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157

Water Practice & Technology Vol 13 No 1
doi: 10.2166/wpt.2018.028

Vacuum sewerage systems – a solution for fast growing cities in developing countries?

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Abstract

Developed more than a century ago, the potential of vacuum sewerage systems remains underexploited. At the same time, the rapid urbanization in Asia brings about major challenges for municipal utilities. In this context, the GIZ (Deutsche Gesellschaft fuer Internationale Zusammenarbeit) project 'Integrated Resource Management in Asian Cities: the Urban Nexus' gives technical advice to stakeholders in the partner cities. Fraunhofer IGB, having operated a vacuum sewer system for more than ten years in the context of a research project, carried out a survey regarding current experiences with vacuum sewer systems and the transferability to countries of the Global South. In an environment with existing infrastructure, it is often not economically reasonable to install an additional sewer system. Nevertheless, with aging infrastructure and an increasing importance of circular economy concepts including water reuse, nutrient recovery and biogas generation, vacuum sewers can pose a viable alternative for refurbishments or new developments in semi-decentralized sanitation approaches involving local treatment and resource recovery.

Key words: developing countries, integrated water management, source separation, technology transfer, vacuum sewerage, wastewater

INTRODUCTION

Since the development of modern sewer systems around 150 years ago, gravity sewers have been the most common practice to transport wastewater. Besides requiring a significant amount of water to provide sufficient flow, gravity sewers face the challenge to rely on a constant slope of minimum 2%. High groundwater tables can also pose a challenge to the construction of a gravity sewer since dewatering might be required during construction, and infiltration or exfiltration are regular issues during operation.

Vacuum sewers use air instead of water to convey wastewater. Differential pressure between the collection pits and the negative pressure inside the network, created by vacuum pumps at the vacuum station, allows for water saving measures at the source and the transportation of highly concentrated wastewater, such as black water. The network is characterized by shallow trenches, small pipe diameters and safety from exfiltration. No manholes are required and operators can carry out maintenance and repairs from the surface. Figure 1 shows the typical layout of a vacuum sewer network.

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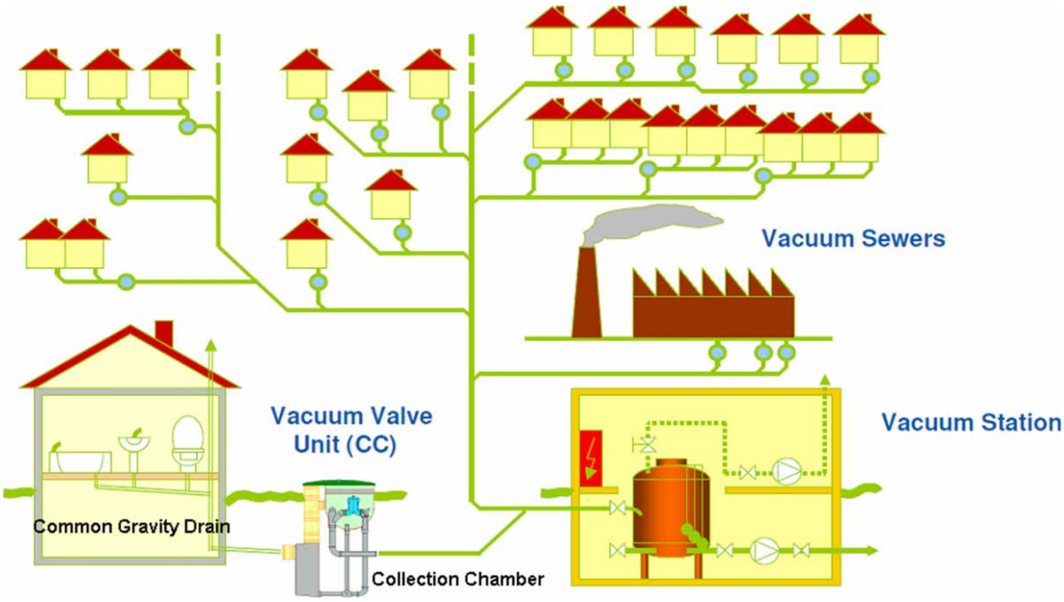

Figure 1 | Overview of a vacuum sewer system involving the vacuum valve unit at the valve pits, vacuum mains and the central vacuum station (Stauffer & Spuhler 2012).

When compared to challenges of conventional sewers, such as deep and costly excavation, exfiltration of sewerage to the environment and difficulty to detect damages, the mentioned characteristics of vacuum sewers seem advantageous. This raises the question whether vacuum sewers can pose a viable alternative in countries of the Global South where sewer infrastructure is often underdeveloped. Despite their development more than 100 years ago and commercial availability since the 1970s, vacuum sewers are still not very common and knowledge on the technology is still not widely distributed.

The second phase of the project 'Integrated Resource Management in Asian Cities: the Urban Nexus', funded by the German Federal Ministry for Economic Cooperation and Development and carried out by the GIZ, started in 2016. Currently, a demonstration of a vacuum sewer system is being prepared in the Vietnamese city of Da Nang (around 1 million inhabitants, high growth rate). Around 110 residential buildings and a food market will be connected to the system. When the system is commissioned it will serve 550 people in Da Nang. Construction of the system is expected to start in February 2018. After successful demonstration of the system the city of Da Nang wants to extend the vacuum sewer to other parts of the Son Tra Peninsula (currently 200,000 inhabitants) and to integrate it into the *Da Nang Sustainable City Development Program*.

In this context, a study on experiences with the vacuum sewer system has been carried out in 2016 in order to define the factors of success for vacuum sewer systems and to base the transfer of the vacuum technology to countries of the Global South, based on the experiences made in countries like Germany.

METHODS

The study evaluated 10 years of operational experience from the demonstration project DEUS21 in which a vacuum sewer was installed in a newly developed residential area in Knittlingen, Germany. Additional systems in Southern Germany were visited to assess the performance of operating vacuum sewers.

In order to explore the boundaries of vacuum sewers and discuss possible solutions to overcome them, expert knowledge is required. A key element of the study was the synthesis of information

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from scientific and technical literature as well as interviews with scientists, operators, planners and system manufacturers. The participants were asked to rate the technology and share their views on pros and cons of vacuum sewers based on their experience. Further, the survey investigated the possible factors preventing a wider application of vacuum sewers and how to overcome them. Finally, the participants gave estimates on the future perspectives of the vacuum technology as well as the demand for circular economy applications.

In addition, an operator survey for around 60 systems in Germany was conducted in order to capture structural, cost and operational data as well as the experience of vacuum sewer operators.

RESULTS AND DISCUSSION

The interviews revealed the opinions of different operators, decision makers, scientists, planners, consultants towards the vacuum sewer concept. The majority of interviewed people referred to their experiences and the situation in Germany. Generally the perception of the vacuum sewer technology was very good. On a scale from 0 (very bad) to 10 (very good) the average rating was 7.9. When asked how others would rate the vacuum technology the average was 5.4, indicating a less positive reputation of vacuum sewers.

Most interviewed people referred to the higher operational complexity of vacuum sewers compared to conventional sewers. The complexity is mostly attributed to the failure frequency at the collection pits or more precisely at the vacuum valves. This is underlined by the findings of Miszta-Kruk (2016) who identified a high failure rate for vacuum sewers when compared with pressure and gravity sewers. The operator survey revealed that 63% of the surveyed systems experience vacuum valve failures at least once a month. Although vacuum valves have a high probability to fail, reconditioning time was less than two hours in 86% of cases and thus much shorter than in the investigated pressure and gravity sewer systems (Miszta-Kruk 2016). The short reconditioning time is attributed to easy identification, access and quick repair of malfunctioning valves.

The interviewed experts also referred to the easy identification of errors and remote monitoring as operational benefits. In gravity sewers, damages are often not detected since they most often occur along the underground conduits. In most cases, neither sewerage leaking into the environment nor infiltrating water into the sewer network are detected. The interviews further revealed that the operational costs of vacuum sewers can be high due to the higher failure rate. On the other hand, the interviewees agreed that in flat terrains, where conventional sewers require pumping stations to ensure sufficient slope, operational costs of vacuum sewers can be lower. The same applies to flood areas where stormwater infiltrates gravity sewer networks. Figures 2 and 3 illustrate the average

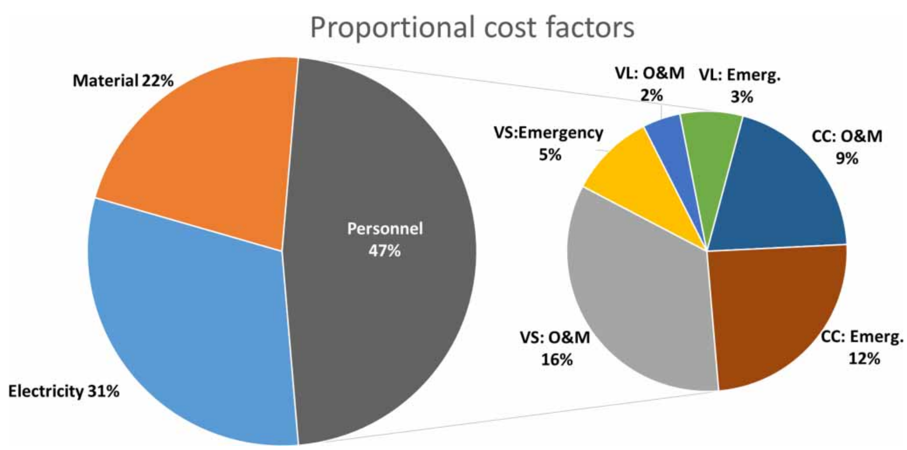

Figure 2 | Relative operational cost composition of vacuum sewers in Germany; VS: vacuum station; VL: vacuum lines; CC: collection chambers (average of 22 systems).

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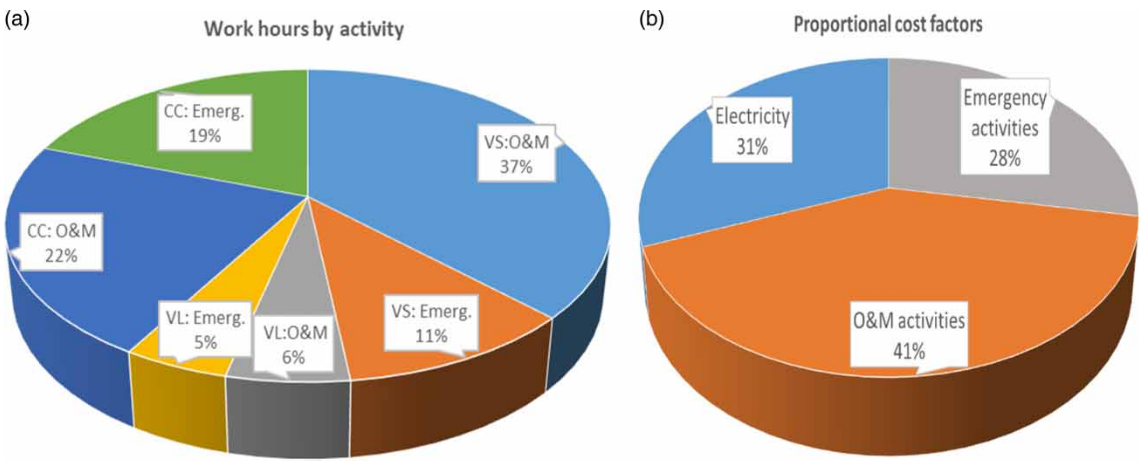

Figure 3 | Operational characteristics of vacuum sewers in Germany (average); (a) Proportional work input according to activity ($n = 45$); (b) Proportional cost factors according to activity ($n = 22$).

composition of annual operational costs in vacuum systems under German conditions. Personnel costs are the largest cost factor. Emergency related personnel costs constitute around 20% of total annual costs. When material costs are included, emergency related costs account for 28% of total annual operational costs.

Despite the high failure rate the work input into reconditioning of malfunctioning components at the collection chambers is fairly low (average 0.70 h/chamber/a; median: 0.44 h/chamber/a). These findings are similar to the findings by Naret (2009) who reports an average of 0.60 h/chamber/a for emergency labor at the vacuum valves. Table 1 shows results from the operator survey. On average total annual work load is 4.7 h/chamber/a for all activities including maintenance. The median is 3.0 h/chamber/a. In terms of operational cost the average is 212 €/chamber/a and the median is 140 €. The costs are highly affected by the hourly rate in Germany which is in the range of 25 to 45 €/h. Cost for labor and electricity can vary significantly between regions. Thus, it can be assumed that the operational costs will be lower in countries of the Global South. Regarding costs and work input the wide deviation for minimum and maximum underline how different systems can be depending on factors, such as design, construction quality and technical knowledge of operators, among others.

While operational complexity and associated costs are referred to as negative aspects of the vacuum technology, the lower installation costs resulting from shallow trenches, smaller pipes and thus reduced excavation are referred to as strengths of the vacuum technology. These benefits especially unfold in flat terrains, areas with high groundwater tables, water protection zones and areas prone to flooding. The interviewed experts agreed that construction of a vacuum sewer is easier and faster compared to conventional sewers but requires high accuracy to ensure tightness of the network. These findings are in accordance with the literature (Little 2004; Elawwad *et al.* 2015; Islam 2017).

Table 1 | Operational data from vacuum sewer systems in Germany

	Related to failure at collection chamber (h/chamber/a)	Total system (including maintenance) (h/chamber/a)	Operational cost (incl. electricity) (€/chamber/a)
Average	0.70	4.70	212.64
Median	0.44	2.96	140.79
Maximum	2.57	24.0	736.4
Minimum	0.00	0.10	46.3
Number of systems	($n = 47$)	($n = 46$)	($n = 22$)

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The tightness of the system is crucial to the environmental benefits of vacuum sewers. The prevention of ex- and infiltration was highlighted as environmental benefit in the interviews together with the potential water savings by using air as transport medium. Further, the surveyed experts referred to the potential of recovering nutrients and energy from the concentrated wastewater as a major environmental benefit. This is supported by the findings of Kjerstadius *et al.* (2015) who state that recovery rates for phosphorous, nitrogen and biogas are highest when using vacuum technology for the separate collection of different fractions of wastewater and organic wastes. Although currently little demand for such circular economy concepts exists, the interviewees estimate increasing importance in the future. According to the experts, increasing demand will also exist for vacuum sewers when new business fields related to circular economy approaches are developed and knowledge on vacuum sewers is wider distributed.

The distribution of vacuum sewers in Germany seems to be hindered by the presence or proximity of existing sewer infrastructure and the majority of experts highlighted that vacuum sewers unfold their greatest potential where no sewer infrastructure is present yet. In addition, reputational barriers seem to be hindering a wider application. The interviews revealed that the bad reputation from few badly executed vacuum sewer projects dominates the overall perception of the technology and leads to skepticism. Only few technical barriers were reported related to the technical complexity. According to the interviewed experts, a lot of awareness raising and education is still necessary. In conjunction with additional larger demonstration projects, the reputation of vacuum sewers could be improved for a potential wider application.

On the example of Knittlingen, the operational data of a system for around 100 residential houses has been analyzed over a period of more than ten years. Figure 4 shows the runtime of the vacuum pumps and the electricity consumption during the operating time. It can be seen that the runtime of the vacuum pumps mainly determines the electricity consumption of the vacuum system. Two periods could be identified when the vacuum pumps were running longer and the electricity demand was increased, highlighted by red dots in the figure. After checking the tightness of the network and repairing small leaks, both parameters decreased to regular values again.

For the longest time the vacuum pump's runtime is between 1 and 3 hours/day resulting in an electricity demand of around 20 to 30 kWh/day. With around 300 people connected to the vacuum system in Knittlingen, the electricity consumption is between 23 and 34 kWh/person/a. This is

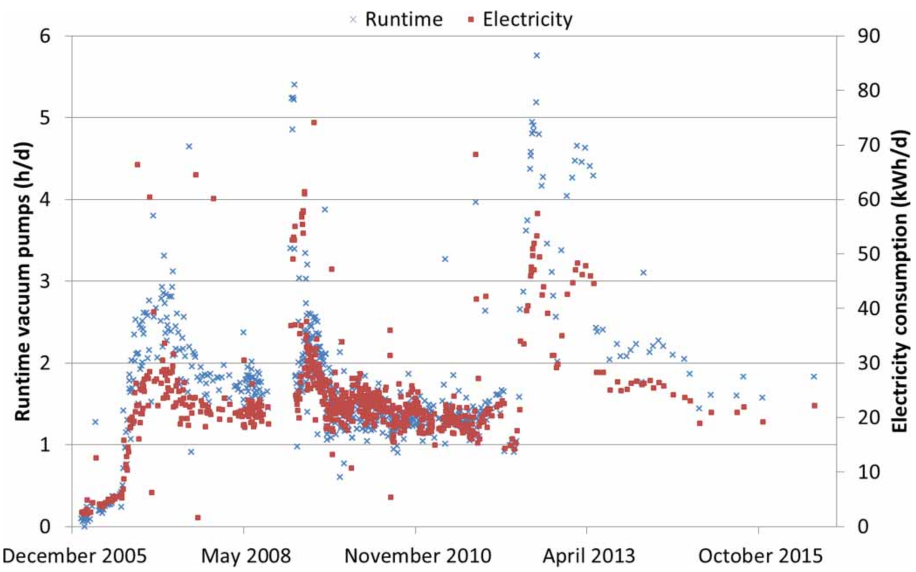

Figure 4 | Vacuum pump runtime (blue crosses) and electricity consumption (red dots) for the vacuum sewer system in Knittlingen, Germany.

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Water Practice & Technology Vol 13 No 1
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within the range of 15–30 kWh/person/a reported in technical papers (Münch & Winker 2009). On the other hand, the operator survey revealed an average electricity demand of around 60 kWh/person/a indicating that the previously reported range is too optimistic. Only seven out of 47 responses indicated an electricity demand below 34 kWh/person/a.

Between 2013 and 2015 the area 'Östlich der Waldstraße' in Böblingen-Dagersheim was developed. 25 existing units and 80 newly developed units were connected to a vacuum sewer which is operating since 2015. In the existing houses, the stormwater system has been separated from the wastewater system, showing that a subsequent separation of wastewater streams is possible with the vacuum sewer system. The old gravity sewers can further be used for the drainage of the stormwater.

Regarding the application of vacuum sewers in developing countries, the majority of participants was confident about the beneficial use and suitability for addressing challenges such as water scarcity, budget and terrain constraints. This opinion is supported by the successful vacuum sewer projects in Outapi, Namibia (Zimmermann *et al.* 2015; Liehr *et al.* 2016), and rural villages in Botswana (Odirile *et al.* 2010; Ridderstolpe & Stenbeck 2011) to which the interviewed experts referred. However, the interviewed actors bound this estimate to specific conditions such as financial security for operation and maintenance activities and good technical knowledge of the operators, since vacuum sewers are perceived as more complex than conventional sewers. Another crucial success factor is the availability and supply of spare parts. These claims are understandable after the challenges of vacuum sewer projects in Cape Town, South Africa (Beauclair 2010; Taing *et al.* 2011), and other projects in rural Namibia (Mäkinen 2015) which have been referred to in the interviews.

CONCLUSIONS

Although the benefits of the vacuum system are widely acknowledged there seems to be stronger perception of the negative aspects related to the failure rate of vacuum valves amongst experts without experience with a vacuum sewer system. The fast identification and repair of malfunctioning components as well as environmental benefits and the quick, cheap and easy implementation seem to be less important factors governing the reputation of vacuum sewers. Unfamiliarity with the technology from all actor groups including end users, operators, planners and construction companies resulted in discomfort and skepticism. Although only a minority of vacuum sewer projects face significant challenges, the impacts on the reputation seem to be much stronger compared to the majority of the systems, which are running well. The wide deviation for working hours, electricity consumption and operational costs highlight differences among the reported vacuum sewer systems in Germany. Additional large-scale demonstrations in conjunction with education are keys to overcome current barriers. Another important aspect is the ongoing digitalization, which can help to make the operation of vacuum sewer systems more cost efficient and less dependent on the skill and motivation of the operators, e.g. by an automatic monitoring system for the vacuum chambers counting the frequency of valve openings.

In an environment with existing infrastructure, it is often not economically reasonable to install an additional sewer system. Nevertheless, with aging infrastructure and an increasing importance of circular concepts including water reuse, nutrient recovery and biogas generation, vacuum sewers can pose a viable alternative for refurbishments or new developments in semi-decentralized sanitation approaches involving local treatment and resource recovery. Especially in the context of fast growing cities the application of vacuum sewers also poses relief to the wastewater treatment facilities since only concentrated wastewater is conveyed while stormwater is excluded.

The projects in Outapi (Namibia) and Botswana illustrate the potential success of technology transfer to developing regions. However, financial sustainability and spare parts availability must be ensured as well as technical expertise of the operator. In summary, vacuum sewers can pose a

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cheap, flexible and environmentally safe alternative to conventional sewer systems with particular advantages in dry, flat areas currently lacking a sewerage system or rapidly growing urban areas where additional treatment capacity is limited. The project currently developed in Da Nang will provide further insights in the transferability of the vacuum sewer technology to urban areas.

ACKNOWLEDGEMENTS

We thank the German Federal Ministry for Economic Cooperation and Development (BMZ) for funding the project 'Integrated Resource Management in Asian Cities: the Urban Nexus' carried out by the GIZ (Deutsche Gesellschaft fuer Internationale Zusammenarbeit). We thank the German Federal Ministry of Education and Research (BMBF) for funding the project 'Decentralized Urban Infrastructure Systems DEUS 21'.

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