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Research article

Sewer-mining: A water reuse option supporting circular economy, public service provision and entrepreneurship

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A B S T R A C T

Water scarcity, either due to increased urbanisation or climatic variability, has motivated societies to reduce pressure on water resources mainly by reducing water demand. However, this practice alone is not sufficient to guarantee the quality of life that high quality water services underpin, especially within a context of increased urbanisation. As such, the idea of water reuse has been gaining momentum for some time and has recently found a more general context within the idea of the Circular Economy. This paper is set within the context of an ongoing discussion between centralized and decentralized water reuse techniques and the investigation of trade-offs between efficiency and economic viability of reuse at different scales. Specifically, we argue for an intermediate scale of a water reuse option termed 'sewer-mining', which could be considered a reuse scheme at the neighbourhood scale. We suggest that sewer mining (a) provides a feasible alternative reuse option when the geography of the wastewater treatment plant is problematic, (b) relies on mature treatment technologies and (c) presents an opportunity for Small Medium Enterprises (SME) to be involved in the water market, securing environmental, social and economic benefits. To support this argument, we report on a pilot sewer-mining application in Athens, Greece. The pilot, integrates two subsystems: a packaged treatment unit and an information and communications technology (ICT) infrastructure. The paper reports on the pilot's overall performance and critically evaluates the potential of the sewer-mining idea to become a significant piece of the circular economy puzzle for water.

1. Introduction

The global urbanization trend has resulted in a constant increase of urban populations. In Europe, for example, the percentage of the urban population is 73.4% of the total and is expected to rise up to 81% by 2050 (UN, 2014a,b). This trend is coupled with water scarcity due to supply-side impacts of climatic changes (Klein et al., 2014) and improving living standards (UNESCO, 2016) resulting in increased pressures on water resources. For this reason, recent EU reports stress the need to encourage European stakeholders to first acknowledge that "water is an essential but limited resource and needs to be carefully allocated and used", and then to endorse and promote circular and green economies (EUWA, 2014).

Turning waste into a resource is an essential part of increasing the efficiency of resources and moving towards a more circular economy (EC, 2015). In the context of the urban water cycle, this translates primarily into using treated wastewater (a waste) to supply (as a resource) a (more often than not) non-potable water use. This can be implemented at several scales, associated with the degree of centralisation of the treatment employed (Libralato et al., 2012).

At the more centralised scale, the use of tertiary treatment in

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existing wastewater treatment facilities can open up non-potable reuse options, especially in large water consumers such as agriculture or industry. Indeed, notable examples of such large-scale reuse include cases in Spain (Mujeriego et al., 2008), Israel and Australia (Jimenez and Asano, 2008). However, as centralised wastewater treatment plants are by definition close to the urban centres they service, they are not necessarily close enough to agricultural or industrial activities and as such the construction and operation of treated effluent conveyance systems can rival in costs even desalination.

Decentralized technologies on the other hand, by their very nature (i.e. *in situ* installation), are closer to the circular economy concept, in that by closing the loop between waste and resource locally, waste water becomes not 'just' a by-product of the urban water system with some potential for reuse, but a resource *per se*, also decreasing (or eliminating) the barrier of transmission costs.

Decentralized water recycling technologies come in a wide variety of options and scales (Rozos and Makropoulos, 2012). At the lowest scale, in-house units treat water from the hand-basin, shower and bath and provide this water for use in the toilet, washing machine and for outside uses (Dixon et al., 1999; Leggett et al., 2001). The problem at this scale is that the maintenance and operational costs are very high to allow economically viable schemes and as such, this scale of reuse (termed greywater reuse (Li et al., 2009)) usually relies on additional motivation, such as drought conditions or positive environmental attitudes of individuals at the household level (Koutiva and Makropoulos, 2016). On the other hand, greywater recycling at a larger scale, the cluster or neighbourhood scale (e.g. Paris and Schlapp, 2010), has much lower running costs but requires extensive work for the installation of dual reticulation, which unless installed during the construction phase, results in considerable costs.

Sewer-mining is a less known option in the toolbox of decentralized wastewater reuse technologies at an intermediate (local-to-neighbourhood) scale. It extracts wastewater from local sewers, treats it at the point of demand and supplies local non-potable uses (such as urban green irrigation) while returning treatment residuals back to the sewer system (Butler and MacCormick, 1996) for eventual treatment in the centralised wastewater treatment plant thus eliminating the need for both expensive conveyance systems from end of pipe treatment installations and dual reticulation infrastructure.

This type of technology was pioneered in Australia to provide non-potable water for urban uses, including for example the irrigation of urban green spaces, sport facilities and even domestic uses (AEDCS, 2005; Sydney Water, 2013; Chanan and Woods, 2006; Fisher, 2012; Xie et al., 2013). Table 1 displays some successful applications of sewer-mining in Australia with capacities ranging from 100 to over 2000 m^3/d. It is worth noticing that apart from the application in Darling Quarter, where the entire treatment system is fitted within a room in the building's basement and extra care had to be taken to ensure no malodour, the average cost of reclaimed water is very close (if not lower) to potable water costs.

Despite the existence of sewer-mining success stories in Australia, several challenges remain currently in the way of such applications in Europe, including public perception, inadequate regulatory frameworks, engineering issues, as well as, importantly, financial constraints. Euro-zone GDP in the final quarter of 2015 was still below its pre-crisis peak of early 2008 whereas America's was almost 10% above its peak of late 2007 and Australia's almost 60% (The Economist, 2016). For this reason, the European Commission has launched an investment plan for Europe to unlock over EUR 315 billion of investment over the next few years and deliver a powerful and targeted boost to economic sectors that create jobs and raise growth (EC, 2016). Regarding the water sector, a GDP growth around 0.2–0.6% is expected as a result of water industry investments alone, to achieve compliance with the WFD (EC, 2015). It therefore becomes evident that this period is quite favourable in Europe for the kind of entrepreneurship that combines circular/green economies with water management.

In this study, we suggest that recent technological advancements, regarding both wastewater treatment and smart ICT technologies, offer an opportunity for Small Medium Enterprises (SME) to become a principal actor in the water reuse sector, creating a real market for water reuse services and increasing its applications in the EU. Specifically, we argue that Sewer-mining could develop into a win-win situation whereby the benefits of market competition will be brought to bear in the water sector due to the ability of SMEs to manage sewer-mining units and sell the treated wastewater (or indeed irrigation services) to city municipalities, while water companies also benefit being able to sell untreated sewage, or at least have some of their wastewater treated at no cost to them. All in all, two major objectives set by the European Commission regarding (i) economic growth (new investments, new jobs, etc.) and (ii) environmental protection (reduce the pressure on water resources while increasing ecosystem services such as heat island effect reduction through urban green irrigation even in water scarce areas) stand to benefit from an adoption of sewer-mining as a dominant form of urban treated wastewater reuse.

To support this argument, what is doubtlessly needed is a demonstration of the technology's ease of deployment, operational efficiency and viability in terms of its business model. In this paper, we present the configuration and operation of a prototype sewer-mining unit, piloted in the city of Athens, Greece, highlighting the

Table 1
Sewer-mining applications in Australia.

Location	Technology	Capacity	Use	Cost
[a]Flemington Racecourse Melbourne, Australia	Dual membrane, UV	100 m^3/d	Irrigation	Estimated unit capital cost 0.42 $/$m^3$, operational cost 0.43 $/$m^3$, prices 2006
[b]Darling Quarter, Sydney's CBD Australia	Moving bed, biofilm reactor, RO, UV	170 m^3/d	toilet flushing, irrigation, cooling towers	unit capital cost 2.2 $/$m^3$ operational cost 2.1 $/$m^3$, prices 2011
[c]Riverside Rocks Park, Sydney, Australia	Reed beds, UV	360 m^3/d	Irrigation	estimated unit capital cost 0.49 $/$m^3$, prices 2006
[d]Pennant Hills, North Sydney, Australia	MBR, UV	1000 m^3/d	Golf field irrigation	estimated unit capital cost 0.49 $/$m^3$, prices 2008
[e]Sydney Olympic Park	SBR, nutrient	2191 m^3/d	Toilet flushing, irrigation	cost 1.05 $/$m^3$, prices 2009 (90% the price of potable)

[a] Clearwater (2016).
[b] ISF (2013).
[c] McFallan and Logan (2008).
[d] WERF (2008).
[e] Listowski (2009).

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