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4.6 Ecological sanitation: Innovative sanitation systems for urban and peri-urban areas, high- and low-tech options with resources recovery

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SUMMARY: *Resources Management Sanitation is a term introduced during the IWA World Water Congress in Marrakech 2004. It covers systems that are designed for the reuse of nutrients, soil conditioners and water. Freshwater use can be reduced by up to 80% while nutrients can be recovered to a large extent. In many cases this is achieved through source separation at least of urine, that contains most of the soluble nutrients in very high concentrations. It can also be advantageous to separate the blackwater flow (toilet wastewater) with little or no water - small volumes are far easier to sanitise and reuse. New toilet systems with very low dilution factors, ranging from vacuum- over urine diverting (UD) flush to UD-dry toilets, have been introduced in hundreds of projects and proven feasible. New ideas as vacuum-biogas-systems, the blackwater-cycle systems and urine-diverting vermi-composting systems are presently realized in different locations mainly in middle and northern Europe. Source separation technology in municipal wastewater treatment does often lead to decentralised or semi-central systems, but combinations with conventional sewerage do make sense as well, as future strategy studies of the Hamburg wastewater utility have shown. However, especially for new construction there are often clear economic advantages of integrated decentral systems. Such modular, flexible and small-scale systems have become feasible through the recent advances in membrane technology. Both high- and low-tech options are available; both can achieve very high efficiencies. The low-tech range of UD dry systems has been successfully implemented around the world, mostly called Ecological Sanitation. This type of sanitation is essential to extend services to the neglected part of the world population as it was promised in the Millennium Development Goals with very high hygienic standards, water efficiency and resources recovery. The high-tech range is needed to change the technological paradigm and to allow prices getting down through mass production. All systems are essential to deal with limited resources in an intelligent way according to the given situation.*

Industrial wastewater management is very successful indeed in achieving higher resources efficiency by the reuse of water and wastewater constituents by source separation. Different flows are collected with little or no dilution and treated appropriately, in many cases with technically sophisticated membrane systems with the purpose of reuse. The advantages of reuse are resulting in far lower or no emissions, having less or no trouble with discharge regulations. Very often these concepts are even more economic than conventional end-of-the-pipe concepts. The same principles can be transferred to the municipal water management aiming at full treatment and reuse of water and human excreta. Full reuse means zero emissions at the same time.

The fundamental and innovative idea of integrated water concepts is based on the principle of separating the different flows of domestic wastewater according to their characteristics. *Fig. 4.6-1* shows the very different characteristics of domestic wastewater flows with reference to their volumes and loads *per capita* and day.

The volume relation of the toilet waste (blackwater) and greywater (household wastewater without toilets) is just the opposite of their nutrient load distribution. Nearly 90% of the nitrogen and the largest part of phosphorus and potassium are found in the small volume of the blackwater, whereas the greywater with its large volume contains only small nutrient concentrations. Separation of nutrients with the purpose of reuse is the easiest at their source where concentrations are still very high. Most of the soluble nutrients including most of the nitrogen are concentrated in urine, so it does make a lot of sense to collect this flow separately.

Concept innovation in water and sanitation

Implementation of new water and sanitation concepts

The water market is characterised by a broad variety of stakeholders. This includes the users, utilities, designers, builders, city planners, supply companies, local authorities and NGOs. Consequently, for a successful implementation of new concepts and new technological solutions, all stakeholders should be involved in a round table in an early phase. New solutions are naturally conflicting with old legislation, open minded people on all levels are required to start with pilot and demonstration projects.

Today, there is a good range of proven solutions that can be implemented without additional risk. However, professional long term maintenance and rehabilitation has to be assured and included into the total costs. With typically around 80% of the investment of central wastewater systems going into transport even under favourable conditions and a lot more in sparsely populated areas, there is a good margin for decentral or semi-central

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alternatives. They will offer a lot more employment especially in operation. Naturally, professional operation of decentral systems is a major prerequisite.

For the design of new concepts for a given settlement it can be a lot more cost efficient to go some steps further. Such systems can be realised without any central water supply or sewerage systems. Only then there is a potential for massive savings because the central pipe networks are usually very expensive. The bottleneck of innovative systems is the technology for black, brown (blackwater without urine) and yellow water flows. These flows can be managed if dilution is very low thus requiring new types of toilets. This will typically be vacuum, urine-diverting flush or dry toilets. At the same time there must be ways to deal with the rainwater runoff either with infiltration or with surface runoff, otherwise too much money is invested on this side. Infiltration combines nicely with usage of the rainwater that is stored underground in a synergistic way.

New settlements are the best places to start with innovative water concepts. Many regions of the world have fast growing cities and resources shortage at the same time; ecological sanitation concepts are clearly the way to go. However, it has to be stated that with humanity facing dramatic challenges especially with respect to water and phosphate reserves there is a dramatic lack of political leadership.

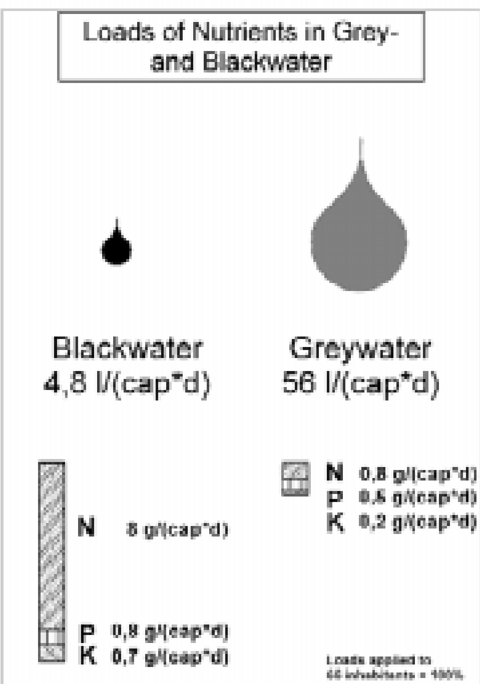

Fig. 4.6-1: Characteristics of domestic wastewater as measured at the housing estate Lübeck-Flintenbreite, Germany. N = Nitrogen, P = Phosphate, K = Potassium.

Examples for innovative water concepts

Almost all water research looks into advancing technology in the framework of existing concepts. Very little work is still done on the level of concept innovation although the potential of technical, economical and ecological improvement is much higher. In addition, advances especially in membrane technology (membrane-bioreactors MBR, Reverse Osmosis) open completely new ways of water-management. There are a broad variety of solutions, which cannot all be presented here. Ten basic concepts have been listed in another publication (Otterpohl et al. 1999) and show the variety of combinations of modules in dependence of the different geographic and socio-economic conditions around the world. Paris & Wilderer (2001) elaborated an extensive overview of realised concepts based on source control. There are three major system designs that have been realised in more than one large-scale project as described in some detail further below:

- Vacuum Blackwater Systems, blackwater/brownwater collection and transport by vacuum toilets and low diameter vacuum pipes usually followed by anaerobic digestion
- Urine-diverting flush systems, transport to decentral or semi central aerobic treatment by gravity
- Urine diverting dry systems, vertical gravity transport of faecal matter to desiccation or composting chambers

In addition there is the promising blackwater loop system that has been realised in a technical scale research installation.

Vacuum blackwater sanitation systems

Historically the Liernur-Systems in Holland in the second half of the 19th century was the first to realise the idea of vacuum collection of blackwater, fabrication of a fertiliser (poudrette) and its use on agricultural land. In Amsterdam approx. 3,100 houses (52,445 inhabitants) have been connected to this system (Kluge 2000). However, lack of technological development at that time, the high demand of firewood for the poudrette production and the logistical problems ended this interesting development despite its huge potential.

Vacuum blackwater systems in modern times are found on airplanes and trains. The major application that has been useful for today's installation in buildings, however, is in shipbuilding. Technology has become mature over some decades and even all the huge luxury cruise ships being a home for several thousand people are equipped with this technology. This can include some thousand toilets and several kilometres of blackwater pipes. Holding tanks collect the blackwater to discharge it to proper treatment in harbours. To demonstrate water saving technologies, vacuum toilets were installed in a block of rental flats in Hamburg around 1988. A survey done by the authors after around 6 years of operation showed that the 8 families living there where satisfied with the system that was not causing any problems after some initial fixings. Ironically, the identical neighbouring house had experienced a major blockage in their conventional gravity system.

Further development of vacuum blackwater systems to the needs in settlements has been performed through the projects Lübeck-Flintenbreite and Freiburg-Vauban that are described below. Vacuum technology in sanitation as well as in blackwater sewer installation was further developed. So items, which make them low-noise and enable better transport through the residential areas, are available today. This development was sparked by the pilot projects is now used widely, e.g. in hospitals, where radioactive blackwater has to be stored for long periods.

In Lübeck-Flintenbreite, Germany, a decentralised sanitation concept has been realised in a peri-urban area. As by now, 100 inhabitants are connected to the plant with a maximum capacity of 350 persons. Grey- and blackwater are collected and treated separately. Inside the houses vacuum-toilets with a flush volume of around 1.0 l per flush are installed and connected to a vacuum sewer system. Blackwater is collected in a central collection tank. After mixing with shredded biowaste the material is thermally sanitised and fermented anaerobically in a biogas plant (OTTERWASSER 2002). The biogas is used in a central heat and power unit for energy and heat production. Greywater is drained by gravity and treated in a vertical flown constructed wetland. Partly the plants are in operation since the beginning of 2000.

Further and more detailed information is reported in other places (OTTERPOHL et al. 1999, OTTERWASSER 2002). The average water consumption for the last 1.5 years was about 68 l/(PE×d), whereof 63 l/(PE×d) is greywater. Greywater here is very short of nitrogen as extensive measurement campaigns have proven. Surprisingly, it showed a relatively high concentration of phosphorous, mostly caused by use of high-P dishwasher detergents. An information campaign and the bulk purchase of a phosphate free brand helped to lower the concentration, however the results in the dishwashers where not encouraging enough for all. There are some efforts made now, to enhance P-removal in the greywater.

In Freiburg-Vauban a similar project has been realised by a group of citizens including the water expert Jörg Lange for a one-storey house with 40 inhabitants (LANGE et al. 2000). Also here, black water is transported from vacuum toilets to a digestor similar as in the project in Lübeck-Flintenbreite. The major difference, however, is the scale, making the Freiburg project specifically very expensive while the Lübeck project is capable to deliver the services at a price that is about the same as in conventional systems. In a pilot project in Norway black water of a settlement with vacuum toilets is treated aerobically under thermophilic conditions (SKJELHAUGEN 1998). Besides the projects being described above, other pilot installations are in the state of planning or already under construction.

The KfW, a large bank owned by the German government and the partner for the financial foreign aid has equipped a whole wing of a new office building with vacuum toilets to demonstrate this water saving source control technology.

Vacuum technology for collection of low-diluted black water is available and functional. The treatment technology for black water is available as well. The professional maintenance of the plants and education of the staff is indispensable.

Urine diverting sanitation systems

Urine diversion does make a lot of sense because urine contains most soluble nutrients in concentrated form and can be used as a natural fertiliser. At the same time it can contain a wide range of micro-pollutants like pharmaceutical residues and hormones. Source control opens new ways of treatment of these micro-pollutants; in conventional systems they are transferred to the receiving waters in a fast way. For many substances there is only little degradation in the wastewater treatment plants. Highly concentrated flows allow specific treatment for the elimination of these substances and their metabolites.

Urine diverting sanitation systems can be designed with and without flush for the faeces. There is also the possibility to combine conventional flush sanitation with urine diversion with the potential to make nutrient removal at the central plant obsolete. Historic examples of urine diversion and reuse from ancient traditional systems like in Yemen (WINBLAD 1998) are reported as well as many designs of historic diverting toilets. All this has largely been forgotten until around 1990, when Sweden took the lead in this development in modern times.

Several larger research projects are dealing with the questions around reuse and treatment of urine. Novaquatis at EAWAG, Switzerland, is performing a multi-disciplinary approach (www.eawag.ch). The Lambertsmühle project (see below) funded by the Ministry of Environment of North-Rhine-Westphalia has also researched across several disciplines including agriculture (LAMBERTSMÜHLE 2005).

The essential requirements for a separating toilet system are: comfort for the users, low dilution of urine and faeces, and a satisfactory drainage of both streams. Urine diverting toilets (also called no-mix toilets) are draining urine with or without water. Especially for buildings with public toilets (schools, motorway service areas, etc.) waterless urinals have a growing market due to their remarkable savings of water. By this way a simple collection of urine and treatment is possible. Undiluted urine can be worked into brown soils as fertiliser. After dilution with the 3–10 fold volume of water, urine can be used directly on grassland, but in vegetable horticulture only after storage for at least half a year. In summary, a source separating sanitation system with treatment of its different flows makes the re-use of urine as fertiliser possible.

Separating toilets have been developed mainly in Sweden. All these toilets are draining urine with more or less flushing water, causing urine dilution and thus enlarging the storage volumes. A new developed separating toilet tries to avoid this disadvantage (s. *Fig. 4.6-2*). This toilet can be used like a normal flushing toilet. The urine drain opens only when pressure is exerted upon the toilet seat. This way urine drains without dilution and nutrients can be collected for utilisation.

Urine diverting flush sanitation systems: As mentioned above Sweden has taken a lead in urine diverting sanitation. There are many systems with dry collection of the faecal matter, but also many with flush for the brownwater. For the flush systems a good solution for the conversion of the brownwater to soil conditioner was missing. For this reason the company Otterwasser in Lübeck, which has pioneered the vacuum-blackwater system in Lübeck since 1994 worked out a solution. For a historic water mill – the Lambertsmühle – converted to a museum a wastewater concept with urine diversion has been designed for the river basin utility Wupperverband and realised in 2000. In a multi-disciplinary research project different details of urine separation and its utilisation have been investigated: experiences with different separation toilets, storage of the urine, use of separated human urine as mineral fertiliser, analysis of pharmaceutical residues in the different flows (LAMBERTSMUEHLE 2005, OLDENBURG et al. 2002). The details will not be discussed here, but a very promising solution for the brownwater treatment shall be mentioned. A pre-treatment system with a filter system has been on the market in Germany, Austria and Switzerland since many years. The basic idea is the alternate collection of solids in two filter bags or through two tanks with filter bottoms. Research at the Hamburg University of Technology has shown that these filters are not really getting to compost, as they keep too wet. Through information on research and installations of vermicomposting in sanitation in Australia (HO et al. 2002) the combination of the two processes separation and vermicomposting were investigated (GAJUREL et al. 2003). Results of this process combination were very convincing at temperatures above 18 °C, even starting with 85% moisture at the beginning.

Several large-scale projects with urine separation in flush toilets are in the planning phase or under construction. For a part (88 appartments and a school) of the large new settlement »Solar City« in Linz, Austria, an urine separating wastewater system is presently built. It was designed by Otterwasser for the water-, wastewater and gas utility of the city of Linz, the Linz AG. The nutrients shall be utilised for agriculture, that has sparked discussion on the safe reuse of this material. A new systems design has been implemented in a demonstration project in Berlin, Germany by the research unit »Centre of Competence for Water«, owned by the worlds biggest water company, Veolia in the framework of the Berlin Water Utility (PETER-FRÖHLICH et al. 2004). Different sanitation technologies and the treatment of the various flows are investigated on a technical level. The technical investigations were accompanied by investigation concerning the use of the nutrients on agricultural land, technical possibilities of the treatment of the collected yellow-water and a life cycle assessments. One part of the project is research on a system that includes new sanitation technology. Here urine diversion with gravity flush toilets is installed as well as vacuum toilets with gravity driven urine diversion. The latter ones are tested in the project as prototypes for possible further applications. The GTZ, the German Development Board is presently equipping parts of her main building with urine diverting toilets.

• Urine diverting dry sanitation systems: Dry sanitation in a conventional way means mostly pit latrines and they are installed in many million of units around the world mostly in developing countries and were installed not so long ago in industrialised countries, too. This type of sanitation can be rather polluting for the groundwater by exfiltration of

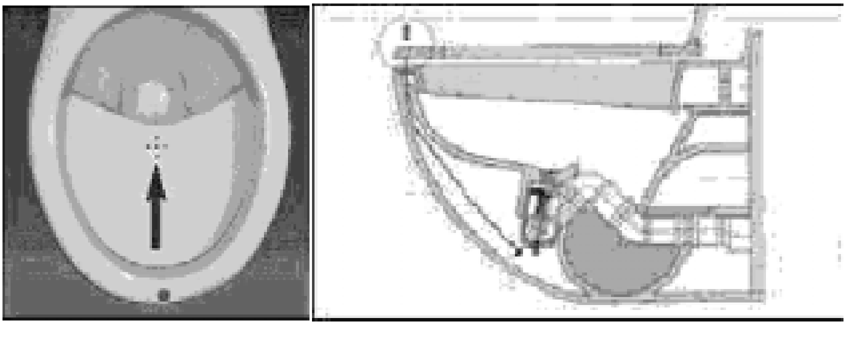

Fig. 4.6-2: Urine diverting toilet without urine dilution, valve opens when a person sits down.

faecal matter and nutrients and is in this from unacceptable for many regions. Urine diversion can be a quick fix at marginal costs. However, there are more advanced concepts with UD-toilets and two chamber processing of faecal matter like the one developed by Paul Calvert in India (Winblad 2004). Experience over some decades has shown that desiccation seem to be advantageous over composting, as the moisture content can be brought down to the minimum instead of trying to control it. The costs of this system are incredibly cheap; in addition it will provide local fertiliser at local spending capacity. A principal sketch of a UD dry sanitation system is presented in *Fig. 4.6-3*. There is even a project by the Swedish EcoSanRes for dry UD-sanitation in Inner Mongolia in an urban area with flat houses up to 4 floors serving 15,000 people (EcoSanRes 2005).

The blackwater loop system

Separate collection and treatment of black water and grey water are the bases of the »black water loop process« (Otterpohl et al. 2004, see *Fig. 4.6-4*). Reclaiming the water for toilet flushing leads to a very high concentration of nutrients during operation. This can be an important contribution for domestic wastewater and nutrient management. With the black water loop technology the freshwater consumption of flushing toilets can be reduced significantly. The method is also possible with urine separating toilets and re-circulating as brown water loop. The black or brown water loop process is shown on the left hand of the scheme. Inputs are urine and faeces (incl. toilet paper) as well as biodegradable kitchen waste as an option, which can be disposed through the toilets or the falling pipes. After treatment of black water in a membrane bioreactor (MBR), the liquid can be reused hygienically safe for toilet flushing again. The solids can be processed further to biogas or compost. The system discharges are limited to the very small flow of 1–2 l/(PE×d) of a clear, odor- and colorless flushing water, being used as a liquid mineral fertiliser. Optional biogas production, digested sludge or

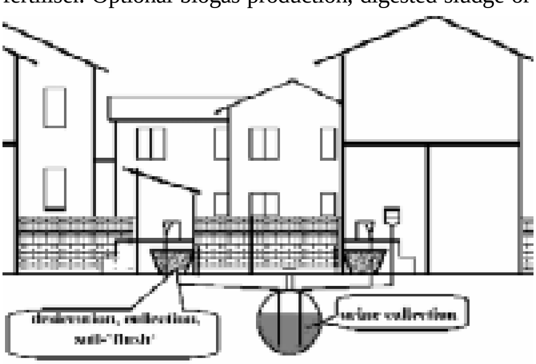

Fig. 4.6-3: Principle sketch of a urine diverting dry sanitation systems in a peri-urban area.

compost are further mass flows. This way the faecal wastewater stream can be closed to a loop, while all contaminants are discharged in a gaseous or solid form after thorough treatment.

In summary, the black and brown water loop processes have a high potential especially in areas of the world, where water and fertilisers are costly and/or scarce. Economic sizes of such plants are estimated to be above 200 residents, preferably in multi storey buildings. By modular production of large numbers, even in cases of small systems, competitive water prices can probably be achieved. These technologies are protected by international patents (Braun 1998). Freshwater demands can become as low as 10 to 20 l/(PE×d).

Adaptation of existing central water infrastructures

By subsequent successive employment of urine separating toilets with storage tanks, the conventional central wastewater system can be changed into one with almost full reuse of nutrients: Urine separating toilets and additional pipes can be installed during renovations. The urine pipes are connected to the sewers in the initial phase. After a sufficient number of connections in a specific neighbourhood is reached over the years, the highly concentrated nutrient solution can be utilised for fertiliser production. In case of sewer nets with little external water influx and a sufficient slope, the collection of urine can be done by a time-controlled emptying of the storage tanks (Larsen et al. 1996). If a separate collection of urine is established, the central sewage plant does still have enough nutrients, but without any need for denitrification. The remaining nutrients will be incorporated by micro-organisms, and thus end up in the sewage sludge. With this method, even a conventional system can reach fairly good nutrient resource efficiency.

Successive de-coupling of toilets and employment of appropriate and decentralised black water treatment systems is another possibility, transforming the central sewage plant into a grey water treatment plant, but including industrial wastewater. Depending on surrounding conditions, the treatment plant can be enhanced for water reuse.

The disadvantage of these scenarios has to be seen in the investment costs adding to the maintenance costs of the central infrastructure. Due to the main cost factor, transport of wastewater, the economic balance has to be examined. On the other hand, the enormous cost of rain storm water storage can be reduced by disconnection of black water. The over-flow of untreated grey water would be much less problematic. The wastewater utility of the city of Hamburg, Germany, is presently evaluating scenarios for the future of their systems for the year 2050. One of the options that are discussed is the conversion to urine or blackwater diversion

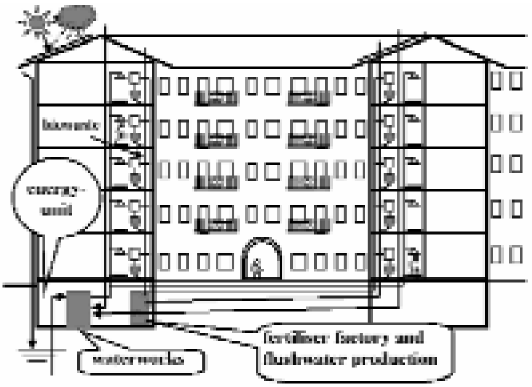

Fig. 4.6-4: Flowscheme of the blackwater loop system.

over the years, including the construction of an anthropogenic fertiliser company.

Socio-economic consequences and models of operation and impact assessment

Many of these innovative concepts demand only minor changes of the user's behaviour. A slightly different looking toilet is often the only visible change. An increasing demand will generate new and more comfortable solutions very fast. At the moment, the sanitary market is absolutely design-oriented, and technically still poorly innovative. User acceptance is the prime issue here. On the other side the producers of sanitation porcelain are mainly interested in the production of large items, therefore the start up of new technologies with low numbers at the beginning is very difficult – the identification of possible partners too.

The »economy of scale« of central sewage plants is very often pointed out in wastewater management. However, this essentially correct fact cannot be seen isolated. In most urban areas with advanced wastewater treatment the collection and transport cause at least 70 to 80% of the total costs. Consequently, savings on the side of the sewage plant do have only a small effect in total. On the other hand, decentralised treatment plants can become very economic if they are produced standardised and in large numbers. But also the much higher operation costs of decentralised plants have to be considered. In summary, investments in decentralised concepts flow into production and maintenance of plants, whereas investments in central concepts flow mainly into large sewerage systems. Thus, decentralised concepts will produce more long-term employment opportunities than central systems. The decentralised wastewater and biowaste management concept in Lübeck-Flintenbreite produced half of the salary for a caretaker including the technical management of energy/water technology, the total costs of the system including labor work being not higher than those of conventional wastewater services.

Professional management of operating innovative water systems is of utmost importance, ideally by local operating companies or co-operatives. In case of small units, regular maintenance by an external company is suitable as well.

In case of catastrophes like floods and earthquakes, central systems are highly sensitive. Failures of central systems will often have more grave consequences, while occurring more seldom compared to decentralised systems. The risk of many decentralised resp. semi-central plants can be effectively minimised by professional maintenance and modern sensor-based controls with alarm messaging and remote inquiry. The large number of plants can cause more disturbances. Altogether, their impact may be much smaller than one failure of a central system.

Conclusions

Innovative decentralised wastewater systems following the principles of resources management sanitation can change the current ways of water management dramatically. They can be designed for almost full recovery of water and nutrients in an economic way. Considering the dramatically increasing water shortages water efficient reuse technology should be put high on the agenda. This is also true for the limited resources of phosphate and counteracting soil depletion by returning organic substances after appropriate treatment. More research is needed, however there are many solutions already available for implementation. There is a vast potential of intelligent integrated concepts, while small improvements are often not very economic. Societies should finally face their responsibility for taking good care of the most precious resources: water and fertile soil. It is good news indeed that decentralised solutions will probably be the choice even in urban areas. This way people in city planning projects can act without waiting for the overall solution that may never come – too many regions are making conventional sewerage very costly. The future is open for decentralisation with integrated water systems and there are many solutions to fit to the situation. It can be expected that the interest in research and implementation in innovative water systems will further increase dramatically as it was the case over the last three years. Several global companies are closely looking for the right moment and the right concepts to go to the market. When this will be done in a massive way, the economies of scale will give theses systems additional advantages in costs and availability of operation and maintenance. The market is there, from high- to low-tech and for several modules that can be combined according to the local cultural, socio-economic, geographical, technical and ecological requirements ♦