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Future trajectories of urban drainage systems: A simple exploratory modeling approach for assessing socio-technical transitions

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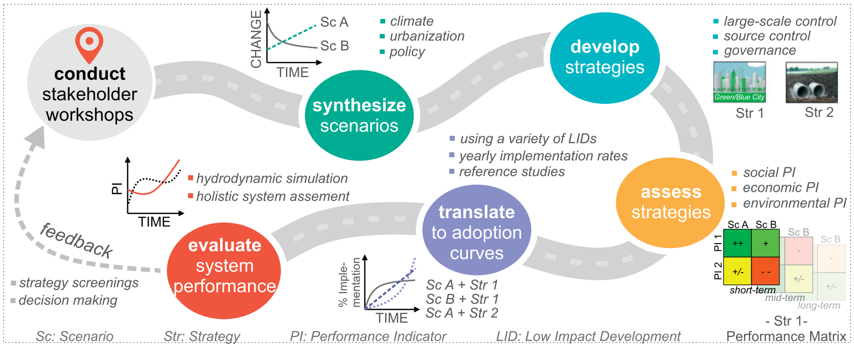
HIGHLIGHTS

- Investigating sustainability transitions by the creation of socio-technical pathways
- Long-term planning of urban drainage systems under changing city landscapes
- Integration of climate, population and policy uncertainties
- High adoption of green infrastructure mitigates the adverse effects of urbanization.
- Raingarden and sand filter designs show the best hydraulic and ecologic performance.

GRAPHICAL ABSTRACT



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ABSTRACT

In this work, we present a novel approach to explore future trajectories in urban drainage systems, emphasizing the adoption and implementation of sustainable 'nature-based' stormwater management strategies. The focus is on the development and long-term assessment of socio-technical pathways to create a multifunctional stormwater system at the city scale. The innovation is to identify and represent the socio-technical pathways by means of adoption curves for such transition processes. We combine urban planning policies and state-of-the-art urban engineering approaches with societal aspects and analyze them with traditional biophysical models (hydrologic-hydraulic sewer modeling). In doing so, different pathways from a current to a future system state are investigated under a variety of political, population and climate scenarios. Results allow for strategy screening by addressing the spatial and temporal implementation of decentralized stormwater control measures, to enable a successful transition to a sustainable future city. The model is applied to an ongoing transition of Kiruna, a city in Sweden, considering 36 different future trajectories over a transition period of 23 years. Results show that the trajectory of raingarden implementation under a sustainability policy can alleviate the adverse effects of urbanization (growth scenario). While this trajectory resulted in, for example, nearly the same sewer surcharge performance as that characterized by declining urbanization (stagnation) and a business-as-usual policy (with expected raingarden uptake rates approximately one-third lower), significantly better ecological performances (e.g. runoff treatment ratios up to 50%) are achieved.

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1. Introduction

Functional changes of urban infrastructure systems are highly dynamic due to external development pressures such as environmental and landscape changes, but also growing societal drives to provide resilient and sustainable infrastructure with high amenity for communities. Urban planning focuses on the geospatial development of a city and will become increasingly challenging for urban areas due to the external pressures of climatic and demographic changes all around the world (Sitzenfrei et al., 2013; Kirshen et al., 2014; Goncalves et al., 2018). To address these challenges through smart, resilient, and sustainable future infrastructures, urban planning and urban engineering must converge to develop suitable and sustainable solutions. Green spaces alleviate the adverse effects of urbanization by improving air and noise pollution, reducing extreme temperatures associated with Urban Heat Islands, supporting ecosystem diversity, increasing flood resilience, among many others (De Ridder et al., 2004; Kong et al., 2007; Gersonius et al., 2012; Kuller et al., 2018; Zhang and Chui, 2019).

In the urban planning process, urban water management is typically of low importance relative to other sectors, often resulting in water servicing being considered once major planning decisions have already been made (Ferguson et al., 2013). This limits the opportunity for early integration between land use and urban water planning processes, which is necessary to enable the identification and pursuit of sustainable water management opportunities. Achieving this integration requires different stakeholders to work together to develop and assess urban planning strategies that support long-term planning and decision-making for stormwater systems (Bach et al., 2013; Urich and Rauch, 2014; Löwe et al., 2017). These strategies encompass the deployment of stormwater infrastructure and related technologies, as well as important cultural, institutional, governance and economic shifts (Ferguson et al., 2013; Barron et al., 2017).

The consideration of societal influences on urban drainage system transitioning towards sustainable and resilient systems is increasingly gaining importance in urban water literature (Brown et al., 2008; De Haan et al., 2014; Dong et al., 2017; Shkaruba et al., 2017), reflecting a recognition that societal processes and needs have been key drivers in the evolution of urban water technologies. Example societal drivers include the need to adapt to climate change (Pyke et al., 2011; Haghighatafshar et al., 2018), the availability of financial resources and willingness to invest, growing aspiration for aesthetic urban environments, inclusive and participatory decision-making processes, and community expectations for drainage and pollution abatement (Kuzniecow Bacchin et al., 2014; Wolch et al., 2014; Moallemi and Malekpour, 2018). Since these types of societal processes are not fixed and are subject to the influence of both available technologies and myriad political, economic and social drivers, the evolution and adoption of urban water technologies by a given population is uncertain. Exploratory modeling allows for the consideration of many future pathways in the context of circumscribing scenarios, instead of considering a single most-likely pathway (Urich and Rauch, 2014; De Haan et al., 2016; Löwe et al., 2017). De Haan and Rotmans (2011) used a multi-pattern approach to describe and understand societal transition dynamics, which has been applied to previous models of investigating the performance of urban drainage system transitions (Rauch et al., 2017). Those models are complex and require large amounts of data and are therefore almost exclusively used for large regional planning.

In this work, we present a novel approach to explore possible developments (future trajectories) of urban drainage systems, emphasizing the uptake and phase-in of 'nature-based' stormwater management strategies at the city scale. We refer to these strategies interchangeably as 'green/blue' infrastructure or Low Impact Development (LID) (Fletcher et al., 2015). The approach investigates different pathways from a current to a future system state under a variety of external political, population and climate influences. The spatial and temporal uptake of green/blue strategies during such transition processes aims not only to counteract the structural and functional dynamics (e.g. city expansion and increasing surface runoff) that stress the urban drainage system, but also to fulfil the societal requirements of, for example, aesthetically appealing urban spaces or low environmental impacts. In this context, socio-technical pathways are developed and translated into a simple mathematical description (adoption curves) for further analysis within biophysical models, where the interactions of the sewer network and the LIDs are analyzed under non-stationary future boundary conditions. This simple application of explorative modeling allows identification of the most resilient and temporal-dynamic strategies for spatial implementation of LIDs under consideration of different socio-technical transitions. The adoption curves are dependent on land use classification and urban development patterns (Bach et al., 2015). The archetype model framework for this work is the spatially explicit model 'DAnCE4Water' presented by Rauch et al. (2017). In contrast to their work, a less sophisticated but more readily applicable approach for smaller case studies is sought.

The paper proceeds as follows: First, we present the modeling concept to (re-)design a city's stormwater management strategy during a transition process and explore possible performance developments for various socio-technical pathways. Second, we present a case study of Kiruna, Sweden, as a context for applying the model. A radical city transition is taking place in Kiruna, which makes it well-suited as a demonstration case, but the model also works for more common urban expansion conditions. Finally, we present the results of the model application to the case study, with an accompanying in-depth discussion of the benefits, shortcomings, and possible future directions of this work.

2. Material and methods

2.1. Modeling concept

Fig. 1 presents the concept for analyzing possible future trajectories of a city's stormwater system. The three main components, urban planning and urban engineering (UP and UE), the socio-technical transition (STT) and the biophysical model (BPM), build the basis for the model framework and are explained in detail in the subsequent subsections. UP and UE include the realization of a city's masterplan describing the geospatial and temporal city development (e.g., network growth and shrinkage). The outcomes are the creation and phased design of urban drainage network models. The STT investigates possible population, policy and climate scenarios, and their effects on the urban drainage system. Depending on the combination of the scenarios, green/blue strategies are developed and represented through adoption curves, which describe the temporal implementation of various LID planning options. The interconnections of the UP and UE and the STT are analyzed with the BPM, where hydrologic-hydraulic simulations are carried out to assess different performances of the drainage system. The model is updated for each time step (e.g., 1 year) and runs from the initial to the final state of the transition process (e.g., several decades). For simplification of the processes and to support the reader, key processes are associated by subsequently presented figures, equations, or references.

2.1.1. From urban planning (UP) to urban engineering (UE)

Urban masterplans aim to guide strategic long-term spatial development, including the design of future stormwater systems. It is usually insufficient to design a system for a single state (e.g. 'final state design'). Common pitfalls include too-early rehabilitation measures associated with high costs or compromised system performances at other states. However, single state design is still common practice. A phased design approach is more efficient, where intermediate states ('time points') are included in the design process to provide sufficient performance at all transition states (Creaco et al., 2015; Zischg et al., 2017b). In Zischg et al. (2017a) such a phased design approach for future urban drainage