# The Challenge of Transforming Urban Supply and Disposal Infrastructures to more Resource and Energy Efficiency

*Helmut Lehn, Franka Steiner, Jasmin Friedrich, Dámare Araya Valenzuela*

(Dr. rer. nat. Helmut Lehn, Karlruher Institut für Technologie (KIT), Inst. für Technikfolgenabschätzung und Systemanalyse (ITAS), Karlstraße 11, 76133 Karlsruhe, Germany, helmut.lehn@kit.edu)
(Dipl. Geoök. Franka Steiner, KIT-ITAS, Karlstraße 11, 76133 Karlsruhe, Germany, franka.steiner@kit.edu)
(Jasmin Friedrich, KIT-ITAS, Karlstraße 11, 76133 Karlsruhe, Germany, jasmin.friedrich@kit.edu)
(Dámare Araya Valenzuela, KIT-ITAS, Karlstraße 11, 76133 Karlsruhe, Germany, damare.araya@kit.edu)

## 1 ABSTRACT

Facing global climate change, the transformation of energy systems in many countries of the world has already been progressed significantly. In line with this development, a shift towards closed loops has been iniciated in some parts of the world by separating urban solid wastes for recycling purposes. In contrast, the more than 5.000 year tradition of urban water supply and urban waste water discharge seems to be without any alternative: cities import fresh water from their hinterlands and flush the sewage to areas situated downstream in order to avoid the appearance of epidemics. This longlasting practice was supplemented by stepwise adding end-of-the pipe technologies of sewage treatment from the early 20th century on. Now in many parts of Europe three treatment stages are standard. The current debate in some European countries about a forth and even fifth stage rise the question whether this development of adding more and more treatment stages to the old sewer pipe technology can be assessed as sustainable with respect to resources and energy consumption on one hand and impacts on the environment on the other hand.

During the last 20 years new and innovative infrastructure systems for water supply and waste water management have been developed and implemented on a pilot scale. Most of the associated technologies make use of the separate collection and treatment of specific waste water streams. The separate handling of these different streams requires physical modifications but also challenges behavioral patterns and institutional frameworks. Therefore, investigation is necessary to know how the implementation of these technologies can be made more convenient in order to achieve a significantc impact on the urban sustainability performance.

Keywords: energy, supply and disposal, urban transition, solid waste, separate waste water treatment

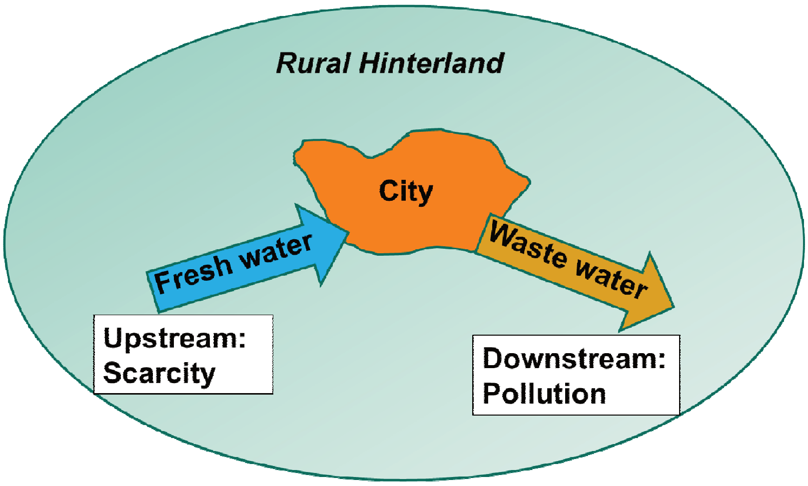


Fig. 1: Water – connection between city and hinterland.

## 2 HISTORY OF URBAN WATER SUPPLY AND WASTE WATER DISPOSAL

### 2.1 The relation of cities with their hinterlands

The high aggregation of many humans within a limited spatial dimension forms a socio-technical artefact which is called "city". The high concentration of people results in a lot of advantages compared to a rural dissipated form of settling (e.g. short distances, accumulation of best brains, better affordable technical infrastructures) but creates relevant challenges as well. Among these challenges are the supply with nutrients and water as well as the save handling of human excreta. In the long run any failings in the excreta management result in the outbreak of epidemics with the risk of a reduced or even liquidated urban population. Thus, the existence of cities was and is dependent on appropriate waste water management systems and the associated infrastructure. Archeological excavations of ancient cities therefore necessarily will not only discover infrastructures of water supply but as well technologies of waste water collection and transport.

The water supply and waste water disposal infrastructure systems from the very beginning until today used the gravity as driving force of transport. Because of this, upstream regions of cities are used as water supply areas whereas sewage is lead to downstream regions. This pattern often results in situations of water scarcity upstream of a city and and regularly in situations of pollution downstream a city (compare fig. 1).

## 2.2 Examples of the ancient world

It can be assumed that ancient societies have been conscient about the fact that fresh water and waste water should be kept separately in order to avoid hygienic problems and related diseases. They made use of the physical separation of surface water and ground water by the soil. In most cases, e.g. Mohenjo-daro in the Indus valley, Greece and in the Roman Empire, water from springs, upstream reaches of creeks and rivers or groundwater was used for water supply and waste water was lead to agricultural areas or lead back to rivers (e.g. Cloaca Maxima in Rome). In Assur, part of ancient Mesopotamia (see figure 2), it seemed to have been the opposite case: Fresh water was taken from the river and waste water has been collected and seeped afterwards into the underground (fig. 3).


Fig. 2: Ancient Egypt and Mesopotamia c. 1450 BC (Source: http://geschichte-wissen.de/blog/assyrien-geschichte-ueberblick).

Fig. 3: Waste water disposal into the underground in Assur (Mesopotamia) 2.500 BC (Source: Illi 1987).

This practise could have been more widespread for a long time periode in the arid and semi-arid countries of the Midle East, as the Greek historian Herodotus (484 – 425 BC) reported 2.000 years later about the customs of the Persians: “They never defile a river with the secretions of their bodies, nor even wash their hands in one; nor will they allow others to do so, as they have a great reverence for rivers” (Herodotus 2012).

### 2.3 Middle Ages and Modern Era in Europe

In Central Europe with the decline of the Roman Empire the knowledge about and the capability to handle the waste water infrastructures of the ancient high cultures got lost. Waste water including excreta was led not only into small trenches between buildings (fig. 4), but it was even poured out into the streets (“gardez l’eau”), latrines were used for defecation and local water courses were used to get rid of all kinds of waste and waste water. Hygienic pollution of ground water and surface waters followed by severe epidemic diseases were the consequences of this unappropriate management of waste water.

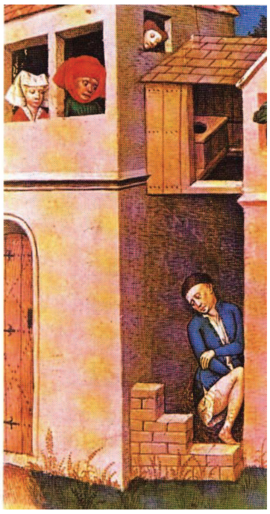

Fig. 4: Defecation in trenches between houses in the Middle Age (Source: Höfler and Illi 1992).

In the 19th century 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, contaminating drinking water with faecal microbes. As a consequence, severe epidemic diseases occurred in Central Europe during this period, for example in London in 1830 and in Hamburg in 1848 [ATV 1999].

More and more towns were cleaned at the cost of the quality of rivers, which often degenerated into cesspools. 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].

| 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 |

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

To avoid these epidemics, the provisional waste water handling of towns and cities had to be changed. From 1850 to 1906, a fierce discussion took place between the advocates of the two alternatives: collecting faeces for agricultural usage or flushing them out of town by sewerage systems. Natural scientists, for example Justus von Liebig, recommended the use as fertiliser, whereas hygienic specialists and technicians proposed the introduction of sewerage systems.

With the invention of the siphon around 1860, which could avoid odours from the sewerage system to enter the houses, the debate ended and the water toilet gained growing popularity as a result of the increased comfort. Consequently, water toilets and sewerage systems became more and more widespread. Nevertheless, the use of drainage systems to transport toilet effluents differed considerably between the individual towns in Germany (table 2).

| Town | First drinking water line | First drainage system | Input of faeces into the drainage system before the year 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) |

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

After 1906, sewers became the standard solution for collecting sewage and for draining settlements. 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 water courses. To avoid this, in the 1960's and 70's a second cleaning stage – the biological - was implemented which transferred the biological cleaning from rivers to purification plants.

## 2.4 Present design of urban water infrastructure

### 2.4.1 Waste water treatment 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. The introduction of this 3rd cleaning step has not been finished when after the year 2000 the political discussion on pollution of water bodies with micropollutants got more and more widespread. Consequently, the attention had been drawn to pharmaceuticals and their residues. To cope with this challenge, in Switzerland 100 of 700 sewage treatment plants (62% of the treated waste water) will be equipped until 2040 with a 4th cleaning step. The investment costs are an estimated 1.2 billion CHF (Reckter 2017).

For Germany the costs of the 4th cleaning step are estimated with 2,50 € to 7,50 €/inhabitant and year. The additional energy demand will be 5% to 15%. In the summer of 2017, 18 of about 10.000 treatment plants in Germany had already installed this 4th cleaning stage on voluntary basis. These pilot plants are operating by different physico-chemical processes: Ozonization combined with a biological filtering, adsorption with pulverisized activated carbon and different filtering steps, filtering with granulated activated carbon with or without a subsequent biological decomposition step, ozonisation combined with granulated activated carbon filters. Different micro pollutants are decomposed by these processes to different degrees (Reckter 2017).

During the equipment phase a new challenge has come up: the pollution of water bodies with multi resistant bacteria. On February 6th 2018, the North German Broadcast informed that scientist from two German universities analysed 12 samples of different water courses in Lower Saxony and found multi-resistant bacteria in each sample, which can be considered as a "really alarming" result according to an expert from German Robert-Koch-Institute (NDR 2018). Hembach et al. (2017) analysed influents and effluents of 7 waste water treatment plants. In each of them, the existence of multi resistant bacteria was detected. Further, it was found that the treatment process could reduce the concentrations of these highly dangerous bacteria only by one to max. two orders of magnitude, which is much too low to protect the receiving water bodies from hygienic pollution.

Current findings point out that the 4th cleaning stage of treatment plants cannot eliminate all bacteria in the waste water (Jäger et al. 2017). By comparing different technical set ups for the 4th cleaing stage Ternes et al. (2017) found that, for example, the "ozonation of treated wastewater reduced the abundance of pathogens and of clinically relevant antibiotic resistance genes significantly but also selected some antibiotic resistance determinants." This indicates that even the 4th cleaning step might not be the final solution of the current end-of-the-pipe systems. If the society decides to hold on to the conventional system, additional cleaning steps seem to be unavoidable (Hiller pers. communication 2017).

### 2.4.2 Sewer system

Not only the outflows of existing waste water treatments plants have an influence on the water quality. The technical performance of waster water collections systems additionally contribute to chemical and hygienic pollution of receiving water bodies. This is especially true in the case of combined sewer systems. In these systems not only municipal waste water is transported but in times of precipitation collected strom water coming from roofs or other paved surfaces is collected and transported together in the system as mixture of waste water and strom water. Because waste water treatment plants in general are designed for the double volume of waste water occuring in dry days and because of the fact that during (heavy) rainfalls, the volume of combined sewage can increase up to the hundred fold compared to dry conditions, the treatment plant can not take the whole volume of waste water during such a periode of precipitation. The surplus volume first is collected in retention basins. When the basins are filled, the combined sewage overflow (CSO) is activated and part of the combined waste water is led untreatedly into receiving water bodies (compare fig. 5). Launay and colleagues (2015) could demonstrate that in the case of a treatment plant situated in the Neckar-catchment (Germany), different substances – depending on their physico-chemical properties – behave very differently and thus are emitted from the sewerage system into the receiving water bodies in very wide variety via the treatment plant and/or by the CSO: whereas the CSO contributed e.g. to 20% of the total emission volume, in the case of COD it has been 30%, for total suspended solids 50% and the range of micropollutants varied between >90% (coffeine) and <5% (Diclofenac). Therefore it will not be sufficient just to add additional treatment steps to the processes running in waste water treatment plants.

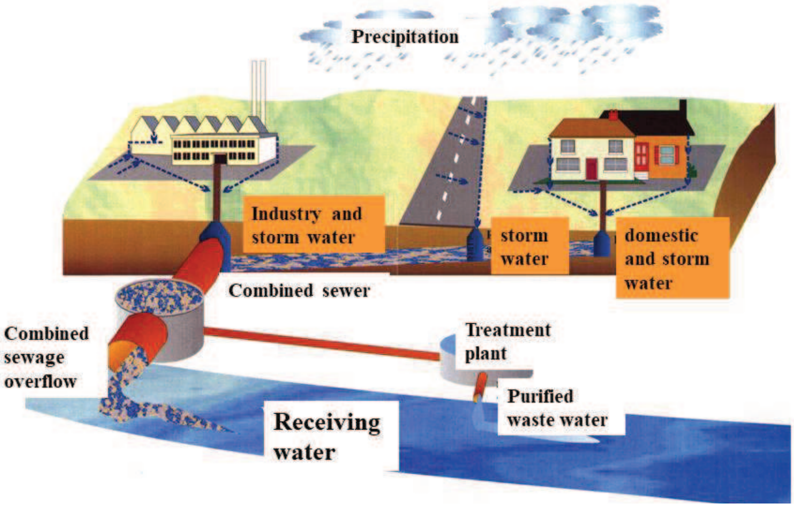


Fig. 5: Combined sewer system under rainy conditions (modified after: Lehn 2002).

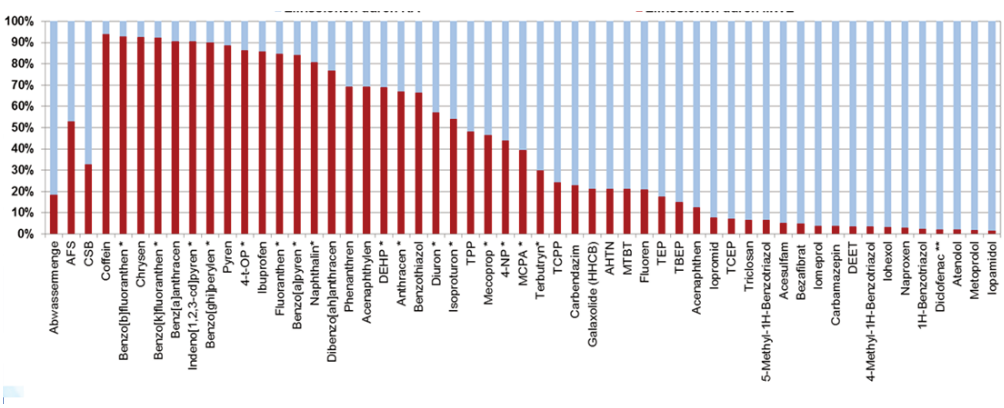


Fig. 6: Emissions of different substances via a waste water treatment plant (blue) and combined sewage overflow (red) (Source: Launay et al. 2015).


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This improvement would include the treatment plant, the overflow system (in case of combined systems) and the – often leaky – pipe system. With regard to more energy and ressource efficiency, water saving necessities in arid or semi-arid regions and the quality of aquatic ecosystems, the introduction of newly developped waste water systems (New Alternative Sanitation Systems = NASS) should be analysed and compared with a completely improved conventional system in terms of ecological, economic and social aspects.

## 3 NEW ALTERNATIVE SANITATION SYSTEMS (NASS)

Because water as a resource, in cities can be part of many and very different products and processes (e.g. foodstuffs, cleaning, cooling, transporting, wellness), water as a waste having passed these processes can show very different properties in terms of quality and quantity. Since the second half of the 20th century the idea of a separate collection and optimised treatment of different waste water streams has grown similar but much more reduced compared to the topic of solid waste.In the year 2008 the German Association for Water, Wastewater and Waste (DWA) published a systematised overview on such new alternative sanitation systems (NASS) focussing on the reuse of water and the use of waste water ingredients (DWA 2008). Waste water contains not only ingredients such as plant nutrients but as well energy in different forms – thermal and chemical. That’s why the approach of recycling water and reusing ingredients should be combined with approaches of a change in energy supply and energy consumption (Energiewende). As a result, the energy saving house could be expanded to a more resource efficient building. Despite the fact, that NASS can show many specific characteristics, the basic idea is to separate urban waste water streams in at least three fractions: a) storm water, b) grey water, and c) black water.

Ad a): Depending on the climatic conditions and the degree of impervious surfaces, storm water can contribute to a very high percentage of the total waste water volume, and its occurance is not constantly. Therefore it has to be calculated very carefully, if it is possible to manage storm water onsite within the settlement e.g. by irrigation of green areas, green roof and green facades and infiltration into the underground after an appropriate treatment. If possible, this way of using storm water can contribute to cool the urban atmosphere (due to the evaporation of water) and thus to counteract the urban heat island effect, and to rise ground water levels (Mann 2013). Because the storm water volumes in this case no longer have to be transported to treatment plants those can be operated more efficiently and the costs for a large dimensioned sewer system could be avoided.

Ad b): Grey water is domestic waste water coming from showers, bath tubs, washing machines, and dish washers. Compared to black water it is less polluted but warm. Therefore the separated treatment of grey water offers the chance to recover thermal energy on a comperatively high level of temperature by a simple heat exchanger. In an apartement house in Berlin with 41 flats built according to the German Passive House Standard this is already in practise. After the heat exchanger a biological cleaning step and UV-disinfection follow before the treated water is used to flush the toilets of the building – compare fig. 7 (Nolde 2013). Treated grey water can also be used for other purposes: irrigation, evaporation and cooling.

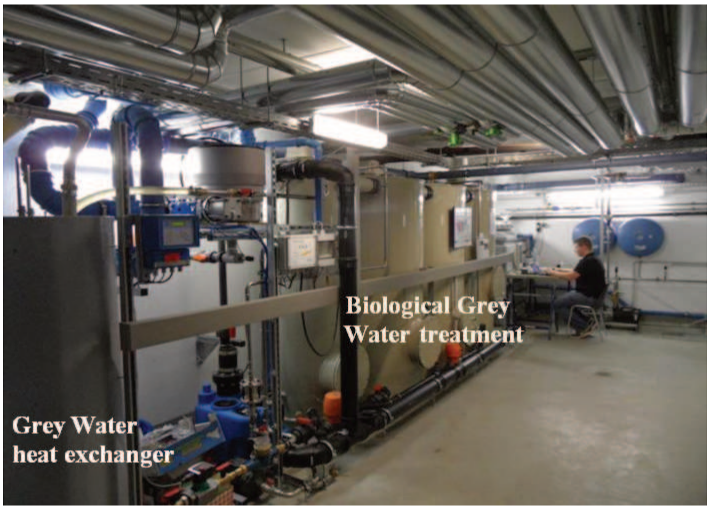


Fig. 7: Heat exchange and biological treatment of separated Grey Water in an apartment house in Berlin (Germany). Foto: H. Lehn

Ad c): Black water is waste water coming from toilets. he volume of black water is comparatively small compared to grey water, especially if vacuum toilets are used instead of traditional flush toilets. Because black water does not only contain plant nutrients (Nitrogen, Phosphorous, Potassium) but as well carbon compounds, black water with little dilution can be used to produce biogas through an unaerobic treatment. The energy output of this process can be increased by co-fermentation of the black water fraction together with organic kitchen waste and other organic waste. In the city of Hamburg the conversion area "Jenfelder Au" will be equipped with this black water treatment technology (Hamburg Water Cycle)

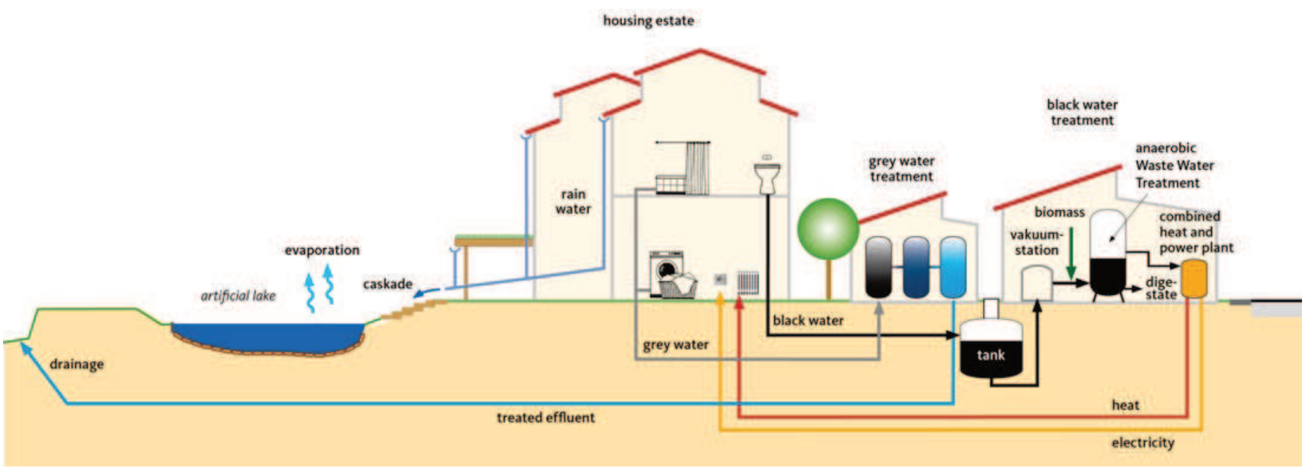


Fig. 8: Separate treatment of storm-, grey- and black water in the new settlement Hamburg Jenfelder Au. Source: Hamburg Water Cycle

## 4 CONCLUSION

Despite the fact that traditional sewer systems in Central Europe have been equipped with tretment plants of more and more stages, the receiving water bodies are still at risk to get polluted chemically by nutrients and micropollutants and hygienically by protozoa, viruses and bacteria. Especially the multiresistant bacteria species seem to survive even very modern treatment stages constructed for the removal of micropollutants. To avoid theses risks, the conventional systems have to be improved at the level of the treatment plant, the overflow system (in case of combined sewer systems) and the pipe system.

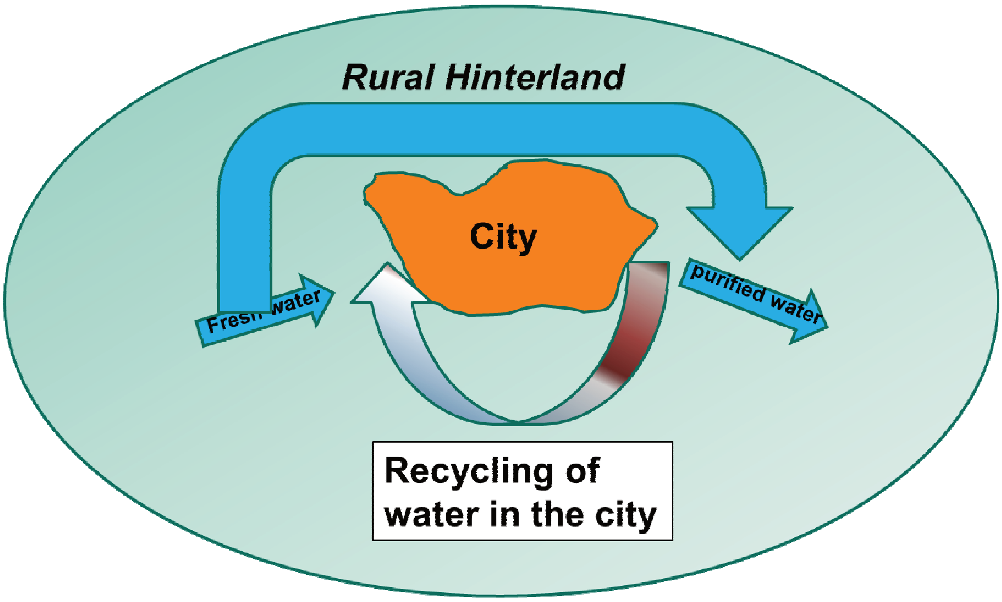


Fig. 9: Water – more sustainable connection between city and hinterland.

New Alternative Sanitation Systems = NASS are options to achieve a better outflow quality, to be more energy and ressource efficient and to save fresh water. Thus these systems represent a big chance for cities to


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improve their sustainability performance and to cope better with the challenges of global changes – compare fig. 9. These systems partly work on other principles than the traditional system, which means that technologies, awareness, attitudes and handling of users, professionals and institutions have to be harmonized to make these systems run smoothly. From a merely technical point of view these systems can be established rather easily in new built-up areas, whereas the change of supply and disposal infrastructures in the existing building stock is more difficult. But also in new built-up areas legal, institutional and social framework conditions make the transformation a complex challenge. Therefore, more research is needed to support decision makers if and under which conditions it is preferable to stick to the well-established technologies of the conventional system and improve it and when time is ready to change to NASS.

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