The 2003 Stockholm Water Prize Lecture
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Water Science and Technology Vol 49 No 7 pp 7–16 © IWA Publishing 2004

Applying sustainable water management concepts in rural and urban areas: some thoughts about reasons, means and needs

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Abstract Serving the world population with adequate drinking water and sanitation is an important prerequisite, not only to hygienic safety, but to prosperity and political stability as well, and will foster the adaptive capacity of the societies in the developing countries and beyond. To avoid hygienic and political disasters impacting the world economy, investment in water supply and sanitation must urgently be made. Whether the classical system of urban water supply and sanitation is appropriate to satisfy the needs of the developing world, however, and whether this system meets the general criteria of sustainability is questionable. The costs and the time needed for installation of sewers and wastewater treatment plants are tremendous. In water shortage areas, the amount of tap water required to transport pollutants to the treatment plant is hardly affordable. Recovery and re-introduction of valuable substances, including water, into the urban cycle of materials is impossible because of mixing and dilution effects inherent in the system. Decentralized water and wastewater management should be seriously taken into account as an alternative. Source separation of specific fractions of domestic and industrial wastewater, separate treatment of these fractions and recovery of water and raw materials including fertilizer and energy are the main characteristics of modern high-tech on-site treatment/reuse systems. Mass production of the key components of the system could reduce the costs of the treatment units to a reasonable level. On-site units could be installed independently of the development stage of the urban sewer system. In conjunction with building new housing complexes a stepwise improvement of the hygienic situation in urban and peri-urban areas could be achieved, therefore. Remote control of the satellite systems using modern telecommunication methods would allow reliable operation, and comfort for the users. Intensive research is required, however, to develop this system and bring it to a standard allowing efficient application worldwide.
Keywords Decentralized water management; materials recovery; municipal wastewater; reuse; source separation

Introduction

During the past hundred years, total withdrawal of water for human activities increased from 600 km^3 to 3,800 km^3. In 1995, 65% of the total withdrawal was used for irrigation purposes, 20% in industry, and 10% for municipal use (Crosgrove and Rijsberman, 2000). Water use has been growing at more than twice the rate of the population increase during this period, and already a number of regions are chronically water short. As the world population continues to grow, the overall water demand will further increase over the subsequent decades, and water shortage will inevitably become dramatic in agriculture, industry, and cities. It is estimated that currently more than one billion people do not have access to safe drinking water. About 2.4 billion people are not served by any type of reasonable sanitation, and one-half of the world's hospital beds are occupied by people suffering from water-borne diseases.

This is bad news, indeed, because the problems are not limited to poor people far away from the developed world. Poverty and inadequate sanitation have been, and remain, a very dangerous breeding ground for epidemic diseases. Affected are not only local populations but the economy of the world as a whole as exemplified by the recent incident of SARS

(Severe Acute Respiratory Syndrome). To avoid hygienic and political disasters investment in water supply and sanitation must be urgently made.

Certainly, some of the problems resulting from inadequate water supply and sanitation could be solved by applying – worldwide – water, wastewater and solid waste management systems as they have been developed and implemented in the industrialized countries. Technically, this could be done within a reasonable period of time, provided the monetary resource was available to finance installation of water reservoirs, water works, water supply and sewer networks as well as plants for water, wastewater and solid waste treatment. In the industrialized countries, installation of this kind of municipal infrastructure has almost been completed. The costs for building up our classical water management systems were tremendous. But by spreading the investment costs over a period of almost 150 years, the financial burden of tax payers has been kept at a reasonable level.

In many parts of the developing world, however, the conditions are very different. Here, we face both rapid population growth and a rapid increase of urbanization. Mega-cities have developed and growth continues to be explosive. It is amazing to notice that access to wireless communication networks is available in the remotest parts of the world. Contrary to the advanced access to telecommunication, supply of safe drinking water and availability of acceptable sanitation, however, are very often terribly under-developed, if existent at all. Considering the overall costs for the installation and operation of our classical water supply and wastewater management system, and given the fact that little time is available to distribute investment costs over a reasonable period of time, it becomes clear that innovative methods must be found to prevent the world's population from slipping into a severe water and sanitation crisis.

At this point one should take the liberty of questioning whether the established system of urban water supply and sanitation is applicable to the "rest of the world". Is the technology as it has been developed over the past 150 years the ultimate solution? Does this technology meet the sustainability criteria the States of the world have agreed to comply with?

The classical concept of urban water supply and sanitation

Urban water and waste management can be considered as a linear flow system as shown in Figure 1. Water is taken from natural resources (reservoirs, rivers, groundwater bodies), transported into an urban area, consumed, polluted, sent to a purification plant and subsequently discharged to "somewhere".

It is noteworthy that a large fraction of the water supplied to the households, offices, enterprises and industries is used mainly as a means to transport particulate and soluble pollutants to the sewage treatment plant located at a distance. It should also be realized that a

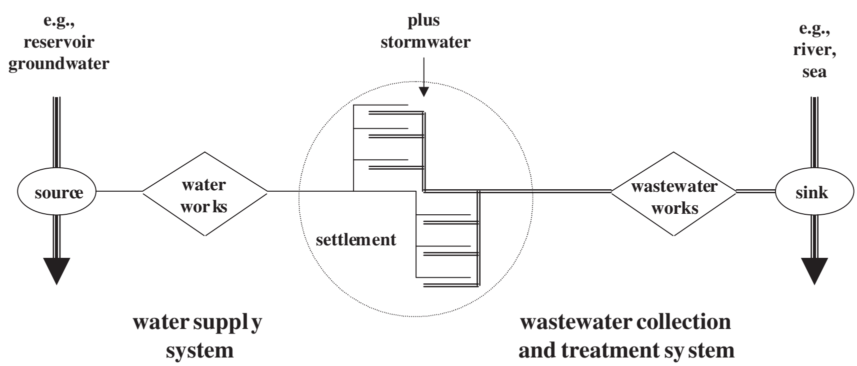

Figure 1 Schematic representation of the linear-flow water management system implemented in most parts of the industrialized countries

wide variety of materials are added to the water in passing through the various households, commercial establishments, and industries making it very difficult to recover from wastewater any valuable substances – including water of reasonable quality – for further use.

Use of drinking water for contaminant transport results in significant dilution, making wastewater treatment even more difficult. In classical wastewater treatment plants, recovery is not even in focus since the main purpose of wastewater treatment is conversion and destruction of materials (biodegradation and conversion into inert compounds such as carbon dioxide and nitrogen gas).

By taking all these aspects into account one must conclude that our classical urban water supply and sanitation system has its merits but is far from meeting sustainability criteria. Water is unwisely used, and valuable materials are not returned to the material cycle but destroyed.

The basic concept of sustainable sanitation

Based on those considerations a variety of concepts have been developed recently in an attempt to overcome the lack of urban sanitation in developing areas, and to implement a water supply and waste/wastewater concept which complies with the major sustainability claims (cost effectiveness, social acceptability, wise use of natural resources).

The concept of sustainable development was first proposed by Hans Carl von Carlowitz in 1713 who was greatly concerned about deforestation of large parts of Germany caused by the extensive use of logs as a support material in mines. His proposal was to cut only as many trees as trees grow per unit of time. In essence this meant that the mining business was to be limited by a biological factor, the growth rate of trees. Much later, the concept of von Carlowitz was adopted and further developed by the famous Brundtland commission (World Commission on Environment and Development, 1987), and interpreted as to "ensure that humanity meets the needs of the present generation without compromising the ability of future generations to meet their own needs".

In the years that followed, many attempts have been made to further refine this concept and get it applied. However, many of the suggestions made lack practicability under the conditions prevailing in our societies, and under the dictate of the second law of thermodynamics (Huesemann, 2001). Often, it was overlooked that the major goal of the Brundtland concept is to maintain and strengthen "the ability of future generations to meet their own needs". In other words, the most important contribution this generation should make to assure survival of mankind is strengthening the adaptive capacity of the various societies and economies on this planet to adjust to the ever changing economical, social and environmental conditions.

In order to strengthen the adaptive capacities of our societies it appears to be most urgent to eradicate poverty in the first place. This can be achieved by provision of education and basic infrastructure to the people, worldwide. Delivery of high quality drinking water and assurance of hygienic safety is one of the most basic needs of any community, and subsequently a precondition of sustainable development of rural or municipal areas. The only question is how to meet the intrinsic right of a community to receive reliable and affordable water and sanitation services, now and in future, and at any location in the world.

As mentioned above, the classical centralized water management concept symbolized in Figure 1 has major disadvantages. The financial resources needed to install sewers and central treatment facilities worldwide and within a reasonable time are not available, and valuable materials are wasted. In contrast, decentralized on-site systems based on the concept of source separation, as depicted in Figure 2, offer ample possibilities to recover and reuse water, nutrients and energy, and to reduce the overall water demand to be covered. Responsive to financial resources actually available per unit of time, those

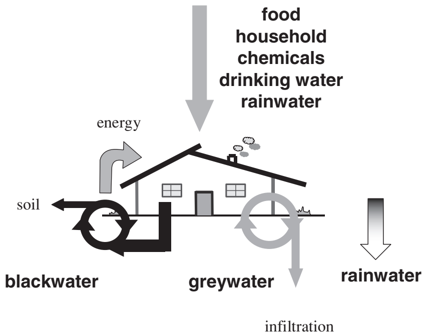

Figure 2 Schematic representation of an on-site water management system based on the concept of source separation, treatment of the individual wastewater fractions, recovery and reuse of valuable materials

systems can be installed step by step irrespective of the availability of transport sewers and treatment plants at the end of the pipe.

The costs for each treatment unit can be brought down to an affordable level by mass production of key components. Reliability and hygienic safety can be provided by specialized service companies using modern telecommunication methods for remote control and in-time maintenance.

Basic concept of advanced on-site water management

Based on the assumptions discussed above, Larsen and Gujer (1996a,b), Otterpohl *et al.* (1997), Vanhuizen (1997), Wilderer and Schreff (2000), Zeeman *et al.* (2000), and Wilderer and Koetzle (2002) proposed during the past years various methods of source separation in households, decentralized wastewater treatment and reuse. These proposals are based – more or less – on the following assumptions:

1. Water management systems should be designed in such way that a maximum of convenience is provided to the users.
2. The amount of water to be supplied should be kept at the lowest possible level to avoid over-exploitation of the locally available water resources, and to minimize the overall costs for water treatment, storage and distribution.
3. Supply of tap water should have priority over delivery of water in bottles, particularly in plastic bottles.
4. Wastewater and solid wastes should be source separated to minimize mixing of substances and to allow recovery and reuse of valuable materials.
5. Particulate materials should be separated from wastewater at the earliest possible moment to avoid uncontrolled dissolution, in particular of organic substances.
6. Attempts should be made to enhance the removal efficiency of devices for solid-liquid separation, possibly by integrating flocculation and/or adsorption in the processes for solid-liquid separation.
7. Organic materials separated from the wastewater, including the organic fraction of solid wastes, should be sent to an anaerobic reactor for controlled hydrolysis, conversion into low chain organic substrates, and possibly into methane gas.
8. Recovery of dissolved inorganic and/or organic substances and return into the cycle of materials, directly or indirectly, should have priority over destruction of these materials by means of physical, chemical or biological processes (e.g. biodegradation, nitrification, denitrification).
9. Attempts should be made to recover water from wastewater, and treat it so that it can be directly and safely used or reused (e.g. for cleaning, flushing, watering).

10. The technical system to treat wastewater should be low in costs but reliable in operation even under highly variable influent conditions.
11. The installation costs should be covered by the property owners, and the operation costs by the tenants. Subsidies should be only given to poor people in order to avoid the outbreak of disease.
12. A servicing network should be established simultaneously with the installation of the treatment units to control the performance of the units, to provide maintenance work and repair. The companies providing this service, after having been certified, are to be regularly monitored by regional water authorities, and fined if not complying properly.

Source separation of wastewater in households

In family and apartment houses, office buildings, cafeterias, restaurants and hotels five categories of wastewater streams can be discriminated:

- wastewater containing faeces (brown water)
- wastewater containing mainly urine (yellow water)
- wastewater containing both faeces and urine (black water)
- wastewater from washing machines, washing bowls, showers, bath tubs and cleaning containing mainly detergents (gray water)
- wastewater from kitchen sinks containing mainly food particles (green water)
- storm water collected on roofs and driveways containing dust, hydrocarbons, abraded materials from rubber, and heavy metals from metallic roofs.

These categories of wastes differ greatly in flow as well as in composition and concentration of the various components. Also their content of problematic and even hazardous substances is very different.

Urine contains great amounts of nitrogen, phosphorous and potassium that could be recovered and used as fertilizer. Otterpohl *et al*. (1997) report that 87% of the nitrogen contained in the influent of municipal wastewater treatment plants, 50% of phosphorus and 54% of potassium stem from urine. Separating urine from wastewater at the source would eliminate the necessity for expensive nitrogen removal processes at the wastewater treatment plant (Larsen *et al*., 2001).

Brown water (faeces) contains organic substances in high concentration, most of them in particulate and macro-molecular form. Of major concern are pathogenic organisms which impose health risks to humans and pets. Since the concentration of organic material is high, conversion into biogas and exploitation of the gas as an energy source appear to be attractive.

Kitchen refuse is also high in organic load, mostly particulate in nature, and readily convertible into biogas and compost. Combination with the brown or black water prior to anaerobic treatment appears to be feasible and advantageous.

Gray water is relatively low in concentration of particulate organic matter. Most of the gray water components, detergents for instance, are readily adsorpable and biodegradable. The concentration of inorganic substances of gray water, in particular nutrients, is very low. This fraction of wastewater can be purified relatively easily, and used thereafter, for instance as a substitute for drinking water for flushing toilets, for cleaning (e.g. first cycle of the washing process) and irrigation. No matter to which purpose the treated water is dedicated it should be converted into water of close-to-drinking-water-quality to avoid any harmful health impacts.

Proposed treatment methods

The treatment methods currently discussed for decentralized (on-site) systems differ in the extent of:

- separate collection of the five major fractions of household wastewater

- in- or exclusion of storm water collected on roofs and driveways into the water reuse concept
- specific technologies applied to treat the various wastewater streams
- re-introduction of the treatment products into the material cycle.

The proposed systems differ also in scale. Solutions are discussed focusing on the treatment of wastewater from single houses, apartment complexes, industrial parks or entire residential areas.

Separate collection of urine has been recommended by Larsen and Gujer (1996 a,b), Larsen *et al*. (2001), and many others. For this specific purpose especially designed toilet bowls are required. Otterpohl *et al*. (1997) advocate application of vacuum toilets as they are widely used in ships, trains and aircrafts. Wilderer and Schreff (2000) proposed traditional flushing toilets operated with treated gray water. The brown water may get combined with urine and organic wastes from kitchen sinks and sent to a high rate digester for biogas production (Figure 3) whereas the gray water is aerobically treated in a biofilm reactor.

A technologically promising method for the treatment of combined brown and green water consists of a sequence of fine sieves and micro-filtration membranes for solid-liquid separation, and anaerobic treatment for conversion of the organic material into biogas and compost. The anaerobic process may be subdivided into two steps. In the first stage reactor, hydrolysis of macro-molecular and particulate matter is achieved by a microbial community as it is found in the rumen of animals like cows, sheep or goats (Dalhoff *et al*., 2003a). The second stage reactor is designed for biogas production. If both reactors are separated by solid-liquid separation membranes only soluble substances, mainly volatile fatty acids (VFA), are allowed to leave the reactor via the membrane, but the microorganisms, even the slow growers, are retained in the first stage reactor. The methane gas could be used for the generation of heat/cold or electricity, the latter possibly by means of fuel cells, in future.

Gray water can be treated either physically by means of adsorption and membrane filtration as demonstrated by Dalhoff *et al*. (2003b), or biologically using biofilm reactors combined with a sand filter. Sequencing batch reactors or sequencing batch biofilm reactors (Wilderer *et al*., 2001) followed by membrane separation (microfiltration membranes) could be used when large volumes of wastewater are to be treated.

Roof and road run-off may be passed through a filter packed with cation exchanger material (e.g., zeolite), and organic material exposing a high adsorptive capacity to remove hazardous materials prior to usage of the water for flushing, cleaning, watering or infiltration (Athanasiadis *et al*., 2003).

One should realize that the effluent quality parameters are to be set significantly more stringent than those applied for traditional small on-site wastewater treatment plants. The following minimum requirements must be met to avoid harmful impacts to the users:

- The treated effluents, both water and solids, must be hygienically safe.
- The treated water must meet chemical drinking water standards, even if the water is not used for drinking or cooking.
- The solids must be fully stabilized and free of noxious odors.
- The biogas must be treated so that it can be used as an energy source without damaging burners, machines or catalytic converters (e.g. corrosion).

It is obvious that a treatment plant that meets these high quality criteria is technically very complex, requires a high degree of control, maintenance work and operator skills. One may assume that the costs to build, implement and operate many small instead of one large treatment plant are enormously high.

Characteristically, modern technical systems of all kinds are complex. A computer, for instance, is a technically advanced, complicated and highly sophisticated device, and so is a

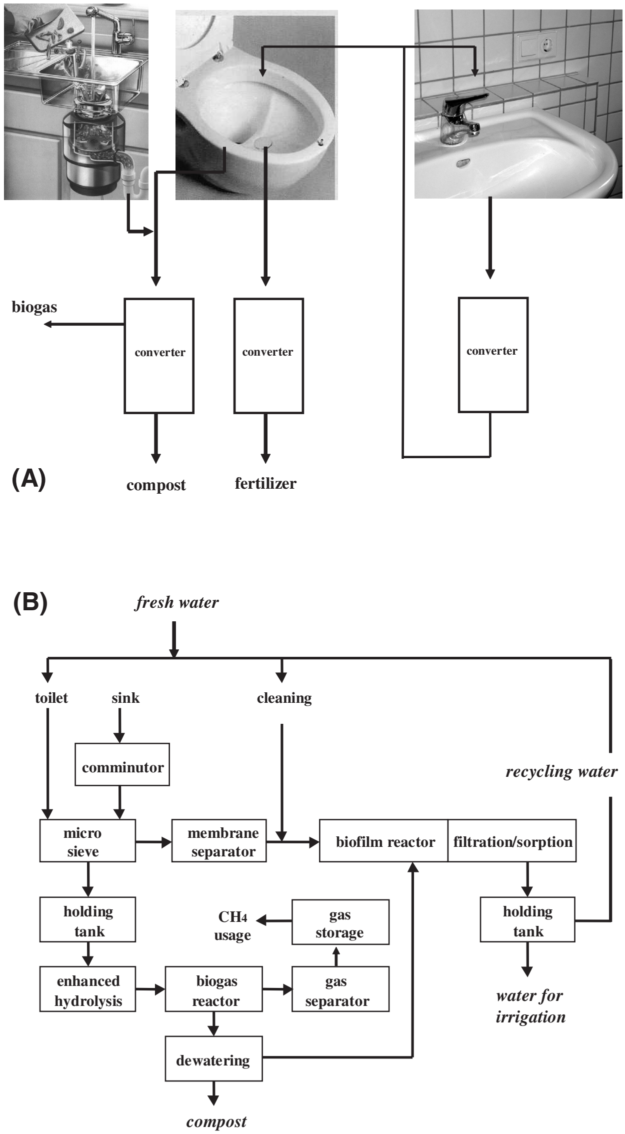

Figure 3 Example of a concept (A), and a flow schematic (B) of a small on-site system to treat separately black, green and gray water

cellular phone or an automobile. But nevertheless, computers, cell phones and cars are used worldwide, even in developing countries, and even by "ordinary" people of limited technical skills. They are surprisingly low in costs despite the high degree of complexity incorporated, and they are reliable. This is made possible because all these high-tech devices are designed by teams of highly specialized engineers, mass produced, and cleverly marketed. When applying sophisticated design, mass fabrication and marketing methods to the sector of wastewater treatment and reuse, it can be expected that the costs for each single treatment unit drop to a reasonable level as well. Professional supervision and service will enhance acceptability of the novel technology, both by the users and the water authorities.

Problems yet to be solved

The scenario sketched above might be very optimistic when critically assessed in more detail. There are a number of problems to be solved before such a technology can be brought to the market. We know by experience, however, that problems once realized will be solved, one way or the other, and sooner or later, provided the proposed product exposes an economical value. Detection of a problem provides challenges for technology developers, and often proves to be a major driving force for technological development.

There are many questions which have yet to be answered. For instance, technology developers will be faced with wastewater and kitchen wastes which are highly variable in composition, volumetric flow and mass flux. Of major concern are the chemicals used in households including pharmaceutical products. Problematic are, in particular, chemicals such as pesticides which may accumulate in the water that is recycled in the house and which may enter into the food chain by irrigation of crops in the garden. Presumably, hormones, hormone-like substances, wasted medicines and metabolites of pharmaceuticals are present in the yellow and in the brown water. The fate of these substances and the effects caused by them is widely unknown, yet. To make integrated decentralized treatment systems applicable, advanced research is necessary as well as a proper response by the chemical and pharmaceutical industry to come up with readily biodegradable household chemicals.

Conclusions

Further development of decentralized water management systems for rural and urban areas of developing countries should be based on the following assumptions and claims:

1. Effective water supply and sanitation needs to be established worldwide as a first and important step to eradicate poverty, to improve hygienic safety, and to achieve sustainable development in rural and urban areas.
2. The classical water supply and sanitation system will remain useful, but needs to be supplemented by novel ways of serving people. Needed are solutions that provide safe hygienic treatment of wastewater in a very short time period, and for a reasonable price.
3. Source separation of waste streams in households and in industry, recovery of valuable materials – including water – and their reuse should become guiding principles of waste and wastewater management. We must overcome the "old" concept of mixing, diluting and degrading materials.
4. Various new water supply and sanitation technologies have been proposed, but efficient and reliable application requires more than technological development. The costs must be kept in an affordable range, and professional service must be provided. Mass production of the components of decentralized systems may greatly reduce costs and should be seriously taken into consideration, therefore.
5. To be able to provide service and maintenance in developing countries an intensive educational programme must be developed and executed. Laws and regulations must be issued and enforced to provide the legal framework of advanced water supply and sanitation. Cultural concerns must be respected in order to not only deliver technology but to get technology integrated in the local traditions and habits.
6. The problems to be solved are extremely complex. Required is research that takes into account not only engineering but also economical, administrative and cultural aspects. Also required is education at all age levels to foster cooperation potentials of people, and general acceptance.

Acknowledgement

The author wants to thank Prof. Edward D. Schroeder and Prof. Takashi Asano for critically reviewing this paper, and for adding valuable thought to it.

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