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Advantages of integrated and sustainability based assessment for metabolism based strategic planning of urban water systems

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HIGHLIGHTS

- Integrated and sustainability assessment was analysed in urban water system (UWS).
- Intervention strategies were evaluated for integrated UWS and water supply system.
- Metabolism type flows were simulated for analysing processes in urban water cycle.
- Strategies supporting water supply, stormwater and wastewater are ranked high.
- Both conventional and sustainability criteria are necessary for strategic planning.

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ABSTRACT

Despite providing water-related services as the primary purpose of urban water system (UWS), all relevant activities require capital investments and operational expenditures, consume resources (e.g. materials and chemicals), and may increase negative environmental impacts (e.g. contaminant discharge, emissions to water and air). Performance assessment of such a metabolic system may require developing a holistic approach which encompasses various system elements and criteria. This paper analyses the impact of integration of UWS components on the metabolism based performance assessment for future planning using a number of intervention strategies. It also explores the importance of sustainability based criteria in the assessment of long-term planning. Two assessment approaches analysed here are: (1) planning for only water supply system (WSS) as a part of the UWS and (2) planning for an integrated UWS including potable water, stormwater, wastewater and water recycling. WaterMet^2 model is used to simulate metabolic type processes in the UWS and calculate quantitative performance indicators. The analysis is demonstrated on the problem of strategic level planning of a real-world UWS to where optional intervention strategies are applied. The resulting performance is assessed using the multiple criteria of both conventional and sustainability type; and optional intervention strategies are then ranked using the Compromise Programming method. The results obtained show that the high ranked intervention strategies in the integrated UWS are those supporting both water supply and stormwater/wastewater subsystems (e.g. rainwater harvesting and greywater recycling schemes) whilst these strategies are ranked low in the WSS and those targeting improvement of water supply components only (e.g. rehabilitation of clean water pipes and addition of new water resources) are preferred instead. Results also demonstrate that both conventional and sustainability type performance indicators are necessary for strategic planning in the UWS.

1. Introduction

Urban water system (UWS) is typically applied to description of the three main subsystems of drinking water supply, stormwater and wastewater collection (Loucks et al., 2005). Assessment of each subsystem separately for particular purposes is a traditional approach which can be done by using physically based models such as the EPANET model to simulate hydraulic and water quality behaviour of water

Abbreviations: BAU, business as usual; CP, Compromise Programming; CSO, combined sewer overflow; D, water demand; DM, distribution main; GHG, greenhouse gas; GWR, greywater recycling; KPI, key performance indicator; MCM, million cubic metres; O&M, operations and maintenance; POP, population; RW, receiving water; RWH, rain water harvesting; S, water supply; SC, subcatchment; SN, sewer network; SR, service reservoir; TM, trunk main; WR, water resource; WSC, water supply conduit; WSS, water supply system; WTW, water treatment works; WWTW, wastewater treatment works; UWS, urban water system.

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distribution systems (Rossman, 2000) and the SWMM model to simulate hydrology–hydraulic behaviour of urban drainage and sewer networks (Rossman, 2010). However, impact assessment of the UWS performance on urban sustainable development would require a more integrated approach for modelling UWS components (Makropoulos et al., 2008).

This aim for assessing the UWS performance can be achieved by conceptually-based models which are able to capture the complex interrelations and interactions between the UWS subsystems (Savic et al., 2013). These models have been widely developed to fulfil the requirements of integrated modelling for assessment of various UWS components and subsystems such as water supply (Sušnik et al., 2012; Collet et al., 2013), drainage or combined sewerage (Fu et al., 2009) and integrated UWS (Makropoulos et al., 2008; Mackay and Last, 2010; Mitchell and Diaper, 2010; Fagan et al., 2010; Willuweit and O'Sullivan, 2013; Behzadian et al., 2014a; Venkatesh et al., 2014; Villarroel Walker et al., 2014; Behzadian and Kapelan, 2015). These models mainly evaluate urban water-related services as the primary aim of performance metrics and thus are limited to the conventional performance indicators. Some models deal with only water quantity-related metrics (e.g. Sušnik et al., 2012) or water quantity and quality (e.g. Fu et al., 2009) or water–energy nexus (e.g. Makropoulos et al., 2008; Mackay and Last, 2010; Mitchell and Diaper, 2010). A literature review conducted by Nair et al. (2014) reveals that integrated UWS modelling through a systematic framework is necessary to capture the dynamics of multiple water–energy–greenhouse gas (GHG) linkages within their components. The performance metrics related to water–energy–GHG nexus have also been provided by some integrated UWS models (e.g. Fagan et al., 2010; Behzadian et al., 2014b). However, the impact of urban water cycle on other sustainability dimensions such as socio-economic factors and environmental impacts is often overlooked (Huang et al., 2013). This multi-dimensional impact on the UWS performance can be envisaged by means of a metabolism concept for input, output fluxes and other processes in between (Venkatesh et al., 2014; Behzadian and Kapelan, 2015).

The concept of UWS metabolism is driven from the definition of urban metabolism as “the sum total of the technical and socio-economic processes that occur in cities, resulting in growth, production of energy, and elimination of waste” (Kennedy et al., 2007). The literature review conducted by Kennedy et al. (2011) manifested the importance of urban water-related fluxes in an urban metabolism analysis. In addition, whilst water is one of the four major components of urban metabolism (water, food, construction materials, and energy) identified by Baccini and Brunner (1991), urban water cycle can influence materials and energy in urban metabolism. In fact, the urban water cycle is a set of various services resembling a human metabolic system (Huang et al., 2013). The UWS metabolism implies a variety of required flows and fluxes (e.g. water, materials, chemicals and cost) to provide UWS services which consequently generate a number of other fluxes (e.g. GHG emissions, acidification and contamination discharge to air and water). Similar to other urban metabolic systems, the UWS metabolism is influenced by and has considerable impacts on other spheres such as social, economic and environmental. Understanding of these impacts is particularly important because this can affect the selection of appropriate interventions including both operational strategies and new infrastructure. All this requires a modelling approach for metabolism based assessment of the UWS performance.

Although numerous UWS models have been developed as listed above in the recent decades, the metabolism based UWS performance was addressed by only a few of them which are briefly discussed here. Fagan et al. (2010) presented a dynamic metabolism model which can provide a comprehensive set of metrics related to sustainability and cost effectiveness in the UWS. Huang et al. (2013) developed a conceptual metabolism model for integrated analysis of both real and virtual water in the UWS. The DMM and WaterMet^2 models are two different metabolism based models developed respectively by Venkatesh et al. (2014) and Behzadian and Kapelan (2015) under the EU TRUST (TRansition to sustainable Urban Systems of Tomorrow) project (Behzadian et al., 2014a). Although both models quantify a number of performance indicators related to various dimensions of future sustainability, the functionality of these two models is quite different. The DMM is a lumped metabolism model based on annually-aggregated of water flows within the entire UWS; hence, fluxes of water-related resources and other environmental impacts are quantified by multiplying annual water flow by a suitable conversion factor (Venkatesh et al., 2015). However, WaterMet^2 is a distributed metabolism model which simulates water related and other resources flows throughout the UWS components with a higher resolution both spatially (e.g. multiple water resources and service reservoirs) and temporally (e.g. daily and monthly) (Venkatesh et al., 2015). The difference of functionality in these models has caused intervention strategies to be simulated differently in these models and due to this, some optional interventions cannot be modelled using the DMM such as water recycling schemes and leakage. Villarroel Walker et al. (2014) also presented a MSA (Multi-sectoral Systems Analysis) tool which explores the impact of water-related strategic technologies on urban metabolism using systems analysis.

Furthermore, each potential and complex intervention in the UWS can result in specific performance and environmental impacts which can be quantified by a metabolism based analysis or other tools. As such, various dimensions of the UWS sustainability may be affected by these impacts (Alegre et al., 2012). Therefore, an overarching analysis of various interventions necessitates considering a multi-criteria performance assessment framework which can be linked to the simulation model (Chrysoulakis et al., 2013; Morley et al., 2014). Various objectives and subsequently performance indicators can be derived from these criteria in the UWS. Some of these criteria have been traditionally employed for the assessment of trade-offs between conflicting criteria such as cost versus reliability representing economic and engineering criteria, respectively. This is due to the fact that conventional urban water management aims to balance water supply–demand with respect to mainly economic criteria (Makropoulos et al., 2008). Relative to these conventional assessment criteria in water systems, assessments including new aspects of the sustainability framework (e.g. greenhouse gas emissions, resilience and social acceptance) may result in lasting benefits for complex socio-ecological systems and ecosystem services (Shah and Gibson, 2013). However, the impact of a holistic performance assessment including both conventional and new sustainability criteria needs to be carefully analysed in the UWS (Lai et al., 2008). Chrysoulakis et al. (2013) has recently employed multi-criteria analysis for the assessment of metabolism based performance of a number of urban planning alternatives such as changing land use and urban design. They also benefited from other existing models for calculating metabolic fluxes in urban areas and combined them into a structured geodatabase (ESRI ArcGIS).

Despite plethora of recent advances in the development of urban water system modelling and metabolism models, to the best of the authors' knowledge, none of the previous works has investigated a metabolism multi-criteria based performance assessment for strategic planning of the integrated UWS including the main components of water supply, wastewater and stormwater subsystems. Hence, the aim of this paper is to explore the detailed impact of integration of the UWS components on the metabolism based performance assessment when a number of optional intervention strategies are applied. This paper also aims to explore the impact of both conventional and sustainability type criteria on this assessment for long-term planning (e.g. 20–40 years) in the UWS. Next section presents the methodology followed by illustrating the case study and the analysed intervention strategies. The results are then discussed along with summarising key findings and recommendations for future works.