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Exploring material stock efficiency of municipal water and sewage infrastructures in China

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ABSTRACT

A secured supply of clean water and sanitation relies on material- and capital-intensive municipal infrastructures, and thus requires a large quantity of material stocks. Major infrastructures sustaining the municipal water cycle from water supply to sewage management in China were probed for the period 1980–2050. The infrastructures proliferated rapidly in Chinese cities during the past three decades. The annual water supply capacity climbed from 11 to 100 km^3, the sewage treatment capacity soared from 1.1 to 50 km^3. To meet the demand of increasing urbanization, these infrastructures may have to more than doubly expand by 2050. Up to 3.3 gigatonnes (Gt) of construction materials, including 170 megatonnes (Mt) iron and steel and nearly 400 Mt cement (approximate to 10% of the global steel and cement production per annum), may be used to build up the infrastructure stocks. An indicator of material stock efficiency was devised to estimate potential and practical services per material stocks in the infrastructures can provide. Key findings include: (i) The conventional network-based water and sewage infrastructures might perform a declining material stock efficiency over the long run. (ii) The stock-based efficiency of the municipal infrastructures decreased by 25% from its peak in the early 1990s. It is driven down by the fact that pipe networks and sewage facilities are more material-intensive and usually developed behind water works. (iii) Nearly a half of the water supply capacity and 20% of the sewage treatment capacity were underutilized, leading to an evident gap between the potential and practical efficiency. The gap can be minimized by improving the utilization of the infrastructure's installed capacity.

1. Introduction

Clean water and sanitation, resilient infrastructure, sustainable cities, and sustainable resource consumption and production are interlinked targets among the 17 Sustainable Development Goals (SDGs) set out by the United Nations in its Agenda 2030 (UN-DESA, 2017). Water scientists and civil engineers made great efforts to enhance urban water sustainability and upgrade municipal infrastructures. In 2015, >90% of the world's population used improved drinking water sources and two thirds used improved sanitation facilities. An integration approach was viewed effective and valuable for water management in cities at all stages of development (UN-DESA, 2017). Not only water supply, sewage, and drainage systems were evolving toward systematic and integrated management. The urban water cycle was coordinated with the hydrosphere and the geography where the city locates. The water targets were also broadly reconciled with the economic, environmental, social, and institutional context (Brown et al., 2009; Hering et al., 2013; Marlow et al., 2013; Bach et al., 2014; Lanea et al., 2015; Larsen et al., 2016).

Environmental and resource considerations had become a crucial component in urban water planning and management. Life cycle assessment and ecosystem-based approaches were employed to make urban water system better meet its environmental objectives, ranging from pollution control, greenhouse gases reduction,

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to ecological regeneration (Lundin et al., 2000; Lundie et al., 2004; Pahl-Wostl et al., 2011; Lemos et al., 2013; Marlow et al., 2013). Sustainable urban water management can also promote resource efficiency by minimizing the use of energy and process chemicals and reclaiming heat and nutrients from wastewater streams (Daigger, 2009; Van Drecht et al., 2009; Larsen, 2015; Zhang et al., 2015). Energy and climate change consequences of water and sewage management, in particular, attracted a body of research in recent years (e.g., Nair et al., 2014; Venkatesh et al., 2014; Smith et al., 2016; Zhang et al., 2017). There was research estimating material use for infrastructure construction and calculating environmental emissions associated with material production. These indirect emissions could account for nearly 20% – a noted portion of the climate change impact throughout the life cycle of urban water systems (Venkatesh et al., 2011; Wu et al., 2015; Zhang et al., 2017). Essentially, the materials were treated as flows rather than stocks in life cycle assessment.

In comparison, material stocks accumulating in water and sewage infrastructures and their function for water services were probably underappreciated. Nearly a half of the natural resources extracted in the past century were found transformed to material stocks in buildings and the built environment (Krausmann et al., 2017), including municipal water infrastructure (Tanikawa et al., 2015). The material stock analysis sprang out after 2000 (UNEP-IRP, 2010; Müller et al., 2014). A number of research focused on the stocks in the whole economy or in buildings, transportation, and energy infrastructure (e.g., Canning, 1998; Davis et al., 2010; Jacobson and Delucchi, 2011; Wang et al., 2015a, b; Wiedenhofer et al., 2015; Krausmann et al., 2017), while a less number of studies were devoted on water infrastructure in urban areas (Meinzen-Dick and Appasamy, 2002; Browder et al., 2007), and fewer with dynamic estimation (Maurer et al., 2013; Pauliuk et al., 2014; Hou et al., 2015). Some work examined the material intensity in infrastructure stocks (Fishman et al., 2014; Schaffartzik et al., 2014), but no sufficient efforts were paid to the stock efficiency (Lwin et al., 2017). The International Resource Panel of the United Nations Environment Programme (UNEP-IRP, 2017) called for further research for material stocks to provide insights into resource efficiency potential.

This present work aims to assess the material stocks embodied in municipal water and sewage infrastructures in China and to explore the stock-based efficiency of water management. The work will be favorable for the following aspects: First, China is already the world's biggest country in terms of municipal water supply and material stock accumulation. It was also a major driver of global resource use over the past decades (FAO, 2016; Krausmann et al., 2017). Analyzing municipal water cycle, water infrastructure, and its material stocks in China will surely enrich our knowledge on sustainable resource and water management. Furthermore, the stock-based method is suitable to examine the evolution of long-standing and material-intensive infrastructures. It may help obtain alternative perspectives that the flow-based methods have not provided. Finally, the work can offer a vivid case to illustrate the interlink between multiple SDGs for material resources, clean water, and urban infrastructure.

2. Material and methods

A dynamic modeling was constituted to explore municipal water and sewage infrastructures in China. Material stock assessment was carried out to estimate construction materials embodied in the infrastructures. Scenarios toward 2050 were probed for the development of utilities and material stocks.

2.1. Municipal water cycle and infrastructure

The system boundary of the municipal water cycle is depicted in Fig. 1. A succession of boxes are plotted from left to right, characterizing processes of (*1*) raw water collection and transmission, (*2*) municipal water purification, (*3*) municipal water distribution, (*4*) water use, (*5*) sewerage, and (*6*) municipal sewage treatment. The water supply infrastructure consists of facilities in process (*1*) to (*3*). The sewage infrastructure includes process (*5*) and (*6*). Only a slight proportion of municipal wastewater was recycled in China (MOHURD, 2013; CUWA, 2013a), the recycling infrastructure was thus not considered by the present research.

The water flow from process (p) to process (q) in the municipal cycle was defined as F_{p-q}. The future water supply flow (F_{2-3}) was estimated first. With this value, the fluxes of sewage generation (F_{4-5}) and treatment (F_{5-6}) can be derived, and the capacity of municipal water supply (Y_2) and sewage treatment (Y_6) can be determined (see details in Table 1 and our previous research (Wang et al., 2017)).

Within the system boundary of the water cycle, the stocks of construction materials embodied in the infrastructures could be ascertained. These material stocks were computed as a product of the infrastructure capacity timing the material intensity per infrastructure. Major variables of the municipal water cycle and the infrastructure were presented in Table 1.

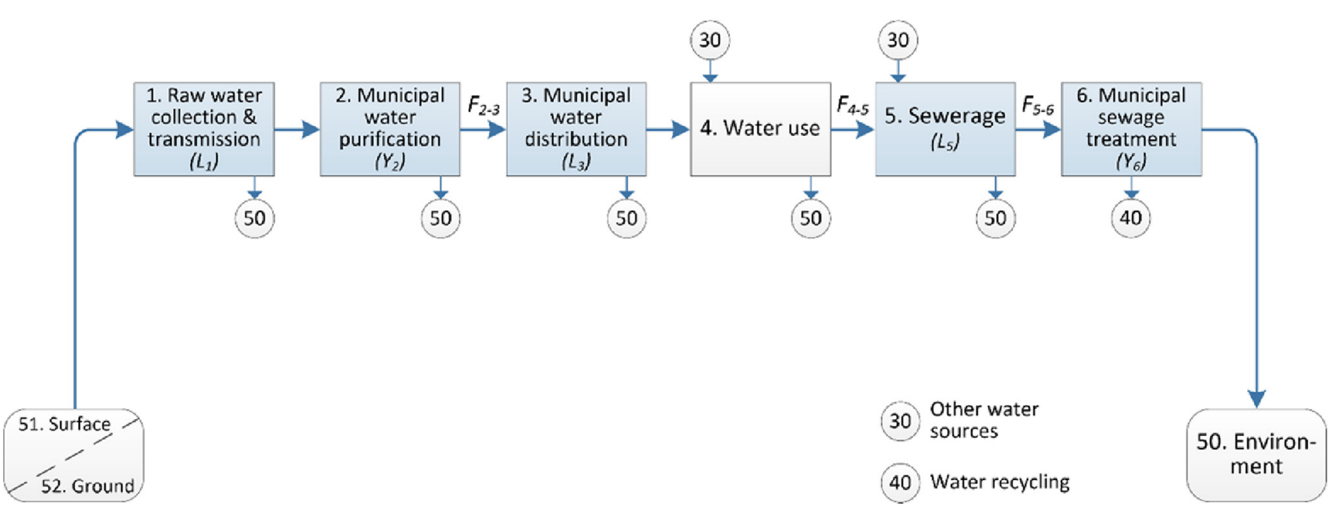

Fig. 1. System boundary definition of the municipal water cycle and infrastructures. The symbols (e.g. F_{2-3}) are interpreted in Table 1.