Low Cost Wastewater Treatment and Potentials for Re-use

A Cleaner Production Approach to Wastewater Management

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Abstract

Current mainstream technologies for wastewater treatment, such as activated sludge and tertiary nutrient removal are too costly to provide a satisfactory solution for the increasing wastewater problems in developing regions. Besides, these technologies do not allow for re-use of valuable energy and nutrients contained in the wastewater. This paper introduces a so called ‘Cleaner Production’ concept to sewage management, which combines two approaches: pollution prevention, and re-use. Pollution prevention includes the shift towards low water use or dry sanitation technology. The remaining, more concentrated waste, automatically becomes more attractive for re-use oriented treatment schemes. The combination of anaerobic treatment, for energy recovery, and duckweed-based lagoons for pathogen removal and nutrient recovery is presented as an example of possible re-use strategies. By selecting optimal applications of the duckweed biomass and lagoon effluent, nutrients will end up as fish protein (via duckweed feeding) and crop protein (via irrigation). The focus on duckweed as a key step in waste recycling is due to the fact that it forms the central unit of a recycling engine, driven by photosynthesis and therefore the process is energy efficient, cost effective and applicable under a wide variety of rural and urban conditions.

Wastewater in a historical perspective

The provision of high quality piped drinking water to households took a fast development during the second part of the 19th century as a response to the rapid expansion of cities and to the wide spread occurrence of cholera epidemics (referred to as the Asian disease) in Europe and the USA. The origin of water borne diseases was not well understood until the famous microbiologists Louis Pasteur and Robert Koch discovered the concept of pathogenic bacteria and their transmission via contaminated water. The resulting technology development for urban water management was based on the following concepts (Gijzen 1999; Harremoes, 2000):

The prevention of water-borne diseases. This has been realised by introducing centralised potable water treatment facilities, extensive distribution systems and multiple tap connections in each household. The success of this approach is guaranteed only if (re-)contamination of purified water is prevented; this requires effective operation and maintenance of the infrastructure. Many cities in developing regions suffer from frequent pressure drops and as a result (waste)water may infiltrate into the distribution system.

The use of water to transport waste out of the city. It is daily practice to use large quantities of clean ‘drinking’ water in the household to flush waste via toilets, kitchen sinks and washing machine into the sewer. The basic function of water in these cases is the collection and subsequent transportation of unwanted waste materials out of the city.

The provision of water was, and to a large extend still is, supply driven. The above functions of water for cleaning and transport of waste materials requires large volumes of water to be
supplied to households. Water companies have been able to supply these large quantities of water at low cost. The low cost level has been possible because not all process and environmental cost components were directly charged to the consumer by the public companies of the past. This is changing now and prices may continue to rise rapidly during the coming decades. As a result, consumption will probably decrease and the policy will change from ‘supply driven’ to ‘demand driven’ approaches.

**Box 1. Cost of wastewater collection and treatment**

According to World Bank, up to 3% of a country’s GNP can be realistically spent on environmental protection (including wastewater treatment). Grau (1994) and Gijzen (1997) estimated the period of time needed to meet EU effluent standards by a number of low GNP countries, assuming that 1.5% of the GNP could be invested in sewers and treatment facilities. As can be seen from the table, this period exceeds, by far, the economic life time of the treatment plant (20-30 years) and in many cases even that of sewers (about 50-60 years), and therefore the implementation becomes unrealistic.

<table>
<thead>
<tr>
<th>Country</th>
<th>Population</th>
<th>GNP/capita</th>
<th>Cost to meet EU standards</th>
<th>Period needed at 1.5% GNP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Million US$/cap.</td>
<td>US$/cap.</td>
<td>Year</td>
<td></td>
</tr>
<tr>
<td>Bulgaria</td>
<td>8.5</td>
<td>2210</td>
<td>3755</td>
<td>113</td>
</tr>
<tr>
<td>Egypt</td>
<td>60</td>
<td>1030</td>
<td>4000</td>
<td>259</td>
</tr>
<tr>
<td>India</td>
<td>935</td>
<td>335</td>
<td>3750</td>
<td>746</td>
</tr>
<tr>
<td>Kenya</td>
<td>29.2</td>
<td>290</td>
<td>4500</td>
<td>1034</td>
</tr>
<tr>
<td>Mexico</td>
<td>92.1</td>
<td>2705</td>
<td>3750</td>
<td>92</td>
</tr>
<tr>
<td>Poland</td>
<td>38.3</td>
<td>1700</td>
<td>1230</td>
<td>48</td>
</tr>
<tr>
<td>Romania</td>
<td>23.2</td>
<td>1640</td>
<td>1422</td>
<td>58</td>
</tr>
</tbody>
</table>

**Cost and rational of inherited concepts**

The standard ‘Western’ service level of water supply comprises of high quality piped water with multiple connections per household. This concept obviously results in high water ‘consumption’ and produces large volumes of rather dilute wastewater that needs to be collected and treated before final disposal. High water use results in corresponding demands for large collection and treatment infrastructure. This has severe cost consequences. Indeed the investments in sewer and wastewater treatment infrastructure over the past century has been phenomenal in high GNP countries. Although industrialised nations have the economic capacity to deal with environmental problems via high-cost technologies, these may not provide immediate solutions for countries with a low GNP (Box 1). Grau (1994) and Gijzen and Ikramullah (1999) calculated that the period of time required to generate the capital investments to meet EU effluent standards in low GNP countries exceeds by far the economic life span of treatment plants and sewer infrastructure. It is not surprising therefore, that the total volume of wastewater treated worldwide is only a fraction of the volume produced.

Although sometimes insufficient to cover actual costs, world-wide there exists a willingness to pay for drinking water services, since drinking water is recognised as a product. The contrary is true when it comes to wastewater; the willingness to pay for wastewater collection and treatment is low or absent. If we compare costs per unit of volume, wastewater management is much more expensive than water supply (see box 2). The lack of willingness to pay in combination with the high cost per unit of volume underscores the complexity and difficulty to face the challenge to develop and introduce sustainable wastewater collection and treatment systems.

**Box 2. Economies and diseconomies of scale in water and sanitation systems.**
Vision21

The *Long Term Vision for Water, Life and Environment in the 21st Century* – or in short, the World Water Vision – was introduced during the first World Water Forum in Marakech, Morocco, in 1997. The Vision document was developed under the coordination of the World Water Council and was presented during the second World Water Forum in March 2000 in the Hague (Cosgrove and Rijsberman, 2000). Vision21 represents the ‘Water for People’ component in the overall World Water Vision. Vision21 is directed to achieving a world by 2025 in which each person knows the importance of hygiene, and enjoys safe and adequate water and sanitation services. To achieve these ambitious goals, we will have to deal with the important shortcomings of the current concept of urban water management described above. Realisation of Vision21 will only be possible if we are willing and able to re-think the current practices and develop new concepts and approaches for sustainable urban water management. This includes the establishment of effective water institutions, the development of modern low water usage and dry sanitation systems, rainwater harvesting, and the extensive use of resource recovery and re-use approaches for wastewater. A holistic approach is required where waste should be seen as a resource, and its management should be linked to that of water resources and of nutrients. In fact resource recovery and re-use approaches could, in addition to water savings, result in financial incentives which can be used to cover part of the cost of wastewater treatment.
The above considerations have been further developed by the Environmental Sanitation Group of the Water Supply and Sanitation Collaborative Council (WSSCC) and have led to the so called ‘Household Centred Approach’ (King, N., 2000). In our view, the urban water and waste management situation can also be addressed from a ‘Cleaner Production’ angle (Gijzen, 1999; Gijzen and Bijlsma, 2000). Cleaner production interventions have been extremely successful in the industrial sector. If we want to give meaning to the word sustainability in the context of water management, we will have to follow a ‘cleaner production approach’, which basically combines two approaches: pollution prevention, and re-use.

If we evaluate the current urban water management practises from a cleaner production point of view, the urgency to re-think our current practises in the light of sustainability becomes evident (Box 3). A cleaner production check results in two main priority areas for action:

a) Pollution prevention
This can effectively be achieved via reduction of domestic water consumption, which will reduce sewage volume and treatment costs. Any level of reduction can theoretically be achieved. On the far end of the scale we find dry sanitation, but significant reductions can also be achieved via demand management and water saving technologies in the household.

b) Resource recovery and re-use
A first step is to keep waste flows separate to optimise their potential for re-use. This approach starts at the level of the household, where grey water could be re-used for toilet flushing or garden irrigation. Besides the separation of grey and black water, also urine could be collected separately for recovery of N and P fertiliser (Larsen and Guyer, 1996). Considering the currently available infrastructure for sewerage, wastewater treatment schemes at the ‘end of the pipe’ should be aimed at maximising energy, water and nutrient recovery.

**Box 3. Questioning the inherited practices – a ‘cleaner production’ check**

In the context of sustainability one may wonder whether it is environmentally responsible to continue to use 50 to 80 litres of high quality drinking water to transport 1 – 1.5 kg of human waste to a water treatment facility or, as is often the case, to a water resource? The cleaner production concept, developed over the last two decades, has brought some innovative environmental thinking into the industrial sector. If we apply some of the basic principles of cleaner production to the current practices in urban water services, we may realise the need for drastic changes:

**Principle 1:** Do not use more input material, energy or other resources per unit of product than absolutely necessary.
**Practice:** We supply between 130 and 350 l of drinking water per capita per day, while less than 2 litres are actually used for drinking.

**Principle 2:** Do not use input materials of a higher quality than strictly necessary for the production process.
**Practice:** We use water purified to drinking water standards to flush toilets, clean floors, wash cars or to irrigate the garden.

**Principle 3:** Do not mix different waste flows.
**Practice:** Already in the household various wastewater flows are combined (urine and faecal matter, grey and black water). After disposal into the sewer this combined waste is mixed further with industrial effluents, and often times also with urban runoff. Obviously this practice makes re-use of specific components in the mixed waste flow less attractive and less feasible.

**Principle 4:** Evaluate other economic functions and uses of by-products before considering their treatment and final disposal.
**Practice:** Domestic sewage is discharged into open water resources either with or without prior treatment. Only few examples of wastewater re-use or (by-)product recovery from wastewater exist.
The main problem with wastewater treatment is that the final result obtained after treatment, the effluent, is not easily recognised as a valuable product (contrary to water treatment for water supply). This explains why many wastewater treatment facilities in developing regions are poorly maintained and eventually become inactive. If the treatment process itself, in addition to purified effluent, could generate valuable products, this would be an important incentive to stimulate the effective operation and maintenance of treatment facilities.

Several examples of large scale re-use of wastewater, yielding important economic returns, exist, notably for aquaculture and crop production. Effluent irrigation has been practised for centuries throughout the world. It provides farmers with a steady supply of cheap nutrient and water. The re-use of wastewater and excreta in aquaculture is a traditional practice in certain countries, particularly in China, India, Indonesia and Vietnam. Below, a brief description is given of the world largest examples of wastewater fed agriculture (Valle Mezquital, Mexico) and of wastewater fed aquaculture (Calcutta wetlands, India).

**Wastewater-fed agriculture: The Valle Mezquital**

The Valle Mezquital represents the world largest area of wastewater irrigated agriculture. The valley is located in the Mexican high plateau, at an altitude of between 1700 and 2100 m above sea level, and about 60 km north of Mexico City (see Fig. 1). The entire valley has an estimated population of about 500,000 inhabitants, most of which are involved in agricultural activities. The standard of living of the population is reported to be higher than that of similar populations in Mexico, which do not apply wastewater-fed agriculture (Romero, 1994). The valley presents a unique example of wastewater irrigation, because of its immense cultivated area (83,000 ha) and its long history (almost 100 years). The area is irrigated using raw wastewater from the metropolitan area of Mexico City (about 1900 million m$^3$/year). This wastewater has received no conventional treatment and is channelled to the area by gravity via a large drainage canal. The principal crops grown are alfalfa, maize, beans, oats, tomatoes, chillies and beetroot. Although prohibited by law, there is some production of restricted crops as well, including lettuce, cabbage, carrot, spinach and radish. The wastewater is highly valued by farmers because of its soil improvement qualities and its nutrient load. The economic importance of wastewater-fed agriculture in this region can be demonstrated by comparing production data with those of other regions in Mexico (Table 2).

<table>
<thead>
<tr>
<th>Irrigation area</th>
<th>Area covered (ha)</th>
<th>Area cultivated$^1$ (ha)</th>
<th>No. of users</th>
<th>Water volume ($10^6$ m$^3$/y)</th>
<th>Production value ($10^6$ N$^\dagger$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>District 03</td>
<td>45,214</td>
<td>55,258</td>
<td>27,894</td>
<td>1,148</td>
<td>255</td>
</tr>
<tr>
<td>District 100</td>
<td>32,118</td>
<td>22,380</td>
<td>17,018</td>
<td>651</td>
<td>85</td>
</tr>
<tr>
<td>Private units</td>
<td>5,375</td>
<td>5,450</td>
<td>4,000</td>
<td>96</td>
<td>-</td>
</tr>
<tr>
<td>Total</td>
<td>82,707</td>
<td>83,088</td>
<td>48,912</td>
<td>1,895</td>
<td>340</td>
</tr>
</tbody>
</table>

$^1$ includes areas with more than one crop per year

$^\dagger$ exchange rate: 1 US$ is about 3.5 N$

**Table 2.** Agricultural productivity of Valle Mezquital compared to non-wastewater irrigation areas (Romero, 1997).
<table>
<thead>
<tr>
<th>Crop type</th>
<th>Valle Mezquital</th>
<th>National average</th>
<th>Hidalgo State</th>
<th>Rain-fed area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sweet corn</td>
<td>5.2</td>
<td>3.7</td>
<td>3.6</td>
<td>1.1</td>
</tr>
<tr>
<td>Kidney bean</td>
<td>1.8</td>
<td>1.4</td>
<td>1.3</td>
<td>0.5</td>
</tr>
<tr>
<td>Oat</td>
<td>3.7</td>
<td>4.7</td>
<td>3.6</td>
<td>1.7</td>
</tr>
<tr>
<td>Barley</td>
<td>22.0</td>
<td>10.8</td>
<td>15.5</td>
<td>13.5</td>
</tr>
<tr>
<td>Lucerne</td>
<td>95.5</td>
<td>66.3</td>
<td>78.8</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Via the irrigation, the wastewater from Mexico City receives a natural land treatment, which is estimated to be equivalent or even superior to conventional secondary wastewater treatment. The environmental benefits include a reduction of 1,150 t per day of BOD load, which would otherwise end up in the Panuco river basin and could affect large coastal areas of the Gulf of Mexico.

In spite of all these benefits, the wastewater-fed irrigation practise of Valle Mezquital receives criticism from a public health point of view. The wastewater is produced from domestic and industrial sources and therefore contains pathogens and toxic chemicals that constitute a health risk for both farmers and consumers. Reliable data on pathogen counts and on the presence and fate of toxic chemicals are scarce. Analyses of faecal coliforms in reservoirs in the valley indicate values which are $10^2$ to $10^4$ higher than the WHO guidelines for re-use. Due to the spread of cholera, the National Water Authority (CNA) has enforced restriction on crops irrigated with wastewater. The incidence of infection by *Ascaris lumbricoides* in children aged between 1 to 14 years appeared to be 10 to 20 times higher compared to areas with rain-fed irrigation (Romero, 1997). These data underscore the importance of effective treatment of wastewater before land application.

**Wastewater-fed aquaculture: The Calcutta wetlands**

The largest wastewater-fed system for fish production is located near Calcutta, immediately east of the city (Edwards and Pullin, 1990). The Calcutta wetland system has developed over the past 100 years due to uncontrolled discharge of wastewater and urban run-off from Calcutta. The wetland receives about 550,000 m$^3$/d of untreated wastewater. Over time, fish farmers have segmented parts of the wetlands into small-scale aquaculture enterprises, which currently yield a total aquaculture area of about 3000 ha. The system generates about 13000 t/y of fish (mainly Indian major carp and tilapia), which is supplied to fish markets of central Calcutta and consumed in the wider region. The aquaculture practise in Calcutta creates employment and provides low-cost protein to the local population. However, public health aspects of both producers and consumers must be considered. Obviously, the above mentioned practise of raw sewage fed aquaculture will not be able to comply with the current WHO criteria for microbiological quality for aquaculture, i.e. zero nematodes, and less than 1000 faecal coliforms per 100 ml. Total coliform counts of $10^5$ to $10^6/100$ml have been reported for the influent of the wetland system (Pescod, 1992). Mara *et al.* (1993) proposed a minimal treatment of the wastewater prior to the Calcuta aquaculture ponds, using 1-day retention anaerobic ponds followed by 5-day retention facultative stabilisation ponds. Although this approach may improve the microbiological quality of the water, industrial pollution may still pose a threat to public health. The Calcutta sewage is a mixture of domestic and industrial wastewater. One wastewater-fed fishpond system in Calcutta receives as much as 70% industrial wastewater. Hardly any data are available on the content of metals, pesticides and other toxic chemicals in the wastewater. No information is available on the fate of such toxic compounds in the current aquaculture
system in Calcutta. It is clear that the public health aspects of wastewater-fed aquaculture requires further study and safe approaches need to be developed.

**Recovery of energy from wastewater**

The above examples deal with the effective recovery and re-use of water and nutrients from wastewater effluents. Effective re-use schemes should also consider the energy component of wastewater and that of wastewater treatment systems. Modern wastewater treatment such as activated sludge require substantial inputs of external energy, usually coming from non-renewable sources. Theoretically 0.8 and 3.0 m$^3$ of oxygen are required for the oxidation of one kg of organic matter or ammonia, respectively. In aerated systems several times this volume must be forced into the water phase at the expense of valuable energy. The treatment of wastewater in a high-rate anaerobic reactor does not require oxygen input and, in addition will yield some 375 l of methane per kg of BOD digested. In fact some 90% of the energy contained in organic matter will end up as methane gas. This is not only positive for the overall energy balance of the system, but also replaces an equivalent amount of non-renewable energy and greenhouse gas emissions.

From the composition of human excreta (Table 3), and assuming about 70% biodegradation of organic matter, a daily production of between 18 and 30 l of methane can be expected per capita. This suggests excellent possibilities for energy recovery from human excreta. Due to the high water consumption, however, the energy recovery per unit of volume of wastewater is relatively small; 200 mg BOD/l at 70% biodegradation will yield some 50 ml of methane gas, of which a substantial part will leave the reactor via the effluent in suspended form.

**Table 3.** Production and composition of human faeces and urine

<table>
<thead>
<tr>
<th></th>
<th>Faeces</th>
<th>Urine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quantity (wet) per person per day</td>
<td>100-400 g</td>
<td>1.0-1.31 kg</td>
</tr>
<tr>
<td>Quantity (dry solids) per person per day</td>
<td>30-60 g</td>
<td>50-70 g</td>
</tr>
<tr>
<td>Moisture content</td>
<td>70-85%</td>
<td>93-96%</td>
</tr>
<tr>
<td>Approximate composition (percent dry weight)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Organic matter</td>
<td>88-97%</td>
<td>65-85%</td>
</tr>
<tr>
<td>Nitrogen (N)</td>
<td>5.0-7.0</td>
<td>15-19</td>
</tr>
<tr>
<td>Phosphorus (as P$_2$O$_5$)</td>
<td>3.0-5.4</td>
<td>2.5-5.0</td>
</tr>
<tr>
<td>Potassium (as K$_2$O)</td>
<td>1.0-2.5</td>
<td>3.0-4.5</td>
</tr>
<tr>
<td>Carbon (C)</td>
<td>44-55</td>
<td>11-17</td>
</tr>
<tr>
<td>Calcium (as CaO)</td>
<td>4.5</td>
<td>4.5-6.0</td>
</tr>
<tr>
<td>C/N ratio</td>
<td>~6-10</td>
<td>1</td>
</tr>
</tbody>
</table>

Polprasert (1996)

**The way forward**

The recovery and subsequent re-use of energy, nutrients and water from wastewater has been discussed above and limitations have been identified. These limitations can be summarised as follows:

- Public health risks due to presence of pathogens
- Public health risks due to presence of toxic chemicals, which eventually may accumulate in the food chain
- Low potential for energy recovery due to very dilute nature of sewage

Attention should be given to interventions that can remove or reduce these limitations.

**Energy recovery via anaerobic treatment**
The generation of biogas from dilute domestic sewage is not attractive and until now none of the anaerobic systems constructed for sewage apply commercial exploitation of the generated gas. Anaerobic treatment becomes much more rewarding when high strength sewage is produced. The past decades have been generally characterised by steady increases in per capita water consumption due to service improvement and the introduction of water demanding household equipment; the way forward will however be a contrary trend. In some countries, including the Netherlands, per capita consumption has decreased over recent years (currently at about 128 l/c.d). This is achieved via public awareness raising, and by water saving and water re-use technologies in the household. It is expected that this trend will continue and will be followed by many more countries all over the world. For the long term, low water use or even dry sanitation practises may be introduced in combination with modern collection and anaerobic composting processes. Another intervention to reduce wastewater dilution is the un-coupling of stormwater from the sewer system. Separate conveyance systems for stormwater and sewage are therefore recommended.

Anaerobic sewage treatment has so far been applied mainly in the tropical regions (e.g. India, Indonesia, Colombia, Mexico). At present anaerobic treatment of dilute sewage is not an option in regions with sewage temperature below 15 °C, since degradation processes proceed at very low rates under such conditions. The trend to produce more concentrated sewage will, in future, favour the introduction of anaerobic systems also in colder regions, since (part of) the biogas may be used to increase the temperature of the smaller volumes of concentrated sewage.

Besides the generation of energy, anaerobic pre-treatment of wastewater may have additional benefits for re-use oriented treatment schemes. The anaerobic conditions in the reactor may reduce the level of (toxic) metal compounds in the effluent due to the formation of insoluble metal-sulphides, which precipitate into the anaerobic sludge. As a result the danger of accumulating metals into the food chain via agriculture or aquaculture applications of the effluent may be significantly reduced. For the long-term, industrial effluents need to be dealt with completely separated from domestic sewage.

An additional positive side effect of anaerobic pre-treatment is expected from the efficient hydrolysis of organic forms of nutrients into mineralised forms. Organic nitrogen in the influent of an anaerobic reactor will leave the system mainly as ammonia. This is the preferred form of nitrogen for most plants and therefore presents optimal conditions for irrigation or for the production of aquatic plants in subsequent pond systems.

Anaerobic treatment is mainly aimed at reduction of the organic load of wastewater; pathogens and nutrients are not removed and therefore require further attention in post-treatment systems.

**Nutrient recovery**

With respect to nitrogen removal most developments are aimed at stimulating the nitrification and denitrification process in mainstream technologies (activated sludge). Modern wastewater treatment systems apply tertiary treatment for the removal of nutrients (N, P) via precipitation or via biological processes. If we look at these processes in the context of the overall food production and consumption cycle, the current practice does not seem to be rational. Let us illustrate this from the point of view of nitrogen.

In order to sustain a secure food supply to feed an ever-increasing world population, intensive agriculture and animal production systems have been developed during the famous ‘green
revolution’. Intensive agriculture requires the use of fertiliser, which is obtained via industrial fixation of atmospheric nitrogen (N$_2$) via the so-called Haber-Bosch process. The world’s annual industrial production of nitrogenous fertiliser has increased sharply, from $10^{10}$ kg in 1960 to $9 \times 10^{10}$ kg in the year 2000. The amount of energy involved in the annual production of fertiliser and chemicals for agricultural purposes amounts to about $18 \times 10^{14}$ KJ, which is equivalent to about $300 \times 10^6$ barrels of oil. Once fixed nitrogen has been incorporated into high quality protein and has been consumed as a human food or animal feed, a major part of the nitrogen is released into the environment again in the form of domestic wastewater and manure. When applying costly tertiary biological nitrogen removal (nitrification-denitrification), potentially useful nitrogen compounds are re-circulated to atmospheric N$_2$. This approach appears very inefficient from both an energy and resource-utilisation point of view.

Comparison of the anthropogenic N-cycle with the cycling of N in the biosphere reveals some important differences. Once nitrogen has entered the biosphere via biological N$_2$-fixation, it is subject to a series of conversion steps, from plant protein to animal protein, and finally ends up in dead organic matter. When this organic matter is mineralised in the soil, most of the inorganic nitrogen compounds produced ($\text{NO}_3^-$, $\text{NH}_4^+$) are immediately taken up again by plant or microbial biomass for the production of protein. Only a fraction of the total amount of organic nitrogen is re-circulated to N$_2$ via denitrification. From the nitrogen fluxes, we can calculate that the average retention time of nitrogen in the biosphere is over 4000 years, before it is eventually re-circulated to atmospheric N$_2$. The reuse of fixed sources of nitrogen such as nitrate, nitrite, and ammonia, therefore contributes to a higher energy efficiency in biological systems. An approach, similar to the situation in natural systems could be adopted in man-made waste management systems as well. In this case, secondary treatment (BOD removal) needs to be combined with the effective re-use of nutrients by aquatic plants and/or by irrigation of crops in agriculture. The Valle Mezquital and the Calcutta wetland re-use systems involve the direct re-use of domestic sewage to culture crops and fish for human food. This is not recommended and pre-treatment to remove pathogens and possible toxic compounds is considered essential prior to re-use applications.

Re-use of water

In view of the rapidly growing shortage of renewable water resources in many parts of the world there is a growing interest in the use of treated effluents from wastewater treatment plants. The quality of the wastewater, in combination with the envisaged type of re-use, define the level of subsequent treatment required, as well as the associated treatment costs. Besides possible industrial and urban re-use options, the most important option for re-use of wastewater is related to agriculture and aquaculture. The effluents do not only serve as a source of water but also provide nutrient input for fish and crops in aquaculture or agriculture irrigation schemes, respectively.

Nutrient concentrations in raw sewage are too high for irrigation of most crops. The aim of wastewater treatment, in addition to pathogen, BOD and TSS reduction, should therefore be to bring back N and P levels to around 15 mg/l for N and about 3 mg/l for P. When applying such effluents at an irrigation rate of about 2 m/y, this results in N and P dosage of 300 and 60 kg/ha.y for N and P, respectively. This practice could significantly reduce or even eliminate the use of commercial fertiliser. With respect to aquaculture, a better way to transfer nutrients from wastewater to fish protein could be via macrophyte-based treatment systems, where the plant biomass is used as a fish feed. Below the application of a duckweed-based wastewater treatment system is proposed as a way to deal with the limitations described previously.

Duckweed based wastewater treatment
The use of aquatic macrophytes

Aquatic macrophytes have been studied for their use as effective scavengers of nutrients from wastewater. Their use has been suggested as a low-cost option for the purification of wastewater and simultaneous production of plant biomass (Araujo, 1987; Brix and Schierup, 1989; Gijzen, 1996; Oron, 1994; Reddy and DeBusk, 1987; Skillicorn et al, 1993). When applying aquatic plants in shallow ponds, a combination of secondary and tertiary treatment may be realised. In addition aquatic macrophytes assimilate nutrients into a high quality biomass that may have an economic value. This contrasts favourably with advanced costly nitrification-denitrification, where nitrogen is converted into atmospheric N\textsubscript{2} and therefore will be ‘lost’ for further re-use.

Various studies have reported the use of water hyacinth (Eichhornia crassipes), pennywort (Hydrocotyle umbellata), water lettuce (Pistia stratiotes) and duckweed (Lemnaceae) for the efficient removal of nutrients. The economic potential of each plant species for wastewater treatment depends largely on its efficiency to remove nutrients under a wide range of environmental conditions, its growth and maintenance in a treatment system, and the possible application of plant biomass. Water hyacinth has been used most widely, due to its high nutrient uptake capability (Table 4), but no economically attractive application of the generated plant biomass has been identified so far.

Table 4. Nitrogen and phosphorus uptake (g/m\textsuperscript{2}.d) by floating macrophytes.

<table>
<thead>
<tr>
<th>Location</th>
<th>Macrophyte</th>
<th>Daily uptake in g/m\textsuperscript{2}.d</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>USA, Florida</td>
<td>Water hyacinth</td>
<td>1.30 (0.25)\textsuperscript{1} 0.24 (0.05)</td>
<td>Reddy &amp; DeBusk 1987</td>
</tr>
<tr>
<td>USA, Florida</td>
<td>Water lettuce</td>
<td>0.99 (0.26) 0.22 (0.07)</td>
<td>Reddy &amp; DeBusk 1987</td>
</tr>
<tr>
<td>USA, Florida</td>
<td>Pennywort</td>
<td>0.37 (0.37) 0.09 (0.08)</td>
<td>Reddy &amp; DeBusk 1987</td>
</tr>
<tr>
<td>USA</td>
<td>Lemna sp</td>
<td>1.67</td>
<td>Zirschky &amp; Reed 1988</td>
</tr>
<tr>
<td>India</td>
<td>Lemna sp</td>
<td>0.50-0.59 0.14-0.30</td>
<td>Tripathi et al. 1991</td>
</tr>
<tr>
<td>USA, Louisiana</td>
<td>Duckweed</td>
<td>0.47 0.16</td>
<td>Culley &amp; Meyers 1980</td>
</tr>
<tr>
<td>Bangladesh</td>
<td>S. polyrhiza</td>
<td>0.26 0.05</td>
<td>Alaerts et al. 1996</td>
</tr>
</tbody>
</table>

\textsuperscript{1} Values between brackets were obtained during winter season

Potential applications of duckweed

Aquatic plants used in wastewater treatment are generally considered to not contribute directly to biodegradation processes taking place. Their role is more of a supportive nature, providing surface area for attached biofilms, providing oxygen for aerobic metabolism, and stimulating quiescent conditions in the water phase which enhance settling processes (TSS, nematode eggs). A detailed discussion on the effect of duckweed based treatment on the removal of nutrients, BOD, pathogens, TSS, heavy metals has been presented in a recent overview (Gijzen and Veenstra, 2001).

Box 4. What is duckweed?

- Duckweed is a small floating aquatic plant belonging to the family Lemnaceae
- The family consists of 4 genera: \textit{Spirodela}, \textit{Lemna}, \textit{Wolffia}, and \textit{Wolffiella}.
- 37 species have been identified so far
Duckweed (family Lemnaceae) is a free-floating aquatic plant with a tremendous capacity to remove nutrients from wastewater. Its growth rate is faster than any other plant and the protein content is very high (25-45% of dry weight). The use of duckweed in wastewater treatment is not well documented, nor are published design criteria available. The scarce experiences reported so far, however, suggest that this technology holds great promise for low cost wastewater treatment, especially when applied in combination with fish production or other animal feed applications. Removal efficiencies of 96 and 99% have been reported for BOD and ammonia, respectively (Alaerts et al., 1996).

Advantages of duckweed

Several full-scale applications of duckweed based wastewater treatment systems exist in the USA, Bangladesh and China. Duckweed systems have been studied for dairy waste lagoons (Culley et al., 1981), domestic sewage (Oron, 1994; Skillicorn et al., 1993, Alaerts et al., 1996), secondary effluent (Sutton and Ornes, 1977), waste stabilization pond effluents (Wolverton, 1979) and fish culture systems (Porath and Pollock, 1982; Rakocy and Allison, 1981). Even in moderate climatic conditions duckweed based systems are being advocated for treatment of domestic wastewater from small communities in Belgium and Poland (Nielsen and Ngo, 1995).

Considering an average annual duckweed yield of 20 t dry weight/ha.y and a protein content of 35%, a protein productivity of about 7 t/ha.y can be calculated. Compared to soy bean, duckweed produces about 10 times as much protein per ha/y. Various authors recommend the application of duckweed biomass as a source of high quality protein in animal nutrition (Hillman and Culley, 1978; Culley et al., 1981; Edwards, 1990). There are a number of concerns that need to be addressed when considering duckweed as a potential feed:

- Due to the efficient absorption of heavy metals and possibly other toxic compounds, duckweed should be cultivated using effluents with low concentrations of such compounds. No information is available on the possible transmission of pathogens if duckweed harvested from domestic wastewater treatment ponds is used as an animal feed.

- Duckweed has high moisture content (about 95%), which will affect the cost of handling, transportation and drying. This characteristic will be less important in an integrated system, where duckweed is used on site.

- The genera *Lemna* and *Spirodela* may contain high amounts of calcium oxalate. The presence of this component may limit the use of certain duckweed species for non-ruminant and human nutrition. When properly mixed with other feed constituents, no harmful effects are expected.

The combination of duckweed based wastewater treatment and fish cultivation is being practised at a small scale in Bangladesh. The pond complex receives wastewater from 3500 capita and is operated at a hydraulic retention time (HRT) of about 21 days. The results over the past years
have demonstrated that the system can be managed with a net annual production of over 12 tons fish per ha, yielding a net annual profit of about US$ 2000/ha. A feasibility study by the World Bank for Pondicheri, a 35,000 inhabitant town in India, shows that a UASB-duckweed system could yield annually 80 tons duckweed, 30-40 tons fish and 150,000 m$^3$ methane gas.

**Duckweed ponds in combination with anaerobic technology**

The application of anaerobic technology results in a substantial reduction of organic matter and suspended solids in wastewater. Anaerobic technology shows very poor N and P removal rates, whereas typical removal rates for coliforms via attachment to and settling of suspended solids is only some 50 to 90 %. Helminth eggs are more susceptible to removal by filtration, entrapment and settling within the anaerobic reactor

As duckweed ponds focus on the reduction of pathogens and dissolved nitrogen and phosphorus compounds, a combination with anaerobic pre-treatment seems to be most effective (van Haandel and Catunda, 1997; Gijzen, 1996, 1997). Advantages of such combination are:

- the design of duckweed ponds can entirely be based on nutrient removal and pathogen reduction rather than on the biodegradation of organic matter and the transfer of sufficient amounts of oxygen per m$^2$ per day. This may lead to a significant reduction of HRT and pond area required to achieve effective treatment results;

- Accelerated nutrient uptake rates can be achieved if substantial COD reduction is realised in the anaerobic reactor prior to the duckweed pond (Oron et al, 1987);

- anaerobic pre-treatment contributes to the liquefaction of suspended organic particles. In this process organically bound nutrients will be mineralised and will become available for duckweed growth;

- anaerobic technology as well as duckweed pond technology can be easily scaled down and can thus be applied to decentralised sewage treatment in (peri-)urban areas in developing countries, or to small communities world-wide.

**Integrated concepts**

*Integrated systems for the rural and urban environment*

Integrated systems have been defined as a combination of processes and practices where optimum use of resources is achieved via waste recycling aimed at the recovery and re-use of energy, nutrients and possibly other components. The conversion processes for different sources of waste are arranged in such a way that a minimum input of external energy and raw materials is required and maximum self-sufficiency is achieved. In rural Asia, integrated systems form an old concept that has been applied for hundreds or probably even thousands of years. In China there are huge farms which are almost completely self-sufficient in terms of energy and nutrients because of effective recycling of their waste streams. The integrated systems concept stimulates the establishment of an optimal balance between productivity (agriculture, aquaculture), resource utilisation, re-use and environmental protection.

Such balance is completely absent in densely populated urban areas, where high consumption rates and concentrated waste production is sustained by the large-scale importation of energy and nutrients into the urban environment. The absence of re-use processes for energy,
nutrients and other valuable components in urban waste has generated serious environmental and public health concerns. It is suggested therefore that urgent attention is given to the development of rational re-use strategies in the urban context. The challenge for the coming years therefore will be to develop integrated concepts and processes for pollution prevention, and recovery and re-use of waste materials in both rural and urban environments in high and low GNP countries. If effective programmes and action plans could be defined by relevant organisations, such as World Bank, United Nations, National Universities and research centres, this challenge could be met within a reasonable time span with the help of modern science and technology.

Duckweed ponds could play an important role in recycling and re-use schemes in both rural and urban areas. The process steps and products of an integrated duckweed based treatment system for rural and urban recycling of waste streams is presented in Fig. 1 and 2. Anaerobic technology is advocated to reduce the bulk of organic and suspended matter. The energy produced in rural biogas digesters or urban high-rate reactors (e.g. UASB or AF) can be used by the community (rural context) or for the operation of subsequent treatment steps (urban application), thereby reducing treatment costs.

**Recreation**

A major limitation for the application of duckweed technology in urban centres is the non-availability of space at a reasonable cost. However, outside the city, land cost will be substantially lower and duckweed ponds may become feasible. It is therefore important to consider waste(water) management in connection with other functions of urban centres and immediate surroundings, such as food production and recreation.

Anaerobic treatment facilities, requiring only limited space, may be planned at convenient locations in or near the city. The effluent of the anaerobic reactors can be channelled outside the city to duckweed pond facilities. The duckweed harvested at regular intervals can be used to cultivate fish in adjacent ponds, while the effluent can be made available for irrigation. The space requirement for the duckweed pond is estimated at about 1 m$^2$/capita in (sub-)tropical climatic regions. Although this is significantly lower compared to conventional stabilisation ponds, considerable land area will be required.

Due to the rapid growth of cities, sufficient land area has to be reserved for recreational purposes. In mega-cities with over 1 million inhabitants large-scale recreational facilities can be planned outside the city at convenient locations. In recognition of the fact that the green duckweed covered ponds provide a pleasant ecological appearance, one might think of a multi-functional use of space, combining wastewater management with fish and food production and with a recreational destination. Part of the duckweed produced maybe used for recreational fish ponds, while the treated effluent can be used for boating and ornamental lakes, before its re-use in crop irrigation and commercial aquaculture activities. The possible production of malicious odours from the wastewater is effectively reduced by the presence of a duckweed cover on the pond surface. Such multi-functional use of the available space may greatly enhance the economical feasibility of the entire system. With the income from the products generated (energy, fish, irrigation water, recreation), the proposed integrated system has the potential to become a commercial enterprise generating substantial revenues.
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