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Economies of density for on-site waste water treatment

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ABSTRACT

Decentralised wastewater treatment is increasingly gaining interest as a means of responding to sustainability challenges. Cost comparisons are a crucial element of any sustainability assessment. While the cost characteristics of centralised waste water management systems (WMS) have been studied extensively, the economics of decentralised WMS are less understood. A key motivation for studying the costs of decentralised WMS is to compare the cost of centralised and decentralised WMS in order to decide on cost-efficient sanitation solutions. This paper outlines a model designed to assess those costs which depend on the spatial density of decentralised wastewater treatment plants in a region. Density-related costs are mostly linked to operation and maintenance activities which depend on transportation, like sludge removal or the visits of professionals to the plants for control, servicing or repairs. We first specify a modelled cost-density relationship for a region in a geometric two-dimensional space by means of heuristic routing algorithms that consider time and load-capacity restrictions. The generic model is then applied to a Swiss case study for which we specify a broad range of modelling parameters. As a result, we identify a 'hockey-stick'-shaped cost curve that is characterised by strong cost reductions at high density values which level out at around 1 to 1.5 plants per km^2. Variations in the cost curves are mostly due to differences in management approaches (scheduled or unscheduled emptying). In addition to the well-known diseconomies of scale in the case of centralised sanitation, we find a similar generic cost behaviour for decentralised sanitation due to economies of density. Low densities in sparsely populated regions thus result in higher costs for both centralised and decentralised system. Policy implications are that efforts to introduce decentralised options in a region should consider the low-density/high-cost problem when comparing centralised and decentralised options.

1. Introduction

1.1. Comparing central and decentral sanitation costs

Costs are an integral criterion for decisions on suitable wastewater management systems (WMS) for both centralised and decentralised scenarios (inter alia Hamilton et al., 2004; Maurer et al., 2006; Libralato et al., 2012; Truffer et al., 2013). Decentralised WMS are increasingly considered as potential substitutes for centralised WMS with sewer networks (inter alia Tchobanoglous et al., 2004; Massoud et al., 2009; Larsen et al., 2013; OECD, 2015). Typically, decentralised WMS – also called on-site (OST) WMS – treat small wastewater flows in individual residences or residential clusters (cf. Tchobanoglous and Leverenz, 2013), which can, as a consequence, save on extensive sewer networks (Libralato et al., 2012). However, it is a complex task to determine the optimal degree of centralisation in water and wastewater management (Eggimann et al., 2015; Poustie et al., 2014; Adams et al., 1972; Guo and Englehardt, 2015; Lee et al., 2013) because the overall costs in a region depend not only on the sum of the costs of all individual technological components but also on how they are spatially distributed. This implies that besides the usual cost-driving factors like context uncertainties, economies of scope, economies of scale or high network infrastructure life-spans (Hansman et al., 2006; Markard, 2009; Starkl et al., 2012), space-dependent cost items such as economies of density and network externalities have to be taken into account.

In the case of centralised WMS, space-dependent cost effects play out in the form of major economies of scale at the level of the

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wastewater treatment plant (i.e. per capita costs decrease with the number of people in a catchment connected to it), whereas the costs of building up a sewer system show diseconomies of scale (i.e. to reach full connection more distant settlements need to be connected). These cost characteristics have been intensively discussed in the literature (cf. Townend, 1959; Downing, 1969; Adams et al., 1972; Haug 2004, Friedler and Pisanty, 2006; Maurer et al., 2006, 2010). Nevertheless, the cost characteristics of OST systems are much less well known. In general, unit prices of OST plants do not depend on the number of units installed in a specific region. However, management, maintenance and regulation schemes may turn out to be very costly, because travel costs for service teams may become important (inter alia Kennedy-Walker et al., 2014; Semiyaga et al., 2015; Hamilton et al., 2004; Kaminsky and Javernick-Will, 2013). An integrated assessment of these different cost components for determining the optimal degree of centralisation in a region is however lacking (Hamilton et al., 2004; OECD, 2015; Eggimann et al., 2015). The optimal degree of centralisation is directly linked to the OST plant density, as this increases in response to growing population percentages serviced by on-site treatment plants. In this paper we examine an essential parts of such an integrated cost assessment, which are arguably the least well understood, namely those that are related to spatial density of OST plants. We present a model-based approach to examining the economies of density[1] of OST plants and conduct a sensitivity analysis of different management approaches. A model-based approach is needed because cost-data collection is challenging and there is a lack of available data to carry out a systematic comparison of the costs of different WMS in a region.

1.2. How space and transportation influence costs

In the field of spatial economics, the important influence of spatial dispersion on service provision has long been postulated (Wegener, 2011): many different theoretical models based on transportation-cost considerations have been developed, such as von Thünen, (1875) ring model, Christallers' (1933) model of optimal provision or the optimal city-size model of Arnott (1979). Such studies highlight the fact that the transportation of material or personnel are critical for efficient service provision. Much research has consequently evolved around space-dependent cost efficiencies in many different infrastructure fields[2]), including the water and wastewater sector (cf. Guerrini et al., 2013; Álvarez et al., 2014). The finding that the operation and maintenance (O&M) costs of point-type infrastructures are particularly dependent on the settlement or population density is especially interesting with respect to OST systems (inter alia Schiller and Siedentop, 2005; Wenban-Smith, 2009). As a consequence, we expect the haulage distance to be crucial for assessing the O&M costs of OST systems (Semiyaga et al., 2015). Despite this long-known influence, the spatial cost effects concerning the O&M of OST plants have not been systematically estimated. Furthermore, the literature often focuses on single cost aspects of decentralised wastewater O&M such as monitoring (inter alia Hug and Maurer, 2012) or sludge transportation (inter alia Steiner et al., 2002). Nevertheless, there are some notable exceptions explicitly focusing on the road-based transportation needed in the case of OST plants: Steiner et al. (2002) propose a simple method for estimating the haulage costs on the basis of geometrical and economic criteria, and have used it to find decreasing costs with higher population densities. Flotats et al. (2009) show that minimising transportation costs is vital for manure management, a factor that is highly relevant to wastewater transportation in OST plants. The authors compare on-farm and centralised treatments and conclude that transportation costs are crucial for deciding between centralised and decentralised strategies. Marufuzzaman et al. (2015) present a method to compare pipeline and truck-based transportation of wastewater sludge and perform a cost analysis based on transported volumes and distances. Whereas different treatment options might result in different operating and maintenance requirements, Etnier et al. (2000) note that cost differences can be expected to result from the different strategies of collecting and maintaining WMS.

We believe the paucity of literature about O&M for OST systems to be responsible for rather speculative and vague overall cost claims (Hamilton et al., 2004; Dodane et al., 2012; Singh et al., 2015; Hendrickson et al., 2015; Truffer et al., 2013; Etnier et al., 2000). As a result, many authors conceive O&M of OST systems as costly, which adds to the conventional wisdom that decentralised WMS are challenging to operate and manage (inter alia Bakir, 2001; Parkinson and Tayler, 2003; Maurer et al., 2006; Buchanan, 2014). The methodological framework introduced in this paper enables the systematic assessment of cost effects relating to OST plant density by examining the most important space-related costs (residual transportation, service and repair costs), and in doing so prepares the ground for an integrated assessment of the optimal degree of centralisation in the provision of regional wastewater infrastructure. It is not the aim of this paper to perform a comprehensive overall cost analysis.

2. Materials and methods

We first identify those cost items which depend on the spatial density of plants in a region and differentiate between two management approaches for sludge emptying at OST plants. We then give a general methodological overview and explain the routing algorithms in detail. Section 2.5 presents the distance parameter estimation, followed by information on cost parameters and a sensitivity analysis. Section 2.8 introduces the case study.

2.1. Tasks sensitive to economies of density

We do not intend to perform a full cost comparison of OST systems or a complete analysis of O&M costs, but only aim to identify space-related costs. Therefore we do not consider investment or capital costs or all fixed costs, and particularly not costs independent of space. By the same logic, we also treat variable costs which depend on the chosen OST system or specific external conditions being constant, such as sludge treatment, energy consumption, chemical acquisition or other expenses such as taxes (see i.e. Fletcher et al., 2007; WERF, 2015). Such costs can simply be added as fixed baselines to the costs calculated in this paper, depending on the chosen technological solution. Further items such as regulatory costs may also be included in this broad conceptualisation. However, we maintain that these items follow the same logic and could therefore be easily added to an overall cost assessment.

We consider three typical tasks that exhibit cost characteristics

[1] González-Gómez and García-Rubio (2008) differentiate between economies of product density and economies of customer density. The former denotes the marginal cost savings of a fixed number of consumers due to increased consumption. The latter refers to the cost savings achieved by the higher efficiency resulting from a larger number of consumers. We focus on economies of customer density, implying that the marginal costs of providing services decrease with an increasing number of customers in a spatially defined area. We refer to Holmes (2011) for an overview of the literature focusing on economies of density in other thematic fields.

[2] Typically, examples can be found in solid waste management (inter alia Zamorano et al., 2009; Tavares et al., 2009; Ghose et al., 2006). See Section 4.3 for further applications.