From waste treatment to integrated resource management

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Abstract Wastewater treatment was primarily implemented to enhance urban hygiene. Treatment methods were improved to ensure environmental protection by nutrient removal processes. In this way, energy is consumed and resources like potentially useful minerals and drinking water are disposed of. An integrated management of assets, including drinking water, surface water, energy and nutrients would be required to make wastewater management more sustainable. Exergy analysis provides a good method to quantify different resources, e.g. utilisable energy and nutrients. Dilution is never a solution for pollution. Waste streams should best be managed to prevent dilution of resources. Wastewater and sanitation are not intrinsically linked. Source separation technology seems to be the most promising concept to realise a major breakthrough in wastewater treatment. Research on unit processes, such as struvite recovery and treatment of ammonium rich streams, also shows promising results. In many cases, nutrient removal and recovery can be combined, with possibilities for a gradual change from one system to another.

Keywords Energy; exergy; minerals; sanitation; sustainability; wastewater

Introduction

Water is used as a medium for waste transportation. The association between sanitation and wastewater results from the historic development of urban hygiene. After the discovery of waterborne diseases, faeces was removed from cities with rain water sewers, which already existed in many cases. This resulted in wastewater treatment to protect both downstream users and surface waters. From this point of view, modern centralised wastewater treatment is very effective. In Europe and North America, water borne diseases are not a significant cause of illness or death any more. Nutrient removal has also become standard technology in wastewater treatment in the last decade.

The responsibility for ensuring safe and good quality wastewater effluent usually rests with an organisation, such as a municipality or water board. The degree of treatment, control and test procedures are agreed upon, standardised and enforced on a national scale. Centralisation of treatment works have until now ensured their relative success. Furthermore, it is generally believed that high-tech biological treatment processes need a reasonable scale. Operation, control and maintenance of wastewater treatment plants are specialised professions. Sludge treatment and incineration also require good control structures. It is still widely understood that the scale of large centralised treatment plants makes them more affordable.

Nevertheless, carbon, nitrogen, phosphorus and sulphur removal requires relatively large amounts of resources (energy and chemicals). Potentially useful minerals are usually disposed of. Removal technologies have to be changed to make wastewater management more affordable and sustainable in terms of nutrient management. This will involve application of presently available technologies as well as completely new concepts in urban water and solid waste management. This has not only technical but also social implications. We report on the conference “From nutrient removal to recovery” where state-of-the-art technology and new concepts were demonstrated.
Integrated resource management

The important resources involved in wastewater are water, energy and minerals. Apart from being used as transport medium, clean water is the main source of animal and plant life, as well as an important habitat. Water is therefore historically the most important resource, with primary emphasis on purification (Larsen and Gujer, 1997). After solving the problems with urban hygiene, the importance once placed thereon gradually shifted towards environmental protection. In some cases nowadays, “sustainable” wastewater treatment seems to be limited to ever-increasing effluent quality standards. Different life cycle assessments show that current investments in wastewater treatment are justified by the improved effluent quality (e.g. Roeleveld et al., 1997). This is true in comparison to other polluters in developed countries. However, there is doubt about the validity of the LCA methodology and general statements on environmental impact deduced from such assessments (e.g. Ayres, 1995). “Environment” also means many different things to different people or cultures. Effluent quality can not be the only criterion of sustainable wastewater treatment. Apart from protecting the water resources, future developments must also consider all other resources, including capital, energy and nutrients.

Energy is limited and its use has become more important in the last decade. Furthermore, energy production causes pollution. Waste in the form of COD contains potential energy (e.g. through methane production). Energy is in fact consumed in wastewater treatment to destroy potential energy. Currently, around 5W/p is consumed in wastewater treatment, mostly through oxidation. If methane were produced with all available BOD in municipal wastewater, around 4W/p could be generated continuously. When this is put in perspective of the total energy consumption in Western Europe of around 5kW/p, it might seem insignificant. However, future scenarios could change the importance of energy consumption in wastewater treatment. Technology involved in all spheres of society, including wastewater management, has to be improved or replaced to realise more sustainable societies as a whole.

Accessibility of energy and sophisticated technology made nutrients widely available for agriculture. In wealthy societies, nutrients from human excretion have therefore lost their value and are now being treated as waste. This leads to high costs for wastewater treatment and causes natural resources to be used faster than their natural recovery rate. A consequence of this approach, is that nutrients might not be available anywhere and at anytime. Evidence for this can already be seen in the problems that developing countries face when adopting the Western approach to sanitation and wastewater treatment (Ujang and Buckley, 2002). An important requirement for sustainable wastewater management is therefore that it should be feasible under poor economic conditions.

Figure 1 Relation between industry, agriculture, nutrients and sanitation
Although nutrient removal is an important aspect of modern wastewater treatment, removal techniques currently applied do not allow for proper recovery of these nutrients (minerals). The most important minerals are considered to be nitrogen (N) and phosphorus (P). However, other minerals such as potassium (K) and sulphur (S) should also be taken into account. Recovery techniques are not necessarily limited to end-of-pipe solutions. Complete mineral cycles must be integrated, from mineral production to final use. Figure 1 shows different facets involved in mineral and nutrient cycles: Raw materials are usually mined and processed in industry to produce industrial fertiliser, which is spread out on farmland. Agricultural products (food) contain minerals, which is taken up in the metabolism of animals and humans. Most of these minerals are excreted via faeces and urine. In most urban societies, human excreta are removed through sewers. Minerals are diluted in sewers by a factor of more than 100 and have to be removed in treatment plants to protect surface waters. If global consumption occurs at a higher rate than natural recovery (or anthropogenic removal) processes, dilute minerals accumulate in the eco-sphere (or stockpiles).

Various routes are available for recovering minerals from waste. The first is obvious: prevention of dilution. Urine separation is a means of direct recovery, as 80% of the nitrogen, 50% of the phosphorus and 70% of potassium in municipal wastewater originate from urine. Lienert et al. (2003) show that (Swiss) farmers are in general willing to accept a urine-based fertiliser, provided it fulfils the function of industrial fertiliser and does not involve smell, inconvenience or risk. Phosphorus can also be recovered from liquid solutions with various techniques requiring resources in the process. Fossil fuels and phosphate rock are theoretically renewable resources, but the rates of these natural renewal processes are on a geologic time scale. Recovery of finite minerals is technically possible, even from dilute sources such as sea water, but this would be far too energy intensive. Good quality ore for phosphorus, potassium and sulphur are all limited. Furthermore, production of these minerals co-produces waste, e.g. 1 kg of P produced leads to 2 kg gypsum, contaminated with heavy metals and radioactive elements. To give the phosphate industry a sustainable future, phosphate would have to be recovered and recycled (Driver et al., 1999). Recovery and recycling is currently rather expensive and has to have a political drive to be realised. The Swedish EPA for example proposes that 25% of P in wastewater be recycled to agriculture in 2015 and 40% in 2025 (Kvarnström et al., 2003).

The natural resources for nitrogen are extensive and universally accessible. However, in order to be accessible to plants and most micro-organisms, atmospheric nitrogen has to be converted to ammonia or nitrate; either industrially or naturally by N-fixing organisms. The amount of ammonia technically produced is of the same magnitude as the natural nitrogen fixation, or even greater. Industrial processes require 35 to 50 MJ kg\(\text{N}^{-1}\) in the form of fossil fuel for energy supply (Maurer et al., 2002).

In densely populated areas, our aquatic environment has to be protected from excessive nitrogen loads. This is conventionally done with nitrification/denitrification processes, also consuming much energy. The benefit of removal or recovery must not be annulled by the demands of the removal/recovery process. We need to find shortcuts in the mineral cycles, requiring the smallest amount of resources to recycle available resources (bold lines in Figure 1).

Three different “levels” of research can be identified in attempts to find these shortcuts, as shown in Figure 2.

Firstly, there is an integration of different systems involving resources (of which wastewater management is only one part) to consider complete cycles. Then there is work being done on improving the efficiency of processes, within an existing paradigm or bridging diff-
ferent paradigms. Lastly there are improvements to unit recovery operations and novel techniques with practical or experimental results. These three different “levels” are discussed in the following sections.

Systems approach
Larsen and Gujer (1997) argue that improvements to urban water management have to fulfil certain boundary conditions (e.g. urban hygiene, flood prevention, recreation), but improvements can be found outside of existing technological paradigms, such as sewers leading to end-of-pipe treatment. In other words, research shouldn’t be limited to improving existing systems’ efficiency. A real breakthrough in improving urban waste and water management would most likely result from a complete redesign of the system. Separate collection of different waste streams at the source is the most important alternative to the existing system. The two best known examples of source separation are urine separation and vacuum transport of blackwater. Since most of the wastewater nutrients are contained in urine and faeces, source separation of toilet wastewater is an obvious measure for recycling of nutrients (Larsen et al., 1997).

An objective method for comparison of alternatives is based on thermodynamics. The second law of thermodynamics states that the quality of energy can be destroyed. The utilizable energy of a system can be defined in terms of its exergy (derived from extractable energy). While energy remains constant within systems, the exergy decreases during all physical/chemical processes. Minerals also represent energy and can be equated with other forms of energy in terms of their exergy content (Szargut et al., 1988). In more sustainable systems, the loss of exergy should be minimised.

The different facets shown in Figure 1 can also be interpreted to represent relative levels of exergy. This means that dilute minerals in the “equilibrium condition” represents the lowest exergy level. On the other hand, concentrated raw materials have higher exergy values. Industrial processes can concentrate minerals available in the “equilibrium condition”, but this requires consumption of more exergy. Dilution in sewers destroys some of the exergy. Wastewater treatment again requires consumption of more exergy.

Hellström (2003) demonstrates the overall efficiency of different strategies in wastewater treatment by means of an exergy analysis. Nutrient recovery could be achieved with a lower overall exergy loss in source separation systems, as compared to conventional treatment systems. The increased exergy efficiency is due to at least two aspects: exergy contained within the minerals, as well as a decrease in the exergy demand in treatment.

Figure 2 Levels of research activity

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<th>1. Integration of different systems and complete cycles</th>
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<td>Process efficiency e.g. improved overall control</td>
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<td>Process combination e.g. separate urine &amp; sewage treatment</td>
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<th>3. Unit processes:</th>
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<td>e.g. Struvite precipitation</td>
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<td>e.g. Sharon/Anammox</td>
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<td>e.g. Partial nitrification of urine</td>
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<td>e.g. Supercritical oxidation of sludge</td>
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<td>e.g. Nutrient availability of recovered fertilisers</td>
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Hellström assumes that urine can be used directly as fertiliser. Nutrient recovery by other recovery processes (such as reverse osmosis) could prove to be much less efficient, due to a higher overall exergy demand.

Another example of this approach is the evaluation of nitrogen recovery via different routes. Nitrogen is abundantly present in the atmosphere and only energy is required for industrial ammonia fertiliser production in the Haber/Bosch process. Nitrogen removal is therefore an indirect way of ammonia recovery. The Sharon/Anammox process is the most efficient technique of biological nitrogen removal (Van Dongen et al., 2001). Ammonia can also be recovered directly in various techniques. The best available techniques involved in these alternative routes are illustrated in Figure 2.

Figure 3 shows that direct recovery can also be less sustainable (e.g. air stripping), whereas other routes are clearly more viable (thermal volume reduction). Maurer et al. (2003) show that the energy required for the indirect recovery (Sharon/Anammox and production via the Haber/Bosch processes) is 60% higher than energy required for direct recovery via thermal volume reduction of urine, but 60% lower than for air stripping. The notion of “energy” used for this comparison includes the production of chemicals as well as primary energy required for electricity production, so that it in fact approaches an exergy comparison.

In the current debate on nutrient recovery, three different approaches can be distinguished:

1. The “conventional” approach (N: nitrification/denitrification, P: direct application of sludge or extraction of P from treatment plants/sludge).
2. Direct use of urine/faeces in agriculture.
3. Production of a urine-based fertilizer, including volume reduction, removal of micropollutants and attention to specific nutrient demand in agriculture.

Besides exergy, other important issues form part of any discussion on different recovery techniques of nutrients from waste. Theses issues determine the strengths and weaknesses of the different approaches:

- Micropollutants may be a concern in (2), but by definition not in (3). In (1), micropollutants may be a concern for P, but not for N.
- Industrial fertiliser composition is designed on specific plant needs and maximum uptake rates, which could differ considerably from urine, black water, or sewage sludge. Limitation of one nutrient and oversupply of another could again lead to diffuse pollution. This is most significantly a problem for (2).
- Animal manure is a problem in many places with intensive bio-industries and is potentially a greater and more concentrated source of nutrients than municipal wastewater. Resources in wastewater (and its potential recovery) can not be viewed in isolation. For (2), this is a problem due to the limited possibilities of transport. The same is true for the recycling of P via sewage sludge (1). For the other options, transport is possible.
• Costs of recovery is at the moment much higher than efficient removal (8 times for the case of air stripping of ammonia in Figure 2). Although cost differences and decisions could change in future scenarios, current costs govern water boards, municipalities and agriculture. Furthermore, the cost to pay for any process has to be “earned” with other economic activities. In a consumer driven economy, higher costs can often be associated with a higher exergy consumption.

To summarise, exergy considerations support approach (2), whereas today’s economic reality favours approach (1). Experience with new technology, probably based on transition scenarios (see below) would be necessary in order to advance approach (3), which combines a number of advantages.

The strength of the systems approach lies in not only taking one aspect like nutrient recycling into account, but in considering the entire system. Besides nutrient recycling, water pollution control remains of paramount interest. With separate treatment of urine and/or faeces, a number of problems like eutrophication and oxygen depletion could be dramatically improved. Source separating measures can also be adapted to different contexts. Low-tech versions are relevant in rural areas, whereas more high-tech variations can be adapted to urban conditions and even integrated into the existing conventional system (Larsen and Gujer, 1997; Rauch et al., 2003). Source separation is also interesting with regard to household water polluters other than the toilet. If effluent from toilets, washing machines and dishwashers are collected separately, 85% of the COD, N and P in municipal wastewater can be addressed with integrated on-site, or in-pipe, high-tech technologies (Larsen and Gujer, 2001). In non-arid climates, cities will probably still need a drainage system, but simple treatment plants would be sufficient for polishing grey water.

The transition phase from one paradigm to another is also important. Localised treatment applications could first be targeted at hospitals (including treatment of pharmaceutical residues and hormones), public buildings such as airports, shopping areas, sport stadiums (places with high human “strike rate”) or office buildings (integrating urban irrigation, landscaping and fertilisation). Innovative use of ideas proposed for new systems can already improve existing systems.

**Improvement and optimisation of the conventional treatment system**

Sewers may remain an efficient transport method of waste in densely populated urban environments. We expect that in the near future, sewers with centralised treatment plants will still be the most common way of sanitation and waste management. Efforts to improve the system are therefore justified, although this also enforces the system. This is also true for arid regions, provided that wastewater is integrated with irrigation. A process such as the combined upflow anaerobic sludge bed/rotating biological contacter (UASB/RBC) can be used for primary treatment. This process produces an effluent with partial nitrification and E. coli removal, suitable for irrigation in parts of the world with less stringent regulations (Tawfik et al., 2003). This is a simple process, requiring little resource input and recycling some nutrients to agriculture.

Some problems prevent direct use of sewage sludge or manure. Where heavy metal and micropollutant content are of no concern, sewage sludge could be directly used as fertiliser even though it is not very efficient. Sewage sludge can only recover a maximum of 30% of the nutrients available in wastewater. Sludge transportation is also a very inefficient (and uneconomical) way to transport nutrients. One should also keep in mind that cities import food from areas outside their own direct agricultural region. Food import/export is a global phenomenon, just as industrial fertiliser import/export is. This obviously limits the direct application of nutrients recovered from waste. Space around cities is to a large extent also not used for agriculture, but rather for industries, transport, recreation, etc.
Over-application of sewage sludge or manure leads to build up of minerals on farmland, which leads to diffuse pollution. The plant availability of nutrients in sewage sludge is also fairly uncertain. Seyhan et al. (2003) show that lime stabilised sludge performed well in comparison to triple super phosphate in pot experiments. Sludge application based on phosphorus needs could prevent the over application of any material.

A way of solving the transport problem is to concentrate the nutrients at the treatment plant, which makes truck transport more feasible. Struvite (magnesium ammonium phosphate) is one such product, which can be produced with relatively simple technology. Although it is generally known that struvite is a good slow release fertiliser, it’s nutritional value for different crops is unknown. The N:P:K ratio in struvite available to plants still has to be researched (Burns et al., 2003).

Phosphorus accumulating organisms present a low-cost low-energy option for phosphorus concentration from dilute wastewater. Lesjean et al. (2003) show how current centralised biological nutrient removal plants could be further optimised with a membrane bio-reactor to recover high amounts of phosphorus with sewage sludge. Up to 99% phosphorus removal was achieved with relatively low sludge production.

Hao and Van Loosdrecht (2003) evaluate a system for optimal use of the resources in wastewater. This process removes a part of the ammonium load via the CANON process (based on the principle of the Sharon/Anammox), uses COD for methane production and recovers phosphorus as struvite. Wilsenach and Van Loosdrecht (2003) show that even partial urine separation could improve nitrogen removal and phosphorus recovery significantly on a centralised scale. This holds for both existing and new treatment concepts, where a main advantage is a net energy production from increased methane production. The immediate benefits of separate urine collection for present wastewater treatment plants provide a bridge between the existing system and possible future systems, such as complete urine separation.

Removal and recovery of minerals are not necessarily fundamentally different. Acid mine drainage is one of the most serious pollutants from mining. Muraviev (2003) demonstrates an ion exchanger to extract and concentrate sulphate from acidic mine wastes to produce K\textsubscript{2}SO\textsubscript{4} fertiliser. Addition of KOH to the waste also removed metal ions and increased the pH. This is a perfect example of combining mineral removal and mineral recovery in treatment.

**Unit processes for recovery and removal of nutrients**

Within existing systems, parts of the system are often a bottleneck for further improvement. Improvements to unit processes are mostly focussed on removal/recovery of nutrients in higher concentrations than municipal wastewater. The capabilities of the phosphate industry to process recovered P is limited because they are set up for utilisation of large quantities of calcium phosphate. Calcium phosphate recovery from liquid waste is technically possible, but might not be the most efficient way. Wastewater treatment boards seem to chose the route of struvite recovery, being a cheap and simple process and requiring less exergy. In Japan, struvite recovery from central treatment plants is becoming more profitable. Shimamura et al. (2003) describe a two tank fluidised bed reactor for struvite recovery from anaerobic digester supernatant. Yoshino et al. (2003) show that high struvite production is also possible from a similar effluent, but using a continuously stirred tank reactor. Struvite in Japan is used for the fertilisation of rice. If micropollutants (or the perception thereof) are a serious concern, struvite could possibly be used in agriculture outside food production, e.g. for the flower industry, animal feed production, plants used for starch production, etc. Although these might be small markets, it is not necessarily a disadvantage. The availability of nutrients from wastewater is also relatively small and between 10–30% of the
total nutrient flow in many societies. Re-use of sewage sludge presents many problems, such as heavy metal content or organic pollutants. One solution is that of phosphorus recovery from sewage sludge, with supercritical water (Stendahl and Jäfverström, 2003). This is impressive technology, removing all organic matter from sludge and allowing phosphorus recovery. Although it is claimed that energy consumption is similar to sludge incineration, the technique would probably have limited application. Capital and operational costs are high and some technical problems could be expected, e.g. corrosion. Many regions will simply apply treated sludge directly to land.

Treatment of source separated urine could make it a good fertiliser. Udert et al. (2003) show that oxidation and partial nitrification of urine reduces the pH sufficiently to prevent ammonia evaporation. This is an interesting option, and hopefully more work will be done to compare the fertilising potential of treated urine with that of industrial fertiliser or struvite.

**Conclusion**

Dilution is never a solution for pollution. In fact, dilution destroys exergy and makes the treatment of wastewater costly. Waste streams must therefore be managed in ways that keep them as concentrated as possible. Concentrated streams also enable easier recovery of energy and minerals.

Another important aspect is the fact that sanitation is not intrinsically linked to sewer systems and end-of-pipe wastewater treatment. They proved to be an efficient and powerful solution, however they are also costly and contain many severe disadvantages.

Wastewater engineers are solving problems created elsewhere. All societies (wealthy and developing) should be made conscious of the fact that wealthy consumption patterns are not sustainable and that technology alone can not solve all technical problems. Highly expensive removal/recovery techniques might not be sustainable. Solutions have to be found with respect to the integrated system: E.g. sanitation ensures hygiene and comfort, while waste treatment protects water bodies and enables recycling of resources. The wastewater engineer of the future should rather be a resource engineer, concerned with both water management and minimisation of exergy losses.

The conference showed that many developments are taking place related to making waste and water management more sustainable. More innovative concepts are clearly needed. Concepts based on source separation and separate handling/treatment are expected to create the most important breakthroughs in water and waste treatment. Such concepts are now becoming feasible. It is also clear that existing wastewater treatment plants would benefit from partial source separation. This provides good opportunities for a gradual change in the systems.

**References**


