems challenging. For water systems, Marlow et al. (2013) discuss system interdependency as one barrier for a transition towards sustainable urban water management. In a similar vein, Geels (2006) and Neumann et al. (2015) used longitudinal analysis to illustrate that wastewater systems follow technological trajectories that are a result of past investment decisions and choices of technology. Spiller et al. (2015) also highlighted this path dependency and the systemic effects of change in water and wastewater engineering. They propose design alternatives including phasing and modulation to reduce this path dependency effect. The aim of this paper is to develop a methodology to evaluate the adaptive capacity of urban wastewater systems by assessing how change drivers and innovation affect existing wastewater technology and infrastructure. By quantifying the impact of change drivers and innovations on the wastewater system (i.e. from user interface to discharge and reuse) the system's adaptive capacity is evaluated.

In the next section the methodology for evaluation of change impact and change propagation is presented for two innovations that focus on energy neutrality of wastewater systems. Thereafter, the results of this change impact and change propagation assessment method are presented, followed by a discussion of the application and implication of this method and proposals of further method development.

2. Methodology: change impact and change propagation

To capture the impact of change and the propagation of change through systems, a Design Structure Matrixe (DSM) is applied to quantify these changes. The results of this matrix are used to guide design procedures in various fields of engineering (Browning, 2001; Fig. 1). The principle of a DSM is best understood by drawing up a change network diagram - Fig. 1a (Keller et al., 2005). It can be seen that element A is changed as a result of an external change, signified by ΔX. This change driver can be related to policy, markets, customer demands or similar changes that take place in the context in which the technology has to function. The change to system component A can be considered the initial change or an innovation as a response to the change driver. This innovation is however not isolated, it rather requires more changes to the system. In the generic example of Fig. 1a the initial change to component A, propagates the change to the component B, C and E, which themselves propagate change from B – > D, F; E – > F and C – > B, E. This type of change is called emerging change (Eckert et al., 2004).

The network diagram can then be translated into the DSM by assigning a score of 1 to each outgoing arrow (Fig. 1b). Thereafter, an overall indicator value for outgoing changes or propagating changes ($\sum$ of column $= \sum$ (out)) and receiving changes ($\sum$ of rows $= \sum$(in)) can be calculated. DSMs are completed using expert judgement elicited during interviews or workshops.

In literature no evidence could be found that change propagation analyses and DSMs have been applied to urban water or wastewater systems. Therefore, the author tested a methodology for change impact and change propagation assessment in a workshop with 6 academic experts on wastewater systems. The methodology comprises 7 steps and is adapted from the work of Martin and Ishii (2002) and Suh et al. (2007) (Fig. 2).

2.1. Workshop with experts

Steps 1–4 aim to assess which components of a system have to be altered as a direct result of an external change driver (ΔX). The first step of this methodology is to obtain a detailed description of the current system by asking experts to draw flow diagrams that show the system components and its relationships (Martin and Ishii, 2002). Thereafter, the stakeholders associated to each of the system components were identified.

Experts were asked to identify key future change drivers whether political, environmental or technological. They were then asked to rank them according to their likelihood of occurring, to focus the analysis on the change drivers of highest urgency (only two change drivers are applied here for the purpose of demonstrating the method: water scarcity and energy neutrality – result Section 3.1, Table 1). Each change driver was associated to an engineering metric or a measurable goal. For water scarcity, the metric was litres per day, while for energy neutrality the metric was 100% of operational energy demand supplied by the treatment system itself. In the next step, the change drivers were combined with the system components in a table (Table 1). Thereafter, experts allocated a score of 1 to the change impact table to indicated the system components where innovations could help progressing towards the set goals (Section 3.1, Table 1).

Steps 5–7 aim at evaluating the emerging changes. In step 5, the engineering solutions that can help in progressing towards a set goal were defined more closely. During the workshop, it was decided to focus on the example of energy neutrality and to explore the change impact of implementation of a district scale treatment process and an upgrade of a municipal treatment plant. Through a discussion between the experts and the use of cause effect diagrams, the propagation of change was mapped. Using the diagram, the DSM was completed by scoring 1 for outgoing changes starting from the innovation implemented (ΔX). Finally, the rows and columns were summed to determine the outgoing/propagating changes and the receiving changes.