Paper No. 9b

Duckweed Based Natural Systems for Wastewater Treatment and Resource Recovery

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Abstract

Adjustment of the traditional concept of urban water management is felt to be necessary, since it has some features that probably contributed to the failure to deliver sanitation services to a large part of the world population. The traditional concept comprises supply of large volumes of drinking water at low cost, the use of drinking water to transport waste outside the city and (mechanical) energy intensive centralised treatment. A new concept is proposed that is focussed on reduction of wastewater generation (household level), on low cost sewer systems and on treatment systems that are aimed at recycling and have a reduced cost and environmental impact. Natural treatment systems, for instance duckweed ponds, fit into this new concept for the treatment of the remaining wastewater. Duckweed is a fast growing floating plant, capable of rapidly absorbing nutrients from wastewater. The nutrients are converted into protein rich biomass, that can be used as animal feed. An integrated system of duckweed based wastewater treatment and fish aquaculture was shown to reduce significantly the overall financial costs.


The traditional concept of urban water management as practised in the developed world and in many cities in the developing world is increasingly reconsidered by scientists and engineers from the water sector (Gijzen, 1999; King, 2000). This discussion was triggered by the recognition that the traditional concept itself may have contributed to the failure to provide sanitation to a very large part of the world population (King, 2000). What is wrong with the traditional concept? The traditional concept consists of (1) Supply of large volumes of drinking water at relatively low cost (2) Dilution and transport out of the city of human waste using large quantities of high quality drinking water, via an extensive sewer network. (3) Treatment in centralised (mechanised) wastewater treatment plants, followed by disposal to the nearest water resource. This water based sanitation approach originated from the 19th century as a result of the need to prevent frequent outbreaks of water borne diseases. Indeed the concept has been very successful in terms of prevention of waterborne diseases. Where the collected wastewater is properly treated before disposal also a high degree of protection of surface or groundwater quality can be achieved. The major disadvantages of the traditional concept are:

(1) Large amounts of water that have been purified to drinking water standards are only used to transport waste (See box 1). Already in 1958 it was recognised that “no higher quality of water, unless there is a surplus of it, should be used for a purpose that can tolerate a lower grade” (United Nations, 1958).

(2) Large wastewater volumes require extensive and expensive sewer networks. The costs make sewer systems unfeasible in many cities of the developing world (Polprasert, 1996). Large wastewater volumes also require large and expensive treatment plants.
Conventional treatment plants, for instance activated sludge systems, are characterised by complicated technology and high costs for construction, operation and maintenance. Although these systems have great advantages in terms of efficient removal of BOD, TSS and nutrients on a relatively small area, these are often offset by high energy consumption, high costs and poor pathogen removal.

Alternative concepts and sanitation systems have been developed for urban water management, aimed at removing disadvantages of the traditional concept without losing the benefits. These concepts are aimed at (1) reduction of wastewater generation (household-centred approach) (See box 1), (2) on-site treatment or pre-treatment (See Box 2) (3) transportation of waste in low cost sewer systems (4) development of decentralised new treatment systems, which enhance resource recovery. This paper further focuses on 'Natural treatment systems', that belong to the group of treatment systems that suit the objective of proper treatment, reuse and recycling of water, energy and nutrients.

Natural Systems for Urban Wastewater Management

Definition of natural systems

Any type of wastewater treatment system is based on natural processes, be it chemical, physical or biological, and its design is aimed at creating the optimal conditions for enhancement of the rate of these natural processes. A specific feature of "Natural systems" is that their design and operation is restricted by the following condition: the rate of reaction of natural processes should not be enhanced by the input of large amounts of energy (electricity) or harmful chemicals. Or differently stated, "The term natural systems [...] is intended to describe those processes that depend primarily on their natural components to achieve the intended purpose. A natural system might typically include pumps and piping for waste conveyance but would not depend exclusively on external energy sources to maintain the major treatment responses" (Reed et al., 1995).

Additionally, natural systems follow 'the logic of nature'. In nature resources are recycled and it may therefore be beneficial to replace a 'linear' view on sanitation (collection, transport, centralised treatment and final disposal) with a 'loop approach'. In a loop approach, one views waste as a resource. Though it may be a resource in the wrong place, still it has economic value and therefore could beneficially be recovered (recycled) (King, 2000).

To illustrate this point, the natural nitrogen cycle is compared with the artificial N cycle as practised in industrialised countries. In the natural nitrogen cycle, atmospheric nitrogen is fixed by certain bacteria and stored as organic and inorganic nitrogen for a long time (4000 years) before it is returned to the atmosphere. Nitrogen is recycled many times before being released. The artificial N cycle starts with fixation of atmospheric nitrogen in chemical fertilisers by an energy intensive industrial process. The fertiliser is used to enhance food and animal feed production and after consumption of the products, the nitrogen turns into a so-called waste product (manure and wastewater). How to deal with this waste? The linear view says that the waste is just to be treated. In many countries this means that the nitrogen compounds in the wastewater are nitrified and denitrified in an activated sludge system at the expense of (again) large amounts of energy (Gijzen, 1999). The loop approach views the nitrogen in the wastewater as a resource. If this approach is followed than wastewater management schemes are designed to recycle the nitrogen. Natural systems, using for instance plants, naturally are fit to realise this objective.
From the definition of natural systems follow the general features of natural systems:

- Natural systems are aimed at recycling of nutrients, water and energy.
- Natural systems use as much as possible anaerobic microbiological processes to remove BOD, because no (mechanical) oxygen input is required for these processes.
- The oxygen for aerobic microbiological processes in natural systems is supplied by photosynthesis (algae, plants) or natural re-aeration.

Wastewater treatment systems that are considered natural systems are: (1) Anaerobic pre-treatment in septic tanks, anaerobic ponds or high rate anaerobic reactors, (2) Waste stabilisation ponds, (3) Macrophyte ponds, (4) Fish aquaculture, (5) Constructed wetlands, and (6) Land treatment systems.

Feasibility of natural systems

The effluent quality that can be achieved after treatment of domestic wastewater in the above mentioned natural systems is given in Table 1. Actually the effluent quality depends mainly on temperature, area available and pre-treatment. Any desired quality can be achieved, but a trade-off between effluent quality and required land area exists. The costs for natural systems depend mainly on land prices and costs for construction. For instance the soil type affects strongly the costs for stabilisation ponds. Anaerobic high rate reactors are expensive but take relatively small area.

Table 1. Overview of Effluent Quality for Natural Systems

<table>
<thead>
<tr>
<th>Natural system</th>
<th>HRT (days)</th>
<th>BOD (mg/l)</th>
<th>TSS (mg/l)</th>
<th>Total N (mg/l)</th>
<th>Total P (mg/l)</th>
<th>FC (#/100 ml)</th>
<th>Ref</th>
</tr>
</thead>
<tbody>
<tr>
<td>High rate anaerobic reactor (pre-treatment)</td>
<td>0.25</td>
<td>50-200</td>
<td>20-350</td>
<td>25-90</td>
<td>5-30</td>
<td>10^5-10^7</td>
<td>1</td>
</tr>
<tr>
<td>Waste stabilisation pond (anaerobic + facultative type)</td>
<td>10-40</td>
<td>20-40</td>
<td>80-120</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Waste stabilisation pond (anaerobic + facultative + maturation pond)</td>
<td>14-23</td>
<td>0-20</td>
<td>&lt;100</td>
<td>3</td>
<td>4</td>
<td>3,4</td>
<td></td>
</tr>
<tr>
<td>Duckweed ponds</td>
<td>14-28</td>
<td>5-40</td>
<td>40-80</td>
<td>3-45</td>
<td>0.5-2.5</td>
<td>10^2-10^4</td>
<td>6, 5</td>
</tr>
<tr>
<td>Water hyacinth pond</td>
<td>30-50</td>
<td>&lt; 10</td>
<td>&lt; 10</td>
<td>&lt; 5</td>
<td>&lt; 5</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Constructed Wetland</td>
<td>3-15</td>
<td>5 - 40</td>
<td>5-20</td>
<td>5-10</td>
<td>10^2-10^5</td>
<td>2,7</td>
<td></td>
</tr>
<tr>
<td>Land treatment (slow rate)</td>
<td>n.a. 3)</td>
<td>&lt; 2</td>
<td>&lt; 2</td>
<td>&lt; 3</td>
<td>&lt; 0.1</td>
<td>0</td>
<td>2</td>
</tr>
</tbody>
</table>

1) HRT = hydraulic retention time. 2) FC = faecal coliforms. 3) n.a.=not applicable; 4) References: 1=Van Buuren, 1991; 2=Reed et al., 1995; 3=Silva et al., 1995; 4=Arridge et al., 1995; 5= Alaerts et al., 1996; 6=Zimmo et al., 2000; 7= Gerba et al., 1999
It has been demonstrated in the United States that natural systems are cost effective in many situations. "Interest in natural concepts was originally based on the environmental ethic of recycle and reuse of resources wherever possible. [...] However, as more and more systems were built and operational experience accumulated, it was noticed that these natural systems, when site conditions were favourable, could usually be constructed and operated for less cost and with less energy than the more popular and more conventional mechanical technologies. Numerous comparisons have documented these cost and energy advantages." (Reed et al., 1995).

Increasingly the feasibility of wastewater treatment systems will be determined by the 'total environmental impact' of the plant. The total environmental impact is the sum of the impacts related to effluent quality, emissions to the air, waste products, consumption of materials, consumption of energy and disposal of materials after the lifetime of the plant (Roeleveld et al., 1997). With the introduction of so-called eco-taxes in many countries also the total financial costs of a treatment system will be linked to the total environmental impact of the system. Natural systems are believed to have a smaller environmental impact than conventional systems and their cost effectiveness will increase the more the "polluter pays principle" is implemented. Natural systems may contribute to reduce costs and 'environmental impact' alike.
Box 1: Water saving measures at household level in the Netherlands

Water supply companies in the Netherlands started awareness raising campaigns to motivate people for water saving measures at the household level. Whereas the consumer is mainly motivated by economics (currently $1-1.5 per m³), the concern of the water supply sector is due to the following reasons:

1. Some regions encounter problems with over-abstraction and decreasing groundwater levels. A decrease in water consumption automatically means less groundwater abstraction.
2. A reduction in water consumption would reduce the investments that are necessary for new infrastructure to provide the growing population with drinking water.
3. Less water production means also less consumption of chemicals and disinfectants and therefore less production of environmentally hazardous sludge.
4. Less water consumption means less energy requirements for distribution, so less costs and environmental impact through energy use.
5. Less water consumption means less wastewater to be treated, therefore less costs for wastewater treatment and a reduced environmental impact.

The following measures are advocated by the water supply companies:

- Installation of water saving flush toilets that use less water for flushing. Presently the average Dutchman uses 43 liters per day of fresh water for toilet flushing, 30% of the total fresh water consumption. Modern closets with a flush-interruption and/or with a smaller water compartment can result in a 50% reduction of water use for toilet flushing (Table 2).
- Installation of water saving taps. A special device introduces small bubbles in the jet of water. The water flow is reduced, but for the consumer it feels as before.
- Installation of water saving shower equipment, resulting in up to 50% less water consumption for showering.
- Collection of rainwater and using it for toilet flushing, washing machine, washing the car, gardening etc.

Table 2. AVERAGE DRINKING WATER CONSUMPTION IN THE NETHERLANDS
(source: VNI/Vewin/Wavin, 2000)

<table>
<thead>
<tr>
<th>Total consumption in m³ per capita per year</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>(liter/cap/day)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>48.0</td>
<td>40.0</td>
<td>38.5</td>
<td>23.6</td>
<td></td>
</tr>
<tr>
<td>(132)</td>
<td>(110)</td>
<td>(106)</td>
<td>(65)</td>
<td></td>
</tr>
</tbody>
</table>

Breakdown:

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Personal hygiene</td>
<td>18.0</td>
<td>13.0</td>
<td>13.0</td>
<td>13.0</td>
</tr>
<tr>
<td>Toilet flushing</td>
<td>13.0</td>
<td>10.0</td>
<td>8.5</td>
<td>1.1</td>
</tr>
<tr>
<td>Washing machine</td>
<td>7.5</td>
<td>7.5</td>
<td>7.5</td>
<td>1.0</td>
</tr>
<tr>
<td>Washing dishes</td>
<td>4.5</td>
<td>4.5</td>
<td>4.5</td>
<td>4.5</td>
</tr>
<tr>
<td>Cooking and drinking</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Cleaning</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Various purposes (garden)</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
</tr>
</tbody>
</table>

Reduction: - 17% 20% 51%

Box 2: Decentralised treatment of grey domestic wastewater in constructed wetlands, to reduce waste volume to be treated centrally (adapted from Niezen and Van Dijk, 2000).

In the city of Groningen, in the northern part of the Netherlands, a newly constructed neighborhood has been developed with the aim to introduce 'sustainable water management'. Measures that have been taken are water saving at household level (see box 1), local infiltration of rainwater rather than collection in a combined sewer system and on-site treatment of grey wastewater. The black wastewater is conveyed to the central treatment plant of the city, but the total volume to be treated centrally has been reduced significantly. Options that were judged not feasible in this neighborhood were composting toilets, rainwater harvesting and a separate distribution system for rainwater.

The grey wastewater of 110 houses is treated in a constructed wetland. The effluent is mixed with surface water and polished in another wetland. The effluent of the second wetland is discharged into the canals that flow through the neighborhood. The retention time in the canals is one month. The constructed wetland was chosen as treatment technology because of low construction costs and simple maintenance and operation. The first wetland was designed based on an influent flow of 40 m$^3$/day and has a surface of 3000 m$^2$ and is planted with reed, depth is 30 cm. The area required is 6 – 14 m$^2$ per capita. Especially in tropical areas the area requirements are much smaller.

The effluent composition and removal efficiencies during the summer season were satisfactory (See Table 3). During the winter the wetland effluent was discharged in the central sewer system. The surface waters in the canals complied with the standards. A disadvantage of this system was some odor emissions from the wetland. The inhabitants of the neighborhood did however not complain, maybe because they did not want to spoil the project or because the smell is similar to a natural marine wetland nearby. Another disadvantage was the high input of labor.

The project demonstrates that on-site treatment of gray domestic wastewater is possible, and that wastewater volumes to be treated centrally were reduced.

Table 3 RESULTS FOR TREATMENT OF GRAY DOMESTIC WASTEWATER IN A CONSTRUCTED WETLAND

<table>
<thead>
<tr>
<th>Parameter (mg/l)</th>
<th>Average influent</th>
<th>Average effluent composition and removal efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1998</td>
<td>1999</td>
</tr>
<tr>
<td>BOD</td>
<td>298</td>
<td>4.4 99%</td>
</tr>
<tr>
<td>COD</td>
<td>550</td>
<td>44 92%</td>
</tr>
<tr>
<td>N-kjeldahl</td>
<td>12.6</td>
<td>2 84</td>
</tr>
<tr>
<td>Nitrate</td>
<td>&lt;0.01</td>
<td>&lt;0.17 -</td>
</tr>
<tr>
<td>Nitrite</td>
<td>0.03</td>
<td>- - -</td>
</tr>
<tr>
<td>DO</td>
<td>2.3</td>
<td>6.3 5.7</td>
</tr>
<tr>
<td>pH</td>
<td>7.08</td>
<td>7.36 7.27</td>
</tr>
</tbody>
</table>
Duckweed Based Systems for Wastewater Management and Resource Recovery

What is duckweed?

Duckweed based ponds represent a special case of natural treatment systems. The technology basically consists of a waste stabilisation pond covered with a mat of floating aquatic macrophytes, duckweed. Duckweed, or \textit{Lemnaceae}, are small floating aquatic plants which can be found worldwide under widely varying climatic and environmental conditions. The family consists of 4 genera (\textit{Wolffiella}, \textit{Wolffia}, \textit{Lemna}, \textit{Spirodela}). The plant morphology is simple and structural components are limited to short roots and a frond with a size of only a few mm for most species (Landolt and Kandeler, 1987). Parameters affecting duckweed growth in natural environments include temperature, light intensity, other climatic conditions, pH and availability of nutrients in the water. Inhibition occurs at high nutrient (ammonia) concentrations (Caicedo \textit{et al.}, 2000).

\textit{Lemnaceae} are considered to be among the most vigorously growing plant species on earth. Although higher biomass yields have been observed in laboratory experiments, biomass yields in full scale ponds will probably be in the range of 15 to 30 t DM/ha.year. Due to the high protein content of duckweed (29-41\%, Culley and Epps, 1973) duckweed has a high potential for protein production. The relatively high protein content of duckweed is generating interest in animal feed applications of this aquatic plant.

Duckweed based wastewater treatment

Various studies, demonstration and full scale projects have reported the use of duckweed for the efficient removal of nutrients from wastewater. The economical potential of a 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 produced plant biomass. Apart from duckweed, also other floating macrophytes are used in wastewater treatment, such as water hyacinth (\textit{Eichhornia crassipes}), pennywort (\textit{Hydrocotyle umbellatta}) and water lettuce (\textit{Pistia stratiotes}). Water hyacinth has been used most widely, due to its high nutrient uptake capability, but no economically attractive application of the generated plant biomass has been identified so far. Other advantages of duckweed over other aquatic plants are its rapid growth and efficient nutrient uptake when exposed to sewage, its low sensitivity to low sewage temperature, harvesting of duckweed plants from the water surface is easy, a complete duckweed cover prevents the development of algae and provides quiescent conditions, which contribute to a more clear effluent with lower TSS and finally the presence of duckweed cover prevents mosquito breeding.

Several full scale applications of duckweed based wastewater treatment systems exist, for example in the USA, Bangladesh and China (Zirschky and Reed, 1988). Duckweed systems have been studied for dairy waste lagoons (Culley \textit{et al.}, 1981), domestic sewage (Oron, 1994, Alaerts \textit{et al.}, 1996), secondary effluent (Sutton and Ornes, 1977), waste stabilisation pond effluents (Wolverton, 1979) and fish culture systems (Porat and Pollock, 1982).
Major treatment parameters affected by duckweed

Aquatic plants used in wastewater treatment are generally considered to not contribute directly to biodegradation processes taking place. Their role is more of an indirect nature, providing surface area for attached biofilms, providing oxygen for aerobic metabolism, and stimulating quiescent conditions in the water phase which enhance settling processes. Plants directly contribute to nutrient removal by nutrient uptake. Typical daily nitrogen and phosphorus uptake rates are 0.4 g N/m$^2$/day and 0.03 g P/m$^2$/day, depending on the growth rate, harvesting scheme and species (Zimmo et al., 2000). Nitrogen removal via microbiological nitrification-denitrification rates may be in excess of 1 g N/m$^2$/day (Culley et al., 1978).

Pathogen removal from duckweed covered lagoons treating domestic wastewater is important in order to produce an effluent quality that allows for further re-use in agriculture and/or aquaculture. The effluent guidelines of < 1000 faecal coliforms/100ml and <1 helminth eggs /1000ml (WHO, 1989) should be met to ensure safe effluent re-use. Other health related concerns are related to manual harvesting of duckweed and its applications as animal feed. Die-off of bacterial pathogens in waste stabilisation ponds is the result of combined and synergetic effects of solar radiation and algae photosynthesis (oxygen radicals and elevated pH). Bacterial pathogens survive significantly longer in duckweed ponds as compared to facultative or maturation ponds (Dewedar and Bahgat, 1995; Van der Steen et al., 1999). Providing long retention times can still yield an effluent with low coliform counts. Islam et al. (1996) monitored faecal coliform removal in a plug flow duckweed lagoon and found a reduction from $4.5 \times 10^4$/100 ml in the influent to values below $10^2$ / 100ml in the effluent, at 20 days retention time. The major removal mechanisms for pathogenic parasites and eggs in ponds is probably sedimentation. Duckweed might enhance this process by improving the conditions for settling.

The role of duckweed in BOD removal is not fully understood, but most probably nor the direct uptake of small organic compounds nor the attached biofilm to the small duckweed roots contribute significantly. Sedimentation and heterotrophic activity in the water column is therefore probably the main mechanism. Reaeration through the surface is decreased by the duckweed mat, but it is unknown whether this is compensated by the diffusion of photosynthetically produced oxygen through the duckweed roots. The oxygen production in the water column of a duckweed pond is significantly lower than in an algae pond, due to the absence of algae. Alaerts et al. (1996) reported BOD removal efficiencies of 95-99% in a 0.7 ha sewage lagoon which was operated with a cover of S. polyrhiza at a HRT of about 20 days. BOD loading rate in the lagoon varied between 48 and 60 kg BOD/ha.d.

Heavy metals are effectively removed from wastewater by duckweed. However, this makes the biomass unfit for consumption by animals. It is therefore important to keep industrial wastewater streams separate from the main flow of domestic wastewater. Industrial wastewater should be treated before discharge in the municipal sewer.

Cost recovery via wastewater-grown duckweed application in fish aquaculture, in Bangladesh

Wastewater-grown duckweed is a good feed material for fish and poultry (Culley et al., 1981). In Bangladesh duckweed technology development and integration of wastewater treatment and fish aquaculture was first introduced by the NGO PRISM. Since 1989 PRISM has been continuously involved in duckweed based wastewater treatment, both in centralised systems as well as in small scale village settings. In 1993 a full-scale system for wastewater treatment and duckweed-based fish culture was installed at the
Kumudini Hospital Complex (KHC) in Mirzapur. The main objectives are to generate (Gijzen and Ikramullah, 1999):

- Low cost wastewater treatment
- Resource recovery via aquaculture
- Economic viability
- Improvement of rural employment and nutritional status

The facility consists of a 0.2 ha anaerobic pond, followed by a 0.7 ha plug-flow duckweed lagoon, fed with domestic wastewater from the school and residential area of the hospital complex. (See Figure 1). A detailed study on the wastewater treatment performance of the lagoon was published by Alaerts et al. (1996). It was found that all major wastewater parameters were removed efficiently (BOD 96%, Kjeldahl-N 72%, NH$_4^+$ 99% and total-P 75%) yielding a high quality effluent (BOD 5 mg/l, Kjeldahl-N 3 mg/l, total-P 0.5 mg/l). The duckweed plants absorbed nutrients at a fast rate, at two-thirds of the lagoon length virtually all NH$_4^+$ and ortho-PO$_4^{3-}$ had been removed. The duckweed harvest removed 60-80% of the nutrient load. The duckweed is harvested regularly and used as fish feed in an adjacent fish farm, operated and owned by the same organisation. Revenues generated by the fish farm are used to cover the costs of the wastewater treatment, and fish revenues even exceed treatment costs (See Table 4). Eventually treatment costs should be recovered by charging the water consumers and those that discharge the wastewater. The fish aquaculture part is highly profitable.

Figure 1. The integrated system of duckweed based wastewater treatment and duckweed-based fish aquaculture in Mirzapur (Bangladesh) (Gijzen and Ikramullah, 1999).
Table 4. Estimated annual cost in Tk and revenue for individual components and integrated wastewater cum aquaculture system at the Kumudini Hospital Complex (Gijzen and Ikramullah, 1999).

<table>
<thead>
<tr>
<th></th>
<th>Duckweed based wastewater treatment</th>
<th>Fish aquaculture</th>
<th>Integrated system</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Costs</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Operating costs</td>
<td>130000</td>
<td>109000</td>
<td>239000</td>
</tr>
<tr>
<td>Cost of duckweed¹)</td>
<td>100000</td>
<td>100000</td>
<td>100000</td>
</tr>
<tr>
<td>Administration costs</td>
<td>29000</td>
<td>25600</td>
<td>54600</td>
</tr>
<tr>
<td><strong>Revenues</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fish sale</td>
<td>301260</td>
<td>301260</td>
<td>301260</td>
</tr>
<tr>
<td>Agricultural products/fruits²)</td>
<td>39600</td>
<td>39600</td>
<td>39600</td>
</tr>
<tr>
<td>Wastewater treatment³)</td>
<td>4640</td>
<td>4640</td>
<td>4640</td>
</tr>
<tr>
<td>Dried sludge (fertilizer)</td>
<td>100000</td>
<td>100000</td>
<td>100000</td>
</tr>
<tr>
<td>Duckweed</td>
<td>100000</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Operational profit</strong></td>
<td>-25360</td>
<td>131860</td>
<td>106500</td>
</tr>
<tr>
<td><strong>Net profit before tax</strong></td>
<td>-54360</td>
<td>106260</td>
<td>51900</td>
</tr>
</tbody>
</table>

1) Duckweed production was estimated at 30 $10^3$ kg dry duckweed/ha.year, 0.47 ha productive area, 0.5 Tk/kg fresh weight (duckweed is sold at minimum 0.5 Tk/kg in Bangladesh, which is about 7 Tk/kg dry weight)

2) Agriculture products are basically grown as co-crops on duckweed pond embankments for wind protection and shading of the duckweed.

3) Currently the producers of wastewater are not charged for wastewater treatment.

Conclusions

- New concepts for urban water management are currently considered and developed to adjust or partly replace the old concept, because the latter probably contributed to the failure to provide good coverage at world scale.
- The quantity of wastewater to be treated can be significantly reduced by saving water at the household level and by on-site treatment, re-use and disposal of grey wastewater.
- Natural systems, such as duckweed systems are yielding good effluent quality, in many situations at reduced costs and it is believed also at reduced environmental impact.
- Duckweed based systems fit into the new concept of recycling and cost recovery. Integrated systems of duckweed based wastewater treatment and fish aquaculture can recover a large part or possibly all the treatment costs.
Recommendations for further R&D of Duckweed Systems

More research is needed to address the further development of duckweed technologies. An important aspect is the possible health hazard associated with the use of wastewater-grown duckweed as animal feed. Although previously executed research indicated that the risks may be very small, the IHE duckweed research group intends to continue research on pathogen die-off and/or pathogen transfer. In addition to this IHE is currently involved in co-operation projects with Palestinian, Egyptian, Ghanese and Colombian universities addressing several aspects of optimisation of the design of duckweed systems (What is the effect of anaerobic pre-treatment? How duckweed ponds perform in comparison with algae ponds? What fish yield can be achieved by using duckweed as feed?)
References


United Nations (1958)


