Resource Recovery Based Sanitation: Integrating collection and transport with treatment and re-use

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Introduction

Resource recovery and in particular phosphorus recovery, will become an unavoidable necessity within several decades (Cordell et al, 2009). As there is no replacement for phosphorus in the growing of crops, this natural resources will become scarce within a foreseeable period. Though there is not a clear view on how long that period will be, it will be in the same order of magnitude as the lifetime of a complete sanitation system in present urban and metropolitan environments.

Historically the present systems were developed over the last 150 years, starting around 1850 in London and steadily growing, leading to very high connections rates nowadays in Western type cities. The present system is based on hydraulic transport of water and solids and aimed at hygiene, safety and comfort. The majority of the present system is a classic combined system dealing with both storm water and sanitary waste water.

In the last couple of decades the importance of treating water before discharging it in the environment became imminent, which led to a literally ‘end-of-pipe’ treatment. The treatment can be characterised as ‘effluent-oriented’, namely to produce an effluent quality that can safely be discharged to the environment. The treatment puts extra demands to the collection and transport system with respect to the total volume collected and offered to the process. Treatment costs are eventually related to this volume and make the separate collection of storm water and sanitary waste water also an economic question.

The need for resource recovery adds, again, a new variable to the design and operation of the sewer system. Treatment is now targeted at recovering substances from the waste water in such a way that it can be re-used. Resource recovery as a new variable is an addition: the other requirement of hygiene, safety, comfort, environmental discharge still are valid and even becoming more stringent. Considering all design parameters it is evident that they may pose conflicting requirement to the collection and transport system. Local hygiene, safety and comfort may be satisfied with a single pipe for all urban water, discharging at a local water body. Regional hygiene, safety and comfort require treatment before discharge and benefit from restricted volume flows offered to treatment. Resource recovery require intensive treatment and is served best with a small, but concentrated flow to be treated.

“During the reconstruction the service will continue” sounds like a generous offer, but is in fact a necessity. In the transition from local to regional an element of transport and central treatment was introduced, which made it relatively easy to continue the service. The transition from regional treatment to resource recovery will be done in the coming decades. This paper explores possibilities for a new system choice.

System development and transition

According to Schot (2009), systems develop following an almost biological growing curve: from initiation to an exponential growth followed by a set of and linear growth eventually stabilising of a maximum level. In most Western countries for the sewer this means an almost 100% coverage in the urban, per-urban and metropolitan areas in a period of 75 to 100 years. The period between the initiation and the exponential growth is a crucial period in which system choices are made that will dominate the entire period of development.

In retrospect the initiation and exponential growth of modern sewer systems started in the 1850's with the construction of a sewer in the city of London. The first system choice was made: a piped collection system with water as transport medium. This system choice resulted in the construction of single pipe systems for all waste water. The second system choice was made around the 1970's with introduction of treatment of waste water. The separated collection of storm water and sanitary waste water became the new standard. New systems were made like that. 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.

Resource recovery may enforce a third system choice, because the flows that must be treated are in fact too large and too diluted to have an efficient treatment.

Re-invent the system or a new locked-in

A point of system choice is a natural point to reconsider the present system and either re-invent the system or come up with another approach. Though it may sound as restricting the freedom to fundamentally reconsider, it is recognised that the need for co-existence with the present piped system enforces a choice for water as the transport medium for (sanitary) solids. This almost automatically leads to the consequence that the collection of the flows is done through pipes.

The need for large scale recovery of resources demands an efficient type of treatment. A basic requirement for efficiency is that the total flow to be treated should be a small as possible but at the same time the load of organics should be as high as possible.

In the second system choice the separated system, in which the storm water and the waste water is collected separately, was the logical step. For new building areas this leads to a dual system and an established way of working has been introduced. Though this choice is also made in many rehabilitation projects, a major drawback are the considerable new investments. The total length of the piped system for the gravity collection system is doubled compared to a conventional combined system. The collection part of the system ("the first mile" in analogy with "the last mile" for supply systems) covers 80% of the total length of the present centralised systems.

The requirement for a highly concentrated flow has led to experiments with further separation of the waste water stream into black and grey water which are the toilet waste water and the other domestic waste water. It leads to a small and highly concentrated black water flow and less fouled grey water flow. Though this system meets the 'treatment' criteria, it doesn't meet the 'transition' criteria. 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. Together with the operational challenges of a vacuum system, this may lead to a locked-in situation in which the transition cannot happen.

To re-invent a practical and operational approach, systematically all elements of the urban waste water chain must be reconsidered in a quest to decrease the flow and to increase the concentration of organics, while maintaining the possibility to gradual transit from and co-exist with the present system. There are two major possibilities: take out the water and/or add organics. Or in summary: Water Out, Shit In.

The urban waste water chain

In the urban waste water chain the total waste water flow is considered, from its generation through the use of drinking water via the collection and transport to the treatment and recovery. In this chain three domain/stakeholders can be recognised:

- 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: Pressure 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 (VEWIN, 2015). Still there are possibilities to reduce that water use. Table 1 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 1 Water use options: present use against 'possible' use

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. However, looking at the location and hydraulics of a toilet in the in 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. A grinder toilet can be applied individually and may counter the possible problems with vacuum toilets.

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 & 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)

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 1. 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 2011) 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.

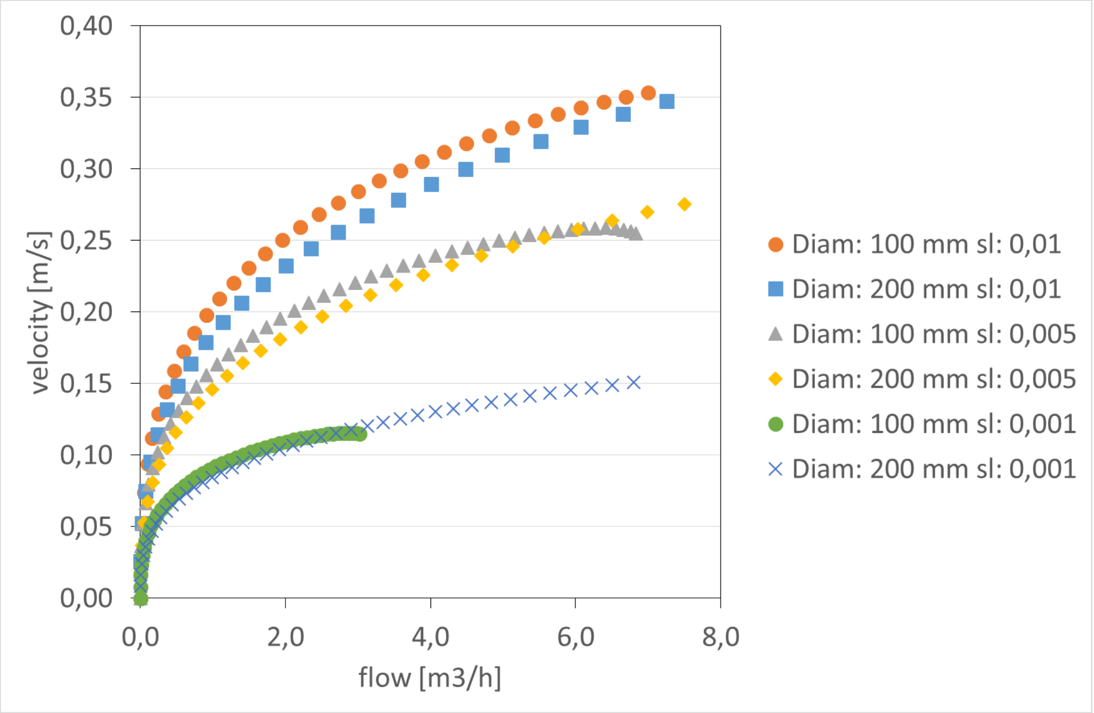


Figure 1 Relation between velocity, flow, diameter and slope for partially filled pipes. The flow is relevant for maximum domestic water use (and waste water production) for 20-40 houses.

domain 3: Pressure transport 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: the second system choice. 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 (Metcalf and Eddy, 2002). The temperature of the water inside the reactor preferably should be between 25 and 35 ˚C, which determines the energy requirements (Metcalf and Eddy, 2002). However, even at low temperatures, many laboratory studies have shown good 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.

Requirements 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). 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 1 shows that daily water use, including a kitchen grinder, may be limited to 40 l/pppd. Theoretically this may be feasible, but some challenge still have to be met, 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.

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.

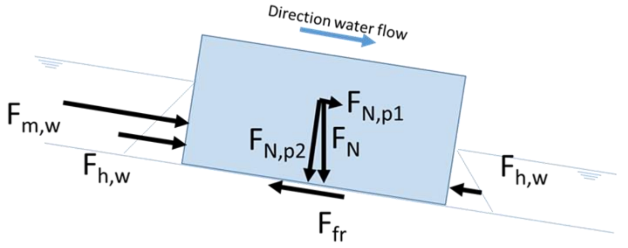
For domain 2 there are multiple challenges. The biggest one is to create a collection system that only collects the sanitary waste water and is not infiltrated (diluted) with rain- or groundwater. Before considering dimensioning and operating of such a dedicated system a short analysis of the interest 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. Also 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 foul water 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. And 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 foul water 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.

Transport of solids

Figure 2 shows a graphical representation of the forces working on an object in a sewer pipe.



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

Figure 2 Forces on an object in a sloped 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. This is similar to the ‘sliding dam’ as described by Littlewood (2003).

Costs

The construction of a smaller pipe is cheaper than that of a larger pipe. Not only in material costs, but also in depth of laying. In total the reduction in construction costs for the foul water sewer may be 30 to 40% depending on local circumstances. These estimations are based on cost effect of downsizing of drinking water distribution mains (Vreeburg, 2009) and since than dully proven in practice in the Netherlands.

Discussion

Transition towards a system that is able to recover resources from sanitary wastewater should be focussed on a dual pipe system for storm water and foul water. Introducing more pipes in the street for further source separation in black and grey water will be too complicated and costly. Instead the focus of the foul water system should be on minimising flow and maximising organic load. As shown in Table 1 this is theoretically possible to a level that allows for anaerobic digestion.

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 sewer collection system. Detailed knowledge of the drinking water end use (Blokker, 2011) allows for a evenly detailed insight in the foul 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 that nowadays; it is not impossible that maintenance will be less, 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 in 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 a good 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 waste water and the possibility to recover the resources more effectively adds to the necessity to further explore these options.

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