Rethinking urban water systems – revisiting concepts in urban wastewater collection and treatment to ensure infrastructure sustainability

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Abstract Technology and economic development has led to the growth of megacities and urban centres with populations in the millions. Such population expansion and densification increases the strain on wastewater collection and treatment infrastructure, which has been largely based on an end-of-line centralised model. However, in megacities new challenges arise, because provision of suitable sanitation is expensive and it requires infrastructure expansion through construction of extensive sewer networks and larger capacity wastewater treatment plants, which consume more energy. Alternative disposal techniques for solid and liquid waste generated during the treatment process are required, because disposal solutions are decreasing as landfill costs rise and environmental standards are tightened, the latter reducing opportunities for land reuse. Additionally, mass wastewater discharge can have a detrimental impact on the ecology of water bodies and on the health of downstream populations, and requires suitable treatment before disposal. These challenges have the potential to offset the savings that the economies of scale offered by the traditional wastewater collection and treatment systems can impart. The need for affordable and effective wastewater systems in megacities requires the re-evaluation of traditional systems and the re-engineering of water and wastewater transport and resource concepts. Alternative concepts in wastewater collection and treatment, such as decentralised treatment, allied with innovative solutions using current and new technology could play a role in providing affordable and sustainable solutions to deal with the wastewater issue. This paper investigates the scope that integrated wastewater treatment and localised water reuse (in-line treatment, sewer mining), resource recovery (biogas, biosolids), operational changes (timed discharge of sewers, vacuum sewers) and biotreatment (e.g. vermiculture, faecal coliform removal) can play to guarantee the longevity of wastewater infrastructure in megacities. These alternatives offer increased treatment efficiency, recovery of value-added products, and reduce infrastructure cost, whilst maintaining health standards and reducing environmental discharge.

Keywords Wastewater; decentralisation; infrastructure; alternative systems; biosolids; resource reuse

Background

The global population has been projected to increase from 6.1 billion in 2000 to 7.1 billion by 2015, and an additional 1.6 billion people will require access to a clean water supply and about 2.2 billion will require access to sanitation facilities in urban centres (WHO, 2000).

Urbanisation, whilst welcome, generates its own sustainability issues, with increases in affluence increasing water consumption. For example, in the Asia-Pacific region, water consumption is 250–300 L/person/day, whilst in developing countries it is estimated to be 160–200 L/person/day (IWA, 2002). The increasing water consumption and the associated demand for sanitation services place large strains on water resources and infrastructure. This is particularly true as megacities develop, i.e. urban hubs of 10 million or more inhabitants.

Growing urban centres require extension of expensive collection networks and wastewater treatment plant (WWTP) capacities due to urban sprawl and inner city densification. The wastewater industry requires high capital investment and maintenance costs for...
sewage collection, transport and treatment, whilst at the same time providing a low return on assets (less than 5% per annum) (WSAA, 1998; Wilderer, 2005). This is partly because reticulation systems are traditionally designed to act only as a conduit to carry wastewater to its destination, the WWTP.

Treatment at WWTPs is also compromised as cities expand because the infrastructure becomes incapable of dealing with the increasing load of wastewater generated. Additionally, expansion of the collection area increases the risk of infiltration, dilutes waste streams and stresses the capacity of the treatment plant, reducing treatment efficiency and increasing energy and chemical requirements at the plant. Disposal of untreated effluent to water bodies is not acceptable and even transport over long distances through aging infrastructure carries the risk of leakage and groundwater contamination (Eiswirth et al., 2000; Burn et al., 1998, 2003).

In the face of growing pressures on water resources and the growing trend for better management of wastewater, governments can no longer afford to employ the end-of-the-line approach to wastewater treatment. The body of work on wastewater treatment and transport has been largely concentrated on WWTP processes and operation, and further understanding of the processes in the wastewater system and research into the specific redesign of the network system need to be explored if quality of life and environmental sustainability are to be perpetuated.

This paper looks at the feasibility of alternative urban sanitation concepts and the current and emerging needs of megacities (including reliability, robustness to neglect, terrorism). The analysis looks at issues surrounding decentralisation, value recovery (energy and product recovery), integration between collection and WWTP, and societal acceptance.

Alternatives to traditional waste and wastewater collection, treatment and disposal need to become the focus of intensive research, based on a range of criteria that combines direct economic costs, environmental analysis and social responsibility in the face of changing community needs (Sonesson et al., 2000; Otterpohl et al., 2003).

Any alternatives for resource utilisation need to be evaluated using whole lifecycle analysis (including material and energy flows) and sustainability, where environmental impacts are also accounted (Schertenleib, 2005; Livingston et al., 2004).

**Decentralisation**

One of the main factors that led to the adoption of the centralised waste collection model was the small capacity of early on-site systems (mainly latrines) in the 19th century, and their inefficiency, which contributed to major disease outbreaks. Decentralised systems have generally been adopted by remote communities located too far from a central WWTP to justify the infrastructure costs, or when the terrain did not allow construction of conventional sewerage systems (e.g. soils of poor drainage, shallow coverage and rocky outcrops).

The majority of the failures of decentralised treatment systems has been caused by inadequate design, improper installation and, more frequently, inadequate maintenance (Crites and Tchobanoglous, 1998). In recent years, the reliability of on-site systems has improved, through technological development, although there still is the need to tailor the system to the specific location where it will be implemented.

As water saving and recycling is encouraged, through greywater reuse, dual-piping systems, dual flushing, sewer mining etc. (Neal, 1996), the volume of wastewater discharged will decrease, whilst increasing its strength as seen in Table 1. This would increase the potential for septicity, odours, contaminant impacts (in re-use schemes) and corrosion in the assets, thus aggravating the problems many of the existing systems experience.
Treatment decentralisation can simplify the design of WWTPs and allow greater flexibility in the design and operation of infrastructure systems. The investment required for infrastructure installation and maintenance is lower as the collection area becomes smaller, and sewage only needs to travel shorter distances for treatment, allowing much smaller pipe sizing to be installed at shallower depths, as well as reducing the need for pumping stations. This would also reduce the need for overcapacity design to cope with network expansion. By dealing with smaller networks, the potential for better control of the operational conditions in the sewage network could be explored. Additionally, the use of infrastructure alternatives, such as septic tank effluent pump sewers, septic tank effluent gravity sewers, vacuum lines, timed discharge and selective operation of combined sewers, could allow manipulation of discharge quality and volume, improving the feed received at the WWTP (Otterpohl et al., 1999).

Smaller networks would also encourage the use of more efficient plastics pipes, which would have the benefit of reducing the leakage and infiltration through pipe joints and defects. Use of these pipes would also reduce maintenance costs (if properly installed) because they have a higher resistance to corrosion.

Treatment efficiency could also be increased as local treatment plants could be tailored for specific waste generation activities as waste flows become more concentrated, e.g. removal of specific heavy metals and/or organic chemicals.

By reducing the dependency on a centralised WWTP, the robustness of the system against failure/sabotage also improves, as a catastrophic breakdown at a WWTP would not cause the whole system to shutdown. Provision for wastewater diversion between decentralised treatment facilities could also be implemented, and this would have the added benefit of providing additional storage capacity (e.g. holding tanks or cisterns) should any part of the system fail.

Decentralised systems could be adapted to the “out of sight, out of mind” concept that is prized by the consumer, operating with minimum intervention by the user. Studies on the feasibility of decentralised system implementation indicate that, in the urban context, on-site systems are effective when designed to service a conglomerate of waste-generation sources, e.g. residential or commercial buildings, districts, residential parks, large sport facilities, universities. A distributed system also facilitates education of the system users for the implementation of alternative technology, such as urine separation toilets (Otterpohl, 2003), because these can be trialled on a limited basis with minimum consequences should they be unsuccessful. Centralised control of multiple systems is also possible with the use of telemetry and remote monitoring, and research into its implementation and optimisation within the urban context is needed; as well as an evaluation of robustness to sabotage. This allows improvements in the design of on-site systems to allow for maintenance schedules at longer time intervals, e.g. six-year

<table>
<thead>
<tr>
<th>Table 1 Wastewater quality based on water savings and source separation strategies (Henze, 1997)</th>
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<tr>
<td>Quality</td>
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<td></td>
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<tr>
<td></td>
</tr>
<tr>
<td>COD^+ (g/m^3)</td>
</tr>
<tr>
<td>BOD^+ (g/m^3)</td>
</tr>
<tr>
<td>Nitrogen (g/m^3)</td>
</tr>
<tr>
<td>Phosphorus (g/m^3)</td>
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</tbody>
</table>

^Assume non-P detergents and solid waste separation at sink. COD (chemical oxygen demand). BOD (biological oxygen demand)
desludging, reducing the frequency of on-site inspections (Hedgeland, 2004). Furthermore, this allows proper maintenance practices to be implemented, as access to the treatment infrastructure can be restricted and maintenance of the system can be performed by properly trained personnel (Bradley et al., 2002). A side benefit would be that a specialised service contractor industry would be likely to develop to conduct maintenance of on-site systems (Hedgeland, 2004).

**Value recovery**

Resource recovery in a centralised system benefits from economies of scale, e.g. equalisation of flow and biomass accumulation allows continuous production of energy and recovery of biosolids. On the other hand, the benefits are not always immediate, as in the case of Victoria, where biosolids are stockpiled for future use, because of contamination issues (Cd, Cu, Hg and Zn) and requirements to store for three years to meet health needs (Bethel, 1999).

In a decentralised system or in hybrid systems, resource recovery could be performed at multiple locations, closer to areas of their potential application, reducing distribution costs. For example, treated wastewater could be recovered through sewer mining and reused for landscape/golf course irrigation; effluent/biosolids could be reused for horticulture or green belts, and energy could be recovered for running small scale self-powered plants in conjunction with solar energy (AGO, 1997).

Smaller scale operations allied with new technologies, such as membrane filtration, allow control of the degree of purity that can be achieved in treated wastewater, hence some value recovery could be achieved, such as the reuse of treated wastewater for urban irrigation or industrial purposes (cooling towers, flushing); and faeces or urine separation (rich in nitrogen and phosphorus) for boutique fertilisers (as detailed in Table 2), thus transforming wastewater into a commodity, which could be off-set against the cost of pre-treatment.

In megacities, there could be the potential that the nutrient balance will not match up with the amount of available land within the city (i.e. golf courses, parks etc.). In such cases, site selection to balance water reuse and alternative resource recovery becomes essential.

In particular, separation of waste at the source offers streams of higher purity and with less cross-contamination, thus reducing the energy and chemical requirements for recovery (Table 3). There are many examples where technologies have been implemented to harness these waste streams. For example, urine separation toilets for nitrogen recovery (Sweden and Switzerland) (Haneus et al., 1997; Otterpohl et al., 1999); night soil treatment in johkasou systems for multiple dwellings (Japan) (Magara, 2003); separation of industrial waste, and fat and grease collection from restaurants and

<table>
<thead>
<tr>
<th>Country</th>
<th>Description</th>
<th>Cost (US$/tonne)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Australia</td>
<td>Cost of producing 1 tonne of struvite</td>
<td>140</td>
</tr>
<tr>
<td>Australia</td>
<td>Suggested market value for struvite</td>
<td>877</td>
</tr>
<tr>
<td>Australia</td>
<td>Conservative market of struvite as &quot;boutique&quot; fertiliser</td>
<td>261</td>
</tr>
<tr>
<td>Japan</td>
<td>Operational costs for producing 1 tonne of struvite</td>
<td>460</td>
</tr>
<tr>
<td>Japan</td>
<td>Cost of purchasing 1 tonne of struvite</td>
<td>250</td>
</tr>
<tr>
<td>Japan</td>
<td>Suggested value of struvite</td>
<td>1885</td>
</tr>
<tr>
<td>Japan</td>
<td>Final product from struvite</td>
<td>500</td>
</tr>
<tr>
<td>UK</td>
<td>Cost of struvite as an ingredient</td>
<td>9</td>
</tr>
<tr>
<td>UK</td>
<td>Cost of phosphate rock</td>
<td>40–50</td>
</tr>
<tr>
<td>UK</td>
<td>Suggested market value of struvite</td>
<td>283</td>
</tr>
</tbody>
</table>
industrial kitchen traps for biofuel production (Thailand) (Stoll and Gupta, 1997); and
timed wastewater discharge for separation of surface run-off from waste streams to send
the remainder of the wastewater for treatment at the plant (Larsen and Gujer, 1996; Otter-
pohl et al., 1999).

Among the resources that can be extracted from wastewater are biogas, biofuel and
soil additives that offer environmental and energy conservation benefits (Figure 1).

**Biogas**

Australia obtains most of its power from thermoelectric stations. Anaerobic processing
of sewage produces biogas, a mixture of methane (approximately 65%), carbon dioxide
(approximately 35%) and 0.5% of hydrogen sulfide, inert gases and water vapour. Utilis-
tation of biogas from anaerobic processing reduces greenhouse gas emissions by reducing
consumption of fossil fuel energy and landfill emissions. In larger WWTPs, biogas could
be recovered for heat and power generation to supply the plant needs and the excess
could be sold back into the grid. Sale of electricity from biogas to date has been ham-
pered by the low cost of electricity from the grid. This could change in the future when
the true price of energy accounts for environmental costs (AGO, 1997).

The majority of the plants that produce biogas are in operation in Europe and the
USA, with the USA at the forefront of the technology development for municipal

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**Table 3** Dilution factors in toilets (Udert et al., 2003)

<table>
<thead>
<tr>
<th>Toilet type</th>
<th>Typical dilution factor</th>
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<tbody>
<tr>
<td>Conventional urinal</td>
<td>600</td>
</tr>
<tr>
<td>No mix trap</td>
<td>30</td>
</tr>
<tr>
<td>No mix tank</td>
<td>4 (range 1–10)</td>
</tr>
<tr>
<td>Waterless trap</td>
<td>1</td>
</tr>
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</table>

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**Figure 1** Examples of alternative wastewater systems with resource recovery (Otterpohl, 2003)
WWTPs, and Europe at the forefront of biogas recovery from industrial wastewater, using mainly effluent from the food industry. In Australia, biogas recovery from landfill is adopted in one form or another, however biogas recovery from municipal wastewater is not common despite the fact that the calorific yield of biogas from WWTPs tends to be higher than from landfill. Re-engineering could impact on the potential for biogas production by providing more concentrated flows (higher BOD) at the WWTP or at decentralised collection stations.

To generate electricity from biogas, the gas needs to be cleaned before it goes into high-efficiency generators or is burnt in a lower efficiency, more robust generator. At smaller sites, the cost of cleaning the gas is usually prohibitive, so lower efficiency generators are used. A demonstration project on biogas recovery from urban settlement is currently being trialled in Lübeck (Otterpohl, 2003).

**Nutrients**

Nutrient recovery through use of effluent (rich in N and P) for irrigation is possible, provided adequate control of heavy metals is addressed and care is exercised to balance water use with plant nutrient requirements. Nutrients could be separated as minerals, hydroxyapatite and struvite for use as fertiliser or even for chemical phosphate use in detergents (Table 2) or from treatment of streams separated at the source (EAWAG, 2003). This is particularly attractive as mineral phosphorus reserves are estimated to last for only another 50–100 years (Driver, 1998). Separation of nutrients at the WWTP would allow economies of scale and would solve additional problems, as their presence in wastewater is responsible for scale formation, blockage of pipes and the shut-down of equipment and operations. In Japan, struvite has been successfully marketed as a boutique and high-grade fertiliser. Investigations are also currently under way to determine the potential of localised struvite recovery through urine separation in Europe (Novaquatis project) (EAWAG, 2003).

Recovery of biosolids for agricultural use, through composting and alternative technologies such as vermiculture, provides a valuable soil additive, improving soil tilth and porosity, and reduces the dependency on mineral fertilisers (Barry et al., 2004). The nutrient value of sewage could be markedly improved in decentralised systems provided pathogens are controlled. Decentralisation also has advantages in this application as transport costs from generation at the WWTP to the place of application (historically rural) are minimised.

**Biofuel**

Biofuel could be a major resource from the decentralised utilisation of biosolids. Manure, beef tallow and other sources of fat can be used to produce alcohols (methanol/ethanol). This is achieved by transforming biogas from anaerobic digestion into methanol/ethanol via a thermocatalytic process. Biofuel causes less pollution than normal fuel and has 600 times more lubricity than traditional diesel, without requiring the addition of sulfur. It also offers 60% reduction in visible pollution and up to 43% reduction in carbon monoxide (Stoll and Gupta, 1997; Kaspers et al., 2001; Higgins, 2004). The feasibility of pyrolysis of biosolids and greenwaste is also currently under investigation to produce bio-oils and charcoal, however the commercial applications to produce only bio-oil have so far not been successful. As an ultimate resource, incineration of biosolids as an alternative to landfill disposal has been implemented in many countries. The fly ash produced in this process can be incorporated into building construction materials for immobilisation of metals. The potential for such applications in a re-engineered environment needs to be evaluated.
Integration of WWTP and sewerage

Many of the barriers that traditional infrastructure poses to in-line treatment could potentially be overcome in a decentralised network. For example:

- **Diluted streams** – sewage in pipelines does not have sufficient biological organisms to conduct the biodigestion process, as dilution of waste streams, infiltration and wet weather flows can destroy the treatment processes; but with more concentrated flows and jointless sewers there could be potential to induce either anaerobic decomposition or aerobic conditions through the supply of oxygen as there would be less risk of leaks.

- **Process control** – poor consistency in the quality of sewage due to seasonal variability and even diurnal variability. In current systems, poor process control also increases the likelihood of odour and corrosion problems, as the potential for anaerobic conditions to be reached will increase if biomass is added to the system, however these impediments can be overcome with timed discharge.

- **Poor nutrient removal** – in current systems the major impediment to the uptake of this type of technology is likely to be the limited nitrogen removal achieved and the potential for odours should the process be difficult to control. Problems associated with low nitrogen removal could be solved by disposing of the treated effluent in applications that are tolerant of high nitrogen levels (e.g. agricultural uses, golf courses) or by preventing urine entry into the waste stream.

Alternatively, sewerage networks could be developed into pre-treatment stations. Sewage quality manipulation and bioremediation within the pipe could be used to degrade chemicals or optimise treatment at the WWTP, increasing WWTP efficiency and reducing the need for larger treatment facilities (Green et al., 1985; Malik et al., 1996). For example, aerobic pre-treatment could be used to prevent the formation of H₂S, which is a proven inhibitor of the nitrification process at concentrations as small as 1–10 mg/L; it also reduces wastewater pH to control the growth of filamentous bacteria responsible for clogging and poor settling at the WWTP. Through pre-treatment stations, reuse in urban areas might be more readily promoted, which is desirable as water becomes more precious and scarce in the future.

Public acceptance

Community involvement and acceptance is the defining point in determining the success of any new strategy. In rural communities wastewater and biosolids reuse is more widely accepted, e.g. irrigation with effluent, biosolids application on crops. However, the urban public still needs to become aware of the long-term implications of current waste disposal practices and the need for reuse.

Adoption of recycled water and wastewater by-products depends on the public’s perception of their risks. Campaigns on water scarcity and acceptance of water reuse are slowly encouraging the adoption of alternative water systems, such as rainwater and greywater reuse for gardening and the installation of dual-pipe systems for non-potable uses in some parts of Australia (e.g. Rouse Hill) and other parts around the world.

However, research is still needed to determine community attitudes and risk perception, and this research will markedly influence the decision-making process on biosolids reuse. Ironically, biosolids/effluent is still viewed with suspicion, in contrast with the high regard of “organic” fertilizers, soil amendments and produce in urban centres.

Progression from water reuse to full wastewater and waste recovery requires a large public commitment. The concept of “personal responsibility” towards waste needs to be owned by the public, industry and commerce if resource recovery is to be implemented. Local reuse of effluents (e.g. greywater) requires more stringent control of chemicals.
entering domestic wastewater, which could be achieved by education of the public, for example in the use of phosphate-free detergents and discouraging disposal of chemicals down the drain. Additionally, technologies such as urine separation toilets would require more challenging user behaviour modification.

Reuse of biosolids raises concerns in regards to pathogen survival, persistence of hormones, pharmaceutical residues and organic chemicals in biosolids and effluent. Not only does the risk of such applications and the processes involved need to be thoroughly investigated, but strategies for dissemination of such information to the public need to be developed.

Most trials on urban resource recovery have focussed on water reuse (greywater) or urine separation for agricultural applications, and have mostly been performed in control groups in Europe (Table 4). Additional source separation pilot projects are planned for 2005 in China (EAWAG, 2003). The results from these pilots are important to determine the weight that social and cultural acceptance carry in the potential for implementation in larger segments of society.

Furthermore, governments and institutions also need to develop an open and proactive attitude towards the risks and benefits associated with such products and technologies. The focus on policy at the moment tends to be narrow and shortsighted, and sustainable initiatives take a long-time to be considered by governmental bodies. In the initial stages, government support would be required in encouraging technology development and adoption in trials (e.g. through tax breaks for developers), before public confidence is gained and markets for technology and recovery products can become established. Institutions and industry organisations (e.g. standard associations) would also need to respond rapidly to the pace of development through changes to regulations and standards to encourage adoption of such technologies, whilst ensuring manufacturer responsibility in regards to products/technologies that could benefit from non-traditional harvesting of resources in wastewater.

**Conclusions**

There is a need to explore long-term alternatives to the centralised wastewater collection and treatment philosophy prevalent in major cities of the world, particularly in megacities. Alternative strategies to integrate sewerage and sewage treatment would open up a range of possibilities to increase WWTP efficiency, facilitate the recovery of value-added

<table>
<thead>
<tr>
<th>Demonstration</th>
<th>Location</th>
<th>System</th>
<th>Current capacity</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flintenbreite</td>
<td>Lübeck, Germany</td>
<td>Vacuum-biogas</td>
<td>400 pe</td>
<td>Otterpohl (2003)</td>
</tr>
<tr>
<td>Lambertsmühle, Cologne</td>
<td>Cologne, Germany</td>
<td>Urine separation toilets and composting</td>
<td>1 house</td>
<td>Otterpohl (2003)</td>
</tr>
<tr>
<td>Basel University of Applied Sciences</td>
<td>Basel, Switzerland</td>
<td>Urine separation toilets, timed discharge into sewers</td>
<td>–</td>
<td>EAWAG (2003)</td>
</tr>
<tr>
<td>Understenshøjden</td>
<td>Stockholm, Sweden</td>
<td>Urine separation</td>
<td>160 pe (apartments)</td>
<td>Jönsson et al. (1997)</td>
</tr>
</tbody>
</table>
products, reduce infrastructure costs and increase environmental sustainability, whilst maintaining health standards and reducing waterwaste. Worldwide, a number of demonstration projects are in progress, but success depends largely on community acceptance and participation in such initiatives, as well as government and institutional participation. Acceptance will need to occur gradually and requires further research into:

- Increasing public understanding of sustainability;
- Shift in mentality from waste to resource through dissemination of information on risks and benefits of reuse to the public, industry and government; and
- Acceptance of waste reuse.

Implementation needs to occur in stages and would require:

- Institutional reform to encourage wastewater recovery and adapt new systems to current infrastructure; and
- Integration of water reuse and biosolids recovery through demonstration projects on technology feasibility and development of markets for by-products.

References


