Use of Naturally Growing Aquatic Plants for Wastewater Purification

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ABSTRACT: This paper examines potential uses of naturally growing aquatic plants for wastewater purification. These plants enhance the removal of pollutants by consuming part of them in the form of plant nutrients. This applies to urban and agricultural wastewater, in particular, where treatment units of different sizes can be applied at the pollution source. The effectiveness of wastewater purification by different plants was tested on laboratory and pilot scales. The growth rate of the plants was related to the wastewater content in the water. Batch and semicontinuous experiments verified that the plants are capable of decreasing all tested indicators for water quality to levels that permit the use of the purified water for irrigation. This applies to biochemical oxygen demand (BOD), chemical oxygen demand, total suspended solids, pH, and turbidity. In specific cases, the turbidity reached the level of drinking water. Comparison of BOD concentrations with typical levels in water treatment facilities across the country indicates the effectiveness of water purification with plants. A major effect of treatment with plants was elimination of the disturbing smell from the wastewater. It is shown that mixtures of wastewater and polluted water from the Kishon River are amenable in varying degrees to treatment by the plants. The higher the wastewater content in the mixture, the more effective the treatment by the plants. In this context, a scheme for rehabilitation and restoration of the Kishon River is presented and technical and economical aspects of the purification technology are considered. Water Environ. Res., 76, 220 (2004).

KEYWORDS: water plants, natural treatment, wastewater treatment, urban pollution, agricultural pollution.

Introduction

The Kishon River, which is one of the largest and most important rivers in Israel, has been contaminated by streams of wastewater and various chemical pollutants. This river, which flourished in the past, provided the stage for a number of biblical stories. Today, there are sections along the Kishon River that are severely contaminated to the extent that they are devoid of life. The river, which is the second largest among the coastal rivers, drains an area of 1100 km² and is perennial for most of its 70-km course.

Contamination of the river by neighboring industries began long ago. Oil refineries and the associated petrochemical industry were established in the region in the 1930s during the British Mandate. Different sections of the Kishon River can be described now as flow systems containing wastewater, petrochemical mixtures, and solutions, including toxic effluents. This particularly applies to the final 7 km of the downstream section of the river (e.g., before its discharge to the Haifa Bay). Typical composition data for Kishon River water (Kishon River Authority Report, 2000) are summarized in Table 1. Apart from the downstream section of the river, which is the most severely contaminated, the whole river does not comply with local environmental guidelines. The urban and industrial infrastructure existing along the river complicates the regional ecological picture. This infrastructure includes municipalities and plants that discharge their waste streams into the river, despite the availability of regional wastewater treatment systems. The Kishon River discharges its highly contaminated water into the Haifa Bay and, consequently, the regional seashore is also polluted. The consequences, as confirmed by continuous river monitoring, are disastrous. This incessant contamination has caused the collapse of the Kishon River's ecosystem and its transformation into an open wastewater canal that flows across and into the Haifa Bay, where it takes a heavy environmental toll.

The volume of wastewater and other liquid waste streams that were discharged into the river in 2000 reached 15.7×10^3 m³/d. The pollution load consisted of approximately 7 tons of solids, 0.5 tons of mineral oil, 1 ton of ammonia (NH₃), and more than 1 ton of biochemical oxygen demand (BOD). The acidic wastes (pH ~0.9) of Haifa Chemicals Ltd. (Haifa Bay, Israel), a world leader in fertilizers and industrial chemicals, are believed to be a major source of pollution of the river (Kishon River Authority Report, 2000). Over the years, this situation has provoked protests from environmental organizations that demand the enforcement of steps to improve water quality. As the Kishon River is polluted along its path by different urban and industrial sources, their specific treatment (e.g., at the source) by natural means, such as aquatic plants, offers a promising and environmentally friendly solution to the problem.

In this context, we first consider general aspects that are related to the application of aquatic plants for purification of wastewater followed by their potential use for reduction of Kishon River pollution. This option is linked to the problem of river restoration, availability of water for irrigation, and the establishment of recreational areas at the natural treatment sites.

Application and Methodology of Operation

Wetlands that are being constructed worldwide are designed for wastewater treatment at the secondary and tertiary level (Gopal, 1999; Kadlec, 1995; Kadlec and Knight, 1995). These systems range in size from 200 m² to more than 4×10^7 m² (Knight, 1997). However, the impression that the constructed wetlands offer a costeffective alternative to conventional wastewater treatment (Hamilton et al., 1993) cannot always be sustained. Several physical, chemical, and biological processes are involved in the transformation and consumption of plant nutrients within the wetland. The major physical process in wetlands is the settling of suspended particulate matter, which is a major cause of reduction in BOD of the treated wastewaters.

The chemical processes, which include absorption, chelation, and precipitation, are responsible for the major removal of phosphorous compounds and heavy metals. Among the biological processes, the most important are those mediated by microorganisms and they include either oxidation or reduction of carbon, nitrogen, and sulphur, depending on the availability of oxygen. Generally, 0

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| Table | 1—Typ | oical a | verage | comp | osition | ofv | vater | from | the |
|-------|----------|---------|----------|--------|---------|------|-------|-------|------|
| Kisho | on River | (data | refers t | to the | period | from | 1996 | to 19 | 99). |

| Parameter | Upstreamª | Downstream ^a | Local standard for the Kishon River ^b |
|------------------------|-----------|-------------------------|--|
| рH | 7.6 | 2.6 | 7–8.5 |
| BOD (mg/L) | 10.8 | 175 | 10 (10-20) |
| COD (mg/L) | 70.1 | 622 | (50-70) |
| NO ₃ (mg/L) | 4.7 | 43.7 | 10 (10-15) |
| Oil (mg/L) | 6.6 | 4.5 | 1 1 |
| TSS (mg/L) | 161.3 | 130.9 | (10-30) |
| Ammonia (mg/L) | 3.04 | 54.6 | . , |
| Conductivity (mS/cm) | 3.9 | 23.7 | |
| Cadmium (mg/L) | 0.006 | 0.188 | 0.005 |
| Chromium (mg/L) | 0.014 | 0.305 | 0.01-0.05 |
| Copper (mg/L) | 0.01 | 0.2 | 0.05 |
| Lead (mg/L) | 0.031 | 0.525 | 0.01 |
| Mercury (mg/L) | 0.007 | 0.003 | 0.0005 |
| Nickel (mg/L) | 0.018 | 0.540 | 0.05 |
| Zinc (mg/L) | 0.02 | 2.75 | 1.0 |

^a Upstream (east section) and downstream (west section) are defined relative to the industrial complex, which pollutes the river.

^b Ministry of Environmental Protection of Israel guideline.

reduction reactions are expected to be dominant when the content of organic matter in the effluents is high and most of the nitrogen is lost through denitrification processes (Gale et al., 1993). The interaction between these processes and the biota are fairly complex, and several elements such as iron, aluminium, and manganese play an important role in the removal of phosphorous compounds (Cooke, 1994). Heavy metals can also be removed to a significant extent (Droste, 1997). Natural wetlands throughout the world are populated by emergent vegetation (Droste, 1997). For example, in Louisiana two water hyacinth plants (*Eichornia crassipe*) multiplied to produce 1200 plants in just 4 months (Jensen, 1988). Harvesting the fast-reproducing plants can provide raw material for agricultural fertilizers, animal food, and high-quality compost.

Wetlands are considered important for wastewater treatment because of their characteristic ability to absorb large amounts of organic and inorganic nutrients as well as a variety of toxic substances. Gopal (1999) pointed out that an erroneous impression is often conveyed that natural wetlands can be used for disposal of domestic wastewater and industrial effluents. In his work, reference is made to the work of Hammer (1989) and Vrhovsek et al. (1996).

Preliminary analysis of existing technologies indicates that the most extensively used aquatic plants in wastewater treatment systems are water hyacinths (E. crassipes) and duckweeds (Lemna) (U.S. EPA, 1988). The major characteristics of water hyacinths that made them an attractive biological support media for bacteria are their extensive root system and rapid growth rate. Biochemical oxygen demand and suspended solids are removed through processes that involve sedimentation, filtration by plant roots, and microbiological activity. Microbiological activity includes anaerobic degradation of bottom sediments and bacterial degradation of organic matter in the water column by both attached and suspended organisms. For example, water hyacinth roots provide a substrate, or media, on which a large population of adhering microorganisms grows. The major advantage of duckweeds is their lower sensitivity to cold climates, while their shallow root systems and sensitivity to wind are considered drawbacks.

Wastewater treatment using water hyacinths has been carried out in California, Florida, Massachusetts, and Texas (U.S. EPA, 1988). The treatment efficiency was typically good. For example, BOD removal efficiencies ranged from 37 to 91%, while total suspended solids (TSS) removal ranged from 21 to 92%. DeBusk and Reddy (1987) performed experiments in tanks with semicontinuous wastewater flow in the presence and absence of water hyacinths and pennywort. In these fixed-flowrate experiments (1.5 L/min) the removal of BOD from 130 mg/L to 10 mg/L was demonstrated.

A list of floating water plants (FWP) is given in *The Book of Water Plants* (1998). Details of wastewater purification capabilities using some of these plants are given in Table 2.

Naturally growing aquatic macrophytes can be used to remove compounds of nitrogen, phosphorous, and heavy metals by consuming them in the form of plant nutrients. For example, the following types of aquatic plants were examined for their nitrogen and phosphorous removal capacities (Tripathi et al., 1991): water hyacinths, E. crassipes; water lettuce or water soldier, Pistia stratiotes; round-leafed water fern, Salvinia; and duckweed (Lemna). Each of these plants was examined in the laboratory as well as in the field using unpolluted, moderately polluted, and highly polluted water. During the summer and rainy seasons, the Eichornia, followed by Pistia, Lemna, and Salvinia, removed the largest amounts of nitrogen. During the winter months, the Lemna had a higher removal rate of nitrogen compared with the Pistia. Higher removal of phosphorous compounds was observed in summer compared with removal during the rainy and winter seasons. During the summer and rainy seasons, removal of phosphorous compounds by macrophytes decreased in the following order: Eichhornia, Pistia, Lemna, and Salvinia. During winter months, Lemna was the most efficient in removing phosphorous compounds. The nutrientremoval capacity of the plants per unit surface area of water increased with increasing concentration in the wastewater. Removal of nitrate by selected macrophytes ranged from 42.0 to 96.2%, while phosphate removal ranged from 36.3 to 70.2%.

The FWP-based technology seems to have the following potential advantages: high sorption characteristics (physicochemical); high rate of reproduction and floating capability (biological); high rate of treatment and short adaptation time (technological); and low cost of installation and operation, profitability and reuse of product, and use of the ponds for agricultural and recreational purposes (economical). It is important to note that the fast-reproducing plants must be carefully contained to prevent their aggressive spreading into other water reservoirs, conduits, and rivers. Thus, natural water systems comprising aquatic plants such as water hyacinths can be expected to provide an efficient, cost-effective technology for environmentally clean wastewater purification worldwide, particularly in Israel. This is true in the face of the present national water shortage and the urgent need to treat wastewater for agricultural purposes. The alternative is the destruction of important and profitable sectors of the national agriculture. In this context, research efforts support the ongoing need to increase the availability and use of water by treatment and recycling.

Results

Each result is given as an average of two or three measurements taken from the same sample. The fecal coliform index and ammonium concentration were measured for a wastewater flowrate of $1.2 \text{ m}^3/\text{d}$ and prior to ozone sterilization. Wastewater in the absence of plants served as the control. The control proved that wastewater properties such as smell (due to the initial high BOD

| Common name (plant species) | Origin | Temperature (°C) | Growth rate (height [m]) | Effects | References |
|---|--------------------------------|---------------------|---------------------------------------|---|--|
| Fairy moss (Azolla californiana) | Cosmopolitan | 0–18 | Fast (Up to 0.03) | Reduction of BOD, COD, TSS, and turbidity | Jacquez and Bacquez and Bacque |
| Water hyacinth (Eichornia crassipes) | Africa, Asia, North America | 22–28 | Fast, in hot climates (Up to 0.25) | Reduction of ammonia, nitrate BOD, COD, TSS, turbidity, and heavy metals | Akoroda, 1990; Brumer, 2000; U.S. EPA, 1988; Droste, 1997; Jensen, 1988; Gopal, 1999; Salati et al., 1999; Jacquez and Walner, 1985; Tripathi et al., 1991 |
| Waterpest (Elodea canadensis) | Cosmopolitan | 0–28 | 0.1 m per week (Up to 0.8) | Reduction of BOD, COD, and TSS | Kadlec, 1995 |
| Pennywort (Hydrocotyle umbellate) | Tropical South America | 2228 | 0.1 per week (Up to 0.6) | Reduction of BOD, COD, and TSS | U.S. EPA, 1988 |
| Duckweeds (Lemna) | Cosmopolitan | 5–25 | (Up to 0.03) | Reduction of BOD, COD, TSS, nitrogen, phosphorus, nitrate, and phosphate | Bonomo et al., 1997; U.S. EPA, 1988; Droste, 1997; Gopal, 1999; Tripathi et al., 1991 |
| Watersalad (Pistia stratiotes) | Cosmopolitan | 22–28 | ``(Up to 0.25) | Reduction of BOD, COD, TSS, nitrogen, phosphorus, nitrate, and phosphate | Brumer, 2000; Tripathi et al., 1991 |
| Floating fern (Salvinia natans) | America | 0–18 | (Up to 0.05) | Reduction of BOD, COD, TSS, turbidity, nitrate, and phosphate | Salati et al., 1999; Tripathi et al., 1991 |

Table 2-Data of wastewater purification by typical floating plants.

level) and other water quality indicators persist in the absence of the plants. A drastic change in these indicators occurs when the plants are introduced. For example, turbidity and BOD levels in the presence of plants were reduced after 2 to 3 days to the level set by the U.S. Environmental Protection Agency (U.S. EPA). In the absence of the plants, this level was not achieved during 10 to 12 days.

The following floating weeds were selected for laboratory experiments: Alodea, E. crassipes, Hydrocotyle, Salvinia, and Lemna. Two experimental setups were used: the smaller unit was operated inside and the larger was operated outside of the laboratory. A diagram of the laboratory unit is shown in Figure 1. Five identical vessels (0.45 \times 0.7 m floor area) supplied with compressed air were used to grow five different types of weeds in parallel. The growth process was monitored by measurements of turbidity and conductivity (e.g., of control drinking water and raw and treated wastewater). The turbidity levels in the presence of all five floating water weeds were significantly reduced (e.g., less than 1 Nephelometric turbidity unit [NTU]) after 6 days of the plants' growth (Figure 2a) in wastewater consisting of 0.035 m³ of fresh water mixed with 0.007 m³ of wastewater (see composition later in this section). After day 6, the turbidity level remained nearly unchanged. Then, after day 8, additional wastewater (0.008 m³) was introduced. This produced a jump in the turbidity levels, which then gradually decreased (after a few days) to the level measured before the dosage of wastewater (Figure 2b). The growth rates of the weeds were tested at different concentrations of wastewater in the water. The growing weeds consumed the wastewater so that water turbidity decreased with time and, in specific cases, even to the levels found in drinking water. The conductivity of the mixture was in the 1.45to-1.55 mS/cm range, compared with 1.3 to 1.5 mS/cm that is characteristic of local tap water. This provided initial evidence that the tested weeds can be effective in cleaning the water from organic wastewater contents. However, the low turbidity levels need to be supported by additional criteria that characterize the water quality before the efficiency of the weeds' performance can be assessed.

A second experimental setup was constructed in the yard of the civil engineering department of Technion Israel Institute of Technology, Haifa. It was used to examine the performance of the floating weeds in the presence of mixtures of wastewater and water from the Kishon River. Three small pools $(2 \text{ m} \times 4 \text{ m} \text{ floor}$ area) were built and used to grow *E. crassipes* plants. The plants, which had dark green leaves, developed a wide root system during the winter months. It is important to note that in winter the growth rate of these plants is significantly lower compared with summer.

Four small (0.45 m \times 0.7 m floor area) containers were prepared with compositions of 100, 90, 80, and 70% wastewater, the balance

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Figure 1—Schematic layout of laboratory setup.

being downstream water (Table 1) from the Kishon River (i.e., 0, 10, 20, and 30%). The volume of the tested wastewater (0.1-m deep) was set at 0.0315 m³ in each container. These tests were performed without aeration.

The wastewater characteristics were 150 to 250 mg/L, 400 to 500 mg/L, 40 to 50 mg/L, and 100 mg/L for BOD, chemical oxygen demand (COD), ammonia, and TSS, respectively.



During the period from December 2000 to January 2001, samples of wastewater were collected from the containers every 3 to 5 days. Standard analyses (APHA et al., 1985) were made, including measurements of turbidity, BOD, TSS, and pH. In the first set of experiments (Figure 3a), the turbidity levels of the 80 and 100% wastewater mixtures decreased after 8 to 10 days from 11 NTU to 6 NTU. In this context, the U.S. EPA requirement regarding water quality for agricultural purposes is 2 NTU. It is important to note that in the 70% wastewater mixture, a smaller decrease in turbidity occurred. The initial small increase of turbidity may have occurred because of the effect of air pollution (experiments were made near a road). The pH level of the polluted Kishon water was 2.6. The presence of floating plants (E. crassipes) increased the pH (Figure 3b). The water plants are more effective at low pH. For example, after 15 days for the 30% Kishon water mixture, the pH rose nearly 1 unit from 3 to 4. In contrast, at 10% Kishon water the pH did not increase by more than one-half a unit (from 7 to 7.5).

A third set of experiments was performed using the same mixtures, but in larger containers $(1-m^2 \text{ floor area})$. The wastewater volume and level (above floor) were set at 0.15 m³ and 0.15 m, respectively. After 19 days retention, the TSS concentration of a mixture containing 30% Kishon water and 70% wastewater was reduced from 99.9 mg/L to 26.9 mg/L. The results (Figure 4a) indicate that all of the treated mixtures were acceptable for irrigation in Israel, for example, in stable areas consisting of soils that do not render them sensitive to underground water pollution (compare to local guideline 2, at a TSS concentration of 30 mg/L). An increase of less than one pH unit was observed in the presence of E.

Figure 2—(a) Variation of wastewater turbidity versus time in the presence of different aquatic plants and (b) effect of the addition of 0.008 m^3 of wastewater after 9 days on time dependence of the turbidity.



Figure 3—Variation of (a) turbidity and (b) pH versus time for different mixtures of wastewater and water from the Kishon River.

crassipes (Figure 4b). After 19 days of retention, pH levels of 7.8 to 8.0 were reached for all of the compositions tested. The turbidity levels were reduced in all four mixtures to the levels required by U.S. EPA (i.e., 1.5 to 2.4 NTU) (Figure 5a). After 19 days, the BOD concentration levels were reduced to the level specified by the Ministry of Environmental Protection (MEP) for irrigation in Israel (e.g., in unstable areas consisting of soils that render them sensitive to underground water pollution, where the allowed BOD concentration is 10 mg/L) (Figure 5b). Figure 5c shows kinetic data of BOD variation with time for the four water compositions tested. A treatment period of 12 days reduced BOD concentration to less than 20 mg/L, while 19 days were required to reach a concentration of less than 10 mg/L.

A fourth set of experiments was performed using water obtained from upstream sections of the Kishon River with no industrial effluents. The BOD concentration for this water was 10 to 15 mg/L and the turbidity level was 4 NTU. After treatment by the floating plants (*E. crassipes*), removals of 28% of the BOD and 39 to 65% of the turbidity were recorded.

A fifth set of experiments was performed using wastewater in containers with 1 m² of floor area and a pilot pool with 18 m² of floor area. The results are shown in Figures 6a and 6b. The COD concentration of the wastewater was 493 mg/L, the BOD concentration was 172 to 233 mg/L, and the turbidity was 11 to 15 NTU (Table 3). After a treatment period of 9 days with *E. crassipes*, 80 to 87% of the turbidity, 72 to 85% of the BOD, and 77 to 87% of



Figure 4—(a) Total suspended solids concentration before and after 19 days of treatment of four different water mixtures and (b) variation of pH versus time of the water mixtures.

the COD were eliminated. Figure 6 shows good agreement between results obtained with containers and the pilot pool.

The decrease in turbidity levels resulting from natural particle agglomeration was 65 to 68% compared with 80 to 87% achieved by aquatic plants under the same conditions. Table 3 summarizes the results of laboratory and pilot experiments. Most experiments were focused on the use of *E. crassipes* for wastewater purification. The observed changes in turbidity, BOD, TSS, COD, and pH because of treatment of the water mixtures demonstrate that floating plants such as *E. crassipes* can be effective (particularly when combined with aeration) for wastewater purification, but less so for acidic water. The plants need pH levels greater than 5 to be effective. Otherwise, there must be a lag time until the pH reaches the required level. As previously discussed, the temperature affects the growth rate of the plants.

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Table 4 gives typical monthly ranges of local temperatures. Thus, in May, the temperature fluctuations in the pilot experiment (Table 3) are believed to range from 18.8 to 27.1 $^{\circ}$ C.

Specific details of Table 3 show the following results. At 25% wastewater and 75% fresh water, all plants (except *Lemna*) were able to either lower or keep the turbidity level below 0.8 NTU. The different initial turbidity levels were set by the different plants used in the test. The plants proved to be effective in further reducing the turbidity from relatively low initial levels. This implies that cascade or stepwise treatment processes with final stages in the low turbidity levels are feasible (e.g., to achieve standards that are closer to those of drinking water). If the initial turbidity is sufficiently low, then the plant may even cause a rise in turbidity, as observed with *Salvinia*. The capability of *Eichornia* to decrease the turbidity from 1.49 to 0.34 in 9 days is notable. The introduction of acidic water from the





Figure 5—(a) Turbidity concentration before and after treatment of four water mixtures, (b) biological oxygen demand concentration before and after treatment of the mixtures, and (c) variation of BOD versus time in the water mixtures.

downstream section of the Kishon River inhibited the capability of *Eichornia* to decrease the water turbidity. It seems that the plants were affected differently by toxic ingredients that were present in the Kishon River at different testing periods. In the series of tests performed during the period from December 2000 to January 2001, the plants were not able to decrease the turbidity below 5.5 NTU and the results varied between 5.5 and 7.9 NTU (e.g., as the content of the Kishon water changed from 10 to 30%). A significant improvement in the capacity of the plants to decrease the turbidity was observed in the tests conducted during February and March 2001. In these tests, the turbidity was brought down to 1.8 to 2.0 NTU in the presence of up to 30% downstream Kishon water. It is important to note that the result with zero percent Kishon water seems to be somewhat anomalous in the sense that it indicates



Figure 6—Comparison between container and pool experiments: (a) variation of COD versus time and (b) variation of turbidity versus time.

possible fluctuation or contamination by external sources during the outdoor experiment. The experiments performed during March, April, and May 2001 proved that the plants are capable of effecting a 65 to 89% decrease in turbidity levels (down to the 1.2 to 1.5 NTU range) in mixtures containing water from downstream as well as upstream sections of the Kishon River.

The capacity of the *Eichornia* plants to decrease BOD (by 80 to 88%) provided a strong indication of their potential applicability for purification of mixtures of wastewater and water from different sections of the Kishon River.

A sixth set of experiments was performed to test the effect of daily dosages of wastewater on the quality of the treated water. Four containers of wastewater were used for this purpose. The volume of water (0.17-m deep) in each container was fixed at 0.05 m³, and wastewater was added daily. During the first 5 days, the dosage was $0.025 \text{ m}^3/\text{d}$; in each of the following three groups of 4 days, the dosage was 0.05, 0.075, and 0.1 m³/d. Initially, fresh water was used to support the floating plants and then, following the dosage of wastewater and mixing, the excess water was withdrawn to set the mixture volume back at 0.05 m³. These experiments were set to prove the water purification efficiency of the plants because if they were ineffective then wastewater.

The tests were performed in each container with aeration of 125 L/h as well as 30 min/h of artificial light at 2700 to 2900 lux. Figure 7 depicts results of COD and BOD concentration versus time, and Figure 8 shows a plot of pH versus time. Figure 7 shows that the rate of wastewater addition in the range of 0.025 to 0.1 m³/d did not change the capacity of the plants to produce water with COD and BOD concentrations lower than the allowed levels set by MEP guidelines. In the case of BOD (Figure 7b), all of the results except for two were less than local guideline 2 (20 mg/L), and those for 0.025 and 0.05 m³/d were less than local guideline 1 (10 mg/L). Figure 7b shows that following a period of adaptation between days

| Table 3-R | esults of I | aboratory ar | d pilot wate | r purification | n experiments." |
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| Period of | | cor | Wa npos | ater ition (| %) | | pł | 4 | | Turbidity (NTU) | | | ty BOD (mg/L) | | | COD (mg/L) | | |
|--|---|-----------------------|------------|-----------------|--|--------------------------------------|--------------------------------------|--------------------------------------|------------------------------------|-------------------------------------|---------------------------------|------------------|----------------------------|--------------------------|----------------------------------|-------------------|---------------|----------------------------|
| experiment, (days) scale | Type of plants | S | F | Ku | Kd | в | E | Change | В | E | Change (% | %) I | в | E | Change (%) | В | E | Change (%) |
| August 2000 (9) L | Salvinia Elodea Hydrocotyle Lemna Eichornia | 25 | 75 | · · ··· | | 7,41 7.75 7.53 7.05 7.06 | 7.72 8.58 7.56 7.53 7.69 | 0.31 0.83 0.03 0.48 0.63 | 0.49 1.6 1.95 4.6 1.49 | 0.59 0.8 0.76 1.12 0.34 | +20 -50 -61 -75 -77 | | | | | | | |
| December 2000– January 2001 (17) L | Eichornia | 70 80 90 100 | | ۰. ب | 30 20 10 | 2.95 4.35 6.5 6.9 | 3.39 6.09 7.38 7.6 | 0.44 1.74 0.88 0.7 | 10.5 10.5 7 11 | 7.9 5.6 5.5 5.8 | -25 -47 +21 -47 | | | | | | | |
| February– March 2001 (21) L | Eichornia | 80 90 100 70 | | - | 20 10 30 | 7.3 7.26 7.4 7 | 8.0 8.01 7.99 7.95 | 0.7 0.75 0.59 0.95 | 7 11 8.6 4.4 | ିଶ .8 1.9 ି 3.1 .2.0 | -74 -83 -64 -55 | 2 5 5 5 | 43 56.6 50.2 32.7 | 8.(9.! 8.(5.! | 6 -80 5 -83 0 -88 8 -82 | | | 1. |
| April 2001 (13) L (10) L | Eichornia | 70 | | 100 | 30 | 6.48 7.59 | 6.74 7.94 | 0.26 0.35 | 14 3.4 | 1.5 1.2 | -89 -65 | | 50.8 13.1 | 8: 9. | 1 –84 5 –27 | | ~ | |
| May 2001 (11) L (9) L (9) P | Eichornia 19718200 | 100 | | 100 51670 | 1. 1. 1. 1. 1. 1. 1. 1. 1. 1. 1. 1. 1. 1. 1 | 8.43 7.27 7.24 | 7.99 6.55 7. 3 3 | -0.44 -0.72 0.09 | 11 15 | 2.2 1.9 | -80 -87 | 1 2 | <5 72 33 | <5 25 65 | -85 -72 | 112 494 493 | 99 11 6 | 9 – 12 5 – 77 5 – 87 |

^a B – beginning of experiment; E – end of experiment; F – fresh water; S – wastewater; K_u – water from upstream sections of the Kishon River; K_d – water from downstream sections of the Kishon River. Scale: L – laboratory, P – pilot.

10 and 14, the plants were capable of reducing BOD less than local guideline 1, even for the highest $0.1\text{-m}^3/\text{d}$ rate of wastewater addition. At day 16, the BOD decreased to 5 mg/L, falling further to 2 mg/L at day 17. Figure 8 shows that the plants were capable of maintaining the pH level in the 7.1-to-8.2 range for all rates of wastewater additions. The conductivity increased moderately from 1.17 to 1.67 mS/cm in the $0.025\text{-to-}0.1\text{m}^3/\text{d}$ range of wastewater addition rates. The increased conductivity reflects the effect of salt content in the wastewater. This set of experiments shows that treatment with aquatic plants can produce water for irrigation in a semicontinuous process where steady daily wastewater dosages are introduced to the processing units.

A seventh set of experiments was performed to test the effect of daily dosages of wastewater on the quality of the treated water under field conditions of the pilot unit. To this end, use was made of a major section (2 m \times 5 m floor area) of the pilot pool. The volume of water (0.33-m deep) in the pool was fixed at 4.0 m³. Wastewater was added daily for 52 days. The dosage was increased in daily steps from 0.1 up to 1.6 m³/d. Initially, fresh water was used to support the floating plants and then, following the dosage of wastewater and mixing, the excess liquid was withdrawn to set the mixture volume back at the operating level of 4.0 m³. The tests were performed at daylight with aeration. Figure 9 depicts results of COD and BOD concentration versus time and the corresponding cumulative specific dosage of wastewater per cubic meter of the fixed-mixture volume. The figure shows that the plants (with aeration) were capable of maintaining BOD below the guideline level (20 mg/L) set by MEP. The specific contribution of the plants in the absence of aeration was estimated at 90 to 96% (compared with 80% in their absence, i.e., in the control) in a separate set of experiments. In the presence of aeration, the total removal rate rose to 99.4%. At day 35, BOD increased to 3.7 mg/L, reaching its highest concentration of 19.4 mg/L at day 51. Typical spring and autumn BOD concentrations of purified water from different Israeli water treatment plants are given in Table 5 (Statistical Abstract of Israel, 2000). Comparing these concentrations with the relatively low concentrations that were reached after treatment with naturally growing plants (Table 3) points at the potential effectiveness of this method (e.g., in the context of national efforts to increase Israel's water resources).

In the case of COD concentration (Figure 9), the MEP guideline (70 mg/L) was exceeded between days 14 and 35, although the concentration remained close to this guideline up to day 50. This shows that a second treatment stage can also reduce the COD lower than 70 mg/L.

The growth rate of the plants was measured during the winter by recording their weight. A two- to fivefold increase in the plants' mass was recorded. The higher the temperature, the larger the increase in mass. Removal of ammonia and nitrite by *E. crassipes* ranged from 80.0 to 95.0% and that of phosphate ranged from 75 to 80%. The fecal coliform index level in this experiment was decreased by an order of magnitude to 4×10^4 most probable number (MPN). A relatively low index of fecal coliform levels per

Table 4—Typical monthly range of local temperature (°C).

| Month | 1 2 | 3.4 | 5. | 6 | . 8 | 9 | 10 11 | 12 |
|---------|-----------|-----------|----------|-----------|------|--------|-----------|--------|
| Minimum | 10.3 10.3 | 3 12.3 14 | .7 18.8 | 22.1 24.7 | 24.9 | 23.4 | 19.1 14. | 5 11.2 |
| Maximum | 18.9 19. | 0 21.0 22 | 2.5 27.1 | 29.5 31.2 | 31.9 | 31.1 2 | 28.1 24.1 | 7 21.7 |



Figure 7—Results of semicontinuous treatment with variable daily dosage: (a) chemical oxygen demand versus time and (b) biological oxygen demand versus time.

10 mL, which ranges from 0 to 8 MPN, were reached after treatment with the plants, followed by ozone sterilization. This demonstrates the effectiveness of wastewater treatment with plants as part of a process for production of irrigation water.

The results obtained hitherto suggest that aquatic plants can be used to purify wastewater that is generated by different agricultural settlements and urban sources. In partricular, this applies to the sources, which vary in location and size, existing along the upstream path of the Kishon River. Because most are relatively small, the wastewater discharges can be treated at their source by processing units of aquatic plants that do not occupy large areas. This can be part of a plan to recycle water from purified wastewater



Figure 8—Results of semicontinuous treatment with variable daily dosage: pH versus time.



Figure 9—Results of semicontinuous treatment with variable daily dosage of 250 mg/L BOD wastewater (BOD and COD vs time and cumulative specific dosage of wastewater).

streams and to restore contaminated sections of the Kishon River to their natural habitat.

Figure 10 shows a conceptual partitioning of the downstream region of the Kishon River into three functional zones. In zone A, the entering water is polluted by agricultural runoff and wastewater from upstream areas. Zone B is characterized by discharge of industrial effluents. Zone C, which extends into Haifa Bay, is characterized by intrusion of saline water that forms a mixture with the industrial effluents. There are no clear boundaries between these zones. The basic concept is to apply aquatic plants at the sources (where wastewater is discharged) to clean the water entering zone A and then to split the flow into two streams. One stream will absorb and continue to carry the industrial effluents and the other will be used to develop a park on both sides of the river. The contaminated stream will continue to flow in a pipe until it is discharged in a proper location in Haifa Bay. In this way, protection of the riverbanks and their vicinity is expected. This concept provides solutions to the needs of industry as well as much needed improvement to the river environment.

The pond areas required for treatment at the source with aquaticplant units can be estimated by one of the following equations (U.S. EPA, 1988; WEF, 1998):

$$S = \frac{(C_0 - C_e)Q_0}{k} \tag{1}$$

$$S = \frac{Q_0 (\ln C_0 - \ln C_e)}{k_t dn^1}$$
 (2)

Where

$$Q_0$$
 = wastewater flowrate (m³/d);
 C_0 and C_e = influent and effluent BOD concentrations or,
alternatively, the BOD loading density (kg/m³):

Table 5—Typical BOD levels of treated water from different locations in Israel (data 1999).

| BOD (mg/L) | Ogg Jerusalem | Tiberias | Akko | Haifa | Ashqeion |
|---------------|------------------|----------|---------|-------|----------|
| Spring/Autumn | 74/320 | 57/105 | 635/348 | 13/30 | 90/70 |



Figure 10—Partitioning of the downstream area of the Kishon River into functional zones (1, 3—park zones; 2—industrial zone; 4—wastewater treatment plan of the Haifa district; 5, 6, 7, and 8—Kishon River streams after purification; 9—wastewater stream; 10—barrier; 11—rain water). The stream (6) entering from zone A consists of water purified by the action of aquatic plants.

- $k = \text{specific BOD loading rate } (kg[m^2 \cdot d]);$
- $k_t =$ first-order rate coefficient (day⁻¹) (valued at 1.1) (Reed et al., 1995);
- d = depth of pond (m); and
- n^1 = drainage voids (0.38 for a bed of medium to coarse gravel) (Reed et al., 1995).

Figure 11a shows a plot of wastewater flowrate per unit of pond area versus influent BOD for the case where the required BOD concentration in the purified water is set at 20 mg/L. Figure 11b shows a plot of required pond area per unit flowrate of wastewater versus influent BOD for the same quality (BOD = 20 mg/L) of the purified water. For example, $1000 \text{ m}^3/\text{d}$ of influent wastewater at an influent BOD concentration of 200 mg/L and effluent BOD concentration of 200 mg/L and effluent BOD concentration of 200 mg/L and effluent BOD concentration of 20 mg/L requires an area of 5500, 7400, and 11 100 m² for 1.0, 0.75, and 0.5 m of water depth, respectively (Figure 11b). Alternatively (Figure 11a), at 200 mg/L influent BOD, the flowrate per unit area for 1.0, 0.75, and 0.5 m of water depth is 0.09, 0.136, and 0.18 m³/(m² day), respectively. Hence, the corresponding areas for a flowrate of 1000 m³/d are 5556, 7353, and 11 111 m².

Pilot data (Figure 9) obtained from a pool with 10 m² of floor area show that the plants were capable of decreasing BOD concentrations from 250 mg/L to 10 mg/L (or lower). Average daily flowrates from days 34 to 39, 41 to 46, and 48 to 51 were 1.040, 1.430, and 1.575 m³/d, respectively. Using these flowrates in eq 1 and solving for C_I gives the following respective values of BOD loading per unit area: 249.6 × 10⁻⁴ kg/(m²·d), 343.2 × 10⁻⁴ kg/(m²·d), and 378 × 10⁻⁴ kg/(m²·d). These values compare well with the recommended BOD loading per unit area (e.g., 0.015 to 0.03 kg/[m²·d]) given in the literature (U.S. EPA, 1988). Thus, if the required flowrate Q_0 is 1000 m³/d, and the same initial and final BOD concentrations are used, the area corresponding to the aforementioned BOD loading is 6350, 7000, and 9600 m², respectively.

The price per cubic meter of fresh water depends on the consumption. There is a stepwise increase in price with an increase in consumption. For example, in Israel the price of purified water



Figure 11—(a) Flowrate per unit pond area versus BOD and (b) pond area per unit flowrate versus BOD for different values of pond depth (effluent BOD = 20 mg/L).

can reach costs as high as 0.5 to $1.0/m^3$ (Hofman and Harusi, 2001). Because of the current water crisis in Israel, water authorities are unable to supply fresh water even at the highest price levels. Therefore, treatment of wastewater at the source by relatively small aquatic-plant units can be a cost-effective solution for the current acute water shortage. Table 6 provides a cost comparison of treatment by aquatic-plant units with other alternatives for water purification.

The cost estimate (in U.S. dollars) is based on a cascade system of processing ponds. The current Israeli practice shows that the expected cost for surface earth development (depth of 0.5 to 1.0 m) is \$2.5 to $4/m^2$ of pond area. The cost of geotextile and plastic sheets is \$5 to $6/m^2$ of pond area, and the expected cost of piping is \$3 to $4/m^2$ of pond area. Any estimate must reflect the effect of topographical conditions on the cost. For example, \$10.5 to $14/m^2$ cost that is estimated for simple planar topography increases to \$12 to $20/m^2$ in the case of a more complex hilly topography. The cost of aquatic plants is estimated at \$4 to $5/m^2$ of pond area.

A typical wastewater flowrate per unit area in aquatic-plant ponds varies from 0.007 $m^3/(m^2 \cdot d)$ up to 1.028 $m^3/(m^2 \cdot d)$. In this work,

Table 6—Comparison of cost of water treatment by different technologies.

| Type of treatment | Processing cost (\$US/m ³) | Intended use |
|--|---|------------------------------------|
| Desalination (Hofman and Harusi, 2001) | 0.65–1.0 | Industry, aquifer replenishment |
| Quaternary (Hofman and Harusi 2001) | 0.46–0.7 | Industry, aquifer replenishment |
| Units of aquatic plant | 1 10.2-0.4 | Industry, agriculture |

the average yearly flowrate per unit pond area is assumed to be 0.1 $m^3/(m^2 \cdot d)$. This gives 36.5 m^3 of treated water from 1 m^2 of pond area per year, or 365 $m^3/(m^2 \cdot d)$ in 10 years. Using a construction cost range of \$16 to $25/m^2$, a processing cost range of \$0.2 to $0.4/m^2$, and a net profit range of \$0.2 to $0.4/m^2$ from sales of the purified water shows that a return on the capital investment can be expected within 1.1 to 3.4 years.

Although water purified by aquatic-plant units cannot be used as fresh water, it may be used in industry and agriculture as part of an effort to increase available water resources in Israel and neighboring countries. The use of natural water-purification technologies provides favorable cost-benefit ratios, as evidenced by

- Reduction of pollutant loading at its source, especially in small towns and villages;
- Effective water reuse as irrigation water;
- Regulation of the hydroperiod of rivers to safeguard baseline flow conditions;
- Restoration of ecological function to polluted regions and facilitation of multiple use of the area for spawning of marine life, conservation of nature, protection of migratory birds, passive recreation, and promotion of ecotourism;
- Service as a model for environmentally friendly and effective water management in arid and hot climate countries; and
- Growing plants as a means to improve water quality and elimination of disturbing wastewater smell.

Conclusions

The potential use of aquatic plants for improving river water quality was considered in this work. Laboratory as well as pilot experiments indicated the viability of this approach, particularly for the section of the Kishon River polluted with wastewater, not industrial effluents. This relates to a reduction in values of major water-quality indicators such as BOD, TSS, COD, and turbidity. The plants (primarily E. crassipes) were capable of reducing these variables to concentrations required by national and local guidelines as well as international standards for irrigation water. Furthermore, the plants eliminated the disturbing smell of wastewater, which poses serious problems in various locations throughout the country. The aquatic-plants system offers an environmentally friendly and cost-effective technology for treatment of urban and agricultural wastewater in Israel. In particular, this applies to small- and medium-size communities and agricultural enterprises. In the case of the Kishon River, aquatic plants can be used to purify water coming from the upstream sections of the river. The treated stream can then be used to nourish new park areas in the

May/June 2004

downstream sections by splitting the stream into two channels. One channel will continue to carry the heavily polluted industrial effluents, whereas the second channel will supply cleaner water to the water parks on both sides of the river. This is expected to rehabilitate the river and its ecosystem.

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