Sustainable Sanitation Systems – dissolving the antagonism between urban comfort and hygienic pollution of urban environs

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Abstract

Infrastructural systems should comply with the ecological and socio-economic requirements of a sustainable development. From the ecological point of view saving of drinking water, recovery of energy (via biogas), and protection of the sea from eutrophication (phosphorus, nitrogen, potassium) are important challenges. High investment and running costs for disintegrated systems for sewage and solid waste contribute to the desolate financial situation of many municipalities. Social aspects of the non-sustainability of the existing sewerage system encompass unequal distribution of financial burdens for waste water treatment regarding country and city population, unequal water treatment requirements for water users upstream and downstream, and the hygienic pollution of streams and rivers, which does not allow swimming.

Examples for new technological solutions are presented. The chances of sustainable sanitation (SuSan) with respect to the three dimensions of sustainability to dissolve the antagonism between urban comfort and hygienic pollution of surface waters in the environment are discussed. The urgent need for social acceptance of new sanitation techniques is emphasized.

Introduction

Within the debate about a sustainable urban development the relationships between the city and its environs is a central topic. Cities are connected to their surroundings in many ways: For example by the import of water, food, energy and manpower on one hand and the export of products, waste, sewage and culture on the other. This exchange between central and peripheral or rural spaces embodies both common interests as well as contradictions. In Germany – for example – the disposal of untreated urban waste has been a flagrant contradiction to the interests of the urban environment till the end of the 20th century. The emissions of sewage to streams and rivers is still a contradiction all over Europe despite the efforts in purification technology. To understand the necessity to change the paradigm of waste water treatment it might be helpful to take a short look at history.

Short history of the urban sanitation system since 1850

In the beginning of the 19th century streets and lanes of the European metropolises were immersed in dirt, mud and carcasses. The authorities of Paris, for example, were urged to construct water towers which were emptied periodically to flush streets and squares. Latrines were discharged by suction pumps which had been installed on horse-drawn vehicles. Narrow housing spaces as a result of increasing population in towns (see table 1) and leaky latrines led to a "small water cycle" between latrines and wells thus contaminating drinking water by faecal microbes. That is the reason why severe epidemic diseases troubled people in Central Europe during this period, for example in London in 1830 and in Hamburg in 1848 (ATV 1999).

Table 1: Population dynamics in European towns between 1800 and 1910 (Simpson 1983).

Town	**1800**	**1850**	**1880**	**1910**
Berlin	172.000	419.000	1.122.000	2.071.000
Frankfurt / Main	40.000	65.000	136.000	414.000
Hamburg	130.000	132.000	290.000	932.000
London	1.117.000	2.685.000	4.770.000	7.256.000
Paris	547.000	1.053.000	2.269.000	2.888.000

The initial drainage systems of towns and cities were converted to sewerage systems, and water closets were connected. From 1850 to 1906 a fierce discussion took place between the advocates of the following alternatives: collecting faeces and bringing them out onto the fields or flushing them out of town by sewerage systems. Natural scientists, for example Justus von Liebig, recommended to collect the outcome from the toilets and to use it as fertiliser, whereas hygienic specialists and technicians proposed the introduction of sewerage systems. With the invention of the siphon around 1860, the water toilet gained the big advantage of a smell stop and as a result of this increased comfort water toilets and sewerage systems became more and more widespread. Nevertheless the use of drainage and sewerage systems differed considerably between individual towns in Germany (table 2).

Table 2: Drinking water lines and drainage systems in German towns in the 19th century (Grahn 1883).

Town	**First drinking water line**	**First drainage system**	**Input of faeces before 1906**
Berlin	1857	1873	Yes (obliged)
Cologne	1872	1881	Yes (1029 WC in 1882)
Frankfurt	1873	1867	Yes
Freiburg	1876	1881	No
Hamburg	1849	1848	Yes
Karlsruhe	1871	1883	No
Leipzig	1866	Before 1882	No (but 5343 WC in 1882)

This hygienic discussion was closely connected to the theory of miasma which argued that exhalations from latrines or even from soils fertilised by faeces would be the reason of epidemic diseases. As a result people regularly became panicked at times when latrines got discharged. This theory still played a role in 1892 in the controversy between Robert Koch and Max von Pettenkofer during the struggle against the cholera epidemic disease in Hamburg (Evans 1987).

After 1906 this discussion came to an end. In Germany sewers became the standard solution for collecting sewage and for draining settlements. More and more towns were cleaned at the cost of the quality of rivers which often degenerated into cesspools. Already in 1869 large quantities of fish died in the rivers Seine and Thames, and in 1892 the cholera epidemic disease broke out in Hamburg because unfiltered water from the river Elbe was used for drinking water (Evans 1987). In 1907 William Philips Dunbar (since 1892 director of the governmental hygienic institute in Hamburg) described the situation of some rivers in England as follows: "Children delighted in lighting the gas bubbles, rising up from the courses of the rivers. The flames coming into being were 6 feet high and were running on the water surface up to 100 m. A great number of carcasses were drifting in the rivers …" (ATV 1999).

In Germany it took more than a century (1880 – today) to retrofit the sewerage systems with purification plants. At first the plants worked only mechanically. Biological decomposition of sewage still took place in streams and rivers. Because of the high oxygen demand this process caused severe oxygen depletion in river systems. To avoid this, in the 1960's and 70's a second biological cleaning stage was implemented which transferred the biological cleaning from rivers to purification plants. From the 1980's onwards, a third stage has been introduced – the elimination of nitrogen and / or phosphorous to avoid eutrophication of the North Sea and of some lakes. In this way our current system to purify sewage became the classic example for a growing end-of-the-pipe-system.

Requirements of Sustainable Sanitation

Infrastructural systems should comply with the ecological and socio-economic requirements of a sustainable development. Despite the fact that sewerage infrastructure is as important as transport or communication infrastructure for the society to function smoothly, there is no public discussion about the chosen technology. The sewerage systems are hidden in the underground and new technological developments come to public mind with a considerable delay compared to mobile telephones in communication or fuel cells in transport.

Table 3: Requirements of sustainable sanitation systems (SuSan).

1 Ecological point of view
1.1 Prevention of eutrophication of the sea
1.2 Avoidance of high fluxes of material and energy as long as based on non-renewable resources
1.3 Water quality similar to primordial condition (groundwater and surface water)
2 Economic point of view
2.1 Prevention of nutrient losses
2.2 Avoidance of nonflexible systems with high capital commitment
2.3 Exportable technology
2.4 Low vulnerability by war, terrorism or natural catastrophes
3 Social point of view
3.1 Dry and hygienically unobjectionable settlements
3.2 As much comfortable as the present system
3.3 Internalisation of toxic and hygienic risks
3.4 High-quality usage of water bodies

In order to "meet the needs of the present generation without compromising the ability of future generations to meet their own needs" (WCED 1987) and to meet the needs of a certain region without compromising the ability of other regions to meet their own needs (everyone lives downstream) a sustainable sanitation system should be in accordance with the requirements listed in table 3.

The non-sustainability of the present urban sanitation system

Three technical components are designating the present sanitation system: sewer system network, purification plant and storage pond – compare figure 1.

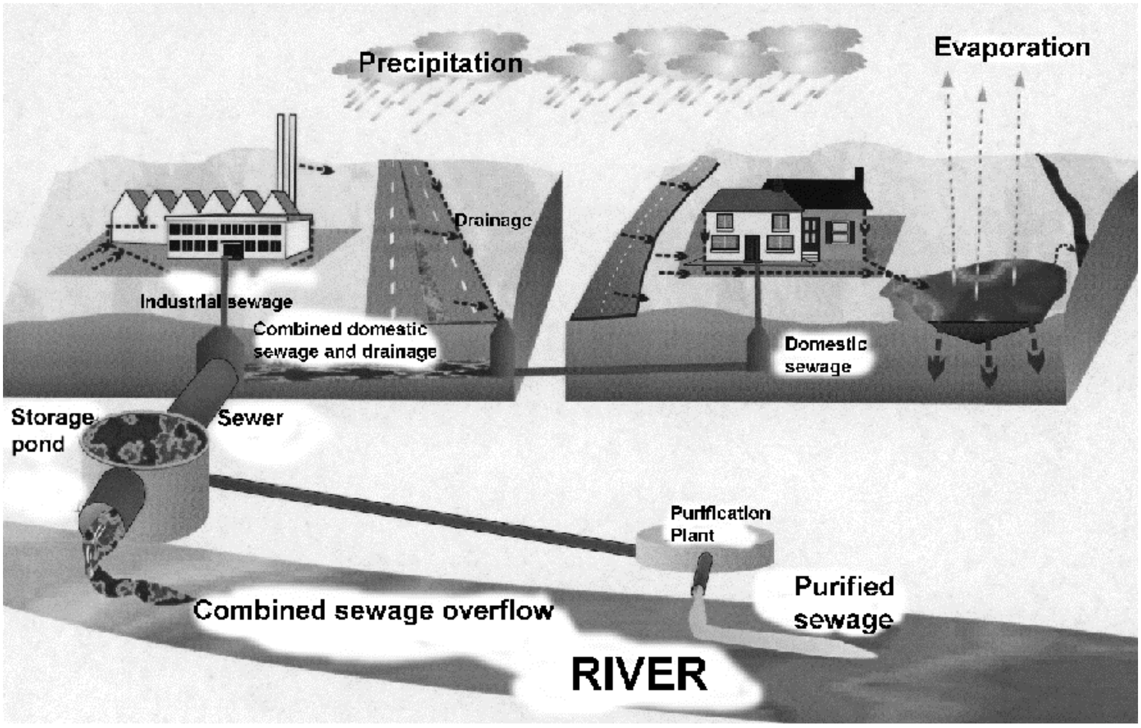

Figure 1: The classic urban sanitation system (combined sewerage system) pollutes run-off capabilities (brooks and rivers) during rainfall by the outlets of purification plants and by combined sewage overflow.

Sewer system

The sewer system comprises urban sewers and private house drains. In the year 2001 urban sewers in Germany added up to a total length of about 445.000 km. The combined drainage und sewerage system in the south of Germany has a total length of about 227.000 km. In the north of Germany the system is divided in sewers of about 135.000 km, and culverts for drainage of about 85.000 km. The private house drains are estimated to have double to triple the length of the urban networks (ATV 2001). Because of severe damages 7 % of the urban sewers (31.000 km) have to be repaired immediately or in short term, additional 10 % (45.000 km) in the medium term. If leaky sewers are situated above the groundwater table the sewage exfiltrates into the groundwater. Dohmann and colleagues estimated for the former Federal Republic of Germany an amount of 31 to 445 mio. m³ of exfiltrating sewage (Dohmann et al. 1999). If the sewers are below the ground water table ground water infiltrates and dilutes the sewage. As a result of this dilution the purification process in the purification plants is less effective. In both cases groundwater or surface water will be polluted, a violation against requirements 1.1 and 1.3 of table 3.

The restoration costs for these 17 % of the total urban sewerage system are estimated to sum up to 45 billion €. In the year 2000 1,6 billion € were spent for restoration and replacement, an amount which seems only to be sufficient to maintain the actual conditions but which is not enough for any improvement (ATV 2001). About 500.000 km (40 %) of the private house drains are estimated to need rehabilitation. Considering these data the question arises whether the current sewer system network complies with requirement 2.2 (table 3). More than 90 % of the sewer material is stone ware or concrete. Both materials need a lot of energy during construction – a violation against requirement 1.2 (table 3).

Purification plants

In Germany more than 90% of the population are connected to one of approximately 10.000 purification plants which clean up about 10 billion m³ waste water each year. Despite the subsequent retrofitting with second and third purification stages, the purification process is still incomplete: Polar hydrophilic substances like boron compounds from washing powders (Lehn et al. 1996), a number of pharmaceuticals, disinfectants and endocrine disruptors (Kümmerer 2004) or faecal bacteria and viruses (Overath et al. 2001) cannot be detained or destroyed by conventional purification techniques. The systematic pollution of surface waters by the emissions of purification plants is contrary to the requirements 1.3, 3.3 and 3.4 of table 3. The aerobic degradation of substances in the biological stage needs a lot of oxygen. The necessary aeration consumes considerable amounts of electric energy (about 1 kWh/m³ sewage), which does not correspond to requirement 1.2.

Within the nitrification/denitrification process, nitrate is converted to gaseous nitrogen which leaves the process and gets lost. Phosphorus is bound to sewage sludge. Because of its pollution (e.g. by heavy metals) less and less sewage sludge can be used in agriculture and has to be burned to an increasing extent. The loss of nitrogen, phosphorus and potassium during the purification process is a contradiction to requirement 2.1 (table 3). To reduce this loss actual research is done on the recovery of phosphorus (and potassium) from sewage sludge and from incineration ashes respectively.

Rainfall treatment systems and combined sewage overflow

Purification plants are designed for double the volume normally flowing in during dry periods. In case of heavy rainfall the mixture of rain and waste water in combined sewers increases up to 100 times and more of the normal volume. The excess volume of sewage bypasses the purification plants and reaches streams and rivers without any cleaning – compare figure 1 and 2.

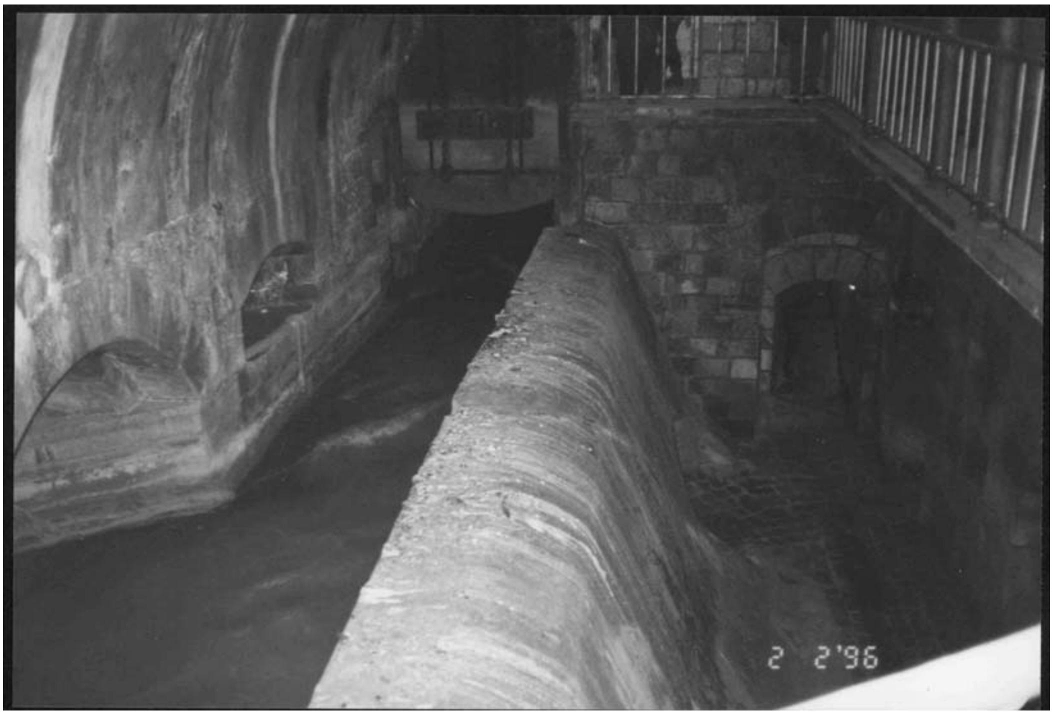

Figure 2: Overflow structure in the sewer network of Vienna (Austria). If the combined wastewater sewer at the left side of the picture is brim-full with the mixture of sewage and stormwater the excessive volume gets discharged directly to the Danube river by overflowing the dividing wall in the middle of the picture. The residues on the wall coping show that it is waste water which gets discharged and not rain water, even though this phenomenon is often called "stormwater overflow" in the literature.

In the meanwhile in Germany roughly 20.000 storage ponds have been installed with a volume of about 13 mio. m^3 to clip at least the first peak of combined sewage overflow in the beginning of a rainfall event. It is estimated that additional 20.000 to 30.000 ponds are necessary to be built. In these ponds only the first flush of a rainfall event can be stored and later been transported to the purification plant. The overflow goes on to bypass any treatment process. The emission of untreated sewage via combined sewage overflow contradicts the requirements 1.1, 1.3, 2.1, 3.3 and 3.4 in table 3.

Urban comfort at the cost of hygienic problems and environmental pollution

As shown in previous chapters both the outflows of purification plants and combined sewage overflows of the sewer network contribute to environmental pollution. In the case of two tributaries to Lake Constance it is obvious that the purification plants cause a constant hygienic basic pollution level (ca. 1000 E. coli in 100 ml), whereas after rainfall and combined sewage overflows the content of E. coli increases up to 12.000 per 100 ml for some hours or a few days – compare figure 3.

As a consequence of hygienic pollution, swimming is not allowed in nearly all German rivers – for example: In the state of North-Rhine Westphalia at the moment no water course is open for bathing (Overath et al. 2001). The capital of the state of Bavaria, Munich, had to close down river baths in 1998 because of hygienic risks. In the meantime, the strategy is to treat the outlets of upstream purification plants by disinfection via UV-rays and to accept a temporary worse hygienic quality in the days immediately after rainfall events. Actual results for the river Neckar in the state of Baden-Wuerttemberg show, on the basis of the European guideline concerning the quality of bathing waters, that none of the examined places from the source in the Black Forest to the mouth into the river Rhine near Heidelberg complies with the required water quality.

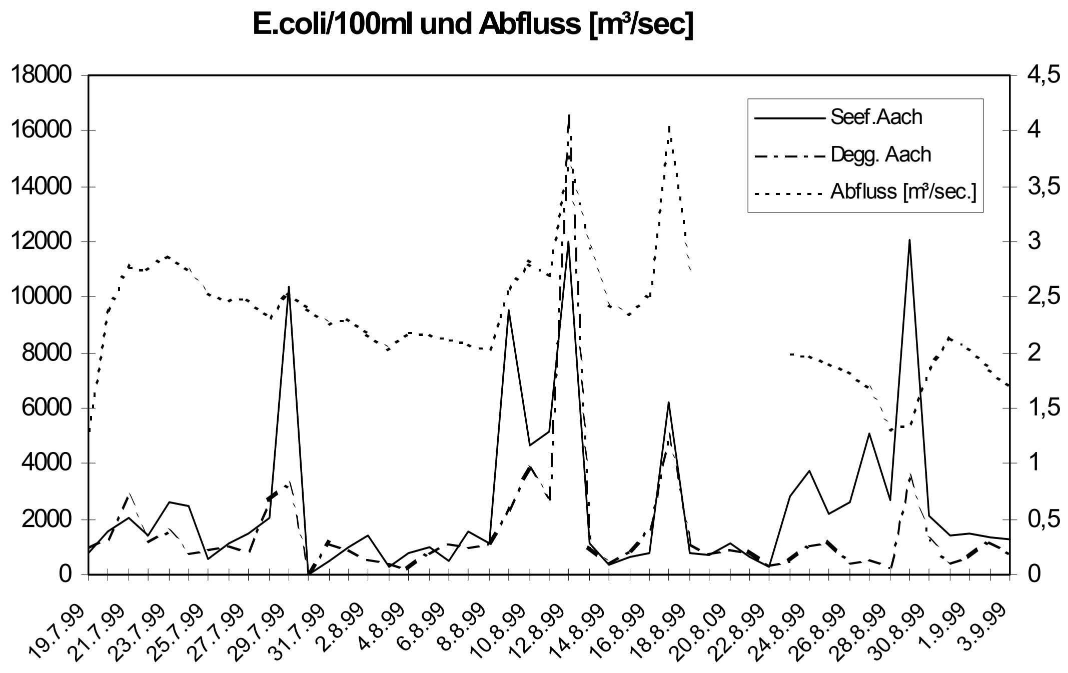

Figure 3: Concentration of E. coli (per 100 ml) and flow (m³/sec) in two tributaries (Seefelder Aach and Deggenhäuser Aach) to Lake Constance in a 6 week periode in summer 1999 (Güde et al. 2000).

From this we can conclude that the current urban sanitation system does not comply neither with the ecological nor with the socio-economic demands of a sustainable infrastructure system. With regard to these sustainability deficits, the German Research Association (Deutsche Forschungsgemeinschaft-DFG) states: There are justified doubts about the resource efficiency and sustainability of today's water management for settled areas. Accordingly, the resource efficiency of existing – but improved - and alternative systems should be reviewed (Deutsche Forschungsgemeinschaft 2003).

SuSan – Sustainable sanitation

To achieve the goals listed in table 3 three principle strategies can be seen:

- Further optimisation of the present system on the centralised level
- Establishing alternative systems on a decentralised or semi-decentralised level
- Establishing the sewage-free house on the individual level

This classification shows that SuSan-technologies have to pay attention to specific local or regional situations. This means the systems will probably differ between rural and urban situations or between water rich regions and regions under water scarcity. Sustainable sanitation in the future is unlikely to consist of one standardised system for all needs.

Adaptation to extreme weather conditions instead of water saving

Water saving strategies may not be the central issue all over Europe. Low water consumption conserves heavily extracted water resources on one hand. On the other hand it can mean long periods of stagnation in the pipes. The installation of a new water pipe network with reduced dimensions could be the consequence. In this case a new system for water supply for fire fighting has to be found. An alternative could be to use the water in the existing pipe work only as service water and to distribute bottled drinking water. Because of the fact, that 80-90% of the costs for the water distribution system are fixed costs, water saving will often lead to higher specific prices. One result could be that the costs for drinking water will not decrease absolutely. Because of these facts SuSan should contribute to water saving strategies whenever necessary but water saving is no central precondition for sustainable sanitation systems in general.

Up to now the observed climate change and prognoses of experts indicate that the climate in Central Europe tends to more extreme situations: dryer summers but presumably with severe tempests, milder winters with less snow but more rain in altitudes up to 1.200 m. The implications for river systems are that the dilution capacity of run-off capabilities (brooks and rivers) will decrease during summer months as it could be seen in the year 2003. If alpine glaciers should be melted off in the middle of the century the situation would go from bad to worse for rivers coming from the Alps (e.g. Rhine, Rhone; Po, Adige, Drau). As one consequence purification of sewage should achieve a standard which makes further dilution dispensable. If the climate will change in Central Europe to circumstances comparable to the Mediterranean, it may be assumed that people desire to use rivers for bathing or swimming. SuSan therefore should enable high-quality-use of surface waters.

More frequent and heavier rainfall events will increase the probability of occurrence and the duration of combined sewage overflows with its negative effects described above. One essential element of sustainable sanitation systems therefore is the separate treatment of rainwater.

Separate treatment of different types of waste water

The separate treatment of different types of waste water is well known in large scale industrial factories. It has the advantage to optimise the treatment of different waste water flows, whereas during the classical urban waste water treatment different waste water quantities and qualities are first mixed and then diluted by considerable amounts of storm water. It is obvious that the purification process has to be suboptimal under such inconstant conditions. The separate treatment of different types of waste water therefore is a constitutive element in the process management of sustainable sanitation technologies. Usually three steps of separation are discussed:

Step 1: Separation of storm water (rainwater)

Under the climatic conditions of Central Europe the main advantage of this step is to avoid dilution of sewage. If the sewage is more concentrated and its volume fluctuates less, hydraulic dimensioning of purification plants can be optimised. The sewers can be constructed in smaller dimensions and combined sewage overflow can be reduced or avoided completely. This would be the first step to reach a more hygienic situation in streams and rivers.

Storm water can be seeped away if geological conditions are appropriate. If this is not possible rainwater can be lead to a run-off capability in open channels to improve the urban environment or underground in a classical rain water sewer. Storm water infiltration can reinforce the problems of rising ground water tables resulting from increasing precipitation and / or from water saving strategies (as to be seen in the Berlin- and Rhine/ Neckar-region) (Pfenning and Lehn 2003). Due to its often higher concentrations of some heavy metals (compare table 4) seepage of storm water bears the risk of groundwater pollution. The seepage should only be allowed if the materials for roofs and pipes the rainwater is exposed to are controlled and / or if a pre-cleaning is guaranteed before seepage.

Table 4: Range of concentrations of important substances carried by waste water in separated sewerage systems and combined sewerage systems (Fuchs 2000).

Parameter	**Separated sewerage system rainwater sewer**	**Combined sewerage system combined sewer**
COD (mg/l)	47 - 120	176 - 720
NH_4-N (mg/l)	0,1 – 4,0	0,1 - 17
PO_4-P (mg/l)	0,3 – 1,7	3,0 – 4,3
Settleable Solid (mg/l)	7 - 446	327 - 758
Cadmium (Cd) (μg/l)	5 - 16	0,7 - 4,7
Copper (Cu) (μg/l)	10 - 235	27 – 136
Lead (Pb) (μg/l)	20 - 422	12 – 213
Zink (Zn) (μg/l)	610 - 6100	411 - 1430

In regions under water scarcity the main advantage of keeping storm water from the combined sewage is saving drinking water by use of storm water in households, hotels and industries. Typical uses are: irrigation, washing of clothes and flushing the toilets, washing cars and trucks. In the meanwhile the technology for rainwater use is well developed and designed (FBR 2001). Cisterns for rainwater storage can be integrated in a pre-cleaning concept because heavy metals often are bound to suspended matter and thus can be retained in the sludge of the cistern.

Step 2: Separate treatment of grey water

Grey water from showers, bathtubs, and hand basins, or from washing machines and automatic dish-washers is relatively low polluted – compared to the sewage from toilets. A separate treatment in reed bed filters or immersed rotating disc plants is often sufficient for subsequent seepage into the soil or for direct input to surface waters. In a similar way to the separate treatment of storm water, separate grey water treatment is also a means to reduce hydraulic burden of treatment plants (compare table 5). Yet some questions are not answered completely. To give an example: The rising amount of water soluble paints will lead to an increasing amount of water soluble residues from paint-brushes and other equipment in the grey water after restoration of houses etc. At the moment it is not known, whether the above mentioned treatment technologies will be able to degrade or take out all the components of paints and other chemicals which can enter the grey water.

Recycling of grey water can contribute to the saving of drinking water. Typical use of recycled grey water is irrigation and flushing of water closets.

Step 3: Separate treatment of black water

After separating storm and grey water, so called black water from the toilets is the remaining fraction of a household. The data of table 5 show that the overwhelming percentage of the central agriculturally relevant nutrients – causing eutrophication in lakes and oceans - is concentrated in less than 1% of the household's waste water volume under the precondition that black water is not diluted by flushing water. Several techniques (low tech and high-tech) exist for separate collection of concentrated black water. For urban situations in developed countries vacuum toilets – known from aeroplanes and modern trains – combined with a vacuum sewer system seem to be the most appropriate technical option.

Table 5: Distribution of nutrients in partial flows of domestic wastewater (Otterpohl 2004).

	Partial flows of domestic waste water (volume per person and year)		
Nutrient Massflow	Grey water (GW) (25.000-100.000 l/P a)	Urine (~ 500 l/P a (~ 1 % of GW))	Faeces (~ 50 l/P a (~1‰ of GW))
Nitrogen (N) ~ 4 – 5 kg / P a	~ 3 %	~ 87 %	~ 10 %
Phosphorous (P) ~ 0,75 kg / P a	~ 10 %	~ 50 %	~ 40 %
Potassium (K) ~ 1,8 kg / P a	~ 34 %	~ 54 %	~ 12 %

The separate collection and treatment of black water provides a set of advantages compared to the traditional waste water treatment:

1. Faecal bacteria and nutrients can be kept out of the water cycle.
2. The hygienic pollution of water bodies and eutrophication could be reduced.
3. Streams and rivers could be rediscovered for bathing.
4. Expensive public baths could partly be abandoned.
5. Nutrients could be recycled.
6. The energy content of concentrated black water could be used via anaerobic production of biogas.
7. Organic waste from kitchen could be added directly to the vacuum system and be co-fermented together with black water. This makes the separate collection of organic waste dispensable.

Step 4: Urine separation

From the data in table 5 it can be seen that urine contains most of the nutrients. Separate collection and treatment of urine can be helpful if a cheap fertiliser should be produced or the expensive third stage in a purification plant should be avoided, for example in growing cities or at sites with fluctuating population like holiday resorts. For separate collection of urine various models of separating toilets (no-mix toilets) have been developed (figure 4). The urine is stored within the house in a tank which gets periodically emptied by a tank lorry. After a storage of 6 months for disinfection urine can be used as liquid fertilizer. Because of the limited acceptance for a liquid fertilizer by farmers, research is necessary about a conversion to a grainy fertiliser. At the Swiss Federal Institute for Environmental Science and Technology

(EAWAG) research is done about the possibility to discharge the urine tanks to the existing sewerage system at times, when no storm water occurs and only little sewage is flowing (at night in dry periods) in order to get a concentrated urine stream which could be treated separately at the purification plant (Larsen & Gujer 1996).

Figure 4: Different models of urine separating toilets (middle and right: Fa Roediger – Hanau, Germany).

Membrane filtration instead of separation of partial sewage flows

Experience with separated collection of garbage shows that the quality of separation depends strongly on the social acceptance of the collecting system. There are some doubts whether a partial flow treatment can be installed under all housing conditions. Therefore actual research and trial concentrates on an improved purification of urban sewage with membrane bioreactors. Depending on the diameter of the pores of the membrane, microbes (0,1-1 µm – microfiltration), viruses (0,001-0,01 µm – nanofiltration), and even salts (<0,001 µm – reversed osmosis) can be detained (Lehn 2002). Membrane bioreactors have been installed in traditional purification plants (for example in Germany: Leipzig, Rödingen, Monheim, …) as well as in treatment units for only one house (Gutsch & Heidenreich 2001). The quality of the effluent waste water complies with the guidelines of the European Union concerning bathing waters. A disadvantage of the system is the high energy demand - about 1 kWh/m³ - only to maintain the pressure across the membrane. The membranes are very sensitive against blockage. To avoid this, meshes with a width of 1-3 mm have to be installed at the inflow to the membranes. At the moment there is still no adequate knowledge about the lifetime of the membranes under the working conditions in a sewage purification plant. To reduce the energy demand it is useful to separate storm water before treating sewage by membrane filtration (volume reduction).

Conclusion

With the traditional method for collecting and treating municipal sewage, a system has been installed which may be called very suitable for spreading faecal bacteria, resistance against antibiotics, endocrine disruptors and medical residues into the surface waters. It has to be stated that comfort and hygiene in villages and towns is based on the hygienic pollution of the urban environment. A wide range of ecologic and socio-economic arguments is in favour of developing and testing new forms of urban water management, with the aim of integrating them in societies' infrastructures. The climate induced changes in the European water balance make it seem sensible not to wait any longer. The conclusions of the Johannesburg Conference 2002 show that an improvement of the hygienic situation of water bodies is urgent worldwide. Sustainable sanitation techniques in Europe could be a significant contribution to solve this problem and may also constitute a relevant export factor.

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