



## 018530 - SWITCH

### Sustainable Water Management in the City of the Future

Integrated Project  
Global Change and Ecosystems

#### Deliverable reference number and title

**D 3.3.7 Design parameters and manual of operation of environmental friendly technologies for upgrading secondary effluent to the quality required for stream rehabilitation and other municipal reuse purposes**

Due date of deliverable: M60  
Actual submission date: M60

Start date of project: 1 February 2006

Duration: 60 months

Organisation name of lead contractor for this deliverable  
**HUJI – THE HEBREW UNIVERSITY OF JERUSALEM**

Revision [Final]

| Project co-funded by the European Commission within the Sixth Framework Programme (2002-2006) |   |    |
|---|---|----|
| Dissemination Level   |   |    |
| <b>PU</b>   | Public  | PU |
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**MANUAL FOR PLANNING, DESIGN AND OPERATION OF  
ELECTROFLOCCULATION-CONSTRUCTED WETLAND HYBRID  
SYSTEM**

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## ABSTRACT

**Reusing or recycling wastewater** in urban areas and stream rehabilitation requires discharge of high quality effluent complying with strict nutrient standards as well as development of feasible treatment alternatives. Constructed wetland is already a proven technology for efficient polishing of wastewater effluents except for phosphorous.

**This manual** is a user's guide based on a hybrid system of constructed wetland- electroflocculation for polishing secondary effluent of Shafdan municipal wastewater treatment plant, Israel. The purpose of this manual is to demonstrate how to calibrate, operate and maintain this hybrid system based on wastewater characterization, so that this technology could be transferred to other sites as well.

**The scientific work** of this research concentrated on the coupling of Electroflocculation (EF) with constructed wetland (CW) for improved contaminants removal, phosphorous in particular, from secondary effluents. The work consisted of three phases: (i) electro-jar testing, (ii) continuous-flow EF-filtration (GF)-CW bench scale experimentation and (iii) field, half-industrial piloting. P, turbidity, TSS and TOC were particularly monitored. Laboratory experiments showed that EF-GF effectively removed phosphate (96%), while CW effectively removed organic matter (85%). Therefore, it seemed that the coupling of both unit processes would enhance the overall removal efficiencies. Field pilot results show that EF-GF removed up to 97% of total phosphorus, resulting in P concentrations of <0.4 mg/L, which are extraordinary results by any comparison. In addition to phosphorus removal, from the ecological point of view ammonia removal is as important as phosphorus. One of the advantages of the CW is efficient ammonia removal (over 90% in the first vertical cell with very low HRT). This is also important as the EF-CW hybrid consist of a vertical subsurface flow wetland which is the best for ammonia as well as low-medium concentrations of BOD and TSS.

The system is capable of reducing some of the TOC (up to 53%) and most of the TSS up to 82%). The EF-CW hybrid action is explained by combining flocculation and adsorption mechanisms produced by the EF with filtration, sedimentation, sorption, and biodegradation processes in the CW beds. **The Manual** covers, among others, operator and management responsibilities, description of the unit processes, treatment requirements/effluent limitations, system general and detailed design, system operation and product water quality control, maintenance program, safety measures and frequently asked questions – potential operational problems and solutions.

**Such a Manual can be used** by city engineers, operators, students and researchers, as well as by strategic planners and decision makers who have been looking for sustainable purification systems, which are still not too many. Dissemination of the manual may be done by using real and virtual bookstores, as well as by seminars and demonstrations.



## **ACKNOWLEDGEMENTS**

This Manual was prepared as a part of a research project sponsored by EU SWITCH Project under the Sixth Framework Programme. The Constructed Wetland used in this research was constructed and operated by support of the Ministry of Territory and Environment (Italy), under the auspices of the Porter School of Environmental Studies, Tel-Aviv University (Israel).

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## **1. INTRODUCTION**

Discharge of effluent into streams and rivers is a common practice worldwide. In arid lands competition for the freshwater for human use diminishes stream flow and effluents often make much of the base flow. In such situations stream health and rehabilitation highly depend on effluent quality. Strict standards for effluent disposal call for economic and efficient treatment alternatives.

### **1.1 Principles of wastewater treatment by wetland-electroflocculation hybrid system**

#### **1.1.1 Constructed wetland**

Constructed wetland (CW) is an environmental friendly technology for treating wastewater or polishing effluent that is becoming increasingly popular in many parts of the world (Haberl, 2003). It is designed and constructed based on natural marshes (Kadlec and Wallace, 2008). CWs are often classified by the pattern of effluent flow in the system (Brix, 2003). In free-flow (surface flow - SF) systems wastewater flows above the ground through emerged, submerged and floating aquatic vegetation. In subsurface flow systems wastewater moves through a porous medium such as gravel or aggregates, in which rooted hydrophytes grow (USEPA, 2000). Subsurface systems are further classified into horizontal flow (HF), in which anaerobic conditions prevail, or vertical flow (VF) which maintains aerobic conditions. Low flow velocities coupled with the presence of roots and solid substrate, promote settling and filtration of particulate material. Biofilm of diverse microorganisms that develops on the surface of the porous medium and the submerged vegetation is responsible for most of the biotransformation and mineralization of pollutants. (Vymazal, 2003; Kadlec and Wallace, 2008). CWs usually remove organic matter efficiently. Vertical flow wetlands can oxidize organic and ammonia nitrogen (predominant forms of nitrogen in municipal effluents) effectively. Oxidized nitrogen forms can be further transformed in downstream HF or SF wetlands to nitrogenous gas (via denitrification), resulting in total nitrogen removal. Since organic carbon is required for denitrification, surface flow wetlands are favored for nitrate removal under low organic matter conditions (e.g. polishing effluent). Under such conditions decomposed plant litter can serve as a source for organic carbon.



Recent investigations indicate that VF CW efficiently removes micropollutants such as estrogens (e.g., Milstein et al., 2009), pharmaceuticals and personal care products (e.g., Matamoros et al., 2007) but are less efficient in removing phosphorous (P) compounds (Kadlec and Wallace, 2008). Retention of P in CWs includes peat/soil accretion (mostly in natural and free flow systems), soil adsorption, precipitation and plant uptake (Vymazal, 2003). In subsurface systems removal by plants is limited and requires plant harvesting annually. The adsorption and chemical precipitation of phosphorus is much more vigorous at the initial operation stage because the process has finite capacity (USEPA, 2000). As a result, CW capacity for phosphorous removal is quite limited. Complement process (e.g. physiochemical process) should be used before or after CW to remove phosphorous efficiently.

#### 1.1.2 Electroflocculation (EF)

Electroflocculation (electrocoagulation) presents an alternative method to conventional (chemical) flocculation with several advantages: easy operation, lower quantities of produced sludge, avoidance of chemical usage and, most importantly, no anions such as chloride or sulfate need to be added to the solution (Mollah et al., 2001). Unlike conventional flocculation in which the coagulants are added to the water as salts, in the EF process, the coagulants (iron or aluminum) are added to the solution by dissolving the anode in an electrochemical cell. These coagulant ions ultimately lead to aggregation of the original particles in the water, which are removed in a later sedimentation or filtration process.

Electroflocculation has been increasingly used in North America for the treatment of industrial wastewater from pulp and paper industries, mining and metal processing industries, foodstuff wastes, oil wastes, dyes, suspended particles, chemical and mechanical polishing waste, organic matter from landfill leachates, deoxygenation of water, synthetic detergent effluents, mine wastes and heavy metal-containing solution (Mollah et al., 2001).

It can be hypothesized, that due to the oxygen and hydroxide radicals formed during the EF process, the EFactor may have additional abilities in removing pathogens; heavy metals, and

possibly endocrine disruptors. These capabilities can provide a considerable improvement over conventional or modified CW systems.

If EF unit (EFactor) is hybrid with constructed wetland, it may result to shorter residence time, better water quality, reduced costs for land, construction and maintenance of the constructed wetlands as well as water loss.

## 1.2 Purpose, intent and manual organization

This manual is a user guide of a hybrid system of constructed wetland- electroflocculation polishing secondary effluent, based on the studies conducted with effluent of Shafdan municipal wastewater treatment plant, Israel.

The main purpose of this manual is to demonstrate how to calibrate, operate and maintain this hybrid system based on wastewater characterization.

## 2. OPERATION AND MAINTENANCE OF CONSTRUCTED WETLAND-ELECTROFLOCCULATION HYBRID SYSTEM (A PILOT TREATMENT OF SECONDARY EFFLUENT FROM SHAFDAN MUNICIPAL WASTEWATER TREATMENT PLANT, ISRAEL)

### 2.1 Flow scheme

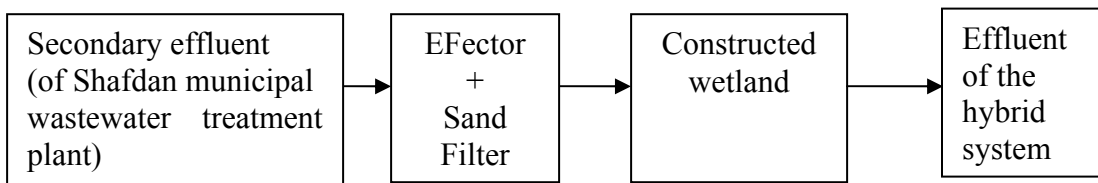


Fig.1 Flow scheme of a hybrid system of constructed wetland- electroflocculation.

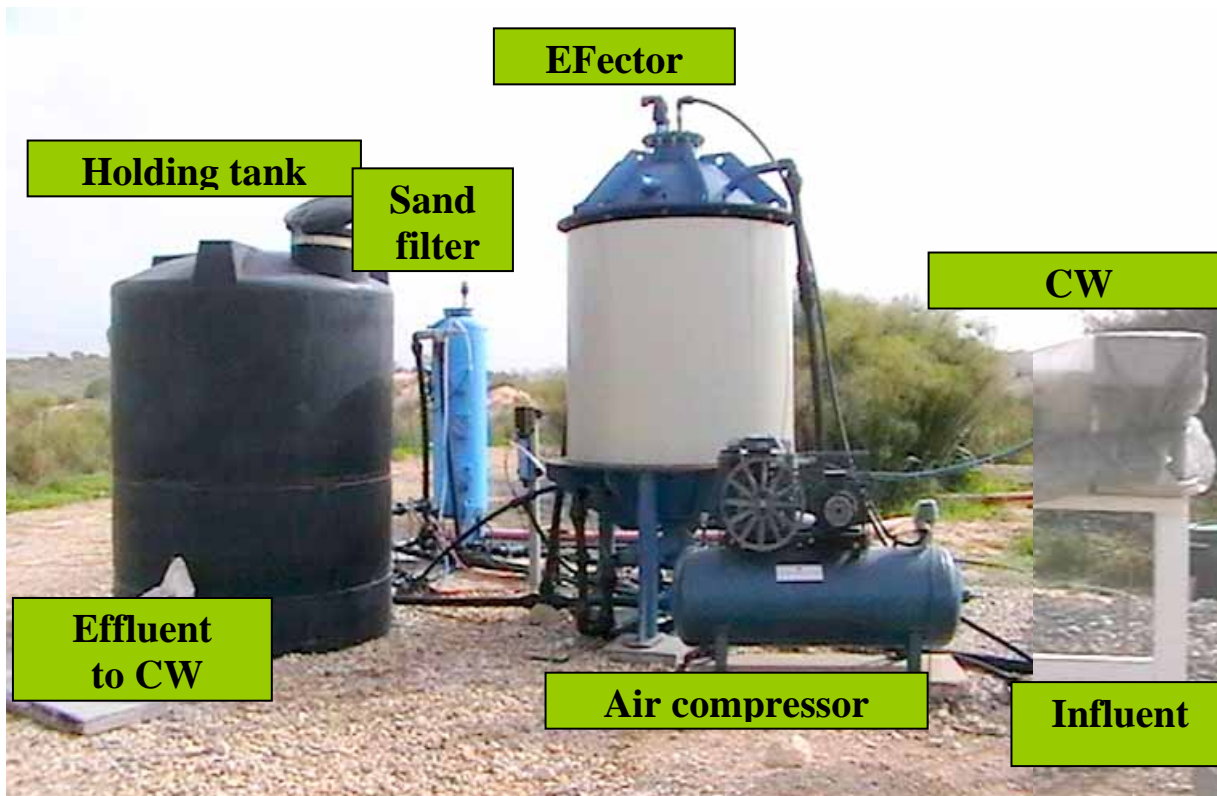


Fig.2 A pilot-scale hybrid system of electroflocculation-constructed wetland in Shafdan municipal wastewater treatment plant, Israel.

## 2.2 General design

### 2.2.1 Characteristics of secondary effluent of Shafdan municipal wastewater treatment plant

Design for this specific pilot-scale hybrid system is based on the laboratory-scale experimental results and the Shafdan effluents characteristics which are (annual average): turbidity 6.4 NTU, phosphate, as P 2.7 mg/l, BOD 12 mg/l, COD 51 mg/l, nitrogen 9.2 mg/l, pH 7.35, Fe<0.1 mg/l.

### 2.2.2 System description

A pilot EF–CW system (Figs. 1,2) was built at the Shafdan municipal, activated sludge wastewater treatment plant, comprising of the following components: (a) pre-strainer, (b) upflow EF generator (EFector, TreaTec21 Industries Ltd.), 1.4 m<sup>3</sup> in volume, 1.25 m in diameter, containing 12 pairs of perforated iron electrodes, (c) granular filter, 1m bed depth and 0.6mm effective grain size, (d) 4 m<sup>3</sup> filtered water tank, used also for system backwash and flushing, and (e) a complex of CW ponds were constructed in the Shafdan WWTP (Tel-Aviv – Dan metropolitan area; Constructor Ofra Aqua Plants, modified by Moran consulting, design, & construction of aquatic ecosystem). The system included seven series of three successive wetland ponds (ca. 30 m<sup>2</sup> each), vertical or horizontal subsurface flow and one free flow. The results reported here relate to a treatment by a single VF pond. The VF ponds were packed from top to bottom with an 8 cm layer of basalt (20-30 mm); 9 cm of basalt (2–3 mm); 8 cm basalt (5–10 mm); 8 cm dolomite (8 mm); 15 cm basalt (3–6 mm) and 20 cm of dolomite (50-60 mm) at the bottom. *Cyperus papyrus*, *Canna sp.*, *Iris pseudoacorus*, *Phragmites australis* and *Juncus ensifolius* were planted, but by the third year *Cyperus papyrus* dominated the system (Fig.3).



Fig. 3 Vertical subsurface flow pond, dominated by *Cyperus papyrus*.

#### 2.2.2.1. *The Electroflocculation system*

There are four main components in the system (Fig.4):

- The Electroflocculation unit (EFector)
- Sand filter
- Holding tank
- Control panel

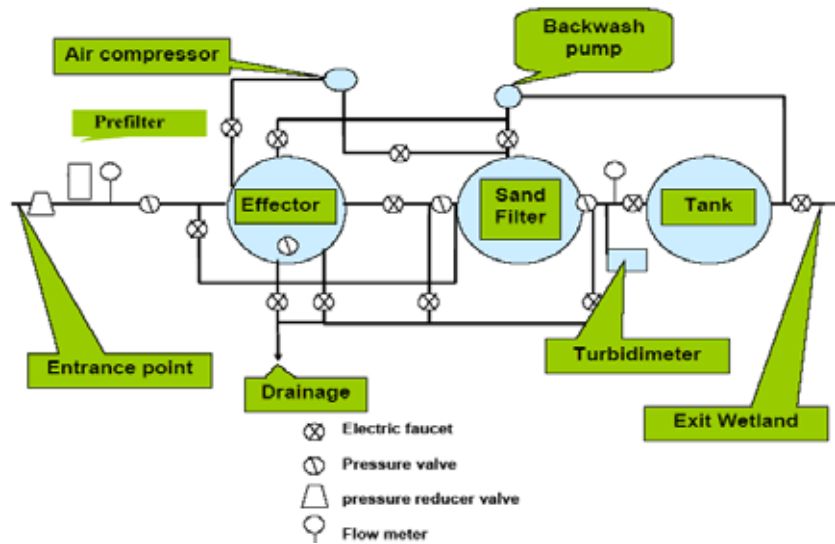


Fig.4. The Electroflocculation system

In general, Shafdan secondary (while testing the first and last alternatives) effluent will flow through the EF–GF to an operation tank, which supplies treated water both for wetland and for backwash (Fig. 5). The granular filter (GF) is backwashed when the head-loss exceeds 0.5 bars while the EFector (Fig. 6) is backwashed after a specified time of operation. During the backwash the filter is drained to at least 15 cm above the bed level in order to avoid media loss. Filtrate water is pumped into the GF from the bottom through the under drain with a velocity that fluidizes the bed (20-40 m/hr at an initial to final stage). For improving the backwash efficiency air is supplied by the compressor through nozzles in the bottom of the filter. The air score is applied before fluidization, after it shuts off the up flow starts until full fluidization is achieved. The EFector is backwashed in the same procedure, except that the air score is applied simultaneously with wash water since there is no need to drain the instrument. When the wetland functions as the solely water source to EFector (second and third alternatives) water is pumped by submersible pump directly from the relevant wetlands pond.

**The above design specifications may serve as basic guidelines for an EF-CW system in various locations. Yet, as common practice suggests, local experts must be consulted as to adaptation to local engineering regulations, climatic and soil conditions, effluent quality, etc. Running pilot plant in situ is important in order to optimize the system and its performance.**

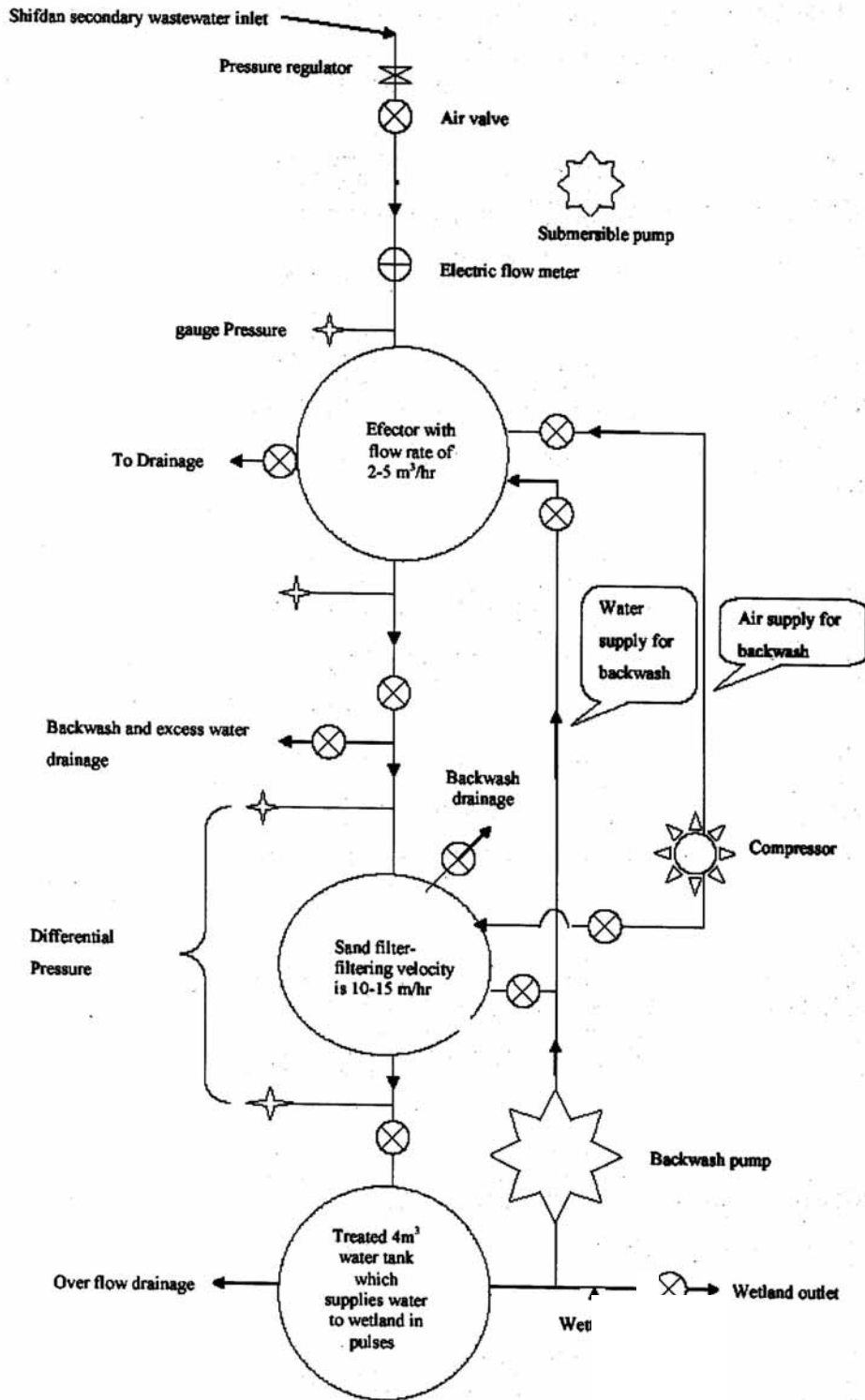


Fig 5: Flow scheme of the EF-CW plot plant at the Shafdan (Israel)



Fig. 6: EFector (Treatec21 Ltd. Israel)

### **3. SYSTEM OPERATION**

#### **3.1. Operation period**

Effluent flow rate determine the residence time of effluent in the Effector. A  $1.5 \text{ m}^3/\text{Hr}$  (25 L/min) gives 1hr residence time in the Effector and filtration velocity of 10 m/Hr. Flow rate has to be checked and adjusted frequently during operation period since filter resistant changes with time. In order to keep flow rate constant one has to change entrance valve position during operation period.



According to Faraday's law, coagulant dosage is determined by  $I \cdot t$  where  $I$  = Current intensity (Amp) and  $t$  = residence time (sec). Therefore, when the residence time  $t$  is kept constant, current intensity  $I$  determines the amount of iron released into the wastewater.

Operation period is set according to a pre-set time/turbidity/ $\Delta P$  on the sand filter. The operator set the operation period in advance at the automatic control panel. Operator checks the control settings and starts the system. A pre-set operation set up open the electrical faucet according to operation protocol.

Upon start-up operation it is advised to run all parts of the system separately. First run the bypass and use the sand filter alone. After a few run-ups run the wastewater through the EFector gradually and check for leakage or excessive pressure on the EFector.

In normal operation, open the valves to the EFector and the sand filter and closes the bypass to the filter. During operation time the operator has to check flow rate, head loss on the sand filter and take samples according to monitoring schedule.

The effluent can accumulate in the holding tank for from the sand filter to the CW. When holding tank effluent is in use it is advised to check effluent characteristic after the holding tank matches the one going out of the filter. A dirty holding tank or residual effluent from previous runs may alter effluent characteristic dramatically.

Since CW systems need constant water supply, if EF system is running periodically and not continuously (24/7), operator must close outside effluent running to the CW and reopen it when operation time is over. Of course, when CW is used as a pretreatment outside effluent supply has to remain constant during all time.

The electrical faucets are controlled automatically by the control panel that gets turbidity values constantly from a turbidimeter positioned after the sand filter. Operation period ends with system backwash.

Field pilot results show that the EFector is capable of removing up to 97% of the total phosphorus. The system can be optimized for phosphorous removal primarily by controlling (a) current intensity, which actually represents coagulant dose and (b) flow rate, which controls the effect of reactor residence time.

### **3.2. Backwashing**

The system is provided with an air compressor and a backwash pump Effector and sand filter backwashing. At the end of the operation period the backwash sequence starts automatically by the control unit. The operator can stop operation and start backwashing sequence through the control panel at will.

Backwashing sequence is about 9 minutes and is set upon 3 stages: filter drainage, air supply and backwashing at a flow rate of 8 m<sup>3</sup>/hr. The control panel can be planned to restart operation when backwash is finished.

### **3.3. Monitoring**

Monitoring schedule should check system operation and sample for effluent control. pH, flow rate and pressure has to be checked frequently in order to maintain normal system operation and look for malfunction up ahead.

Contaminants removal (TSS, COD, TOC, TP, particle count etc.) are checked upon different coagulant dosage in order to optimize the process on different parameters.

Samples are taken according to calculated residence time. Influent and effluent are sampled through out operation period.

Sampling valves are positioned at the entrance to the system (after the ring filter and water meter), after the EFector, at the sand filter exit point, at the entrance to the CW and after the CW pond. Sampling after CW pond is carried out from an underground container using a



small manual pump. Sampling has to be carried out from a depth of 10–20 cm under container water level.

At every sampling the sample container has to be washed twice with sampling water and only then sample is taken.

#### **4. MAINTENANCE**

##### **4.1 Maintenance procedures**

###### **4.1.1 EF-GF unit:**

###### *1. Disc pre-filter cleaning:*

a. Open disc filter.

b. Wash discs with hose until all discs are clean.

c. Occasionally take all discs off, soak in chlorinated water for half an hour and rinse well.

d. Close disc filter (make sure all sealing are in place).

###### *2. Air compressor – call a certified technician for annual check up.*

*3. Change the electrodes – replace by new electrodes about once a year, depending on influent quality and continuity of operation (watch for change in performance).*

###### *4. Electrical wires on the Effector:*

a. Remove plastic cover from the Effector.

b. Clean all leaves and dirt accumulating around the Effector.

c. Check wires are all intact.

d. Close plastic cover.

5. *Add sand/change the sand in the filter – inspect sand level in the filter every 3 months. Add sand if missing. Change the sand bed every 5-10 years – consult with filtration specialist.*

#### 4.1.2 Wetland (pond) unit:

1. *Biofilm prevention (for experimental systems and systems equipped with sensitive flow control equipment only):*

Biofilm is accumulating with time along pipelines inner walls, in filters and automatic valves. That may cause clogging problems, spoiled valves, etc. As a preventive measure it is advised to perform chlorine disinfection with sodium hypochloride. The chlorination is aimed at all tubing, filters and valves, attention should be given particularly to chlorination of small diameters pipes which are susceptible to clogging.

2. *Routine inspection:*

It is highly important to walk along the ponds and verify that there is no leakage or ponding, that the water is evenly distributed on the surface of the pond, that no damage occurred, etc.

3. *Vegetation:*

Our experience showed that it is may not be necessary to maintain the original characteristics of the ponds vis-à-vis the type of vegetation. Cleaning of the pond area from weeds should be done at the early stage of its development so as to enable better development of the water plants.

## **4.2 Maintenance schedule of all equipment**

### 4.2.1 EF-GF unit:

1. The ring filter has to be washed daily.
2. The air compressor needs to be checked annually by a technician.
3. Change the electrodes.
4. Rats – check electrical wires occasionally for rat/mice damage.
5. If EFector is located on ground, weeds need to be taken care of occasionally.



6. Change the sand in the filter.

#### 4.2.2. Constructed wetland:

1. Routine inspection – twice a week is normally fine.
2. Weed cleaning – once a week.
3. Chlorination – once every 1-2 months. By demand.

### 5. FREQUENTLY ASKED QUESTIONS

#### 1. *I started the system but there is no flow:*

- a. Check valves are open (electrical valve can be set manually off).
- b. Check the control panel for malfunction.

#### 2. *Malfunction light is on at the control panel:*

- a. There are two types of malfunction on the control panel – breakthrough and clogging.
- b. Check for leakage through out the system and check valves are open.

#### 3. *There is a problem and I want to backwash the system now:*

- a. Go to the control panel and set operation period on '0'.

#### 4. *I use intense current in the Effector but water turbidity after the Effector is low and no Iron is seen:*

- a. Check if residence time is over since starting the system. Turbidity will show about 1 Hr after starting.
- b. Check voltage and current intensity on the panel.

## **6. GENERAL SAFETY**

Working with wastewater, electric equipment and chemicals should be done under the local safety regulations.

## **7. APPLICABILITY AND LIMITATIONS OF EF-CW HYBRID SYSTEM**

The different configuration has different advantages in contaminants removal from wastewater effluents. The combination of the two treatments (electrofloculation and constructed wetland) contributed to the removal of contaminants in every inspected aspect. Contaminants removal was at best when the constructed wetland preceded the electroflocculation unit, but a good sand filtration is needed in order to remove turbidity. A full scale system may be in use both for river and lake rehabilitation and tertiary wastewater purposes. It can be modular, with relative small footprint and automatically controlled according to pre-set currents and backwash sequence. The process dependency on electrical source, although little consumed, could be a drawback in some places to the hybrid process. The area necessary for constructed wetland may still be an impediment in densely populated areas, where open land is either unavailable or very expensive. In such areas a fully mechanical plant might be advantageous.

As mentioned earlier, that when transferring to other parts of the world, local experts (or international advisors together with local experts in case local experience is unavailable) must be consulted as to adaptation to local engineering regulations, climatic and soil conditions, effluent quality, etc. Plenty of further information may be found in the presentations made at EF-CW WORKSHOP, SWITCH PROJECT, WP 3.3 Tel Aviv, 19.12.10 which have been placed in SWITCH internet site.

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## APPENDIX

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## ELECTROFLOCCULATION – CONSTRUCTED WETLAND HYBRID FOR IMPROVED PHOSPHATE REMOVAL IN EFFLUENT REUSE

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**Abstract** Reusing or recycling wastewater for stream rehabilitation require discharge of high quality effluent complying with strict nutrient standards as well as development of feasible treatment alternatives. Constructed wetland is already a proven technology for efficient polishing wastewater effluent except for phosphorous. We investigated the coupling of Electroflocculation (EF) with constructed wetland (CW) for improved contaminants removal, phosphorous in particular, from secondary effluents. The work consisted of three phases: electro-jar testing, continuous-flow EF-filtration (GF)-CW bench scale experimentation and field, half-industrial piloting. P, turbidity, TSS and TOC were particularly monitored. Laboratory experiments showed that EF-GF effectively removed phosphate (96%), while CW effectively removed organic matter (85%). Therefore, it seemed that the coupling of both unit processes would combine their treating abilities. Field pilot results show that EF-GF removed up to 97% of total phosphorus, resulting in P concentrations of <0.4 mg/L, which are extraordinary results by any comparison. In addition to phosphorus removal, the system is capable of meaningfully reducing some of the TOC (53%) and most of the TSS. The hybrid action is explained by combining flocculation and adsorption mechanisms produced by the EF with transport, attachment and biodegradation mechanisms in the CW beds.

**Keywords** Phosphate removal; electroflocculation; constructed wetland; water reuse; stream rehabilitation; tertiary treatment

### INTRODUCTION

Discharge of effluent into streams and rivers is a common practice worldwide. In arid lands competition for the freshwater for human use diminishes stream flow and effluents often make much of the base flow. In such situations stream health and rehabilitation highly depend on effluent quality. Strict standards for effluent disposal call for economic and efficient treatment alternatives. Various sources of wastewater contain growing concentrations of phosphorous and nitrogen cause eutrophication of natural water bodies (Feng et al., 2003). One of the consequences of eutrophication is decreasing of dissolved oxygen which adversely affects fish and other aquatic life, diminishing biodiversity.

Constructed wetland (CW) is an environmental friendly technology for treating wastewater or polishing effluent that is becoming increasingly popular in many parts of the world (Haberl, 2003). It is designed and constructed based on natural marshes (Kadlec and Wallace, 2008). CWs are often classified by the pattern of effluent flow in the system (e.g., Brix, 2003). In free-flow (surface flow) systems wastewater flows above the ground through emerged, submerged and floating aquatic vegetation. In subsurface flow systems wastewater

moves through a porous medium such as gravel or aggregates, in which rooted hydrophytes grow (USEPA, 2000). Subsurface systems are further classified into horizontal flow (HF), in which anaerobic conditions prevail, or vertical flow (VF) which maintains aerobic conditions. Low flow velocities coupled with the presence of roots and solid substrate, promote settling and filtration of particulate material. Biofilm of diverse microorganisms that develops on the porous medium is responsible for most of the biotransformation and mineralization of pollutants. (e.g. Vymazal, 2003; Kadlec and Wallace, 2008). CWs usually remove organic matter and nitrogen (N) compounds efficiently but are less efficient in removing phosphorous (P) compounds (Kadlec and Wallace, 2008). Retention of P in CWs includes peat/soil accretion (mostly in natural and free flow systems), soil adsorption, precipitation and plant uptake (Vymazal, 2003). In subsurface systems removal by plants is limited and requires plant harvesting annually. The adsorption and chemical precipitation of phosphorus is much more vigorous at the initial operation stage because the process has finite capacity (EPA, 2000). As a result, CW capacity for phosphorous removal is quite limited. For the latter reason we considered coupling CW with physicochemical process that is expected to complement the naturally occurring processes by removing phosphorous efficiently.

Chemical precipitation is widely used for phosphate removal. The common precipitants used are aluminum sulphate and ferric chloride. Chemical treatment involves the addition of high amounts of chemicals resulting in undesirable ions residues and extra salinity being discharged in the treated wastewater (Feng et al., 2003). Electroflocculation (EF) is an electrochemical method that utilizes an electric current to separate and clear solid and dissolved pollutants from wastewater. This method enables water treatment free of additional chemicals, thus offers an alternative to the use of metal salts. EF has been increasingly used in North America for pretreatment of a variety of industrial wastes (Mollah et al., 2001). EF can be considered an alternative process to conventional flocculation, although they are somewhat different. The difference between these processes is manifested in the chemical and physical characteristics of the treated suspension and resulting aggregates (Harif and Adin, 2007). The flocs formed by EF are relatively large and contain less bound water. They are also more stable and therefore amenable to filtration (Abuzaid et al., 2002). The optimum pH for turbidity and phosphate removal is around 5–9 in electroflocculation-electrofloatation by using aluminum and titanium electrodes. In that range the hydrolysis and polymerization of  $\text{Al}^{+3}$  give rise to the formation of such species as  $\text{Al}(\text{OH})^{+2}$ ,  $\text{Al}_2(\text{OH})_2^{+4}$ ,  $\text{Al}(\text{OH})_3$  and charged hydroxo-cationic complexes such as  $\text{Al}_{13}(\text{OH})_{32}^{+7}$ , which are efficient coagulants (Ge et al., 2004). Current density is a major factor in determining the removal rate of phosphate by EF, low initial concentrations of 10–50 mg/l existing in effluents may achieve 90% phosphate removal under low current density values of  $5\text{mA}/\text{cm}^2$ , duration 7 minutes (Bektas et al., 2004). The overall goal of the investigation was to assess the utility of a tertiary treatment that couples a physicochemical process, i.e., electroflocculation, with natural processes taking place in constructed wetland, to facilitate compliance with stringent standards for river rehabilitation as well as for other uses of treated effluents. Here we examine phosphorous removal applying iron electrodes and vertical flow CW treatment.

## MATERIALS AND METHODS

The research work consisted of three successive phases, two in the laboratory and one at constructed wetland field site: (a) Jar testing, including development of EF–jar testing batch system, (b) continuous-flow, bench/semi-pilot scale experiments, and (c) field, pilot plant experiments.

Standard (chemical) jar tests with extended settling time of 2 hrs were conducted with secondary effluent, aluminum sulfate (alum) or ferric chloride that served as coagulants. In "modified jar tests" a sample was withdrawn from the jars, immediately after flocculation period, and filtered through a filter paper (Whatman 545). An EF cell was built where various electric current intensities were applied during different time cycles (represents coagulant dose) while rapid mixing 800 ml of secondary effluent, followed by 10 minutes of slow mixing and filtration through a filter paper. 12-cm<sup>2</sup> aluminum or iron strip served as anode.

The continuous flow bench-scale experiments were conducted using 1-liter cell equipped with two perforated iron electrodes with an area of 114.22 cm<sup>2</sup>, preceding a filter of 39 cm bed depth and 1 mm grain size. Artificial wastewater was prepared as described elsewhere (Egozy, 1996) with additional phosphate stock solution containing 2.865 g/l KH<sub>2</sub>PO<sub>4</sub>. Wastewater flow rate was 130 ml/min, implying contaminant injection flow rate of 0.65 ml/minute for a dilution ratio of 1:200. A bench-scale, horizontal-flow CW consisting of two units (basalt and dolomite beds) with a total area of 0.216m<sup>2</sup> followed. Filter backwash was activated when a pre-set time/turbidity/ΔP was reached. pH was adjusted, turbidity, particle count, TOC, DOC, phosphate, aluminum and iron were analyzed (specific on analytical equipment may be obtained from the authors).

A pilot EF–CW system (Fig.1) was built at the Shafdan municipal, activated sludge wastewater treatment plant, comprising of the following components: (a) pre-strainer, (b) up-flow EF generator (EFector, TreaTec21 Industries Ltd.), 1.4 m<sup>3</sup> in volume, 1.25 m in diameter, containing 12 pairs of perforated iron electrodes, (c) granular filter, 1m bed depth and 0.6mm effective grain size, (d) 4 m<sup>3</sup> filtered water tank, used also for system backwash and flushing, and (e) a complex of CW ponds were constructed in the Shafdan WWTP (Tel-Aviv – Dan metropolitan area; Constructor Ofra Aqua Plants, modified by Moran consulting, design, & construction of aquatic ecosystem). The system included several series of three successive wetland ponds (ca. 35m<sup>2</sup> each), vertical or horizontal subsurface flow and one free flow. The results reported here relate to a treatment by a single VF pond. The VF ponds were packed from top to bottom with an 8cm layer of basalt (20-30mm); 9 cm of basalt (2-3mm); 8 cm basalt (5-10mm); 8 cm dolomite (8mm); 15 cm basalt (3-6 mm) and 20 cm of dolomite (50-60mm) at the bottom. *Cyperus papyrus*, *Canna sp.*, *Iris pseudoacorus*, *Phragmites australis* and *Juncus ensifolius* were planted, but by the third year *Cyperus papyrus* dominated the system. 'Shafdan' secondary effluents characteristics (annual average): turbidity–6.4 NTU, phosphate–2.7 mg/l as P, BOD–12 mg/l, COD–51 mg/l, nitrogen–9.2 mg/l as N, pH 7.35, Fe<0.1 mg/l.

## RESULTS AND DISCUSSION

### Jar tests.

The effect of pH levels on phosphate removal by chemical flocculation and EF is shown in Figs. 2, 3. Fe:PO<sub>4</sub><sup>-3</sup> molar ratio was similar for both experiments (1.6 and 1.95, correspondingly). For EF treatment, PO<sub>4</sub><sup>-3</sup> removal was improved as pH increased, up to 85% removal at pH 8. In contrast, chemical flocculation showed a stable removal at all pH ranges (up to 69%). Those results indicate that the neutral pH ranges are optimized for phosphate removal by EF technology with iron electrodes. A similar picture appears for residual Fe concentration. Chemical flocculation showed a relatively stable level of residual Fe (0.9–0.2 mg/l at pH 4-6 and a constant 0.2 mg/l at pH 6–8) while residual Fe levels for EF decreased as pH was neutralized. Those results may explain why turbidity levels worsened by hundreds percents in the EF treatment case, except for a 38% removal measured at pH 8, in contrast to chemical flocculation, where turbidity removal varied between 41–22% as pH increased.

### Laboratory scale coupled unit.

Phosphate removal with CW bedding alone was low, resulting between 18% removal to 12% contribution to the initial level (Table 1). The most beneficial in this configuration was organic matter removal, ranging 25–85% dependently of initial concentration and time. In addition, it lowered turbidity to values of 0.3–0.6 NTU.

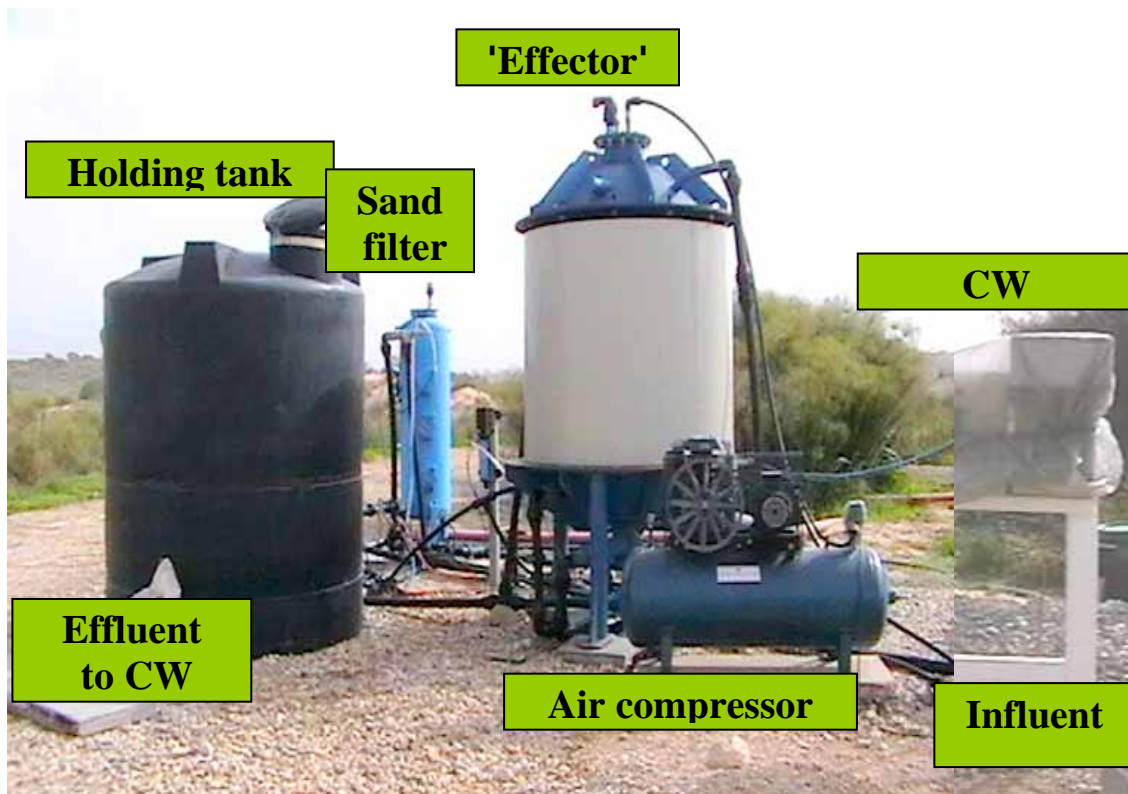


Fig. 1. The EF–CW pilot system

At the first 20 days, turbidity was reduced by 20–72% of 2–6.9 NTU initial values. Beyond that period, the wetland contributed up to 27% to the turbidity. When EF-GF preceded the

CW gravel beds, this combined treatment was very effective in turbidity and iron elimination, which could be attributed to efficient transport and attachment mechanisms of the colloids, provided by the flow and surfaces of the wetland porous media. Phosphate removal by EF–GF was up to 92% (lower detection limit was 0.4 mg/l  $\text{PO}_4^{3-}$ ). Turbidity breakthrough correlated with high residual ferric concentrations, which could be explained by overdosing when raw turbidity was low (0.5 NTU). That EF–GF–CW configuration encouraged green algae development in the CW bed, enriching the water with oxygen by average of 13%. The development of green algae added organic matter particularly when initial concentration was low. Oxygenated water creates a defensive layer over the sediment, reducing phosphate release to the water, caused by anaerobic conditions (Braskerud et al., 2003, Ahn & Mitsch, 2002). As time passes, biofilm layer grows thicker and oxygen diffusion to the substrate is prevented. With time, microorganism mortality grows and leads to the release of biofilm segments to the water (Egozy, 1996). That could be the reason for organic matter addition to the effluent by the CW and also for the depletion of turbidity removal with time. Another possibility for that variability was the lack of vegetation in the CW bed, an important building block in its stabilization (Braskerud et al., 2005).

When considering reverse flow (CW–EF–GF), the combined treatment lost its advantages. Filtrate turbidity deteriorated despite considerable reduction in coagulant dose, until the filter bed has been replaced with finer one. The new bed showed better turbidity removal efficiency, while the coarse grain showed a moderate head-loss development. Organic matter removal by the CW was divided: the first cell (basalt bed) removed 12–40% of DOC while the second cell (dolomite bed) added organic matter. The EF–GF treatment abilities varied between 12–85% in DOC removal.

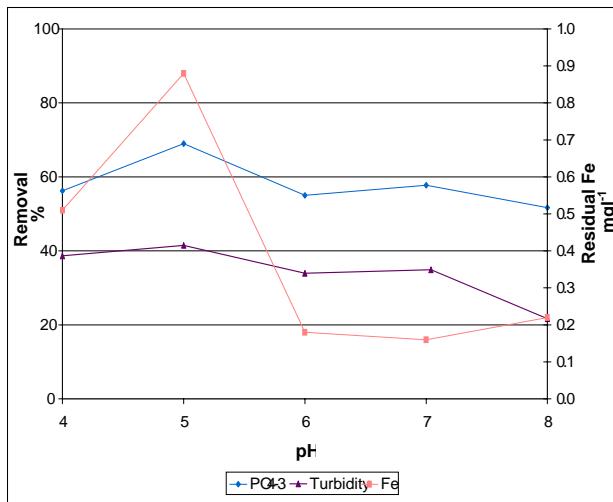


Fig.2. Phosphate removal by a modified jar-test as a function of pH

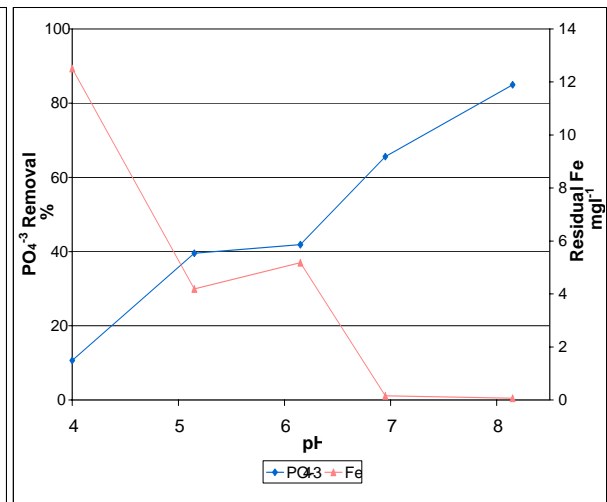


Fig.3. Phosphate removal by a modified EF jar-test as a function of pH

### Field pilot stage

*CW performance.* Wetland performance was evaluated after three years of operation (mature system). The following average removal efficiencies (n= 6, Table 2) were recorded after treatment in the first VF pond. Relative to inflow concentrations BOD and TSS removal was high (>60%) resulting in concentration suitable for stream rehabilitation. Excellent ammonia removal (>90%) was achieved following efficient nitrification in the first VF pond. As a result the effluent of the first VF pond was enriched with nitrate. Nitrate removal was attained in the last, free-flow pond (final concentration  $0.8 \pm 0.8$  mg/l nitrate-N) and overall total nitrogen removal was >50% (final concentration  $2.1 \pm 1.1$  mg/l). No removal of phosphate occurred in the wetland mature system

**Table 1.** Continuous flow, bench-scale constructed wetland performance as a function of operation period treating artificial wastewater.

| <i>Operation period (day)</i> | <i>Inlet TOC concentration (mg/l)</i> | <i>TOC % Removal</i> | <i>Inlet DOC, mg/l</i> | <i>DOC % Removal</i> | <i>Inlet <math>PO_4^{-3}</math> (mg/l)</i> | <i><math>PO_4^{-3}</math> % Removal</i> |
|-------------------------------|---------------------------------------|----------------------|------------------------|----------------------|--|---|
| 10                            | 31.7                                  | 86                   |                        |                      | 5.94                                       | 9                                       |
| 18                            | 18.3                                  | 59                   |                        |                      | 6.21                                       | 13                                      |
| 26                            | 21.3                                  | 46                   |                        |                      | 6.10                                       | -2                                      |
| 35                            | 15.9                                  | 69                   | 12.4                   | 85                   | 4.50                                       | 5                                       |
| 43                            |                                       |                      | 9.8                    | 50                   | 4.60                                       | -12                                     |
| 50                            |                                       |                      | 11.1                   | 25                   | 4.77                                       | 18                                      |

*Phosphorous removal by EF-CW systems.* Total phosphorous (TP) removal by different treatment configurations is depicted in Fig. 4. CW alone removed up to 20% of TP, while EF alone removed 10–40% of TP regardless of Fe concentration. Filtration improved TP removal to an average of 90% when Fe concentration exceeds 5 mg/l, with optimum 97% TP removal reaching TP concentration <0.3 mg/l. For Fe<5 mg/l TP removal by EF–GF–CW ranged 75–89% resulting in TP concentration <0.7 mg/l at all times. Laboratory experiments presented earlier had shown similar results. When EF-GF preceded CW treatment, TP removal depleted to a maximum of 83% removal for Fe>5 mg/l, with TP concentration of 0.3-0.7mg/l. Comparing the later with the above mentioned results indicate that CW consistently contributed additional phosphorous to the effluent; that could be explained by formation of a phosphorous 'reservoir' supplied by (a) Shafdan's secondary effluent between EF treatments, and (2) plants decay, and released by water of lesser concentration.

**Table 2.** Average removal efficiency and effluent concentration of selected water quality variables after treatment of Shafdan secondary effluent in vertical subsurface flow constructed wetland

| <i>Parameter</i> | <i>Removal (%)</i> | <i>Final concentration (mg/l)</i> |
|------------------|--------------------|-----------------------------------|
| BOD              | 63±16              | 2.3±1                             |
| TSS              | 67±20              | 1.5±0.9                           |
| NH4-N            | 93.2±5.5           | 0.15±0.12                         |
| NO3-N            | -211.2±237.9       | 1.9±1.45                          |
| PO4-P            | -11.3±49.3         | 1.3±0.6                           |

CW-EF-GF configuration showed similar results to the EF-GF treatment, reaching an average of 90% TP removal, re-convincing that CW did not affect the TP level after granular filtration. Those results indicate that the latter is the best configuration for TP removal from wastewater. Still, it is possible that a long term flow of low phosphorous wastewater through the CW would have eliminated the phosphorous reserve and so would improve on the EF-GF-CW results. This long term operation could not have been carried out under current conditions for technical limitations. When observing residual Fe concentration after EF-GF, results show that only for initial Fe concentration >12 mg/l there is a 95% Fe removal by granular filtration and only for initial Fe concentration >15 mg/l there's less than 0.5 mg/l Fe in the filtrate. This indicates that raising coagulant does effect both phosphorous removal and residual coagulant concentration. Raising coagulant dosage, with the enhanced conveying streams, induced by the increased current intensity, creates more opportunities for successful particle collisions and flocs formations, which can be further removed by the sand filter.

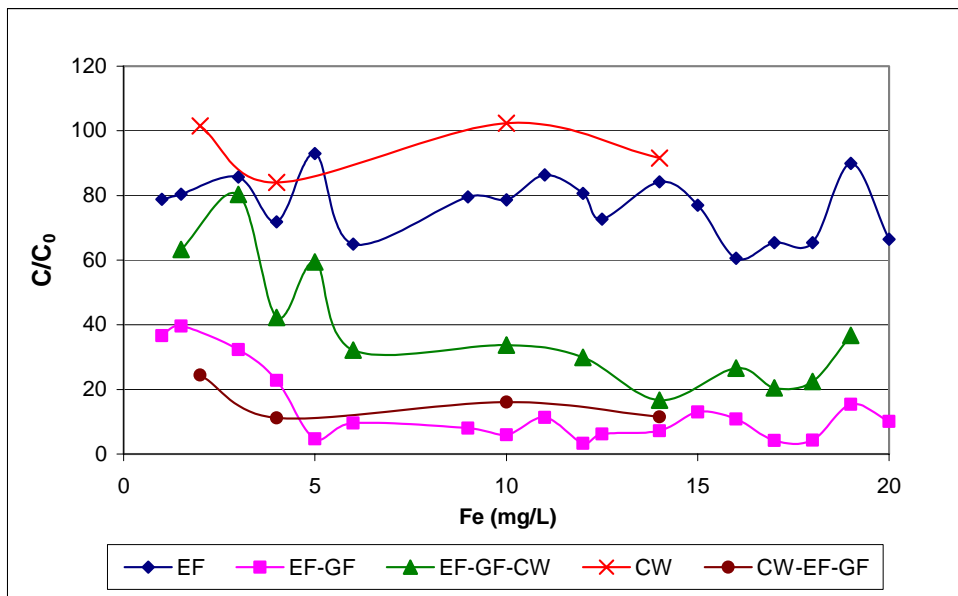


Fig.4. Residual phosphorus in ‘Shafdan’ secondary effluent for different treatments. C<sub>0</sub>=1-3 mg/l TP. Flow rate 1.5 m<sup>3</sup>/hr.

*Turbidity, TSS and TOC removal by EF-CW systems.* Table 3 summarizes the field pilot results of the different system configurations experimented in this work. Extra turbidity is formed within the system by the ferrous/ferric addition. It is possible that the extra turbidity is a result of a delayed oxidation of bivalent to trivalent iron. That mechanism has to be further investigated. Turbidity removal is optimized only with enhanced sand filtration. The wetland constantly reduced residual Fe concentration by at least one order of magnitude but not less than levels of 0.2–0.5 mg/l Fe. Some amount of Fe passes through the sand filter and the CW bed causing lowest residual turbidity of 0.88 NTU. Results for carbon load removal showed a similar picture with EF-GF capability of reducing about 20–30% of the TOC in the system, depending on coagulant dose, as shown in the bench scale study. Again, adding the CW improved organic matter removal and when CW preceded the electroflocculation unit, TOC removal was 53% at best.

**Table 3.** Field pilot results of different configurations.

|                | <i>Influent</i> | <i>Outlet<br/>EF-GF</i> | <i>Outlet<br/>CW</i> | <i>Outlet<br/>EF-GF-CW</i> | <i>Outlet<br/>CW-EF-GF</i> | <i>No. of<br/>exp.</i> |
|----------------|-----------------|-------------------------|----------------------|----------------------------|----------------------------|------------------------|
| TP, mg/l       | 1.40±0.54       | 0.22±0.18               | 1.10±0.15            | 0.53±0.33                  | 0.17±0.04                  | 35                     |
| Turbidity, NTU | 3.3±0.8         | 3.2±1.7                 | 09±0.3               | 2.4±0.9                    | 12±0.38                    | 30                     |
| TOC, mg/l      | 12.2±2.3        | 10.8±1.4                | 8.0±0.8              | 9.4±1.4                    | 6.4±0.6                    | 20                     |
| TSS, mg/l      | 4.9±2.6         | 4.8±2.1                 | 1.4±1.0              | 2.5±1.3                    | 0.6±0.2                    | 25                     |

Practically thinking, the EF unit (EFector) – constructed wetland hybrid system implies shorter residence time and better water quality, thus reduces land, construction and maintenance costs of the constructed wetlands as well as water loss. Overall, the different configuration has different advantages in contaminates removal from the wastewater. The combination of the two treatments (electrofloculation and constructed wetland) contributed to the removal of contaminates in every inspected aspect. Contaminants removal was at best when the constructed wetland preceded the electrofloculation unit, but a good sand filtration is needed in order to remove turbidity. A full scale system may be in use both for river and lake rehabilitation and tertiary wastewater purposes. It can be modular, with relative small footprint and automatically controlled according to pre-set currents and backwash sequence.

## CONCLUSIONS

1. Complementing CW treatment with a physicochemical process of electrofloculation can provide a tertiary treatment that effectively polishes secondary municipal effluent. While EF effectively reduces phosphate in both soluble and particulate forms CW treatment provides a transport-attachment trap to turbidity that escapes the electro-physico-chemical process and removes organic matter and N compounds.
2. Laboratory tests showed that electrofloculation coupled with sand filtration effectively removed phosphate and suspended particles in contrary to the wetland gravel performance. The wetland gravel removed effectively organic matter, possibly by microbial degradation, as opposed to the EF-GF configuration.
3. Field pilot results show that the EFector is capable of removing up to 97% of the total phosphorus, getting final concentrations smaller than 0.4 mg/l. Former electro-jar tests followed by continuous-flow, bench-scale results showed similar capabilities of up to 96% removal. The system is optimized for phosphorous removal by controlling current intensity, which represents coagulant dose and by controlling flow rate, which controls reactor residence time and turbulence.
4. The hybrid process also enhances suspended solids (87%) and organics removal (53%) in addition to phosphorus removal. A well designed sand filtration following the EFector is highly recommended.



## ACKNOWLEDGEMENT

This investigation was partially supported by the Italian Ministry of Environment through Tel-Aviv University and the EU-SWITCH project. The research is part of MSc graduate work of Barash and Ozer, and of Milstein's PhD

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