WATER REUSE: AN OVERVIEW

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ABSTRACT

This paper describes some aspects of water shortages, particularly in relation to food production. Out of different measures used to overcome water shortages, water reuse for irrigation and as service water has become of particular interest. By using treated wastewater for agricultural irrigation, the nutrients - namely nitrogen and phosphorus - serve as fertilizer. However, large water demands combined with high nutrient concentrations can lead to over-fertilization and could negatively affect groundwater quality. Thus the nutrient content can be a limiting factor for the used amount of treated wastewater for irrigation.

To overcome this problem, this paper shows how wastewater treatment plants can be operated differently in summer – where the water is reused as irrigation water – and winter, where nutrient removal may be required to protect the receiving water body. Furthermore, it is shown that adequately treated wastewater can be reused as service water, such as for toilet flushing. Such inner urban water reuse fosters the instigation of semi-centralized treatment and supply centres which combine the advantages of conventional centralized systems - such as professional operation and maintenance, monitoring and compliance - with high quality standards and the use of advanced and energy-efficient technologies. Additional advantages include higher flexibility and sustainable reuse of water as proposed for decentralized systems.

INTRODUCTION

Whereas the annual per capita water requirements for households, services and industrial activities averages 25 m³ in Africa, 232 m³ in Europe and 366 m³ in USA, the overall annual amount of water per person can only be called sufficient when it exceeds 1,700 m³. This apparent gap is caused by the amounts of water necessary for food production. To calculate, Zehnder [2003] provides some general guidelines: for 1 kg of bread, 1 m³ water is needed and ten times more water is needed per unit of energy from meat than from plants.

Thus, to cover 2,500 kcal per day per person, 500 – 1,000 m³/a is actually needed for vegetarians and 1,200 – 1,500 m³/a for carnivores, equivalent to 20 percent of energy derived from meat. This leads to the following classification of the annual per capita water requirements [Zehnder, 2003]:

<table>
<thead>
<tr>
<th>Classification</th>
<th>Requirement (m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sufficient</td>
<td>&gt; 1,700 m³</td>
</tr>
<tr>
<td>Water stress</td>
<td>1,000 – 1,700 m³</td>
</tr>
<tr>
<td>Scarcity</td>
<td>500 – 1,000 m³</td>
</tr>
<tr>
<td>Extreme scarcity</td>
<td>&lt; 500 m³</td>
</tr>
</tbody>
</table>

The renewable water per capita in Iran was 1,830 m³/a in 1996, but in 2020 will be only 1,200 m³/a [Mahmoodian, 2001]. Considering these figures it is likely that Iran might suffer from a lack of water in future and in fact, in some regions of Iran water scarcity is already a problem today.
OPTIONS

To solve the water shortage problem, a number of different measures are proposed, including:
- integrated water resource management, that incorporates sustainable, ecological and economical aspects;
- more efficient water use;
- importation of water from external sources as "virtual water", whereby importing 2 kg wheat replaces 1,000 L water;
- use of additional sources such as: runoff water / "rainwater harvesting", saline water / seawater and treated wastewater / water reuse.

As described, water reuse options are manifold. Adequately treated wastewater may be used for irrigation, in aquaculture, as service water in industry and households, for ground water recharge or even - after high tech multi barrier treatment - to produce potable water, as, for example in Windhoek, Namibia.

The following section of this paper will now focus on agricultural reuse for irrigation and reuse as municipal service water.

QUALITY REQUIREMENTS AND STANDARDS

Water reuse quality requirements are determined by the desired purpose or final use of the treated water and can be categorized according to short and long term aspects. In the short term, factors to be considered include: the health protection of farmers and users (pathogens, etc), acceptance by users (smell, taste, colour, etc), quality demands of plants (salt concentration, nutrients, etc) and technical issues (clogging, corrosion). In contrast, long-term environmental considerations like groundwater protection (nitrate, oxygen depleting compounds) and soil protection (salts, nutrients, heavy metals) must be considered.

Further, for irrigation purposes, the following compounds are of concern:
- pathogenic viruses, bacteria, protozoa and helminthes
- salts (especially Na-salts)
- plant nutrients (nitrogen, phosphorus, potassium)
- trace nutrients (copper, iron, zinc)
- trace elements
- inorganics (heavy metals)
- organics (endocrine disrupters, antibiotics, halogenated compounds).

Whereas microbiological recommendations for agricultural irrigation water indicated by the World Health Organization [WHO, 1989] distinguish three different quality standards for irrigation water and categories for different agricultural applications, the chemical and physical requirements stipulated by the Food and Agriculture Organization of the UN (FAO), specifies salinity, sodium and chloride concentrations or the content of Boron and other compounds to protect soil, plants and ground water.

For the reuse of water as service water, less regulations and recommendations are available, but some general principles apply: the water should be free of pathogens to protect public health; free of colour or smell so as to enhance acceptance by users; and low in suspended solids to protect the technical systems. Other specific requirements might also apply, depending on and differing between countries and states.

AGRICULTURAL IRRIGATION
Agricultural irrigation has by far the highest water demand, totalling about 70 percent of the world’s water demand. As water availability and demand may differ regionally because of different climates, irrigation water demand depends on different local kinds of plants, soil and irrigation techniques. In relation to irrigation, for example, this could mean flood irrigation, sprinkler irrigation or drip irrigation.

As irrigation water is basically only needed during vegetation periods, the demand varies seasonally. Thus year-round water reuse requires large storage facilities. Natural, above-ground storage is impeded by high evaporation losses and, as a result, an increase in salt concentration. Sub-surface storage, for example storage in the aquifer, requires high water quality to prevent groundwater pollution.

Water reuse for irrigation allows the reuse of the wastewater’s nutrients. The nutrient concentrations (N, P) may be the limiting factor for a specific amount of water \[ m^3/(ha-a) \]. The necessary removal of nutrients from water used for irrigation is controversial: whereas some countries remove nutrients from wastewater, others use the nitrogen and phosphorus it contains as fertilizers. The latter option leads to different treatment objectives throughout the year: within the irrigation periods, nutrients could remain in the treated water, but outside the irrigation period the water must be treated for its disposal or for subsurface storage, thus nutrient removal may be required. In the following section, some aspects of nutrient treatment and water demand are first given. A concept for a wastewater treatment plant with different seasonal operation modes is then introduced.

**NUTRIENTS**

Wastewater contains major plant nutrients (nitrogen, phosphorus and potassium) and also trace nutrients (such as copper, iron and zinc). In Germany, total nitrogen concentrations in raw wastewater are usually about 70 mg/l and phosphorus concentrations are about 11 mg/l for a water consumption of 150 l/(PE-d). In wastewater treatment plants (WWTP) without nutrient removal, the effluent concentrations are about 50 to 54 mg/l for ammonium-N (loss of 3 mg/l by settling in the preliminary clarifier and 0.02 - 0.025 mg/mg COD-concentration by incorporating into bio-mass) and about 7 to 8 mg/l for phosphorus [ATV-DVWK A 131/2000]. In treatment plants with nutrient removal the inorganic N-concentrations are between 10 and 15 mg/l and the phosphorus concentration is below 0.5 to 1 mg/l depending on the size of the treatment plant.

In Germany, an agricultural area of only 237,000 ha (47 percent of the total agricultural area with irrigation equipment (500,000 ha) in Germany) was irrigated in 1998 with 163 Mio m³ [Statistisches Bundesamt 2001], thus the average water consumption was 688 m³/(ha-a). With this specific amount and the above-mentioned concentrations of 50 to 54 mg N/l and 7 to 8 mg P/l, it is possible to fertilize while irrigating with about 36 kg N/(ha·a) and 5 kg P/(ha·a), which seems to be only a small amount of the needed quantities of 170 kg N/(ha-a) and 26 kg P/(ha-a) [Könemann 2003].

But this average number is misleading. Even in Germany – where, in general, there is seldom the need for irrigation – the maximum reported is a specific irrigation water amount of 5,500 m³/(ha-a) which translates in about 285 kg N/(ha-a) and approximately 43 kg P/(ha-a), for which the soil would have been fertilized with nitrogen and phosphorus, with the risk of nitrate entering the groundwater.

Thus the ratio between water and nutrient demand is important and has to be considered and controlled. In that respect, the different needs of different plants is important. Table 1 depicts some annual nitrogen and phosphorus application rates for a variety of fruits and vegetables.

Table 1: Annual nitrogen and phosphorus application rate in kg/ha
Depending on the climate, plant, soil and irrigation system, it is possible to substitute the whole fertilizer demand by using treated municipal wastewater for irrigation. Hence it is important to treat the wastewater for irrigation use according to the regional and seasonal conditions and in order to avoid fertilizer entry into and contamination of the groundwater body.

### ACTIVATED SLUDGE TREATMENT WITH SEASONALLY ADJUSTED OPERATION MODES

#### General considerations

Although a number of different possibilities for wastewater treatment exist, the following section will focus on the activated sludge process. It will be shown that different operation modes in summer and winter might be advantageous for the production of treated water suitable for agricultural reuse in summer and meeting effluent stringent effluent standards in winter. Although a variety of different water quality parameters must be observed, the following section will focus only on the nutrient nitrogen.

Thus, according to this idea of different operation modes in summer and winter, the mechanical treatment - consisting of screens, grit chambers and preliminary clarification - remains unchanged in conventional wastewater treatment plants. A short, preliminary clarification time (30 to 45 min) is advantageous when denitrification in wintertime is required. Chemical precipitation of phosphorus rather than enhanced biological phosphorus removal (EBPR) is recommended, considering the higher flexibility and the slower re-start of its enhanced biological P-removal. Because of the very slow growth rate of the nitrifying bacteria, a special operation mode is compulsory. As different seasonal operations of wastewater treatment requires three or more parallel trains, it seems to be suitable only for large treatment plants that service more than 100,000 people.

#### Example: wastewater treatment plant

Here the example treatment plant is designed for 500,000 population equivalents (PE), a flow rate of 75,000 m³/d and loads after primary sedimentation of 22,500 kg BOD/d, 45,000 kg COD/d and 5,000 kg N/d. The MLSS-content in the activated sludge tank should be about 3.5 g/l. The treatment plant was designed in accordance to the German guidelines for municipal wastewater treatment [ATV-DVWK A 131 2000 ].

The treatment plant was designed to ensure that N-removal could be achieved at temperatures down to 12°C. For the activated sludge tanks, a total volume of 60,000 m³ is calculated (20,000 m³ for denitrification, 40,000 m³ for nitrification) with a ‘sludge age’ (sludge residence time) of 9.5 days at 12°C. The wastewater treatment plant has three equal lines (trains In summer months at water
temperatures greater than 18°C and without specific N-removal, a sludge age of less than two days would be sufficient, which would result in an aeration tank volume of less than 12,600 m³ by a MLSS-content of 3.5 g/l (Figure 1).

Figure 1: Sludge residence time (SRT) vs. water temperature, $V_{anoxic}/V_{total} = 0.66$

Figure 1 shows the minimum sludge residence time (SRT) or sludge age for nitrification and nitrification/denitrification at different temperatures, according to the standard established by the German Association for Water, Wastewater and Waste [ATV-DVWK A 131 2000] The added correlation for “C-removal” characterizes the sludge residence time that is long enough for an almost complete C-degradation but short enough to avoid nitrification. This correlation was calculated using the reciprocal growth rate for the nitrifying bacteria.

With respect to seasonal, in principal two operation modes are possible:
- operation with N-removal by operating all lines at sludge ages above the required minimum sludge age for nitrification/denitrification
- operation without nitrification/denitrification at sludge ages according to the solid line in Figure 1

The main challenge is the transition between the two operation modes, thus restarting N-removal after several months without nitrification. The lack of nitrifying bacteria will prevent a fast re-start of nitrification because of the slow growth rate. Therefore it is suggested to keep the nitrifying bacteria in one line (line 1) by operating this line together with nutrient removal, whereas line 3 is shut down and line 2 is operated at a low sludge age to remove just the organics without nitrification. The third line (line 3) can be used as a storage tank for treated water to equalize the daily fluctuations in inflow and water demand as well as reaction-zone for disinfection (see Figure 2 below).

Thus, during the vegetation period, the Wastewater Treatment Plant (WWTP) is operated as follows:
- Line 1: with nutrient removal (Removal of C, N and P (optional))
- Line 2: without extra nutrient removal (only C-removal)
- Line 3: storage, equalization and reaction zone for disinfection (optional)

To enable the described operation modes, independent controllable lines are required, each with its own recirculation of return sludge.

One of the advantages of such an operation mode is that different nitrogen and phosphorus concentrations can be reached by mixing the effluents of line 1 (low in N as nitrified and denitrified and optional low in phosphorus when operated with P-removal) and line 2 without any extra N- and
P-removal. Thus a desired fertilization by blending the effluent of the two lines is possible. In Figure 2 (below) such a plant scheme during the vegetation period is shown.

Figure 2: Operational mode in vegetation period

Three lines are enough to achieve the operational adjustments. Line 1 (with a MLSS-concentration of 3.5 g/l) receives one third of the inflow and line 2 comparatively receives two thirds of the inflow with a MLSS-concentration of about 2.5 g/l. The calculated effluent concentrations for ammonium-N and nitrate-N are 2 mg/l and 8 mg/l, based on pre-denitrification with a recirculation rate of 4.2 in line 1 and 43 mg NH$_4$-N/l and 0 mg NO$_3$-N/l in line 2 (calculated with ASM 1). The more lines there are the more flexible and appropriate the operation mode can be for a given situation.

After the irrigation period, the operation mode has to be switched to N-removal in all three lines. This comprises two steps. First, line 3 has to be put back to operation by:
- transferring surplus sludge from line 2 for two to three days in tank 3 while aerating
- reconnecting the secondary clarifier to line 3 and feeding line 3 with one third of the influent

After these measures, lines 2 and 3 have a MLSS concentration of about 2.5 kg/m$^3$. For example, this is enough for C-removal, but with very little or no concentration of nitrifying bacteria. Comparatively, line 1 remains unchanged by nitrification and denitrification. Secondly, lines 2 and 3 have to be enabled for N-removal as described below.

The fastest way to increase the population of nitrifying bacteria is to transfer the daily excess sludge from line 1 to lines 2 and 3 for about 10 days.

This example shows that seasonally adjusted treatment offers the possibility to adapt the water qualities to the required goal in an ecologically sustainable and economically affordable way. Similar concepts exist for other demands, for example, for those plants where denitrification is not required because water is not used or stored in winter, and thus the effluent standards for receiving water do not require total N-elimination.

**WATER REUSE AS SERVICE WATER**
The use of service water instead of potable water directly reduces drinking water consumption and contributes to the conservation of natural resources and a reduction in costs for long distance pipelines and water treatment. Water reuse is inevitable not only in arid and semi-arid areas, but also in all rapidly growing regions and megacities where local demand always exceeds local supply.

Service water can replace about 35 to 45 percent of the drinking water in households (e.g. for toilet flushing, garden irrigation, air conditioning), all irrigation water within the cities (as in residential areas, road planting, parks, sport fields, golf courses), as well as water used for small industries, car washing, road cleaning or fire protection. The overall savings of drinking water could be as high as 50 percent. As water availability and demand are synchronous in space and time, its reuse therefore requires only small storage spaces.

Potable water reuse as service water leads to decentralized systems because it fosters:

- higher flexibility and incremental growth (modularization)
- shorter distribution and collection systems
- better overall economy
- the separation of industrial and municipal wastewaters
- dual supply of potable and reclaimed, non-potable water
- dual collection systems (optional)
- individual awareness of water origin.

However, the size of decentralized units may differ according to different categorizations which each have different corresponding figures, as indicated below:

- household < 10-20 Population Equivalent (PE)
- cluster < 1,000 PE
- housing developments > 1,000 PE
- commercial, residential facilities 1,000 – 10,000 PE
- satellites, suburbs semi-decentralized 10,000 – 200,000 PE

As a household-based system will be presented at this conference, the idea of a semi-decentralized supply and disposal center will now be explained. This innovative, new concept - currently under development - links the different fields of infrastructure (water, wastewater, waste, energy, heat) in semi-centralized, town/district-based supply and disposal facilities. The combined treatment offers new technical possibilities such as mass and energy flows within the facilities e.g. the co-treatment of organic wastes and wastewater or residuals of wastewater treatment and the direct use of biogas or heat for distribution or generation of electricity.

The result is a more efficient system and less residues to be disposed of. Short pipes between locations of the consumer and wastewater treatment are more economical and offer the possibility of economical water reuse. Treated wastewater can be discharged to the next receiving water body or reused for inner urban irrigation without any need for long-distance transportation out of town. Nearby waste treatment facilities minimize traffic and optimize the recycling of resources. Further, supply and disposal are conducted by qualified personnel thus maximizing safety to achieve good and reliable quality standards, hygiene in water distribution and water reuse, and surveillance of material flows and disposal.

The optimal size of such semi-centralized facilities in urban areas might service a population in the range of 20,000 to 200,000. This depends on variables such as specific water consumption and amount of waste, requirements for reuse, demand for heat and cooling energy and existing infrastructure. It is also influenced by population-density, financing structure, system of payment and charges and others.

Figure 3 Black-box model for an integrated semi-decentralized supply and disposal center
The advantages of this system compared to conventional centralized systems include:
- more sustainable reuse of water; the possibility of splitting of industrial and municipal wastewater;
- feasibility of dual piping;
- higher flexibility (planning, technical adaptation on specific conditions);
- better overall economy (water treatment and supply, sewer system, wastewater treatment waste disposal);
- incremental growth (modularization); and
- users’/customers’ individual awareness and responsibility of customers of the waters origin and different qualities of portable water and service water.

Compared to decentralized systems (on the household level), the following advantages might be claimed:
- more professional operation and maintenance
- monitoring and compliance of quality standards
- use of advanced and energy efficient technologies
- holistic approaches to water, wastewater and waste management

CONCLUSION

To solve local and global water scarcity, an integrated water resource management, efficient and customized use of the water resources and importation from external sources as ‘virtual water’ is needed. From various different options for the reuse of water, its reuse for agricultural irrigation and as municipal service water has been addressed. The water quality standards depend of course on the reuse application. Besides short-term quality parameters to protect workers and users, long-term environmental aspects like groundwater and soil protection have to be considered when reusing water for irrigation applications.

Agricultural irrigation has by far the highest water demand. As the nutrients contained in wastewater can be used as fertilizer, a balance of nutrient and water demand is inevitable. Salt and especially the
Na⁺-concentration might be a limiting factor in order to avoid negative impact on plants and soil. As irrigation and fertilization periods are limited to vegetation periods, WWTP should be operated seasonally, using the nutrients in vegetation periods and removing nutrients to protect the environment in the wintertime.

Water reuse as service water leads to decentralized systems because it fosters:
- higher flexibility and incremental growth (modularization)
- short distribution and collection systems
- better overall economy (cost-saving benefits)
- separating industrial and municipal wastewaters
- dual supply of potable and reclaimed, non-potable water
- dual collection systems (optional)
- individual awareness by users.

The degree of decentralization differs from household-based systems (< 10 - 20 Population Equivalents (PE)) to satellites and suburbs of 10,000 – 200,000 PE (semi-decentralized). Semi-decentralized supply and disposal facilities in particular seem to constitute a sustainable, flexible and holistic approach. They combine the advantages of conventional, centralized systems - such as professional operation and maintenance, monitoring and compliance - with high quality standards and the use of advanced and energy-efficient technologies. They also provide more flexibility, better overall economic value and the same sustainable reuse of water as that proposed for decentralized systems.

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