Comparative multi-criteria performance assessment of alternative water infrastructure systems

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ABSTRACT

This paper presents a new multi-criteria assessment tool enabling the comparison of conventional and innovative infrastructures and its application to a specific case in a mid-size German city, Lünen. The assessed infrastructure alternatives are a conventional system with centralised supply of drinking water, wastewater collection in a combined sewer system and central tertiary treatment in one case. In the other, more innovative system, one part of the wastewater is used decentrally to extract the contained heat, substitute one part of the drinking water and, after being passed into a park-like constructed wetland, improve the microclimate and biodiversity. The assessment method employed is utility analysis using a set of 21 criteria and 33 indicators. The comparative assessment of both infrastructure alternatives shows the superiority of the innovative system for most criteria.

Key words | multi-criteria assessment, performance assessment, utility analysis, water infrastructure

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INTRODUCTION

The combination of changing framework conditions and low flexibility of existing water and wastewater infrastructures will require the further development and adaptation of not only individual components, but entire infrastructure systems in future. In recent years, new technical solutions have been developed for various challenges. Examples of such systemic infrastructure innovations include the separate collection and reuse of wastewater components such as water, nutrients, organic matter and even heat (Hillenbrand *et al.* 2016; Mitchell & Matzinger 2016; Oldenburg *et al.* 2016). All such innovations are intended to secure safe water supply and wastewater disposal at the lowest possible cost in terms of resource use and harm to the environment. The examples also show that the systemic view of infrastructure systems cannot be confined to water supply and wastewater treatment. Instead, various linkages to energy and food supply as well as waste management, to mention just a few, elicit the integrated nature of the infrastructure systems (UN 2011). Eventually, the systemic view also refers to the changes infrastructure systems are facing in time. While most systems need to grow in the context of increasing urbanisation, others shrink due to aging societies or because they lie outside an urban area. Obviously, a variety of criteria need to be fulfilled for a water and wastewater infrastructure system to be qualified as eco-friendly, socially inclusive and adaptive.

However, a great deal of uncertainty regarding the advantages and disadvantages of such innovations currently hinders the further dissemination of these solutions. This uncertainty is not only due to the use of novel technical components, but also to the variety of the affected impact categories and their complex interaction. Specific impact

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categories (for example, climate impact or recycling of water and nutrients) were investigated more closely. However, the recording of *all* effects relevant for an infrastructure alternative is usually lacking as well as a comprehensive assessment system that maps the effects and relates them with each other. Only this would enable decision-makers to compare infrastructure systems and choose an alternative.

In order to facilitate such decisions, an assessment instrument was developed that can be implemented at a not too high effort for the planners and makes it possible to compare integrated concepts of water supply and wastewater disposal with each other and with the conventional alternatives currently prevalent, taking into account all relevant assessment dimensions. In the following methods section, the main features of the evaluation are presented. In the results section, the infrastructure alternatives are assessed in detail. Finally, the methodological and assessment results are discussed and summarised.

METHODS

In order to be able to assess novel water infrastructures comparatively with each other and with conventional water supply and wastewater treatment concepts, we developed a method for the comprehensive assessment of water infrastructures, *MuBeWis* (Methode zur umfassenden Bewertung von Wasserinfrastrukturen). For this, we had to choose first the criteria according to which the assessment shall be conducted and second the method where the criteria are applied.

Like Lienert *et al.* (2015), DWA (2015) lists criteria for such an evaluation in its worksheet A-272. Despite some structural differences, both sets of criteria show a high degree of agreement in their contents and were used as a basis. This basis was supplemented additionally by requirements arising in drinking water supply and spatial planning, which were not contained in the latter lists, and by more criteria collected in the course of brainstorming among stakeholders and experts. Beside a broader assessment basis, the latter process was intended to increase the acceptance of the assessment method among those who should use it later on. Stakeholders (and experts) involved were the developers of the innovative infrastructure (research institutes and companies), water utilities and the potential operators, owners (house owners or equipment suppliers) and users (residents) of the infrastructure. The large set of criteria was then restructured by eliminating double counting, sorting out inoperable ones (e.g. macroeconomic effects) and integrating the remaining criteria into a multi-level system of objectives oriented towards the infrastructure systems requirements (Lück & Nyga 2017). Ecological, safety-relevant, economic, social and technical objectives comprise the top level, which is then broken down according to the requirements. At the highest level of detail, the individual targets are criteria, each of which is measured by at least one indicator (see Figure 1).

In order to assess different infrastructures on the basis of this multitude of criteria, a variety of multi-criteria assessment approaches is available. Among others, Hein *et al.* (2015) mention utility analysis, multi-attribute utility theory, a simple multi-attribute rating technique, linear programming and compromise programming. The suitability of each of these approaches depends on a variety of conditions, which differ from assessment to assessment. In order to select the approach most suitable for the actual type of assessment, the following criteria were applied:

- Data availability: Are the required data accessible and, if so, in which form? How much effort does it take to apply the data?
- Completeness: Does the assessment method enable the inclusion and adequate consideration of all objectives according to their relevance?
- Uncertainty: How does the method account for the uncertainty of all input data and how is it depicted in the assessment result?
- Transparency: How evident is the coming about of the assessment results in the course of the method application? Is there an overall assessment result and, if so, how easily is this result interpreted with respect to the partial objectives?
- Flexibility: Is the assessment method adaptive with respect to most or all conceivable types of infrastructure systems and changes in the respective operating conditions?
- System borders: Does the method enable the adjustment of system borders?

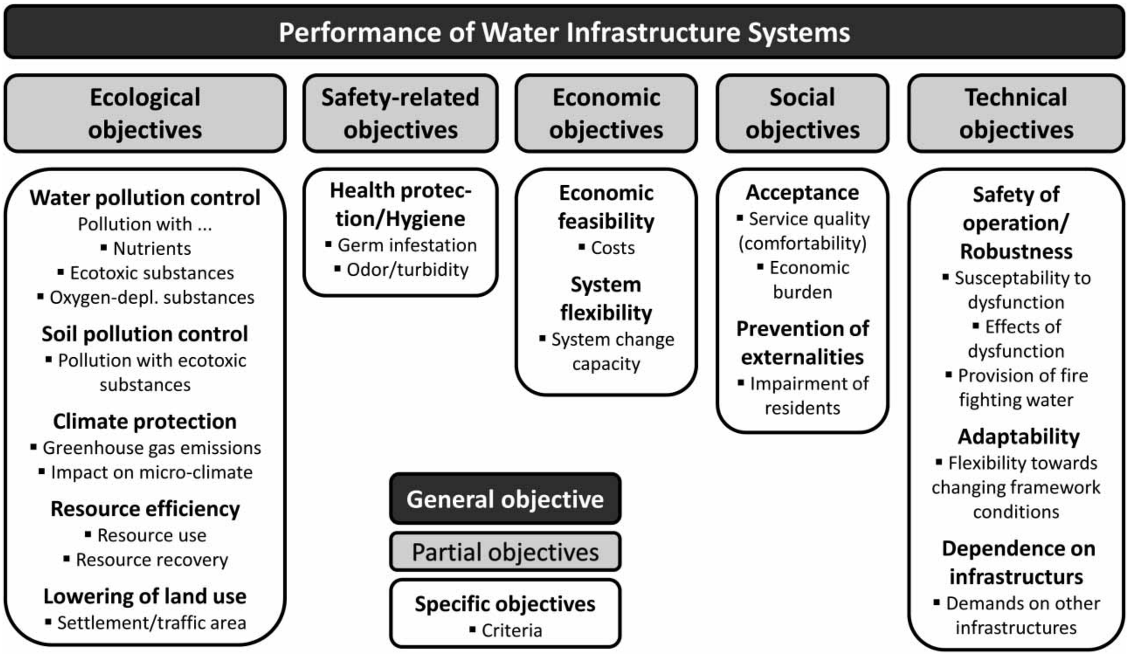

Figure 1 | Hierarchy of objectives for the assessment of water infrastructure systems.

Based on these criteria, utility analysis was selected as the best suited assessment approach. As a multi-criteria procedure, it meets the assessment requirements of complex water infrastructure systems better than other existing assessment procedures. Most notably, different dimensions can be incorporated, the transparency of the procedure can be upheld, and the effort required for data collection can be kept rather low (Hein *et al.* 2015).

In the case of utility analysis, the contribution to the respective target fulfilment is first determined for each criterion using one or more indicators. For the purpose of comparability, each indicator is then used to calculate the respective normalised partial utility value (PUV) using a linear transformation function. For biochemical oxygen demand (BOD)-related pollution (assigned to 'water pollution control'), for example, this means that the BOD load of the receiving waters is estimated and converted into a concentration by means of the expected wastewater quantity. From this concentration, the (normalised) PUV is calculated by correlating the expected concentration to the respective highest legally permissible concentration, which is set to a PUV of 0. No BOD emissions would correspond to a PUV of 1. If there is no legal threshold value for one criterion, as in the case of greenhouse gas emissions, the interpolation or extrapolation is done between a PUV of 1 for no emissions and a PUV of 0.5 for the average emissions of water and wastewater infrastructures in Germany. In principle, the transformation functions converting indicators in PUV can also be non-linear. However, since this mainly affects the level of assessment, but far less so the differences between different alternatives (Zheng *et al.* 2016), the simpler linear approach is chosen here. Normalisation with respect to the size of the infrastructure and/or the duration of operation occurs by referring respectively to the number of connected persons and a time period of one year. If several indicators are used to assess one criterion, the mean value of the respective PUVs is formed, if not stated otherwise. With some criteria, which cannot be measured quantitatively or at least not at a reasonable cost, bonus malus systems are used to at least partially quantify qualitative differences (see Sartorius *et al.* 2016a).

The determination of all PUVs occurs within system borders comprising the entire system to be assessed. Since the infrastructure systems of interest comprise a number of sub-systems (e.g. energy, rain water, process water beside the basic water supply and wastewater collection and treatment), their borders can be quite wide and the collection of the required data rather laborious. To the extent that some sub-systems are not subject to change in the comparison of the assessed infrastructure system alternatives, such parts can be omitted, as the assessment focusses on the (decision-relevant) differences in their rating rather than their absolute values. Doing so, the system borders could be limited and the effort for the assessment of the systems reduced substantially.

Eventually, the PUVs are weighted according to their respective significance for an overall assessment and aggregated through adding up. In the literature, other aggregation methods are described which, for example, reflect preference orders in which a poor assessment in one criterion cannot be offset by a positive assessment elsewhere. However, since these preference orders differ widely between decision-makers (Zheng *et al.* 2016), the respective aggregation methods are not applied. The required weighting factors are determined by means of the AHP (analytical hierarchy process) method on the basis of a survey of stakeholders and experts. On the basis of these weighting factors and the respective PUVs, (partial) utility values can be calculated, which allow a direct comparison of the evaluated infrastructures (Nyga *et al.* 2016). In order to better classify the assessment results, each alternative water infrastructure is assessed in comparison to a reference infrastructure, which is usually the existing conventional infrastructure. If uniform assumptions, in particular regarding the system limits, are applied, the results for different infrastructures are also comparable between different model areas and projects.

RESULTS

In the following, the principles of the assessment are exemplified by the conventional (existing) and the alternative, innovative water and wastewater infrastructure (planned) in the German city of Lünen. To this end, a brief characterisation of the planned alternative water infrastructure is given.

Alternative water infrastructure system i.WET in Lünen

The core of the alternative infrastructure to be introduced in the model area 'Süggelquartier' in Lünen is the i.WET (Integrated Water Energy Transition Concept) developed at Fraunhofer ISI. It is characterised by a combination of the (re)utilisation of rainwater and treated greywater with heat recovery and the production of bioenergy (Hillenbrand *et al.* 2016; Niederste-Hollenberg *et al.* 2016). Two ways of recycling are distinguished. In the 'blue' path, rainwater is collected on roof surfaces, processed and stored as process water. In addition, heat is recovered from the (weakly polluted) greywater from showers and baths; thereafter, as long as the process water requirement is not already covered through the rainwater, greywater is treated to cover the remaining demand. The 'green' recycling path is used for the near-natural processing of the excess grey- and rainwater in the outdoor area in a horizontal soil filter called 'energy alley'. On the surface of the soil filter (which is sealed towards the bottom) is a short-rotation coppice which not only evaporates most of the water (and thus contributes to the improvement of the urban microclimate), but also takes up the nutrients contained in the greywater in the course of biomass production. The soil filter itself absorbs pollutants in grey- and rainwater so that the excess filtered water can be used, for example, for the irrigation of plants.

Ultimately, the decoupling of rainwater and greywater by i.WET makes it possible to replace the gravity sewer system with a vacuum sewer system which exclusively feeds heavily contaminated greywater (e.g. from the kitchen) and black water to the sewage treatment plant, where it can then be treated in an increasingly anaerobic and energy-saving way. However, in the first design stage of this infrastructure system evaluated as an example here, there is no vacuum sewer yet. Black- and more heavily contaminated greywater are still disposed of into the existing combined sewage channel, while rainwater and less contaminated greywater no longer are. As a result, the volume of the wastewater stream is significantly reduced while the pollutant load carried along is less markedly reduced. In the case of sewage separation, the rainwater sewer would be superfluous.

Application of the assessment method MuBeWis on the first stage of i.WET in Lünen

In the following, the procedure for the assessment of the individual criteria is broken down and presented sorted by sub-target. The detailed results are presented elsewhere (Sartorius *et al.* 2016b).

Ecological objectives

The ecological objectives encompass water, soil and climate protection, efficient use of resources, and reduction of land consumption. Regarding water protection, two criteria with several indicators each are applied. One criterion is the nutrient load, which is assessed via the N- and P-loads emitted into the water bodies. Compared to the German average (PUV = 0.5), the conventional system existing in Lünen has a slightly better performance for N and a significantly better performance for P retention, yielding a PUV of 0.52 and 0.69, respectively. In a system with i.WET, the volume of the sewage flow directed to the sewage treatment plant is much lower, since the light grey- and rainwater are used differently. Since it is assumed that in the sewage treatment plant the outflow concentrations of N and P can be kept the same despite the higher feed concentrations, this results in a higher purification performance, which is shown in a PUV of 0.56 and 0.73, respectively.

The second criterion for water protection is the entry of eco-toxic substances, of which the metals copper and zinc, the pharmaceutical diclofenac and the biocide terbutryn were chosen as representing indicators. Of these substances, only 20, 19, 17 and 39 per cent, respectively, are retained in the conventional system, which corresponds in this case directly to the corresponding PUV. Since copper and zinc are mostly washed off by rainwater from the respective surfaces, a large portion of them in i.WET consequently enters the energy alley and is largely adsorbed there. Only a small remainder is fed into the normal wastewater stream. The situation is similar in the case of terbutryn; however, the proportion flowing to the energy alley is significantly smaller. In contrast, i.WET does not have any effect on the elimination of diclofenac since it is essentially removed with the black water. As a result, the PUV for copper (0.37) and zinc (0.29) improves significantly through i.WET, whereas the PUV hardly improves for terbutryn (0.17) and diclofenac (0.39).

The assessment logic for the third water protection criterion, pollution from BOD-relevant oxygen-consuming substances, is similar to that of the first criterion (nutrient load) with one important difference: the reference value corresponds to the legally binding threshold value (with PUV = 0) instead of average pollution in Germany (with PUV = 0.5). The actual average load is only 45% of the legal threshold value, which corresponds to a PUV of 0.55. Through i.WET, as in the case of the nutrients, the sewage treatment plant feed is more concentrated, which (assuming an unchanged outflow concentration) results in an increase in the purification performance and a PUV of 0.6.

As regards the soil protection objective, exposure to eco-toxic substances is the criterion, which is measured by three indicators: cadmium, lead and polycyclic aromatic hydrocarbons (PAHs). In the conventional system, all three substances enter the soil mainly with the agriculturally utilised sewage sludge. Therefore, the assessment in principle would be carried out in the same way as for the BOD load, based on the maximum permissible soil content of these three substances defined in the German Fertiliser Ordinance. However, since sewage sludge is *not* used for agricultural purposes in Lünen, the PUV is actually 1.0 in the conventional system and based on the mineral fertiliser (which is often contaminated with cadmium) substituted additionally through biomass generation in the energy alley of i.WET even 1.03.

The emission of greenhouse gases (GHG) takes place mainly through the (fossil) energy sources required for the provision of water and the collection and treatment of the wastewater and the CH_4 and N_2O emissions generated in the conventional treatment process (Umweltbundesamt 2014), resulting in a PUV of 0.51 in the conventional case. With i.WET, a GHG debit arises from the operation of the greywater treatment and credits for the produced biomass, the mineral fertiliser substituted, the reduction of the amount of used water supply and sanitation and, above all, the heat recovery from the greywater, which reduces the emission of GHG by 95 per cent, yielding a PUV of 0.98.

Also affecting the climate is the influence on the microclimate, especially through building measures. Here, the calculation is made based on a PUV of 0.5 for the existing system and maluses or bonuses of −0.2 to +0.2 are assigned respectively for the greater or lesser extent of sealing or unsealing of cold-air development areas or for blocking or re-establishing air-conducting lanes. Since the energy alley in Lünen would replace existing conventional roadside planting and therefore no special effects emerge in i.WET, the PUV of 0.5 remains unchanged. The same argument applies to the land use of the water infrastructures, which therefore also yields a PUV of 0.5 for both infrastructure alternatives.

The consideration of efficient resource use is based on two criteria: resource consumption and resource recovery. In order to account for the resource requirements for the provision of various substances, the measurement of the consumption is typically done with the aid of the respective prices. For the conventional water and wastewater infrastructure, the operating costs were assumed to be German average, yielding a PUV of 0.5. In the system with i.WET, the operating costs are reduced by more than half, resulting in a PUV of 0.76. The degree of resource recovery is determined for four substances relevant to the water sector: water, carbon, phosphorus and nitrogen. The evaluation is derived directly from their individual recovery rates weighted by the respective prices. Since no recovery occurs in the conventional system, the PUV is 0. In the i.WET system, 27 per cent of the water is saved by the rain and greywater recovery, and smaller amounts of phosphorus and nitrogen are recycled through the short-rotation coppice, resulting in a PUV of 0.26.

Safety-related objectives

For the assessment of the harmlessness of the drinking water, the criteria germ load as well as smell and turbidity are used. With respect to germ load, drinking water must not contain any coliform bacteria (0 colony forming units (cfu) per 100 ml). If this condition is met, the PUV is 1. Since the conventional drinking water supply in the assessed part of Lünen shows stagnation in the supply network of 10 per cent of the households, leading to an increased probability of hygienic impairments, the PUV is reduced to 0.9. In the alternative system, 27 per cent of the drinking water is replaced by process water from treated rain and greywater, for which a different assessment scale, the EU Bathing Water Directive, is to be applied. While the greywater treatment used in i.WET complies with this limit, yielding a PUV of 1, this advantage is lost due to the reduced consumption of drinking water and the slightly higher probability of stagnation resulting from that. The resulting PUV (0.9) is the same as for the conventional system.

Odour and turbidity are safety-relevant indicators in the drinking water context, which themselves do not necessarily cause damage, but point to circumstances which can adversely affect health (for example, by increased contamination with germs). Since these conditions include the stagnation of drinking water in the relevant pipes, the assessment yields the same PUV as in the case of the germ load (but with process water being irrelevant): 0.9 and 0.87.

Economic objectives

The economic objectives include, on the one hand, the costs of the infrastructure, on the other the flexibility and system transformation capability. While the former allow for a comparison of different infrastructure alternatives under the current conditions, the latter provide a long-term perspective into how easily a switch to other infrastructure alternatives can be made, for example in the case of changed framework conditions.

The cost of water supply and wastewater disposal alternatives is determined dynamically on the basis of the life cycle cost approach. In this case, all costs (and, if applicable, revenues) incurred during the course of the useful service life (USL) are discounted with an interest rate of 1.5 per cent to a base year (Umweltbundesamt 2012). Costs include investment and reinvestment costs (for the life of the entire infrastructure, i.e., approximately 80 years), as well as operating costs, which represent the balance of all ongoing costs and revenues. In the case of i.WET, the costs of the drinking water supply are reduced by the reduced consumption of drinking water, but only to the extent of its variable costs (i.e., 20% of the total costs). These savings are offset by the expenditures for rain and greywater treatment, heat recovery, process water distribution and the energy alley. Adding up all costs, it turns out that i.WET is more favourable, yielding a higher PUV (0.46 instead of 0.42).

Two indicators with different time perspectives are used to assess flexibility and the system change readiness. The book value to be depreciated (BVD) determines which value would become obsolete at the time of the changeover if the present (conventional) infrastructure were replaced by a (more innovative) alternative and would therefore result in costs correspondingly. The USL of the infrastructure to be newly built influences the possibility of a change at a later date if this would seem to be necessary due to changes that are not yet foreseeable. The fact that the sewer system in Lünen is currently in dire need of rehabilitation indicates that the BVD is small in this part of the conventional infrastructure, and thus a good opportunity (i.e., a window of opportunity) for the conversion to i.WET exists. Since the innovative infrastructure (i.WET) has not yet been implemented, the PUV is 1 in both cases.

Once i.WET has been installed, the system change readiness is measured in the same way as that of the conventional alternative. In the conventional system, the sewer system with its USL of 80 years is most relevant. In the alternative infrastructure, the sewers are only relevant for the 73 per cent of conventional wastewater. The 27 per cent share flowing through the energy alley is only relevant for 27 years, yielding an average USL of 65 years and a PUV of 0.19.

Social targets

Both the user's acceptance of the infrastructure and the avoidance of externalities, i.e. impairments of third parties, are subsumed under the social targets. Acceptance is measured via two criteria. To determine convenience, we estimate the time expended by users for the provision of water and wastewater services, which in the conventional system in Lünen is mostly limited to reading the water meter and written correspondence from the utility. Customer satisfaction can therefore be seen as high and assessed with a PUV of 0.9. If i.WET is, as planned, operated by the operator of the apartments/houses and the incurred costs passed on to the inhabitants via the ancillary costs, the same procedure and assessment as in the conventional system applies.

The second criterion is the economic burden, which is concerned with burdens or alleviations for the users going beyond the costs already assessed in the economic context. Examples of this could be high one-off burdens such as the private investment in a small sewage treatment plant. In the case of i.WET, users save at least in the short term the full price of 27 per cent less drinking water. (In the long term the general saving of 27 per cent of the drinking water would likely lead to an increase in the specific water price due to the fixed costs staying the same, and possibly higher maintenance costs for the care of the pipe network). For the assessment, this implies a PUV of 0.5 for the conventional and 0.56 for the alternative, i.WET-based infrastructure.

The conventional water and wastewater infrastructure is generally regarded, apart from those living directly next to sewage treatment plants, as being free from inconveniences. Because the ideal state is not fully achieved, a PUV of 0.9 is assigned to it. Otherwise, depending on the load intensity (i.e., frequency, intensity, and number affected), maluses between −0.1 and −0.3 per load medium (e.g., smell, noise, aesthetics) would be employed. Since there are no additional burdens expected for i.WET, the PUV is also 0.9.

Technical targets

With regard to the technical objectives, the following subaspects are taken into account: susceptibility to process disturbances (in normal operation), impacts of a failure state, provision of water for firefighting via the drinking water network, flexibility regarding changing framework conditions, and requirements for other infrastructure areas.

The susceptibility to process faults is equated with the probability of faults occurring during normal operations. In doing so, indicators used are the expected damage and the availability of know-how, which would be necessary to identify and correct damage as quickly as possible. Compared to the conventional infrastructure rated with an (average) PUV of 0.5, the alternative with i.WET offers bonuses for the increased redundancy (+0.3) due to the lower drinking water consumption and the additional use of process water, as well as from the fact that, in the case of damages, fewer users are affected due to the decentralisation of the wastewater treatment (+0.1). On the other hand, there is a PUV deduction of −0.2 for the availability of know-how compared to the conventional system, for which know-how can be regarded as widespread (PUV = 0.8).

In the event of a failure of the wastewater treatment, contaminated water ends up in the environment untreated. As an indicator of the effects of this failure, the resulting BOD concentration in the water body can be used. For the assessment, this figure is related to the maximum allowable

BOD in the WWTP effluent. For the conventional infrastructure in Lünen, this yields a PUV of 0.83. For the innovative infrastructure, the reduction of the BOD load by 10 per cent caused by the decentralised greywater treatment results in a reduced overshoot of the threshold value and a PUV of 0.93.

Basically, the reliability of the firefighting water supply is assessed by means of a bonus-malus system, which takes into account the redundancy of alternative sources (for example, bodies of water) as well as the redundancy within the water network. However, the provision of firefighting water is irrelevant for the evaluation of i.WET, since i.WET does not contribute to this. Instead, the conventional infrastructure is used both in the i.WET and in the reference case. Since the drinking water network in Lünen in the current state is a largely interconnected system with an emergency power supply, which can verifiably provide the legally stipulated quantity of firefighting water at any location in the investigated subnetwork, a PUV of 1 is applied in both cases.

The flexibility criterion is intended to determine whether and how capacity adjustments can be made to changing framework conditions. In the evaluation, a PUV of 0 indicates no, a PUV of 1 complete flexibility. For the implementation, the assumed 100 per cent flexibility is divided between the relevant components of the system, with a higher proportion being allocated to more important (key) components (e.g. pipe network). For each component, it is then assessed whether it is easily adaptable (complete % ratio), is not adaptable at all (0% ratio) or lies between. Finally, the percentages are added up. In the conventional infrastructure, the distribution networks and channels (weight: 0.5) can be dismantled or expanded only with great difficulties (factor: 0.2) and the water treatment and treatment plants (weight: 0.5) with substantial restrictions (factor: 0.4), resulting in a PUV of $(0.5 \times 0.2 + 0.5 \times 0.4 =)$ 0.3. In i.WET, one part of the system (weight: 0.2) is significantly more flexible (factor: $+0.5$) due to the decentralised, modular grey- and rainwater treatment, resulting in an increase of 0.1 and a total PUV of 0.4.

The higher and more diverse the requirements of water and wastewater infrastructure towards other infrastructures, the more vulnerable they are to their failure. Relevant dependencies exist with respect to power supply, waste disposal and data networking. The PUV for the conventional infrastructure is set to 0.5. In comparison, the alternative infrastructure with i.WET is characterised by a higher autonomy due to the energy alley, but a higher dependency due to the grey- and rainwater treatment as well as the operation of toilets. Overall, the dependency on other infrastructure elements in i.WET therefore appears to be somewhat higher than in the conventional system. Therefore, a PUV of 0.4 is considered appropriate. All results of the evaluation are summarised in Table 1.

DISCUSSION

When comparing the PUV of the comparative assessment, the alternative infrastructure planned for the model area in Lünen is superior in almost all aspects to the conventional one. Regarding the ecological objectives, it is particularly important that the greywater is treated to a large extent in the energy alley, and thus the sewage treatment plant is disencumbered (environmental protection); water and nutrients are also recycled (resource protection). Economically, it is an advantage that i.WET makes the conversion to a conventional separated sewer system unnecessary and allows a more flexible response to changing framework conditions due to its shorter USL. The drinking water savings due to the use of process water result in a lower economic burden for the end user and lead to a higher degree of social acceptance. From a technical point of view, the advantages in terms of the susceptibility to malfunctions, the effects of failure states and flexibility outweigh the small disadvantage of the higher dependency on other infrastructures. In terms of security alone, the conventional infrastructure is just as good as the alternative, which is not surprising given the existing high standards.

The overall assessment in favour of one of the two infrastructure alternatives is particularly clear, as this alternative (including i.WET) performs equally well or better than the other in all categories. Based on the weighting factors, an overall assessment would also be possible if the evaluations in different categories were not clear-cut; however, errors in the determination of the indicators and the PUV could tend to make the overall result ambiguous. In this context, we would like to point out with regard to error propagation, that the determination of indicator values and the resulting

Table 1 | Evaluation of conventional and novel water infrastructure in the urban model area in Lünen

	Criterion	Indicator	Weight (%)	Conventional	i.WET
1. Ecological criteria			**22.0**	**0.49**	**0.63**
1.1	Nutrient burden	N	1.29	0.52	0.57
		P	1.29	0.69	0.73
1.2	Ecotoxic substances/water	Cu	0.77	0.20	0.37
		Zn	0.77	0.19	0.29
		Diclofenac	0.77	0.39	0.39
		Terbutryn	0.77	0.17	0.17
1.3	Oxygen-consuming substances	BOD	2.62	0.55	0.60
1.4	Ecotoxic substances/ soil	Cadmium	0.95	1.00	1.10
		Lead	0.95	1.00	0.99
		PAK	0.95	1.00	0.99
1.5	Greenhouse gas emission	GHG equivalents	2.44	0.51	0.98
1.6	Effect on micro climate	Cold-air lanes	1.91	0.50	0.50
1.7	Resource use	Energy, operating materials	2.52	0.50	0.76
1.8	Resource recovery	P	0.02	0.00	0.01
		N	0.03	0.00	0.01
		H_2O	2.28	0.00	0.27
		C (organic)	0.05	0.00	0.00
1.9	Land use	Soil sealing	1.84	0.50	0.50
2. Safety-relevant criteria			**26.7**	**0.90**	**0.90**
2.1a	Germ infestation/hygiene	Total bacteria count, coliform CFU	22.8	0.90	0.90
2.1b	Smell/turbidity	TON, NTU	3.92	0.90	0.87
3. Economic criteria			**16.4**	**0.46**	**0.52**
3.1	(Net) costs	Investment and operation	8.90	0.42	0.46
3.2	Flexibility, system's readiness for change	Depreciated cost	3.74	1.00	1.00
		Useful life	3.74	0.00	0.19
4. Social criteria			**16.0**	**0.74**	**0.77**
4.1	Convenience (service quality)	Expenditure of time	5.18	0.90	0.90
4.2	Economic burden	Special cost burden	6.28	0.50	0.56
4.3	Nuisance	Number of sensoric media	4.49	0.90	0.90
5. Technical criteria			**18.8**	**0.66**	**0.70**
5.1	Vulnerability to damage	Spare capacity	1.53	0.50	0.80
		Damage potential	1.53	0.50	0.60
		Knowhow availability	1.53	0.80	0.60
5.2	Effect of system failure	Share of BOD in river/lake	4.05	0.83	0.93
5.3	Supply of firefighting water	Share of safe supply	3.89	1.00	1.00
5.4	Flexibility w/resp. to changing conditions	Modularity	3.65	0.30	0.40
5.5	Dependence	Number/intensity	2.61	0.50	0.40
Total			***100***	***0.67***	***0.72***

PUV in each category for both infrastructure alternatives is in most cases not independent but interdependent. For example, the cost of the alternative infrastructure is calculated by adding and subtracting to the reference infrastructure's values. For the uncertainty of the valuation difference therefore not the sum of the errors of the costs of the two alternatives, but the much smaller errors in the differences are relevant.

CONCLUSION

The MuBeWis assessment approach is able to describe quantitatively the advantages and disadvantages of various conventional and novel infrastructure alternatives in detail and to make them comparable through standardisation and the application of weighting factors. In addition, this approach allows aggregation to an overall assessment. It must be borne in mind, however, that such an aggregation always also entails the loss of important detail information. The weighting factors were determined by means of a survey of experts and stakeholders. In the event of changes in the framework conditions or changed perspectives and new problem areas, this weighting must be discussed and adjusted if necessary. In the case of Lünen, where the alternative infrastructure performs equally well or better than the conventional infrastructure with regard to all partial objectives, such an adjustment would not have any significant effect on the overall assessment. In less clear-cut cases, however, a change in the weighting can also shift the overall assessment in favour of or against an alternative.

By virtue of the fact that, in the case of standardisation, frequently general variables, e.g. Germany-wide average or threshold values are used, the comparison of the assessments is in principle not limited to specific model areas, but can be carried out beyond these. A prerequisite for this however is the uniformity of the system borders. On the other hand, the case-by-case adjustment of the system borders can be used to reduce the time and effort required for the evaluation, particularly the effort required for data collection. Both arguments must be weighed before a valuation.

By including a large number of relevant assessment criteria from the literature (DWA 2015; Lienert *et al.* 2015), experts and stakeholders, the assessment can be regarded as comprehensive. Of particular importance in this context is the assessment of the adaptability of infrastructure alternatives. Conventional water supply and wastewater disposal systems often have disadvantages due to very long useful service lives and the resulting inflexibility regarding new alternatives. In MuBeWis, this aspect is explicitly taken into account.

The transition to an alternative infrastructure is often implemented along a transition path with different intermediate stages, where many advantages are not apparent from the outset or temporary disadvantages have to be accepted. In these cases, the evaluation should be carried out with MuBeWis for various points in time during implementation. In this context, the long-term perspective should be considered as equally important as the medium- and short-term.

It remains to be seen whether MuBeWis will find acceptance among the designers of alternative infrastructure systems. If so, it should be reassessed later on, whether its results are robust and in line with real experience, where deficits concerning its operability accrue, and how they can be eliminated.

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