

## Blue Diversion: a new approach to sanitation in informal settlements

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### ABSTRACT

The sanitation concept 'Blue Diversion' ([www.bluediversiontoilet.com](http://www.bluediversiontoilet.com)) was developed as a possible answer to the sanitation crisis in urban slums. It is based on two main elements: (1) diversion of urine, feces, and water at the source as the basis for efficient resource recovery, and (2) linking different scales (family toilets and semi-centralized resource recovery). Our objective was to develop an attractive 'grid-free' (i.e. functioning without piped water, sewer, and electrical grid) dry urine-diverting toilet, which provides water (through recycling on-site) for flushing, personal hygiene (anal cleansing and menstrual hygiene), and hand washing. This service, including the entire sanitation value chain, should eventually be made available as a profitable business with total user fees of 5 c/p/d. The results presented in this paper are (1) a toilet design model, (2) the development of a new type of membrane bioreactor for treating flush and wash water, (3) main results of a geographic information system-based stochastic service model to link the family-scale toilet to a community-scale Resource Recovery Plant, and (4) a business model that yields maximum profit for the local community. We conclude that the approach is feasible, but challenging from a technical as well as an organizational point of view.

**Key words** | innovation, resource recovery, source separation, toilet design, urban, wastewater treatment

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### ABBREVIATIONS

BMGF Bill & Melinda Gates Foundation

RRP Resource Recovery Plant

UDDT urine-diverting dry toilet

UF ultrafiltration

### INTRODUCTION

In 2010, around 10% of the deaths occurring in children below the age of five could be attributed to diarrhea (Liu *et al.* 2012). This corresponds to more than 800,000 deaths a year, with the highest numbers in Africa and Southeast Asia. Hygienic sanitation and hand washing can reduce

the incidence of diarrhea significantly (Curtis & Cairncross 2003; Fewtrell *et al.* 2005). It is well-known that the millennium development goals for improved sanitation will not be reached, but as pointed out by Baum *et al.* (2013) the situation may in fact be even worse than normally anticipated. The reason is that 'improved sanitation' is defined only with respect to personal hygiene, while all aspects of urban hygiene, which would include safe disposal or treatment of excreta, are neglected.

This may be one of the reasons that the Bill & Melinda Gates Foundation (BMGF) launched the reinvent the toilet challenge in 2011 (Anonymous 2011). Although most of the BMGF sanitation grants are directed toward projects

following the state-of-the-art for sanitation projects in low-income countries, the foundation also wanted to challenge other parts of the scientific community to invent unconventional ‘high-tech’ solutions.

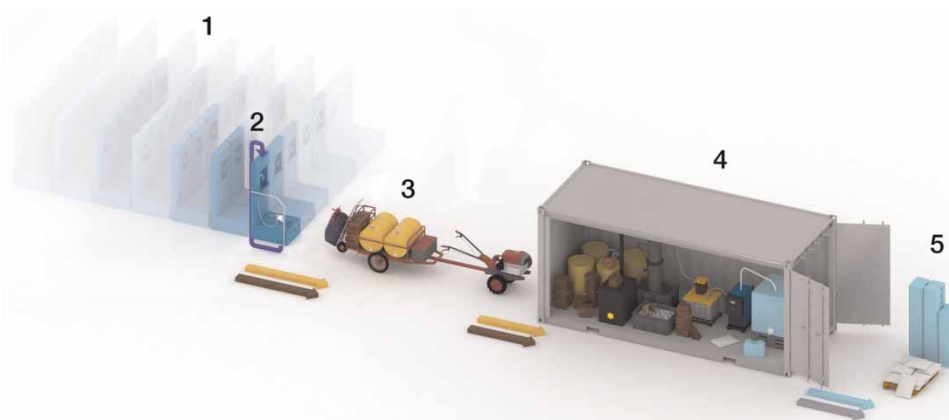
The requirements of the call were ambitious: to develop a private or public toilet for dense urban areas (especially informal settlements), providing high personal comfort at a price of 5 ¢/p/d. Valuable products should be extracted from the toilet waste, and no connection to running water, grid electricity, or sewers could be assumed. In essence, there was a requirement for ‘zero-emission’, which would take into account urban hygiene as well as environmental aspects.

A total of eight projects were initiated (including one from our institution, Eawag in Switzerland), ranging from electrochemical treatment of combined toilet waste to plasma gasification of source-separated feces (Anonymous 2011). We chose to focus on toilet design and logistics and not on processing excreta on site. We based this choice on compelling evidence that in many developing countries toilets are of poor quality, not only from the perspective of user satisfaction (e.g. Tumwebaze 2014), but also with respect to the entire sanitation value chain (Evans 2013). Our approach, ‘Blue Diversion’, was based on two main concepts: (1) separation of urine, feces, and water for better resource recovery in the sanitation value chain and (2) adaptation of two different scales: the household scale for the toilet

and a semi-centralized scale for treatment and resource recovery.

Source separation only became popular during the last 20 years (Larsen *et al.* 2013), but this idea is gaining ground in developing countries (Katukiza *et al.* 2012). The main advantage of source separation is an increased resource efficiency as discussed by Larsen *et al.* (2009), primarily because it is more energy-efficient to extract valuable resources from a concentrated ‘pure’ stream (like urine or feces) than from a diluted mixture (e.g. of excreta and flush water). Urine-diverting dry toilets (UDDTs), however, are often not well accepted by users, especially in an urban environment (Cordova & Knutz 2005). Since they cannot be flushed, they tend to end up dirty and unattractive, and the lack of water for personal hygiene reduces the hygienic improvements achieved by these toilets. For these reasons we chose to develop an attractive source-separating dry toilet with an integrated water cycle.

Resource recovery from urine and feces is easier from a toilet with many users, but as shown by Tumwebaze (2014), user satisfaction is negatively correlated with the number of users per toilet. We therefore chose different scales for toilet and resource recovery and linked those by a simple transport system as shown in Figure 1. We considered that the main concerns about transport are related to hygiene and aesthetics for the people emptying the toilets, whereas costs are the main issue from a business point of view. We thus focused on these two aspects.



**Figure 1** | Conceptual setup of the ‘Blue Diversion’ system with the following features: (1) attractive source-separating toilets; (2) wash and flush water is recovered and recycled onsite; (3) a transport concept is set up; (4) semi-centralized resource recovery from source-separated urine and feces; (5) a market-based business model. An important source of income may arise from the sale of fertilizer chemicals extracted from urine.

Here, we present key features of our approach to reinvent a toilet, which can be integrated into a sanitation value chain in informal settlements. Our main focus is on toilet design and toilet technology, which are the most innovative parts of the project.

## METHODS

The project was developed in an interdisciplinary team (engineering, social science, business administration, sanitation in developing countries, and design). We also involved different stakeholders in workshops and focus groups, based on good practice for implementation of sustainable sanitation in developing countries (Lüthi *et al.* 2011).

The design process was initially supported by three workshops: (1) an internal Eawag workshop, additionally attended by two international experts; (2) a workshop at the Makerere University (Department of Civil and Environmental Engineering); and (3) a local workshop in an informal settlement in Kampala, Uganda. Furthermore, a research log was set up to document the state-of-the-art in the area of UDDTs (EOOS & WEDC 2014). A first working model was pilot-tested in Uganda and a second modified working model in Kenya (unpublished data).

In a number of internal Eawag workshops, technical alternatives for the water recovery unit were developed by different groups of engineers. We aimed for a high diversity in the groups with respect to age, competences, and experience. In a final workshop, the technical alternatives were evaluated and the most promising ones were tested (unpublished data).

A numerical model was developed in order to evaluate and optimize transport in a variety of spatial setups (Schmitt 2012). We used geographic information system data for the housing structures and road networks of four informal settlements in Africa and India. Regression techniques were used to analyze the spatial data (especially the influence of population density on travel distances). Moreover, bivariate regressions were applied in order to identify the interdependencies of the system parameters, e.g. of service time on costs and capacity.

Different business model solutions were developed based on a 1-day, participatory workshop with participants

from different disciplines (from Eawag and ETH Zürich) and one PhD student from Kampala, Uganda. The workshop was inspired by the base of the pyramid protocol 2.0 (Simanis & Hart 2008), but only covered the first, qualitative part of the process.

## RESULTS

### Attractive source-separating toilet

A major goal of the 'Blue Diversion' project was to design an attractive source-separating toilet that will appeal to users. Based on the preferences of the participants in the Kampala workshop, we chose to design a squatting toilet, but the same principles apply for a sitting toilet. In order to counteract the lack of hygiene associated with dry sanitation (Katukiza *et al.* 2012), the toilet provides running water for hand washing and personal hygiene, and a comfortable 'flush' button for cleansing the front part of the pan. These familiar functions are translated into a 'next generation' product that works off-grid by applying a radical low-cost innovation approach. An important feature of this low-cost approach is the fact that most parts of the toilet can be produced locally in simple processes, e.g. rotational molding.

The toilet is laid out for use by approximately 10 people as a compromise between acceptance, size, and costs. According to the proposed WASH post-2015 targets of the Water Supply and Sanitation Collaborative Council (WSSCC), a toilet can be considered acceptable if it is shared by a maximum of five families (WSSCC 2014). However, as the risk of a social dilemma in the collective cleaning behavior of a shared toilet declines with the number of families sharing the toilet (Tumwebaze & Mosler 2014), we defined the Blue Diversion toilet for the scale of two moderately sized families.

As a (re)movable piece of furniture, it can be retrofitted into existing toilet superstructures, thus allowing a 'rent-a-toilet' system to be set up. Rental solutions are seen as a promising solution for informal settlements dominated by tenant populations that rent their structures from absentee landlords. Previous research in informal settlements of Kampala has shown a high willingness to pay for this kind of arrangement (Horst *et al.* 2011; Tumwebaze & Lüthi 2013).

This retrofitting concept as well as the toilet functions and esthetics were tested in an initial reality-check workshop in an informal settlement in Kampala, where the concept was well received.

The toilet features an innovative dry source-separating pan, where the front part can be cleaned with water from the on-site water recovery unit. The toilet's core is the back wall containing the compact water recovery technology. While feces and urine are collected under the separating pan (like in a normal UDDT), the polluted water from hand washing, cleaning of the front-end of the pan, anal cleansing and menstrual hygiene is fully recycled on site. Soiled water is pumped to the treatment tank and clean water to the clean water tank. In the first version of the toilet, this was done by combined foot pumps, whereas in the second version, electric pumps were installed (Figure 2). Important design features of the water recovery wall are a hand wash basin with running water, and a shower head providing a comfortable cleansing device for personal hygiene (Figure 2). The feces cover and a specially developed urine–water separator (hidden below the pan) are both activated by the flush and the hand shower in order to prevent mixing of excreta

and water (see [www.bluediversiontoilet.com](http://www.bluediversiontoilet.com) for technical details).

### On-site water recovery

The core principle of the on-site water recovery technology is a gravity-driven ultrafiltration (UF) unit originally developed for obtaining drinking water from river water (Peter-Varbanets *et al.* 2009). The advantage of this technology is the ability to produce hygienically safe water (by UF) at low energy consumption (filtration is gravity-driven) and without maintenance (in the low-loaded filter, grazing by metazoa maintains a low but stable flux by keeping the fouling layer under control; Derlon *et al.* 2013). Owing to the more heavily polluted wastewater to be recovered within the toilet (as compared to river water) and recirculation of the treated water, the original concept was modified. In experiments with simulated flush & wash water polluted with feces, urine, soap, and blood (unpublished data), it could be shown that a stable flux could be obtained with the simplest possible aerobic reactor, contained within the water recovery wall (Figure 2). The key technical design parameters for sizing the reactor are the water permeability and the trans-membrane pressure, as these determine the water flux. Initial results confirm that about 75 l of water can be made available per day (corresponding to 1.5 l of water per toilet visit, assuming 10 users and 5 toilet visits/user/day).

As the filtered water contains around 30–40 mg COD/l (COD = chemical oxygen demand, a unit for organic matter) and is slightly colored, we recommend polishing of the effluent to minimize the risk of re-growth and ensure color removal. Preliminary results showed chlorine-producing electrolysis to be successful (unpublished data), and an energy-optimized version of electrolysis functioned well in the second field-test in Kenya (unpublished data).

We found that safe water recovery through gravity-driven UF is feasible and maintenance-free operation is stable. Polishing by electrolysis makes the water more acceptable and increases the safety level. Energy consumption could be optimized to around 30 Wh/p/day, which are provided by a small solar panel on the roof connected to a battery built into the back of the toilet.



**Figure 2** | Working models of the 'Blue Diversion' toilet: (a) the first working model tested in Uganda; (b) the second working model tested in Kenya. The second working model has been modified based on the results from the first pilot tests in Uganda (unpublished data). Primarily, this toilet is more compact (people found the first model too large), and foot pumps have been replaced by electrical pumps to make it easier to use for people with little physical strength, e.g. children and elderly people.

## Transport logistics concept

The conceptual transport logistics comprise of one collector per Resource Recovery Plant (RRP), collecting feces and urine twice a week from the toilets. In order to ensure hygienic and esthetic working conditions, feces are removed in a self-sealing container and urine by pumping. These features, however, still only exist as design studies (not presented).

We explored whether a collection service system would be feasible at a reasonable price, despite labor-intensive collection in complex contexts. Analysis of the spatial data showed that travel distances are significantly related to user density. However, even at moderate densities from 100 to 350 users per hectare, this has only a minor influence on the system performance. Instead work productivity was identified as the key driver for efficiency (Schmitt 2012). At lower user densities, travel distance plays an increasing role and at very high population densities, space will clearly limit the applicability of the concept, e.g. in Bangladesh, where Angeles *et al.* (2009) found population densities up to 2,550 inhabitants per hectare. This implies that the logistics system is suitable for a range of typical spatial setups, but only provided that work productivity is high and space is not limiting for toilets and treatment facilities. We conclude that one of the most important system integration parameters is the optimization of the feces collection process, urine pumping and discharge to the RRP, all features strongly influenced by design.

For the calculation of a business case, we chose Kampala in Uganda, with a user density of 150 inhabitants per hectare and a service time per facility of 20 minutes (two toilets per facility), resulting in an RRP for 860 users and logistic costs of 1 ¢/p/d (Schmitt 2012).

## Semi-centralized resource recovery from source-separated urine and feces

Many technologies for treatment of source-separated feces and urine are known, but most of them are still in their infancy (Larsen *et al.* 2013). The optimal choice of technology in a RRP depends on the boundary conditions of a specific site and further technology development (for a discussion, see McConville *et al.* submitted).

## The Blue Diversion business model – a market-based sanitation approach

The ‘Blue Diversion’ business model follows the market-based sanitation approach (London & Hart 2010; Osterwalder & Pigneur 2010). Sanitation entrepreneurs would generate sufficient revenues to cover the costs and obtain an attractive profit. This business model addresses two different customer groups: two families renting a single toilet and wholesalers buying end-products. The value proposition for toilet users is to offer attractive and affordable rental toilets with safe and reliable emptying; the value proposition for wholesalers is the secure delivery of nutrients or fertilizers at a stable price (independent of market fluctuations). The relationship with toilet users is managed via mobile payments and twice-a-week visits by the collector. Efficient resource recovery creates another stream of revenue from the sales of end-products. These two revenue streams make the business model robust and assure a positive cash flow while still allowing for the provision of attractive toilets at an affordable service fee. The corresponding revenue streams are the service fee of 5 ¢/p/d, which covers toilet rent, emptying, and maintenance costs, as well as most of the RRP costs. Sales of end-products such as recovered water, nutrients, and energy are estimated to reach about 2 ¢/p/d.

Key competencies for executing the business model include logistics, operational, and management skills. Logistics skills ensure the safe and hygienic removal of excreta, operational skills are necessary to convert urine and feces in the RRP into valuable end-products, and management skills promote and market the ‘rent-a-toilet’ service. Entrepreneurial skills to develop and scale-up the business model are another key element. Andersson (in press) showed that smallholder farmers in Uganda even accepted fresh urine and there is thus little doubt that a non-smelly, concentrated nutrient solution will have some value amongst farmers, provided that fertilizer value and safety are proven by appropriate tests.

Necessary business partners are local toilet manufacturers, who produce the user interface, UF membrane manufacturers, treatment technology equipment providers, and local contractors, who assemble and retrofit the toilet into the existing superstructure and provide the service of

repairing the toilets and RRP machinery. Finally, to make the business model successful, the local community has to support the development of the sanitation business.

### Pilot testing of the Blue Diversion toilet

A first model of the 'Blue Diversion' toilet was tested in two slums (Kifumbira and Kisalosalalo) in Kampala, Uganda (unpublished data). Although the toilet was generally well received, a number of critical points were identified by the users. The toilet was perceived as too large, foot pumping was considered too strenuous for persons with little strength (children, elderly, and disabled people), and the water quality was not always good enough for hand washing (too much urine entered the water cycle and gave rise to some smell). Improving on these issues gave rise to the second working model, which was field-tested in Mukuru, an informal settlement in Nairobi, Kenya, in cooperation with Sanergy (<http://saner.gy/>). This second generation toilet was better received than the first one, showing the importance of rapid field-testing and short development periods. People showed a pragmatic attitude to the recycled water: if they could be convinced that it was safe and if it did not smell, they generally accepted using it for hand washing. From a technical point of view, however, there is still much work to be done in order to obtain the robustness required for large-scale implementation.

## DISCUSSION

The sanitation solution presented in this paper is innovative, but it builds on many existing sanitation solutions. Both the UDDT and the pour flush toilets, where small amounts of water for flushing are used, are common toilet types in many low-income countries (Katukiza *et al.* 2010). Transporting feces and urine over short distances to a semi-centralized plant is also done in other projects, e.g. by Sanergy (<http://saner.gy/>), and mobile toilet units are found in the MobiSan approach (Naranjo *et al.* 2010).

However, the 'Blue Diversion' toilet combines those features and can thus be considered a further development of the UDDT: (1) the toilet can be flushed without water

entering the urine or feces container; (2) the feces container is self-sealing, posing no risk for the service personnel (not yet developed); (3) water for hand washing, anal cleansing, and flushing is recovered and reused for the same purpose on-site; (4) washers do not have to displace themselves for anal cleansing; (5) a hand washing facility is included in the toilet design.

Although the toilet has already been field-tested twice in order to test for general acceptance – especially for the acceptance of reuse of treated water for personal hygiene – it is still far from an industrialized product. Technical robustness, willingness to pay, and acceptance of the features are only a few of the many barriers to a successful introduction of this new toilet design. These features can be tested and improved in small pilot projects. For the toilet to be applied at scale, however, the business model must also be refined and successfully implemented. The low fee of 5 ¢/p/d is based on large-scale production of all parts of the toilet and marketing of the fertilizer chemicals produced. Important next steps are thus:

- (1) technical progress to improve robustness and drive down costs of mass production. Some parts of the toilet have not been developed yet; other parts like the solar panel depend on other industrial developments;
- (2) further field-testing in diverse environments (for acceptance and robustness);
- (3) further development of the business model and cooperation with organizations already working in the field along the same lines.

Despite the potential advantages of the 'Blue Diversion' toilet, there is still a long way to go before the concept can be implemented at scale. Considerable investments must be made over years in order to make this apparently high-end toilet available for the poor at a price that they are both able and willing to pay.

## CONCLUSION

We conclude that:

- the systems approach presented in this paper is based on existing concepts, but improves on critical issues like water availability and acceptance;

- it is in principle possible to provide water for personal hygiene and flushing of the front bowl without compromising on the general advantages of a urine separation dry toilet;
- transport of feces and urine in densely populated slums is cost-efficient if service time can be kept low;
- with very short development cycles, we were able to improve significantly on the acceptability within the available project time (unpublished results). However, rapid development cycles come at the cost of lower technical perfection;
- people generally accept using recycled water for personal hygiene if they are convinced about the safety of doing so. Furthermore, the water must be perceived as pleasant;
- the urine-water separation technology is a very sensitive part of the 'Blue Diversion' toilet. Biologically treated urine gives rise to a characteristic smell leading to rejection of the water by the users. Since the water is kept in a nearly closed cycle, already small amounts of urine in the flush water give rise to this smell;
- a preliminary business model shows that the 'Blue Diversion' sanitation is in principle viable if low production costs of the toilet can be combined with a long life-time. However, not only are these more technical aspects critical, also the complex organization of a transport-based sanitation business is challenging.

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