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# D11 - Water Out Shit In: a new paradigm for resource recovery


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## Abstract

Phosphate is the most essential nutrient that must be recovered from waste streams in the future, because the easily minable phosphorus rock reserves will be depleted within 50 to 100 years. For an efficient recovery and reuse, a waste water flow with a high concentration and a low volume is needed. However, the present system of production, collection, transport and treatment of sanitary waste water is aimed at safe disposal of waste water and focussed on health and minimisation of environmental effect. This resulted in a diluted, large volume of sanitary waste water from which the resource recovery is less efficient. To accommodate the new requirement of recovery of nutrients, a novel approach combining the health and environment requirements with the recovery necessity is needed.

A new approach “Water Out Shit In” (WOSI) is proposed in this perspective paper. Application results in a single concentrated flow of waste water with a high concentration of organic load. Main feature of the WOSI approach is its system wide approach addressing all elements of the urban waste water chain from production to transportation to treatment and recovery. WOSI starts at the individual houses, ends at the resource recovery and reuse. In each stage, the main question is: how to remove water or prevent it from entering and how to increase the organic load.

The chain starts in the houses. Reducing water consumption of the biggest sanitary waste water producers, i.e. the toilet, the shower and the washing machine, is a potentially effective step in this approach. Household and kerbside organic waste should be added into the sanitary sewer as much as possible. A small diameter gravitational in-house sewer is proposed to be used for collecting and transporting such highly-loaded flow. Within the transportation from household to the treatment, the storm water collection system could be disconnected from sanitary sewer system for preventing further dilution. The chain ends at the waste water treatment, which will be transformed into a resource recovery center via integrating several novel biotechnologies. Overall, a new paradigm for urban infrastructure and inner installation serving resource recovery is emerging.

## Keywords

Low flush toilet, cascading shower effluent, small diameter sewer pipe, resource recovery, innovative biotechnology

## 1 Introduction

The necessity for resource recovery, in particular phosphorus recovery, is emerging (Cordell et al., 2009). For one reason, there is no replacement for phosphorus in the growing of crops. For the other reason, the easily minable phosphorus rocks will become scarce in the coming decades. Several immediate measures are needed to promote the phosphorus recovery from waste streams such as manure, agricultural residues, municipal organic waste and sanitary wastewater (Neset and Cordell, 2012). In addition, the need for recovering organic matter from waste streams for the decreasing soil fertility is also emerging.

Metropolitan area, being the place where all materials flow through and transform intensively and frequently, represents a place of interest for resource recovery. However, challenges exist as the current urban infrastructure setup was designed based on the public health, safety and comfort rather than on the need for resource recovery. The origin of current sanitary system can trace back to 150 years ago in the city of London. It utilises water as the main hydraulic transport media and pursues the public health and comfort. The public safety, e.g. flood prevention, was also incorporated into the design and resulted in the classic combined sewer system that handles both storm water and sanitary waste water in a single-pipe solution. Such solution features removing hydraulic flows with risks as far away and quickly as possible; the adoption of flush toilets together with the sewer system is the outcome as well as the paradigm that has been used until nowadays. Consequently, resource saving, e.g. reduction on water consumption of the household utilities, and resource recovery was not within the scope of this current sanitation paradigm. Furthermore, possibly due to the fear of potential blockage, in the current sanitation paradigm, organic solid waste is separately collected via vehicular transportation instead of the hydraulic system within the sewer.

The importance of treating waste water before discharging was acknowledged later, making the end-of-pipe treatment a logical choice. The end-of-pipe treatment was originally designed to serve only one purpose: producing an effluent that is safe and dischargeable to the environment. Organic matter and nitrogen are converted into carbon dioxide and nitrogen gas and released into atmosphere. The design serving the environmental protection has proven to be effective in the last couple of decades, until the rapid population growth and urbanisation making the resource recovery necessary. The need for resource recovery adds a new variable to the design and operation of the sewer system. The sanitation paradigm starts shifting from treatment towards recovering substances from the waste water in such a way that it can be re-used. The awareness towards resource scarcity as a consequence of population growth and urbanisation has existed before the sanitation paradigm shift; actions based on this awareness in the urban area have been taken, with the adoption of dual-flush toilet for water saving as a vivid example.

While resource recovery gradually emerges as a new variable, the existing requirements of public health, safety, comfort, environmental discharge are still valid and will becoming even more stringent given the changing climate, rapid population growth and urbanisation. The design criteria for the collection and transport system may encounter conflicts when considering both the emerging and existing requirements. During the transition from local to regional development (e.g. urbanisation), an element of transport and central treatment was introduced, which made it relatively easy to continue the service. In contrast, resource recovery requires intensive treatment and operates efficiently with a small, but concentrated flow. The transformation of current urban infrastructures poses a new challenge in continuing the service while transiting. The transition will take five to seven decades, which is in the same order of magnitude as the estimated approaching phosphorus scarcity. As the human excreta are anticipated as one of the main future sources for recoverable phosphorus, in addition to animal manure and agricultural residue, the transition needs to begin now and start with the sanitation paradigm shift. Removing water from and adding organics into the sanitary sewer system for creating a small but concentrated flow is the current fashion within the sanitation paradigm, which can be summarised as “water out, shit in”. This paper reflects the current realisation of such concept, e.g. the source-separated sanitation and explores possibilities for a new system choice.

## 2 Transition towards the resource-recovery-oriented sanitation

### 2.1 Separate collection of storm water and sanitary waste water

Although not designed for serving resource recovery, the emergence of separate collection of storm water and sanitary waste water have contributed to the reduction of waste water volume and the prevention of further dilution of sanitary waste water due to the addition of storm water. The waste water treatment capacity could not catch up with the fast pace of metropolitan area growth, and the separated collection of storm water and sanitary waste water became a logical system choice and the new standard, especially for the areas with relatively abundant rainfall like the Netherlands. Rehabilitation and reconstruction of old combined systems mostly lead to separating the flows. These two systems may co-exist for a long time: the old system is gradually replaced by the new system. During the whole transition period, that will take decades, both systems must and can co-exist.

### 2.2 Source-separated sanitation system

More advanced solutions for recovering resources within the sanitation system have been proposed, examined and even upscaled (Zeeman and Kujawa-Roeleveld, 2011). A well-known example is the source-separated sanitation system, also known as “new sanitation”, that develops into a new paradigm in the last two decades. A separated collection of flows according to their distinct hydraulic properties and compositions are applied. Grey water composed of effluents from shower, washing machine and sink features its high volume and low organic/nutrient concentration. Black water composed of mainly the toilet flush water and human excreta features its high organic matter and nutrient concentrations. Urine may be further separated from the black water, as it contains most of the nutrients (nitrogen and phosphorus) in the black water and can be directly used in biological nutrient recovery process (Tuantet et al., 2014). Different treatment options are applied to recover distinct resources from each flow, which was extensively studied and realised in practice(Zeeman et al., 2008).

The main advantages of source-separated sanitation system are the creation of effluents with a high organic or nutrient concentration and the use of vacuum toilet to facilitate the transportation of the concentrated flow. An effluent with high organic and/or nutrient concentration is beneficial for resource recovery via biological and/or anaerobic processes. The use of vacuum significantly reduces the water consumption for toilet flush (1 litre with vacuum versus minimal 4 litres without vacuum) and consequently increases the organic concentration of the black water with or without urine separately collected. In some cases, household organic waste is added into black water via the application of food waste disposal unit to further increase the organics in the black water.

Transition towards the source-separated sanitation system, however, is challenging. The plumbing within the households and the collecting and transportation to the treatment system is at least tripled (black water, grey water and storm water), implying a considerably higher cost and risk of misconnection in practice. The black water collection system is almost by default a vacuum system, which makes a gradual transition impossible. For newly built areas it can be applied, but for renovation project it cannot. Several operational challenges and cost of a vacuum system increases the vulnerability of the source-separated sanitation and decrease the potential of popularization. These include the flushing function dependence on electricity, the expensive maintenance and repair of the vacuum system and even the public acceptance towards it nuisance and noise (Hegger and van Vliet, 2010).

### 2.3 Water out, shit in: rethink the entire urban waste water chain

The separation of storm water collection and the source-separated sanitation system both aim at reducing the amount of water entering the sanitary waste water and preventing the possible dilution of sanitary waste water. Such aim can be expressed shortly but concisely as “water out, shit in”. We reflected the entire urban waste water chain, from its generation through the use of drinking water via the collection and transport to the treatment and recovery, using the Netherlands as an example. Based on the reflection, we proposed a systematic transition towards a resource-recovery-oriented sanitation and identify potentials and gaps within this proposal.

In this chain, three domain/stakeholders can be recognised(Vreeburg, 2017):

- Domain 1: The individual household, using drinking water and consequently producing waste water
- Domain 2: The collection and local transport of the waste water to points of local storage
- Domain 3: Transport to treatment location and treatment itself.

For each domain, the possibilities for decreasing the flow and increasing the concentration are considered.

### Domain 1: domestic water use and waste water production

In the Netherlands, the domestic water use is relatively low: 116 litre per person per day (van Thiel, 2014). Still there are possibilities to reduce that water use. Table 15 gives an overview of present day use versus possibilities to reduce the water use of various end uses of water. The options given in the table are result of an internet search with criteria that the technology should be available at least on an experimental scale and applied in pilots.

**Table 15 Water use options: present use against 'possible' use (Vreeburg, 2017).**

| Source | Water consumption (L/capita/day) (VEWIN, 2015) | Implied option | Water consumption (L/capita/day ) | Water savings (%) |
|---|---|---|---|---|
| Toilet | 33.3 | Vacuum or grinder toilet | 5.9 | 82.3 |
| Kitchen sink | 9.3 | Flow delimiter | 5.78 | 39.8 |
| Shower | 51.4 | Recirculation shower | 6.41 | 87.5 |
| Wash basin | 5.2 | Water saving taps, sensor | 3.77 | 27.5 |
| Dishwasher | 2 | Water and energy saving dishwasher | 0.79 | 60.5 |
| Washing machine | 14.3 | Water and energy saving washing machine | 11.14 | 21.3 |
| Adding food waste | | kitchen grinder | 4.62 | - |
| Total | 115.8 | | 38,41 | 66.8 |

Theoretically this reduces the domestic waste water flow with almost 70%. A crucial point, however is the application of a vacuum toilet, which is not fit for a gradual transition. A grinder toilet can be applied individually and may counter the same potential problems with vacuum toilets. An ozone washing machine can be used to save the water consumption for laundry.

Another potential solution would be cascading the household water use; for example, the use of shower effluent for assisting the toilet flush. Looking at the location and hydraulics of a toilet in the house installation, the crucial part is the actual connection of the toilet to a main sewer in which also water from other equipment is discharged. Research shows that solid transport over this distance in a relatively small pipe is very well possible. For further transport, water from the other equipment may serve. Theoretically, the shower effluent is sufficient for facilitating the toilet flush and transport of human excreta within the sanitary sewer (Table 1).

## Domain 2: Collection and local transport

Though the collection and local transport part covers 80% of the total length of the sewer system, there is not much research available for the dimension and even less research or reliable data on the functionality of the system. There is a worldwide propensity to dimension these sewers based on assumptions for a minimal diameter of 200 to 300 mm. and relatively crude rules of thumb. An exception is Brazil where sewer systems are dimensioned to values of 110 to 160 mm pipes (Mara and Broome, 2008). Data on functionality, again very scarce, do not indicate that they function less: 2,24 for the small sewer vs. 2,77 incidents per km for conventional sewer (Melo, 2005).

In the Netherlands, the main stakeholder responsible for the collection of waste water is in many cases the municipality; dimensioning of the system is mostly done by technicians rather based on tradition than on hydraulic analysis. Design of collection sewers are made based on a minimal sheer stress, which can be translated in a velocity or self-cleaning velocity. However, the diameter has only limited effect on that value as can be seen in Figure 21. The volume flow range for which this basic hydraulic phenomenon is presented, represents the actual flows that can be expected for the collection of waste water based on the use of drinking water. The drinking water use is modelled with SIMDEUM (Blokker et al., 2010) with the condition that drinking water is almost instantaneously converted into waste water. The delay for e.q. the washing machine is of limited interest.

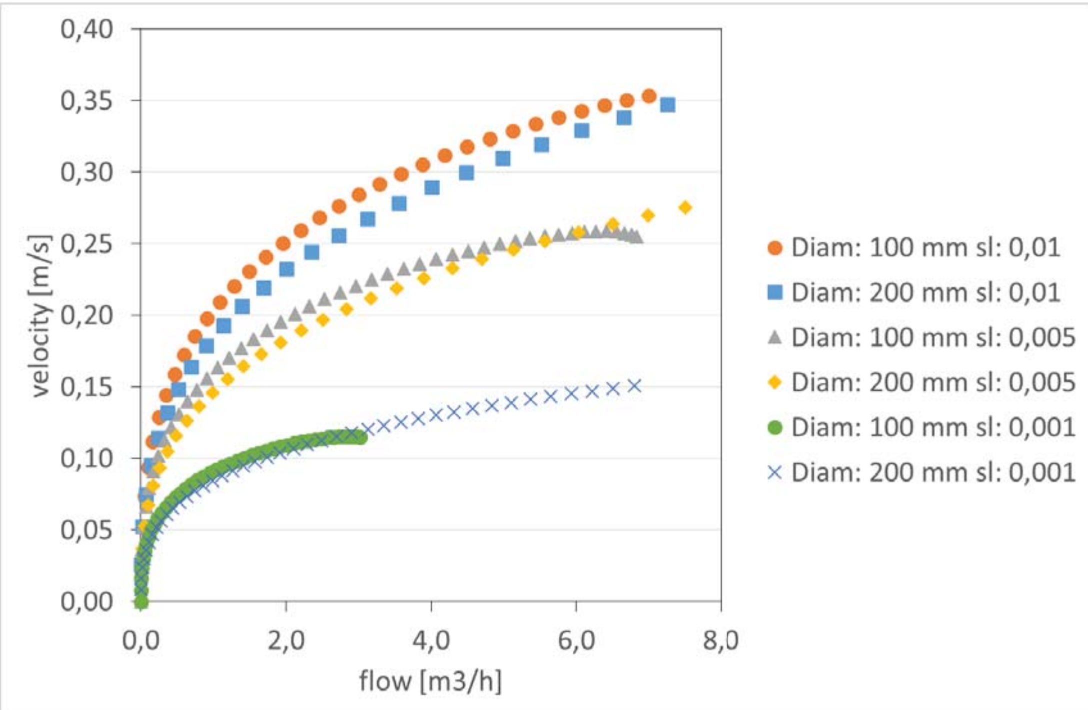



**Figure 21 Relation between velocity, flow, diameter and slope for partially filled pipes. The flow is relevant for maximum domestic water use (and waste water production) for 20-40 houses (Vreeburg, 2017).**

**Domain 3: Transport to treatment and treatment**

After collection in gravity systems, waste water is transported to treatment locations. Typically, this element has been added in the transition from local systems to regional systems. Most treatment is based on aerobic treatment because of the relatively low concentrations of organics. The resulting sludge may be treated anaerobically to further recover resources. The feasibility of anaerobic treatment is affected by the wastewater characteristics and temperature. The temperature of the water inside the reactor preferably should be between 25 and 35 ˚C, which determines the energy requirements (Metcalf et al., 2003). However, even at low temperatures, many laboratory studies have shown reliable performance, even at 5 °C (McCarty et al., 2011). In general, COD concentrations higher than 1500 to 2000 mg/L are needed to produce enough methane to heat the wastewater without an external fuel source.

## 3 Requirements and challenges for transition

Tervahauta (2013) showed that the total average COD-production per capita per day can be 120 gr (50 gr through feces, 11 gram through urine and 59 gram through kitchen waste) (Tervahauta et al., 2013). If only this parameter is considered for the efficient application of anaerobic treatment, the threshold concentration of 2000 mg/l may be reached if water consumption can be limited to 60 liter per person per day. The inventory presented in Table 15 shows that daily water use, including a kitchen grinder, may be limited to 40 liter per capita per day. Theoretically this may be feasible, but there are still challenges to overcome, especially in domain 1 and 2, the individual user and the collection.

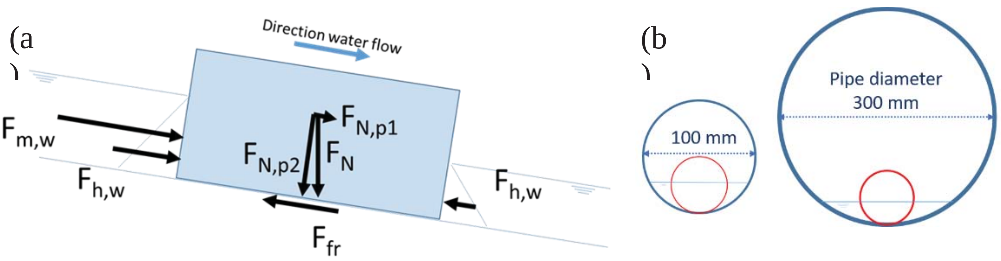
For domain 1, the biggest challenge will be to limit the use of water for showering and the toilet flushing. Toilet flushing will be possible when a different concept for toilets is developed in which the basic use of water is limited to rinsing the bowl. The other functions of water in a conventional toilet are filling the siphon and transport of solids. The first may be changed through construction of a valve, similar to the present vacuum toiles and the second may be taken over by other water in the system, discharged upstream of the toilet. How this can be done in real-life conditions and how end-users cope with the new setup need more practical experiment and research.

The second challenge in domain 1 is the shower water use, now limited through a recirculation system. However, if focusing on the amount of water entering the sewer system, this could also be addressed by using the technique of a dynamic multiple outflow: when the water is suitable for recycling, determined by sensors, it could also be redirected for infiltration in the ground. The hypothesis that the water after a few minutes of showering is almost not loaded with contaminants anymore may mean that it can be infiltrated, e.g under a house or in a gravel layer. If 50% of the shower water is redirected this would result for a 4 person family in 100 liter per day. With a 100 m$^2$ area this equals a 1 mm rain event. Alternatively, the water after a few minutes of showering can be used for toilet flushing as previously suggested.

For domain 2 there are multiple challenges. The biggest one is to create a collection system that only collects the sanitary waste water and is not infiltrated (diluted) with rain-

or groundwater. Before considering dimensioning and operating of such a dedicated system a short analysis of the interest of a correctly dimensioned collection system is made.
The introduction of the separated sewer systems took off in the early 1970's and coincided in the Netherlands with a huge activity in building houses and cities. Meanwhile, other European countries experienced this 'baby-boom' driven increase in building activities. The municipality, as main stakeholder responsible for the water household in the city and, was an important client for contractors that realised the subsurface infrastructure. Within the group of municipalities and the contractors there was a need for uniformity. Following that a national code for design and operation of sewers was made. Remarkably, in that code there is hardly a difference in dimensioning a sanitary sewer and a storm water sewer: they both end up with a minimum diameter of 250 mm for the gravity collection system. In the course of the years the difference between the two pipes faded away, also in the light of standardisation during construction. Nowadays, the experience is that both systems work satisfactorily, confirming that the design criteria are correct.

There are two reasons why the present design criteria for sanitary sewers may hamper a transition towards a resource recovery based sanitation: the first one is the extra costs for construction of a large dual pipe system and the second one is the hydraulic performance of small sewer pipe compared to larger ones for the transport of solids. Figure 2a shows a graphical representation of the forces working on an object in a sewer pipe. The main effect of the diameter in the relevant flow regime is an increase in the water depth (Figure 1). The effect of that is more buoyance of the solid to be transported leading to a smaller downward force (Normal force) resulting in a lower friction force. In fact, that is the only counter acting force in the direction of movement. Though possibly counter intuitive, smaller diameter sewer pipes will theoretically be more efficient: compared to larger diameters, the velocity will stay more or less the same, but through a higher water depth buoyance will be larger (Figure 2b). This is similar to the 'sliding dam' as described by Littlewood (2003)(Littlewood and Butler, 2003).




| | | |
|---|---|---|
| $F_{m,w}$ | Momentum (hydrodynamic) force of the water flow | [N] |
| $F_{h,w}$ | Hydrostatic force of the water | [N] |
| $F_N$ | Normal force due to net weight of object and buoyancy force | [N] |
| $F_{fr}$ | Friction force | [N] |

**Figure 22 (a) Forces on an object in a sloped pipe (Vreeburg, 2017); (b) With the same amount of flow, the water depth behind the object in a smaller diameter sloped pipe is higher and offers more buoyance for transporting the object.**

## 4 Concluding remarks

Transition towards a system that can effectively recover resources from sanitary waste water should focus on promoting the installation of household water-saving utilities, though preferably without involving vacuum system, and the redesign of the sanitary sewer system.

The installation of household water-saving utilities not only reduces the drinking water consumption but also helps create a smaller, more concentrated sanitary waste water that are beneficial for resource recovery via biological processes at the end-of-pipe treatment. Use of vacuum system to assist water-saving, however, is debateable considering its cost, nuisance, transition challenges and dependence on electricity to fully functioning.

Considering the transitioning challenges, a dual pipe system for storm water and sanitary waste water is preferred over the source-separated sanitation system. Introducing more pipes in the street for the collecting black and grey water separately will be too complicated and costly. The focus of the sanitary sewer system should be on minimising flow and maximising organic load. As shown in Table 15 this is theoretically possible to a level that allows for an efficient anaerobic digestion. Nevertheless, a 1L flush toilet without vacuum system and the cascading of shower effluent are key components to be developed or sought for facilitating this transition.

The total flow will be much smaller than presently discharged; even for a modest drinking water use as in the Netherlands it results in a 60 to 70% reduction. This enforces also a reconsideration of the sanitary sewer collection system. Detailed knowledge of the drinking water end use allows for an evenly detailed insight in the sanitary waste water production and pattern. Applying that to a dedicated system results in pipes with diameters that are intuitively impossible. It should be born in mind though that the arguments for the larger diameters (inspection, buffer capacity and sediment storage capacity) are based on malfunctioning of the system. A smaller diameter system will probably need more skill and craftsmanship in installation, which may increase costs. Maintenance should not be more than nowadays, because the hydraulic performance in transporting organic solids is better due to the higher water depth and consequently more buoyance.

80% of system length of a completely centralised system is within the first mile: the gravity collection system (in analogy with the last mile in distribution systems). With that it is the most expensive part of the total system, though the costs are very spread both in space as in time. A considerable saving in projected costs for rehabilitation is an argument to further examine the possibility of a smaller diameter sewer system. However, this favourable effect investment should not cloud the possibility that the smaller system may perform better than the conventional system, especially with the prospect of less water used in the near future. The effect on concentration of the sanitary waste water and the possibility to recover the resources more effectively adds to the necessity to further explore these options.

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