Water Research 103 (2016) 472–484

Contents lists available at ScienceDirect

Water Research

journal homepage: www.elsevier.com/locate/watres

The cost of hybrid waste water systems: A systematic framework for specifying minimum cost-connection rates

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ARTICLE INFO

Article history:
Received 21 April 2016
Received in revised form
23 July 2016
Accepted 25 July 2016
Available online 28 July 2016

Keywords:
Urban water management
Engineering economics
Urban structural unit
Geographical information system
Decentralised waste water management
Sustainability transition

ABSTRACT

To determine the optimal connection rate (CR) for regional waste water treatment is a challenge that has recently gained the attention of academia and professional circles throughout the world. We contribute to this debate by proposing a framework for a total cost assessment of sanitation infrastructures in a given region for the whole range of possible CRs. The total costs comprise the treatment and transportation costs of centralised and on-site waste water management systems relative to specific CRs. We can then identify optimal CRs that either deliver waste water services at the lowest overall regional cost, or alternatively, CRs that result from households freely choosing whether they want to connect or not. We apply the framework to a Swiss region, derive a typology for regional cost curves and discuss whether and by how much the empirically observed CRs differ from the two optimal ones. Both optimal CRs may be reached by introducing specific regulatory incentive structures.

1. Introduction

Sanitation services in a region may in principle be provided by centralised or decentralised on-site waste water management systems (WMS) (Libralato et al., 2012). On-site WMS enable waste water to be treated geographically close to the point of generation (Tchobanoglous and Leverenz, 2013), making costly investments in sewer networks obsolete and potentially allowing cost savings. Despite the potential advantages, however, centralised WMS have gained much higher market shares in most OECD countries over the past century. The primary rationale for this was to assure high levels of 'urban hygiene' (O'Flaherty, 2005; Sedlak, 2014). Moreover, centralised WMS were promoted by public regulators because of compatibility with currently existing systems, known manageability, well-defined performance as well as economies of scale in both waste water treatment and sewer management (Townend, 1959; Downing, 1969; Abd El Gawad and Butter, 1995; Libralato et al., 2012). Over the years, institutions, organisations and the technology have co-evolved, leading to shared values, a professional culture based on civil engineering competences, and particular organisational forms dominated by utilities under public ownership (Dominguez, 2008; Kiparsky et al., 2013; Fuenfschilling and Truffer, 2014; Fane and Fane, 2005; Lieberherr and Truffer, 2015; Lieberherr and Fuenfschilling, 2016). These alignments created strong path dependencies (Arthur, 1989), so that today's catchments are dominated by large centralised waste water treatment plants (WWTP) and extensive sewer networks connecting large percentages of the population. Empirically, we observe a wide variety of connection rates (CR): whereas most emerging economies and developing countries are characterised by very low (typically << 50%) CRs (UN, 2015), some OECD countries (e.g. Switzerland, Austria, the Netherlands and the United Kingdom) have pushed for very high CRs ($CR_{present}$) of >95%, whereas other OECD countries (e.g. Ireland, Slovenia or Poland) have a $CR_{present}$ of between 60 and 70% (OECD, 2015).

The long-term superiority of very high CR has lately been questioned, and this has led to a call for a 'sustainability transition' towards more hybrid configurations combining centralised and on-site WMS (Fane and Fane, 2005; Daigger, 2007; Truffer et al., 2010; Larsen et al., 2013; Marlow et al., 2013). A wide range of criteria (e.g. technical, environmental, public-health related, institutional, social, economic) can be used to determine the optimal mixing rate.

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http://dx.doi.org/10.1016/j.watres.2016.07.062
0043-1354/

In recent years, however, we can observe an increasing predominance of economic efficiency criteria in the planning of network-based infrastructures (Knops, 2008). Economic assessments of optimal infrastructure dimensioning have also gained increasing attention in the field of water management, not only for waste water (Eggimann et al., 2015; Lee et al., 2013), but also for drinking water (Poustie et al., 2014; Guo and Englehardt, 2015), hydro power (Kaundinya et al., 2009) and seawater desalination (Shahabi et al., 2015). This heightened interest is due to strained public budgets, often leading to infrastructural underinvestment (WEF, 2010), the demand for more infrastructure flexibility and recent advances in on-site treatment technology. Furthermore, a modular approach to infrastructure planning is becoming increasingly cost competitive: new sensor and communication technologies allow automation and mass production which drive down the cost of small standardised units (Dahlgren et al., 2013). Determining the optimal connection rate (OCR) therefore remains a relevant question to reconsider.

In the present paper, we focus exclusively on cost assessments, as they often play an important role in designing WMS (Maurer et al., 2006). The goal is to develop an encompassing framework for assessing the total costs of hybrid WMS (Tchobanoglous and Leverenz, 2013) in a given region. Even though much effort has been spent on the cost considerations of WMS (Townend, 1959; Downing, 1969; Adams et al., 1972; Etnier et al., 2000; Hamilton et al., 2004; Maurer et al., 2010; Libralato et al., 2012; Eggimann et al., 2015), there is a paucity of conceptual work focusing on systematic total cost assessments. We build on an extensive body of work and present a framework within which we deduce generic cost curves for all key cost elements of a hybrid WMS. On the basis of these considerations, we will provide alternative interpretations of the OCR depending on specific institutional arrangements and organisational set-ups of providers of WMS services. This will enable us to discuss just what 'more sustainable' WMS configurations in specific regions could be, and in particular to discuss to what extent the $CR_{present}$ deviates from the various OCRs.

2. Material and methods

2.1. Framework for total cost assessment

This section starts by introducing the general assumptions of our framework (Section 2.1.1), and continues by identifying all key cost components of centralised and on-site WMS needed for a total cost assessment of hybrid WMS in a region (Section 2.1.2).

2.1.1. General assumptions

The framework for assessing total costs of hybrid WMS in a region presented here draws on the following general assumptions:

- Households and utility operators prefer each system only on the basis of average cost considerations.[1]
- All households have to be served either by being connected to the sewers or installing on-site WMS.
- The average regional total costs at each CR are defined by the average per capita costs of both systems as well as being annualised on the basis of the expected life-spans of the corresponding assets.
- We use average costs as a meaningful approximation for individual household sanitation costs. We are aware that actual tariff systems often diverge from these average costs, as they may include block tariffs, subsidies, base fees or connection fees (OECD, 2010).
- To ensure human and environmental health, centralised and on-site WMS need to fulfil the same functionality and provide an equivalent service. This implies that on-site WMS have to be equipped with treatment performance comparable to that of centralised WWTPs, and that on-site effluent disposal is possible (e.g. infiltration or on-site discharge into waters). We consequently assume that the sewers are built exclusively for waste water transportation and no synergies with storm water evacuation have to be accounted for (cf. Section 4.3).
- We assume that our region consists only of households and aggregated households in urban structural units (see Section 2.2.2) and no industry.[2]
- We neglect transaction costs, i.e. the costs of switching from one WMS to another.

2.1.2. Total costs of hybrid WMS

The total WMS costs C_{tot} can be subdivided into waste water treatment $C_{treatment}$ and waste water transport $C_{transport}$ costs. For centralised WMS, treatment occurs in one large WWTP $C^{cen}_{treatment}$ whereas for decentralised WMS, treatment is on-site $C^{dec}_{treatment}$. Transportation is either road-based in case of decentralised WMS $C^{dec}_{transport}$ or sewer-based for centralised WMS $C^{cen}_{transport}$. The total regional cost C^{region}_{tot} of a WMS can thus be specified as:

$$C^{region}_{tot} = \underbrace{C^{cen}_{treatment} + C^{dec}_{treatment}}_{\text{treatment}} + \underbrace{C^{cen}_{transport} + C^{dec}_{transport}}_{\text{transport}} \tag{1}$$

Fig. 1 shows the generic functional forms of the cost components of C^{region}_{tot} as a function of the CR along the respective sensitivity bands. The average total costs of either system (e, f) can be calculated on the basis of the cost function of the centralised (a, c) and decentralised WMS (b, d). Finally, the average total regional costs at a specific CR (assuming that this CR corresponds to a share p of households connected to the centralised system, whereas 1-p have on-site treatment) can be expressed as the weighted sum (dotted red line in g):

$$C^{region}_{tot}(CR) = p * C^{cen}_{tot}(CR) + (1-p) * C^{dec}_{tot}(CR) \tag{2}$$

Each of the specific shapes of the cost curves is based on different assumptions (outlined below): they are either derived directly from explicit cost data (a, b) or are model-based (c, d). The shapes are idealised, i.e. they vary depending on the specific case study. However, although we have varied the underlying assumptions to obtain cost ranges for each cost element, we find that the behaviour of each cost curve can be described in fairly generic terms:

Centralised treatment ($C^{cen}_{treatment}$ Fig. 1a): the prevailing key economic argument given in the literature to realise high CRs relates to economies of scale (inter alia Townend, 1959; Downing, 1969; Libralato et al., 2012). The likely decrease in average per capita costs for a large WWTP is inversely proportional to the number of households connected. In the literature, it is commonly implicitly assumed that the WWTP perfectly fits the demand of the connected users for each CR, and idle capacities are neglected. However, as investments in WWTP are typically based on the peak

[1] We conduct the entire cost assessment procedure by means of average cost calculations for each system. As we are interested in long-term optimal equilibrium solutions, this assumptions may be justified.

[2] However, this restriction is not decisive for the general argument that we develop and merely implies that the cost curves of the centralised WMS have a much bumpier shape than our idealised representation.

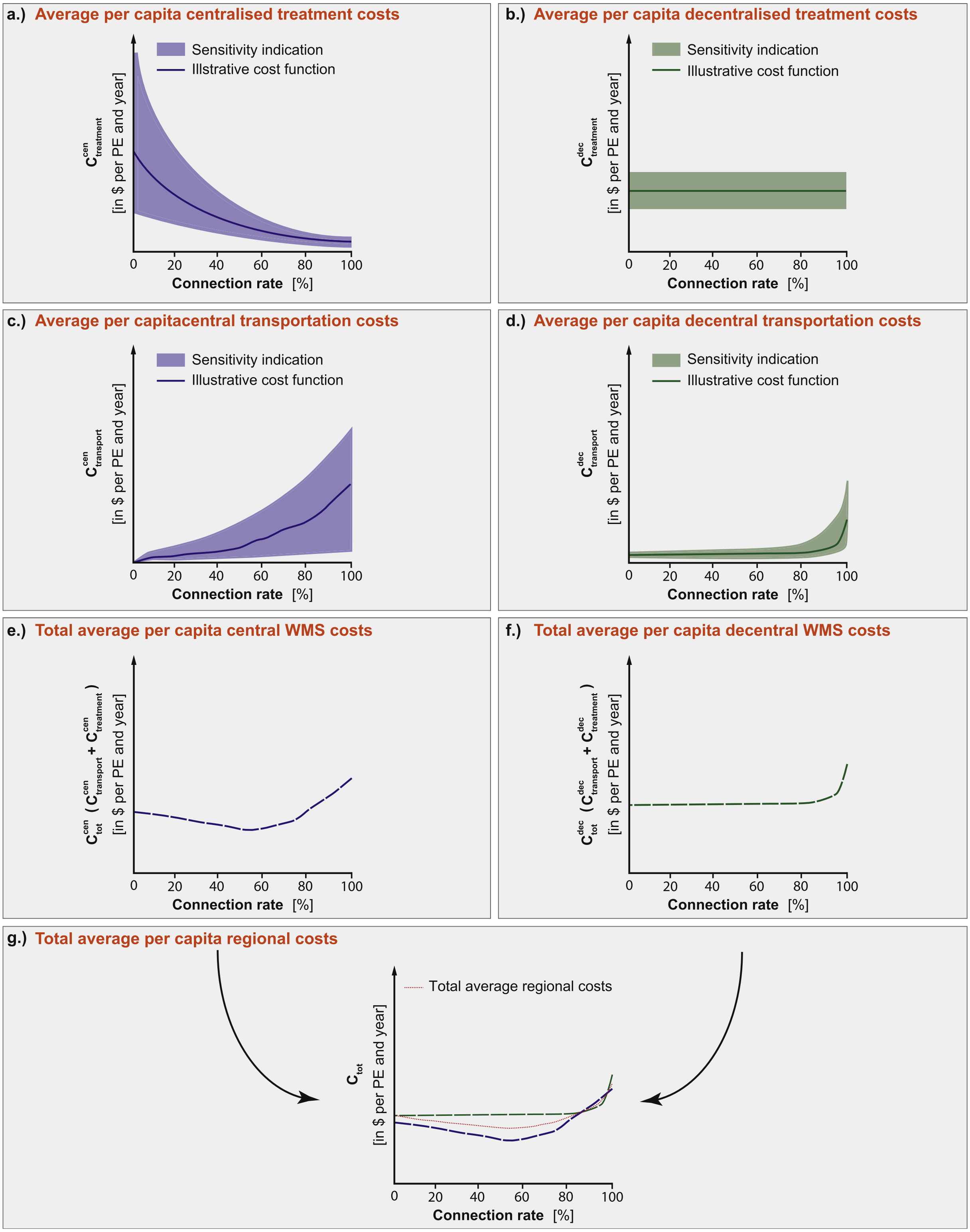


Fig. 1. Idealised average per capita cost functions over all CR. The final cost curve (configuration g) corresponds to the cost type C in Fig. 10. See also Section 2.2.3 for the underlying material and methods.

performance during the planning horizon (typically 20–30 years) (Hug et al., 2010), neglecting idle capacities underestimates treatment costs in catchments with positive or negative growth. The sensitivity indication in Fig. 1a reflects two extreme cases of idle capacities: the bottom border neglects idle capacities altogether while the top border indicates an investment scenario that considers maximum idle capacities. For the latter scenario, we calculate an initial expenditure of one WWTP serving the whole catchment and distribute this investment equally amongst the connected population at each CR.

Centralised transportation ($C^{cen}_{transport}$, Fig. 1c): sewer networks enable the transportation of waste water to the WWTP. Sewer construction and operation costs are heavily influenced by geography, settlement distribution or population density. We consequently find decreasing marginal costs for higher CRs and complex cost functions depending on the geography (cf. Adams et al., 1972; Hamilton et al., 2004; Maurer et al., 2010; Eggimann et al., 2015). In reality, most sewer systems are built up iteratively, where each new settlement structure to be connected leads to particular cost curves in terms of shape and cost level. Thus clustered settlement structures prevent constant cost increases and lead to 'jumps' (Zvoleff et al., 2009) in the cost curve. Fig. 1c shows a generic sewer cost function with increasing average per capita costs for higher CRs as a result of heterogeneous settlement structures, and correspondingly higher costs for connecting more distant settlements.[3] The sensitivity indication reflects differences in the cost curve depending on the catchment context factors outlined above. Whereas cost curves can be derived from the detailed cost data of existing networks, model-based approaches allow us to overcome the lack of data or the influence of legacy infrastructures and to systematically assess sewer costs across different catchments.

Decentralised treatment ($C^{dec}_{treatment}$, Fig. 1b): the costs of on-site treatment are largely independent of specific CRs, and the generic cost function is thus constant (Fig. 1b). However, the installation costs may differ depending on local conditions (e.g. rural or urban setting) and on the system type (Singh et al., 2015). We also find economies of scale for on-site treatment, i.e. per capita costs are typically lower for a 20-person system than a 4-person one. The level of the cost curve can consequently differ, which we represent by the respective shaded area. We assume that the housing structure does not change for different CR, so that the cost curve remains constant over the entire CR range.

Decentralised transportation ($C^{dec}_{transport}$, Fig. 1d): in the case of on-site WMS, well-functioning operation and maintenance (O&M) schemes are necessary to achieve full functionality. Road-based transportation needs result from professionals having to access the plants as well as from residual evacuation. For operating and managing on-site WMS, we find economies of density (Eggimann et al., 2016), i.e. cost savings due to the numbers and spatial proximity of on-site WMS. However, this effect is limited to a rather small range of treatment plant densities. A generic cost function describing all transport-related costs is given in Fig. 1d, where the range of different cost functions is due to different O&M concepts.

Total costs: the total cost curve of centralised WMS is shown in Fig. 1e with its characteristic 'u-shaped' form (Adams et al., 1972). The total cost curve of on-site WMS results in a 'hockey-stick' shape as seen in Fig. 1f (Eggimann et al., 2016). The resulting total average regional costs (C^{region}_{tot}) for hybrid WMS can now be derived from the total costs of both centralised and decentralised WMS (Equation (2)).

2.1.3. Optimal connection rate

The total regional cost curve and the respective centralised and on-site total cost curves exhibit some notable characteristics (Figs. 1g and 2). Firstly, we argue that the basic shapes of these curves are quite generically valid: both the 'u-form' shape of the centralised system and the 'hockey stick' of on-site systems have been identified in earlier literature (Adams et al., 1972; Eggimann et al., 2016). Secondly, by ignoring the trivial cases where one curve dominates the other, we expect two intersection points between these curves to exist almost independently of the specific cost characteristics. Thirdly, there will be a minimum on the regional total cost curve.

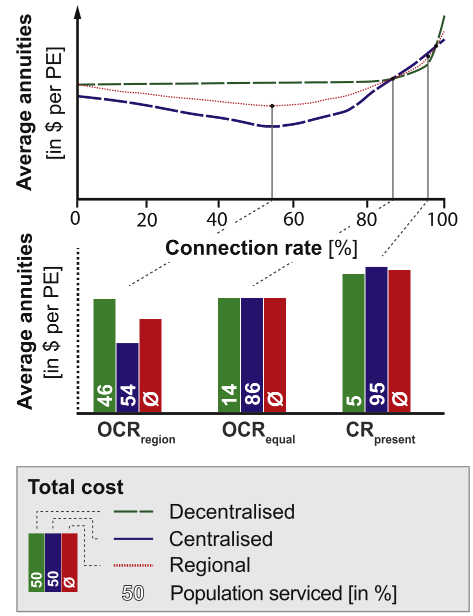


Fig. 2. Calculated OCR, costs and distribution of central and on-site WMS from an exemplary cost curve configuration. A CRpresent of 95% is shown. With help of the bar charts, the costs of the three total cost curves are visualised for all three CR. The numbers on the bar charts show the percentages of the population serviced with centralised or decentralised systems respectively for each CR.

These points may be interpreted as different candidates for potential OCRs. The difference between these OCRs and the $CR_{present}$ can be interpreted as the regional cost improvement potential of WMS. The two relevant OCRs can be characterised as follows:

- The OCR_{region} is defined by the minimum on the regional total cost curve where the average aggregated costs for the entire region are minimal. However, the specific costs of the different systems are not equal at this point, in view of higher costs for on-site treatment.
- The lower intersection point $OCR_{equalcost}$ marks the CR where the specific costs of the two WMS options are equal. This point would be reached spontaneously if all households could opt for the cheapest system in their specific location.[4] The sanitation costs for each household are the same, irrespectively of the system choice.

2.2. Case study application

In this section, we apply the framework outlined here to an empirical case-study region in order to test whether and how the different OCR can be identified. We aim to derive general cost patterns in the form of a configuration typology from the various case-study catchments.

[3] For the idealistic cost curve representation in Fig. 1c we assume that the dimension of the CR is ordered in a way that enables a monotonic presentation of the sewer cost curve, i.e. the x-axis proceeds from houses that are near the WWTP to those more distant from it. At the same time, we assume that the settlement density is highest around the WWTP and decreases over distance.

[4] The higher-level intersection would fulfill the criterion of equal costs equally well, but it represents a substantially higher level of total regional costs, so we do not elaborate further on its significance.

2.2.1. Canton of Glarus

We select the Canton of Glarus, a region with a population of ~40,000 in the north-east of Switzerland and covering an area of 685 km^2 (Fig. 3). We chose Glarus because it is a diverse region in terms of topography and settlement distribution which provides diverse contexts with respect to cost-curve configurations. This can be seen in the fact that we already find different CRs there (Fig. 3). The region underwent an organisational reform in 2011 - the 'Glarner Gemeindereform' - where 25 communities were merged into three. We will consequently calculate cost curves for both sets of communities, before and after the merger.

In Switzerland, waste water catchments are not organised purely along administrative borders but depend on topographic settings. That is why we currently find three different waste water catchments, indicated with red borders in Fig. 3. In this paper, we only focus on the largest WWTP catchment, which we henceforth call the 'case-study catchment'.

2.2.2. Aggregation of urban structural units

For regional or medium-scale analysis, data aggregation is generally required to reduce computational complexity (Haggag and Ayad, 2002). To run the heuristic sewer generation algorithm efficiently (Section 2.2.3), we choose an aggregation technique based on urban structural units (USU), as sanitation planning is closely linked to urban patterns (Spirandelli, 2015; Bach et al., 2015). USU are defined as *'areas with a physignomically homogeneous character, which are marked in the built-up area by a characteristic formation of buildings and open spaces'* (Wickop, 1998). With the emergence of geographical information systems, USU are increasingly used in different contexts (inter alia Osmond, 2010; Wang et al., 2013; Behling et al., 2015), but have so far been rarely applied to the field of sanitation (for exceptions, see Schiller, 2010; Eggimann, 2013). Different approaches have been developed to classify the physiognomies of urban building which can be used to define USU (Steiniger et al., 2008; Meinel and Burgdorf, 2008; Lüscher et al., 2009). To derive USU, we choose an approach based on the spatial intersection of linear urban features (street and railway networks) within the settlement area. This intersection is followed by a post-processing step in which USU containing no buildings are removed and smaller USU (<0.5 km^2) are merged with neighbouring ones. To estimate the population per USU, we disaggregate the community population data according to a volumetric estimation by Lwin and Murayama (2009). The population data of the USU centroids is in a last step projected to the closest point on the street network (see Fig. 4).

2.2.3. Key cost components

For the cost calculation of the case study, we convert all local currencies to US$ using purchase power parities for the year 2014 (World Bank, 2015). All levelised costs are given in annuities (A) calculated from the net present value (NPV):

$$A = NPV \frac{q^n(q-1)}{q^n - 1} \tag{3}$$

where q is the discount rate + 1 and n the number of years over which the infrastructure is depreciated (Crundwell, 2008). We adjust on-site treatment costs to the year 2014 using conversion factors for the U.S. price index (U.S. Census Bureau, 2015). We derive the various cost elements as follows (cf. Section 2.1.2):

Central treatment: we use typical Swiss replacement costs to estimate the large-scale WWTP costs (Fig. 5). As centralised costs

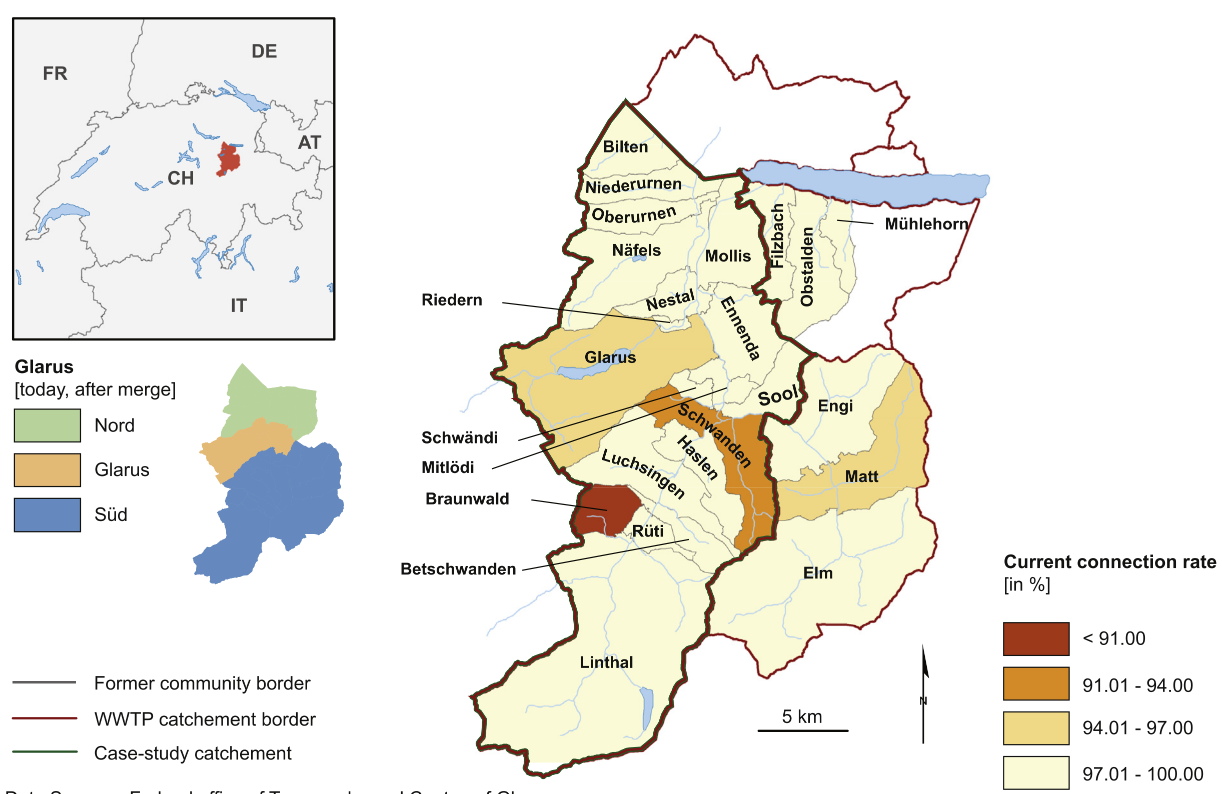


Fig. 3. Case study area showing the present and former community boundaries as well as different WWTP catchments. White areas belong to external catchment areas or are not part of the Canton of 'Glarus'.

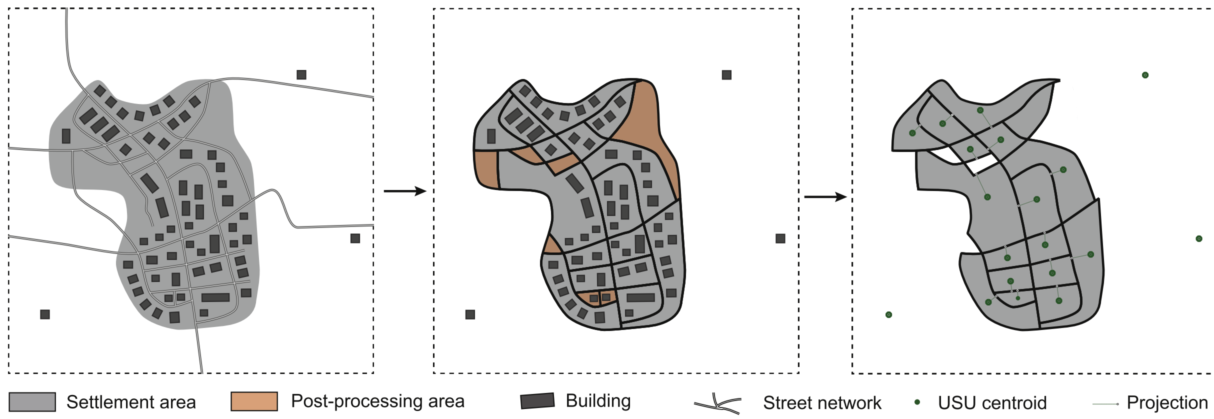


Fig. 4. Schematic representation of USU generation.

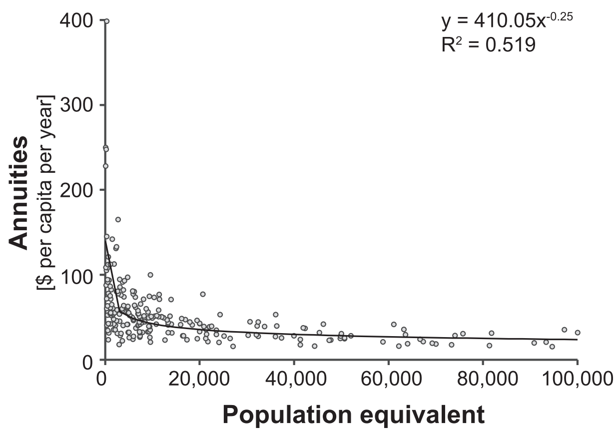


Fig. 5. Swiss capital and O&M expenditures for centralised treatment (VSA, 2011), assuming an average lifespan of 30 years and a discount rate of 2%.

are very unreliable for small treatment plants, we use on-site treatment costs for plants smaller than 20 population equivalents (PE).

Central transportation: in order to estimate the costs of the sewer network along the whole CR spectrum, we adapt and apply a heuristic sewer network generation algorithm developed by Eggimann et al. (2015) which is based on sewer-design principles from the real world. The adapted algorithm allows us to iteratively simulate a sewer network starting from a single connected household up to full catchment connection to a single WWTP. For in-depth explanations of the applied algorithm and the terminology used as outlined below, we refer to Eggimann et al. (2015). Compared to the original algorithm, we make three adaptations:

1. We do not consider semi-decentralised solutions but iteratively simulate an interconnected network. So there is no need to execute the merging module, as only a single WWTP exists at each iterative step. We therefore always force a sewer connection in each iteration, and thus reduce the system design module to two options.
2. Due to this conceptual change, the introduction of further distance weighting factors of the Prim-based expansion module yields visually more realistic sewer networks. At each iteration step, we check whether there is a local elevation or depression ('hill' or 'valley') <25 m between two nodes under consideration. If so, we multiply this distance by a weighting factor d_w ($d_w = 30$). Moreover, we always weight nodes which are topographically lower by d_w ($d_w = 10$), as pumping is necessary and is to be avoided.[5] The only exception is where the nodes under consideration form edges leading to the WWTP. This is because the network position of the WWTP can be switched with the considered node so that pumping can also be avoided.
3. We remove the a* algorithm in the case of missing connections to street networks to reduce the computational burden, and use straight-line distance approximations instead.

Decentralised treatment: it is challenging to determine the average on-site treatment costs because a wide variety of possible system alternatives exist (Maurer et al., 2012). But even more importantly, the functional equivalence of on-site WMS is hard to operationalise. We therefore opt for a fail-safe option and include disinfection costs derived from systems based on sodium hypochlorite and UV radiation (WERF, 2010). We additionally assume that further costs arise due to the need to dispose of effluent on-site, ignoring possible synergies with storm-water management systems. We estimate the average non-spatially dependent costs of on-site WMS on the basis of a selection of international cost literature considering the costs of materials, planning and installation, sludge treatment and electricity (Fletcher et al., 2007; WERF, 2010; JECES, 2015). The assessed treatment systems are either of class C according to DIBt (2014), or where the provision of nitrification or denitrification was not specified we classify the systems with a range as class C-D.[6] Fig. 6 shows the total cost function, including the costs of a drip disposal system and for a UV disinfection unit (WERF, 2010) which fall in line with other cost estimations for Switzerland (cf. Abegglen, 2008).

Decentralised transportation: To derive transportation-related costs for on-site WMS, we use model-based cost data from Eggimann et al., 2016, who provide a cost-density relationship (treatment plants per km^2) at regional level for a Swiss case study. The authors model a cost-density relationship in a two-dimensional geometrical space by means of a heuristic routing algorithm. To estimate the transportation costs in relation to the treatment plant density on a local scale, we derive the relationship between the CR and the on-site WMS density over all CRs for the

[5] The choice of these distance weighting factors is arbitrary and based only on visual quality inspection. We consider this a valid approximation given the intention and scope of this paper and the low sensitivity of this parameter.

[6] Nutrient recovery is especially promising for on-site WMS and affects the overall economic performance. However, we do not include this analysis in view of the scope of this paper.

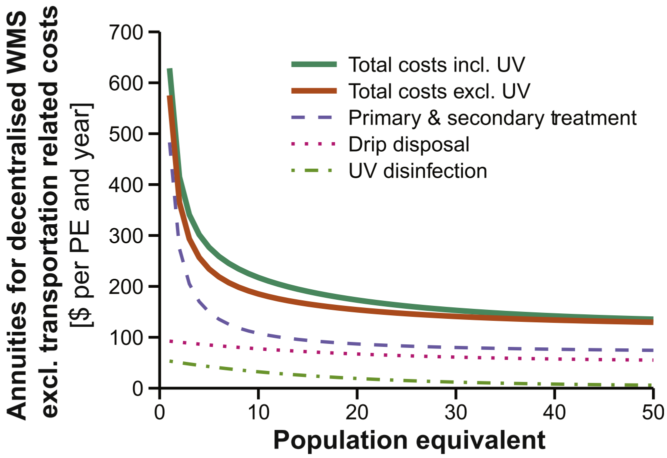


Fig. 6. Average treatment cost data for on-site WMS.

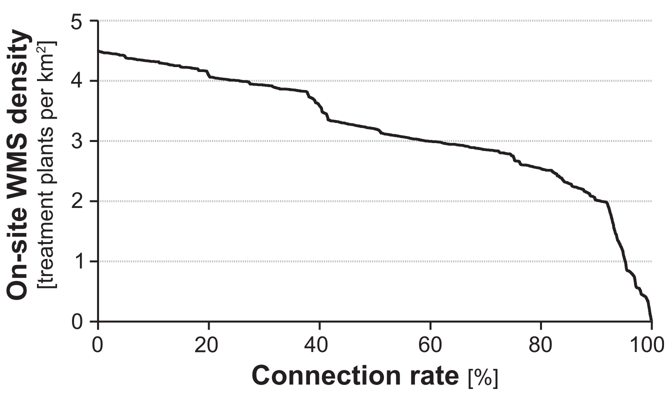


Fig. 7. Calculated relationship between the CR and the treatment plant density for the whole case study region as a basis for estimating local transportation-related costs.

whole case-study region (Fig. 7).

2.2.4. Sensitivity analysis

To evaluate the model sensitivity, we calculate three different cost functions for each key cost element by systematically varying the underlying assumptions (Table 1). A systematic combination of all resulting cost functions yields 81 different scenarios. With this approach, we aim to produce diversity in order to indicate sensitivity rather than statistical representativeness.

3. Results

3.1. Cost curve configurations

Appendix A gives all standard parameter calculations of the former communities of Glarus. Fig. 8 shows the results over all cost scenarios (see Section 2.2.4) with respect to the different OCR. We find very diverse OCR at the former communal level with broad sensitivity ranges resulting from the cost scenarios. For today's more dispersed southern community 'Süd', we find lower OCRs than for the more urbanised communities of 'Nord' or 'Glarus'.

The detailed cost curve configuration of the case study catchment in Glarus is given in Fig. 9. We notice that the OCR_{region} and the $OCR_{equalcost}$ are at very low CR of around 0.2 and 0.4 respectively. However, the total regional cost curve is more or less horizontal until a CR of around 0.6–0.7. The standard parameter calculation is thus very sensitive to small changes of any single cost component.

3.2. Typology

We can identify basic cost-shape behaviours on the basis of the configurations of all the communities. This enables us to build a typology that distinguishes between three major configurations (see Fig. 10 for typical examples):

- *Type A:* This cost curve configuration type has no $OCR_{equalcost}$, and centralised WMS costs are typically lower for all CR. The OCR_{region} is typically very high.
- *Type B:* For this type, we do not find a distinct $OCR_{equalcost}$ because the intersection point is highly sensitive to cost-curve changes due to a more or less horizontal total regional cost curve (we may find multiple cost curve intersections). The OCR_{region} is typically in the middle CR range. On-site WMS costs only become noticeably expensive at very high CR.
- *Type C:* For this type, we find distinctive $OCR_{equalcost}$ and OCR_{region} with clear cost differences. Typically, we observe a distinctive exponential increase of the centralised costs at relatively low CR, leading to low OCRs.

4. Discussion

We now reflect critically on the case study application and our framework in general. We then elaborate the institutional conditions under which the different OCRs could be realised. Finally, we identify potential research needs.

4.1. Case study application and OCR typology

The case study application confirms that we can indeed identify the conceptually outlined OCRs on a real example. We find very different OCR_{region} and $OCR_{equalcost}$ for the former and merged communities depending on the local geography, ranging from very low to very high CR. For example, we note that the WWTP catchment along the new community 'Süd' is unsuitable for a large centralised WMS. We see that the OCR depends on the chosen scale and catchment boundary, which is to be expected, as the topographic characteristics also depend on the chosen system boundaries. Specific characteristics of the various catchments enabled us to derive a typology of cost curves. However, the boundaries of this typology are fuzzy, so it only represents a broad classification.

An important finding for our case study catchment is that both

Table 1
Overview of cost scenario assumptions for all key cost elements. Standard scenario values are given in bold.

Cost element	Description	Unit	Scenario assumptions
$C^{cen}_{treatment}$	Assumed idle capacity	%	**0**, 50, 100
$C^{cen}_{transport}$	Different minimum sewer slope ($f_{minslope}$) for running the sewer network generation algorithm	%	0.5, **1**, 1.5
$C^{dec}_{treatment}$	Assumed on-site WMS dimension	PE	5, **10**, 15
$C^{dec}_{transport}$	Systematic cost variation	%	−20, **0**, +20

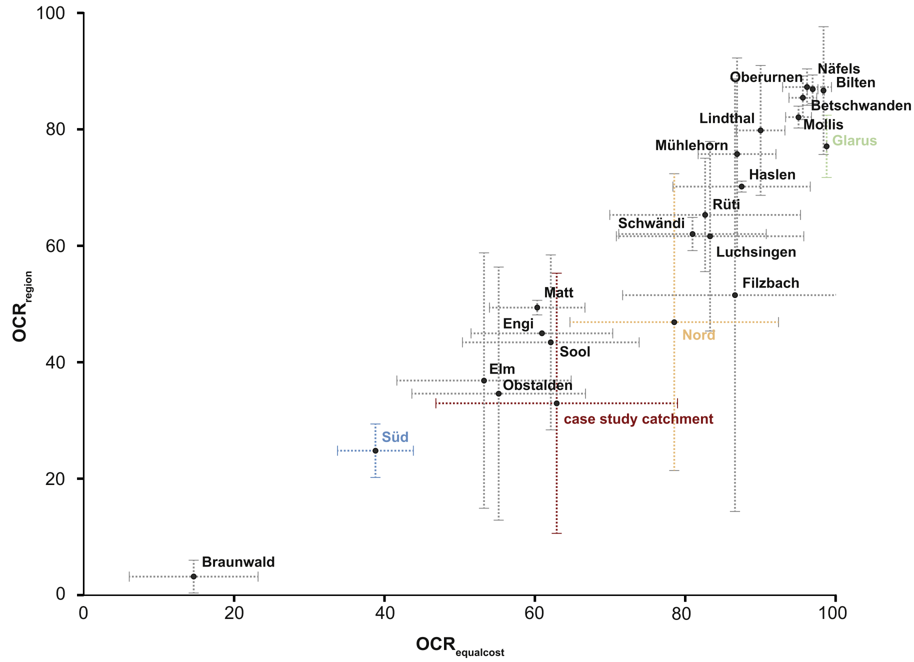


Fig. 8. Visualisation of the cost scenario calculations for all former (black) and current merged communities of the case study region 'Glarus' (coloured), including the case study catchment. The scenario sensitivity is indicated by error bars representing one standard deviation.(For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

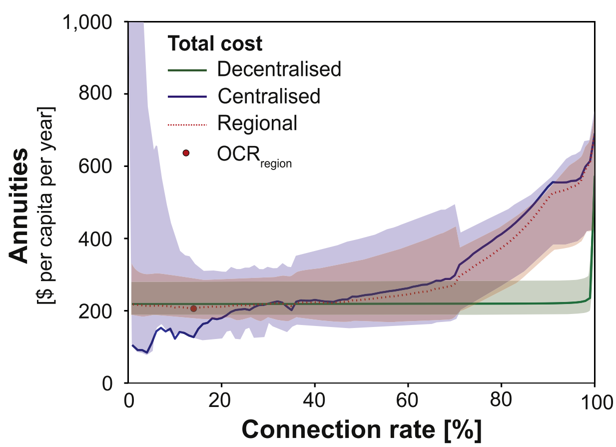


Fig. 9. Thick lines show standard parameter calculations, shaded areas indicate scenario uncertainties (maximum extent over all 81 scenarios).

the calculated OCRs are lower than the $CR_{present}$. We argue that this is because these sewers were not constructed primarily from a cost optimisation point of view and the regulators have often introduced a mandatory connection rule in order to force a higher number of households to connect to the sewers than a direct cost comparison would suggest. The reason for these regulations often lie in the argument that centralised systems are easier to control than a myriad of on-site WMS, or that the latter cannot cope in terms of treatment performance criteria (inter alia Moelants et al., 2008; Buchanan, 2014). However, for this paper we assume that neither of these arguments will be valid if on-site WMS are properly designed and if appropriate business models are installed to run them. We thus presume that the role of institutions responsible for applying the mandatory connection rule or investment subsidies for centralised WMS explain why $CR_{present}$ is much higher than $OCR_{equalcost}$ or OCR_{region} in countries like Switzerland (cf. Eggimann et al., 2015).

High uncertainties result from the various cost scenarios. This is largely due to the cost curve configurations: for many communities (including the case study catchment estimated here), the total regional cost curve is rather flat and the cost values of OCR_{region} and $OCR_{equalcost}$ are thus very close. Consequently, only minor cost differences would lead to very different intersection points on the cost curve. This suggests that a focus on $OCR_{equalcost}$ might be a viable option if OCR_{region} is hard to implement.

Finally, territorial reforms are a challenge in water governance (OECD, 2015b). The organisational centralisation in Glarus is in line with the general tendency to centralisation throughout Switzerland. We argue that this creates an opportunity to reach lower-cost CR because larger organisations are likely to develop higher professional competencies to run both centralised and on-site WMS (Maurer et al., 2012b). This is especially interesting in the case of on-site treatment, where larger contracts result in more standardised and professional operation and management.

4.2. The institutional and organisational setting of OCR

In order to decide which of the two candidate OCRs is more likely to be implemented, we have to take a closer look at the incentive structures and regulatory arrangements in the specific regions:

i.) To reach the OCR_{region}, a central decision maker would have to determine the total regional cost curve and identify the lowest cost point. In most empirical cases, this will coincide with the lowest cost point of the total centralised cost curve. It would therefore be sufficient to require central operators to connect new households as long as their total average cost curve decreases.[7] Beyond that point, households would have

[7] Following this logic, the central operator may not maximise his profit and consequently needs to be regulated, as he would otherwise connect too many households (the profit maximum lies somewhere between both OCR).

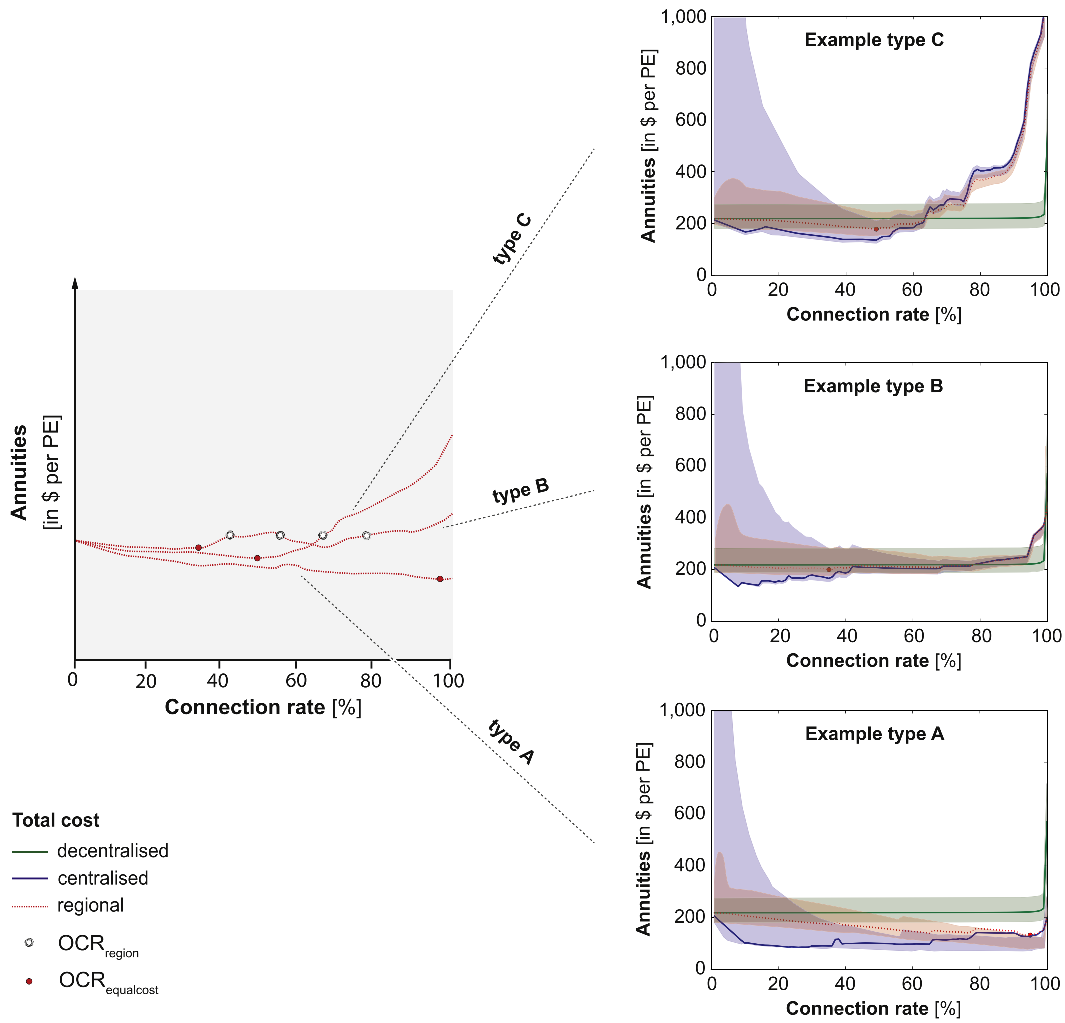


Fig. 10. Cost curve configuration typology with examples. For each example type, standard parameter runs (thick line) and scenario uncertainties are provided (cf. Fig. 9).

to seek services from companies that offer on-site alternatives. As a consequence, users connected to the centralised WMS would have lower costs than those serviced by on-site WMS. The rationale for this arrangement is that the total amount of money spent in the region would then be lowest. However, this solution would imply that users connected to the centralised WMS would pay substantially lower tariffs for their WMS services than those that have to rely on on-site solutions.[8] Such price differences could lead to political protests. This problem could be circumvented if the provision of WMS services for the whole region was delegated to a monopoly provider who would be obliged to charge households equal tariffs while minimizing the overall costs in the region. One way to implement such a solution would be for a public utility to build up equal professional competence in both centralised and decentralised WMS and be subjected to tight price regulation. Alternatively, the OCR_{region} could be reached by a private monopoly operator who bids for a long-term service contract through a public call for tenders (Demsetz, 1968).

ii.) However, it may not be feasible to reach the OCR_{region} under specific conditions: there may be strong political preferences in the region for individual households to choose their service provider freely, and monopoly providers (public or private) may meet with resistance. Moreover, it may prove difficult to build up professional competencies in both centralised and decentralised WMS within a single organisation. In these situations, the $OCR_{equalcost}$ might be a second-best option, as the costs would be the same for all households while various organisations could compete to supply them. The $OCR_{equalcost}$ could be reached if a public or private organisation running the centralised system were required to offer its services at average cost and would be prohibited from turning down customers. Households would be free to choose either to connect to a sewer or to accept services from one of the potentially many suppliers of on-site WMS. In this case, the centralised system would expand to the point where the average cost curves of the two systems intersect, i.e. the $OCR_{equalcost}$.

We can deduce from the general cost-curve characteristics of our case study that the following relationship holds for countries with very high $CR_{present}$: $OCR_{region} < OCR_{equalcost} < CR_{present}$. The first inequality is given by the shape of the cost curves and is generic. The second is very likely to hold in countries which have

8 In order not to complicate matters, we assume that utilities would be able to charge tariffs on a cost-plus basis.

installed regulations such as mandatory connection rules. Otherwise, competition would likely lead to market shares that are close to or at around the $OCR_{equalcost}$.

We may summarise our framework for calculating the total regional cost for hybrid WMS systems as follows: the shape of the type C cost curve indicates two potential OCR that would be superior to the present CR. However, which of these OCR is actually reached depends on the role specification of households, the central system operator, the on-site suppliers and the regulator. Getting away from current mixing ratios will therefore depend on comprehensive reforms (including organisations and regulations) and cannot be considered purely as a matter of cost.

4.3. Critical reflection and research needs

The full cost assessment for regional WMS represents at least a first step towards determining more sustainable WMS services. However, it is not enough merely to assess the costs.

Most cost assumptions relating to the costs of on-site treatment were chosen on the conservative side in this paper (including for disinfection and on-site infiltration). However, these may be subject to considerable changes in the future, for instance if economies of scale could be reaped in manufacturing (Adler, 2007; Dahlgren et al., 2013). On the other hand, assumptions about effluent disposal would require a more sophisticated analysis including storm water evacuation. As far as transportation costs are concerned, lacking economies of scale and the challenges involved in establishing fully functional O&M schemes are usually considered as the key disadvantages of on-site WMS (cf. Eggimann et al., 2016). However, off-grid infrastructure systems also possess specific advantages, although these are hard to express in monetary terms: the independence from a sewer network increases the flexibility to respond to socio-economic or technological boundary conditions (Panebianco and Pahl-Wostl, 2006; Hug et al., 2010). It also reduces interdependence-related disruptions (Rinaldi et al., 2001) and lessens the potential environmental impact in case of failure of a single plant, whether due to malfunctions, earthquakes (Hamada, 2014) or terrorism (Panebianco and Pahl-Wostl, 2006). Centralised and on-site WMS thus offer unique strengths and weaknesses which are often intangible and difficult express in to monetary terms (cf. Gikas and Tchnobanoglous, 2009; Libralato et al., 2012; Larsen et al., 2013; Vousvouras, 2013). However, the quantification of non-monetary advantages or disadvantages goes far beyond this study as it would require a research approach of much greater scope (cf. Morera et al., 2015; Arora et al., 2015; Naik and Stenstrom, 2016).

With the aid of the framework presented here, we can address the question of the degree to which on-site WMS can be considered as substitutes from an economical point of view. However, we refer to the literature (inter alia Larsen et al., 2013; Libralato et al., 2012) concerning the key assumption as to whether on-site WMS can be considered as functionally equivalent from a technological point of view.

In this study, we assume stable context conditions even though many exogenous factors affect infrastructure planning, such as changing public goals or environmental concerns (Hansman et al., 2006). Furthermore, WMS are exposed to different long-term dynamics (e.g. population, role of industry, water consumption trends), making it very challenging to plan optimal systems (Dominguez and Gujer, 2006). However, this study provides valuable insights into changing population and settlement dynamics related to sanitation costs: we showed that different catchments result in diverse characteristic cost configurations, which gives an indication of what cost configurations may look like and evolve for future projected catchments. For instance, let us assume an anticipated increase in settlement area together with sprawling tendencies of the settlement distribution for an urban catchment classified as type A. For such a case, we might expect a cost configuration shift from type A towards type C. On the other hand, for catchments classified as type A, urban infill or settlement shrinking in rural areas (Siedentop and Fina, 2010) shifts the cost curve from type A towards type C. A final assumption of the framework outlined here is that the basic choice for households in a particular region is either between a fully centralised or a small-scale on-site WMS. We believe that in reality the choice is indeed often limited to these basic two options, namely either to connect to a large centralised WWTP or to select small-scale package treatment plants.

5. Conclusion

In this paper, we have prepared the way towards achieving a cost-based identification of lowest cost connection rates (CR) in a given region. We thus contribute to the broader debate about sustainable CR with a cost analysis over the whole CR continuum. In particular, we identify a potentially optimal CR (OCR_{region}) from a total regional cost point of view, and a second-best CR ($OCR_{equalcost}$) which may be easier to implement under specific institutional and organisational conditions.

The framework presented here suggests that the OCR_{region} may be achieved if the operator of the centralised WMS is required to expand his service as long as his average costs decrease. Alternatively, the OCR_{region} is reached if a single operator runs both WMS alternatives and tariffs are regulated either explicitly or through a call for tenders relating to service contracts. The second-best $OCR_{equalcost}$ could be reached if individual households can choose freely between central and on-site WMS. A potentially intermediary form would be for households beyond the OCR_{region} to be charged tariffs proportional to the costs for a sewer connection on the basis of actual household connection costs, thus increasing their incentive to choose on-site WMS. In our case study, we find relatively small cost differences between the two OCR, which suggests that opting directly for the $OCR_{equalcost}$ is an advisable option. We argue that neither OCR can be reached without regulating the centralised WMS and introducing adequate policy measures.

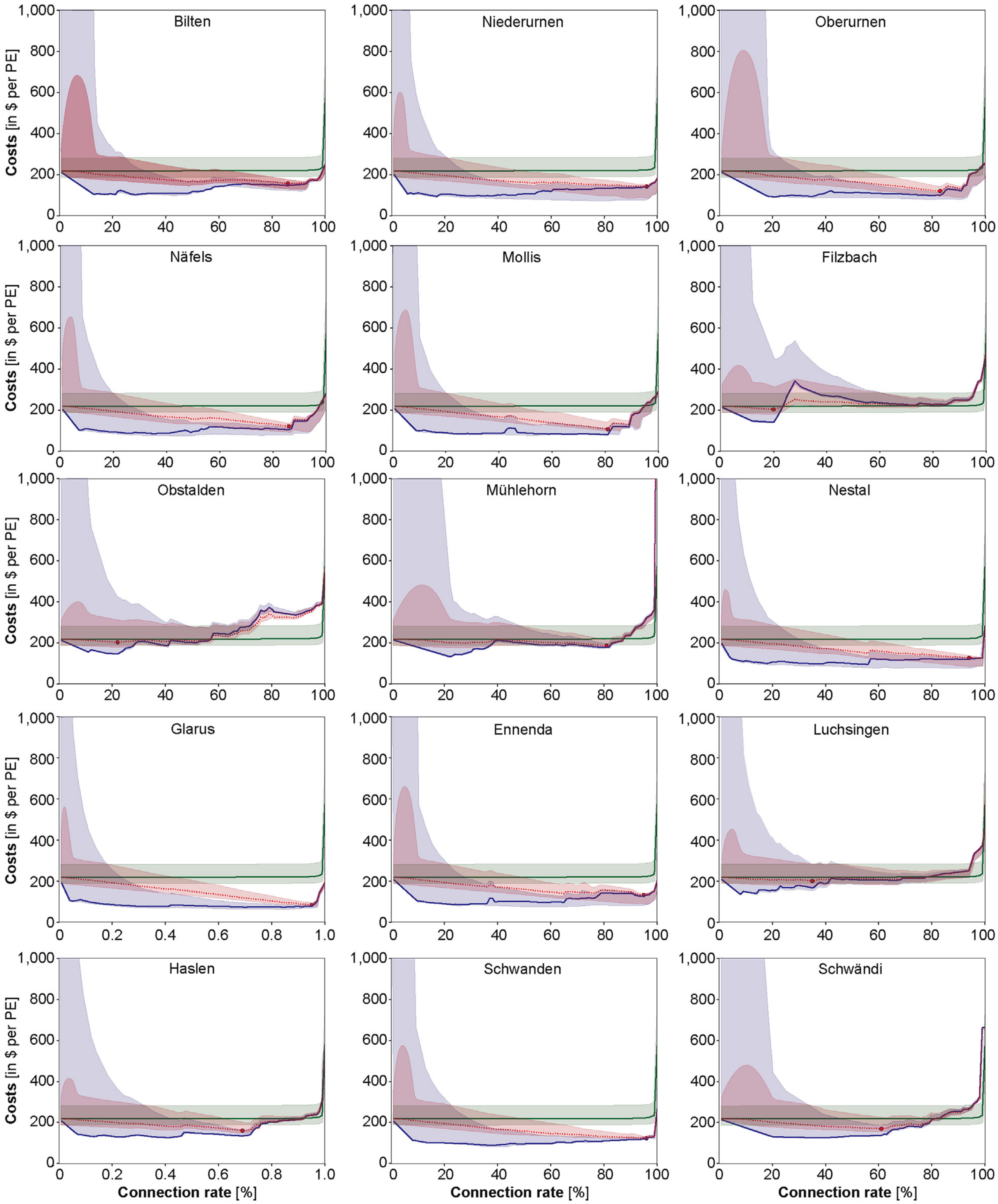
We optimise CR by building on long-term average costs, thus assuming that the context conditions remain static in the long run. In further elaborations of the framework, it would make sense to include dynamic considerations (e.g. changing settlement patterns or population dynamics).

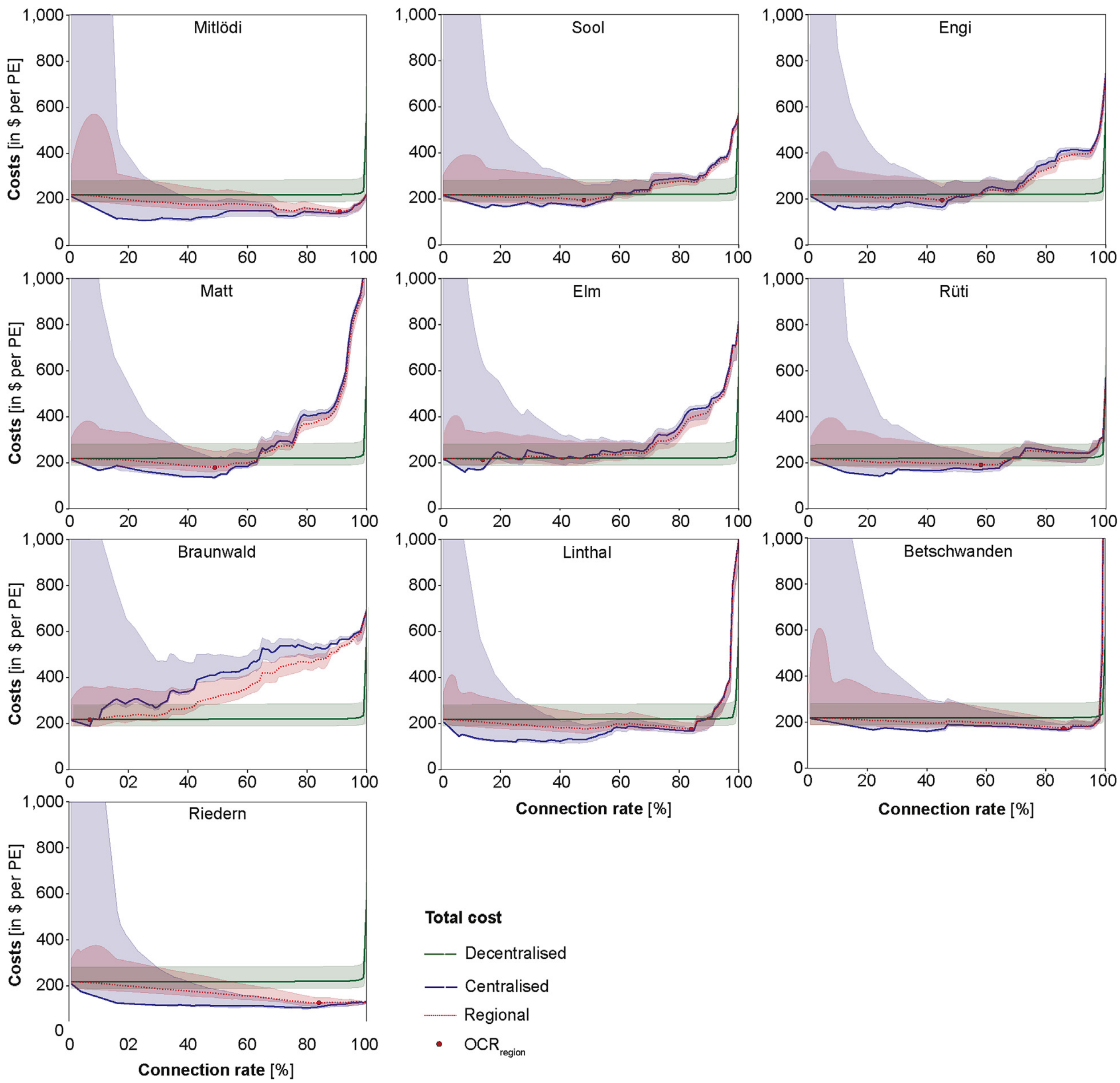
Finally, we believe that a holistic consideration is needed in view of the complexity of the question of cost-efficient CR for sustainable urban water management. We conclude that this discussion cannot be separated from analyses of the respective organisational, institutional and regulatory arrangements in a region and argue for a co-evolution of technological advances in on-site WMS with the prevailing institutional and organisational arrangements.

Acknowledgements

Our special thanks go to Ivana Logar, Roy Brouwer and Matteo Mattmann for their suggestions to improve the manuscript. We thank Rachel Barrett for her help with the data preparation and Richard Michell for the proofreading. We also thank the Canton of Glarus for their data provision.

Appendix A


Bilten
Niederurnen
Oberurnen
Näfels
Mollis
Filzbach
Obstalden
Mühlehorn
Nestal
Glarus
Ennenda
Luchsingen
Haslen
Schwanden
Schwändi
Costs [in $ per PE]
Connection rate [%]
0
200
400
600
800
1,000
20
40
60
80
100
0.2
0.4
0.6
0.8
1.0



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