

COMPUTER MODEL FOR FULL-SCALE PHYTOREMEDIATION SYSTEMS USING RHIZOFILTRATION PROCESSES

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Summary:

Microcomputer software was developed to provide decision support information for design and operation of a rhizofiltration system, a phytoremediation based technology utilizing plant roots to remove heavy metals and radionuclides from contaminated waters. A Michaelis-Menton based model was developed and incorporated into a series of algorithms which process information relevant to the system design of the rhizofiltration process. Physical components of the phytoremediation system - plant production, rhizofiltration, pre and post treatment of water, and post treatment of spent plant materials are coupled with engineering and biological aspects of systems design. An engineering economic analysis tool within the software allowed for analysis of the impact of critical design variables on system efficiency.

Keywords:

phytoremediation, rhizofiltration, decision support, mathematical modeling

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COMPUTERIZED DECISION SUPPORT SOFTWARE FOR PHYTOREMEDIATION SYSTEMS USING RHIZOFILTRATION PROCESSES

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ABSTRACT

Microcomputer software was developed to provide design and operation guidelines for full scale rhizofiltration systems, a phytoremediation based process utilizing plants to remove heavy metals and radionuclides from contaminated waters. A process model based on a modified form of the Michaelis-Menton equation was developed to quantitate the ability of plants to accumulate toxins within the rhizofiltration system. A series of algorithms process and incorporate this information with a rhizofiltration systems model. Physical components of the phytoremediation system - nursery, the rhizofiltration system, pre and post treatment of water, and post harvesting of spent plants are coupled with engineering and biological aspects of systems design including processes, operations, facilities, and systems integration. An engineering economic analysis tool within the software allowed for analysis of the impact of critical design variables on system efficiency.

INTRODUCTION

High costs associated with the treatment of heavy metal and radionuclide wastes have created an opening in the environmental remediation market for innovative, cost effective technologies. Phytoremediation systems based on utilizing the metal accumulating ability of certain plants for removal of heavy metals and radionuclides from soils and water, promise efficient lower cost clean-up of sites contaminated with low levels of metals/radionuclides (Raskin et.al, 1994; Dushenkov et.al., 1995). Field trials ranged from the removal of radionuclides from a contaminated pond at Chernobyl using sunflowers, to the treatment of lead contaminated soil in New Jersey using successive croppings of a cultivar of Indian mustard. While these experiments are indicative of the success of this technology on the experimental scale, the leap to a marketable, full-scale remediation system poses certain challenges in integrating engineering with biological knowledge.

Phytoremediation systems focused on heavy metal and radionuclide treatment are classified into three processes, phytoextraction, phytostabilization, and rhizofiltration (Salt et.al, 1995). Phytoextraction and phytostabilization refer to decontamination/detoxification of contaminated soils using special metal accumulating plants. Rhizofiltration processes focus on using plant roots to purify contaminated waters. Terrestrial plants are hydroponically grown and supported so that their roots are immersed in the target water. The toxins in the water are removed by the roots via physical and active biological processes, resulting in a purified effluent and a small amount of hazardous biomass requiring disposal.

The ability to provide decision support guidelines for design and operation is critical for the implementation of large scale systems based on these processes. To appreciate the nature of this challenge, consider the development of a full scale rhizofiltration system. First, relevant physical and biological processes are identified and linked to physical components of the full scale facility. Operation of these components must then be considered in light of facility flow patterns. The physical facility design and layout must also be addressed - since phytoremediation systems use living plants as engineering components, greenhouse structures with adequate environmental control must be used. Finally, the

processes, operation, and physical facility aspects should be integrated into a coordinated system which can be optimized with engineering economic analysis.

Specific physical components of the rhizofiltration system are identified in figure 1. Pre-treatment, post-treatment, and the rhizofiltration component address water treatment. The pre-treatment process equalizes the contaminant concentrations before the influent enters the rhizofiltration system, ensuring optimal plant root/toxin interaction. The rhizofiltration system consists of hundreds or thousands of troughs through which the contaminated water is treated by plant roots. Post-treatment, consisting of a screening or filtration unit process, is required to remove any plant debris introduced into the water by the rhizofiltration system before the water is discharged.

The demand for a steady supply of fresh plants for the rhizofiltration component necessitates an on-site biomass unit, or nursery (fig. 1). Processing of spent plant material leaving the rhizofiltration component includes separation of hazardous and nonhazardous plant portions, de-watering, and shipment to final disposal. These processes take place in the post harvesting component.

Cooperative efforts with scientists from Rutgers Ag/Biotech Center and Phytotech, an environmental biotechnology company located in Monmouth Junction, New Jersey, provided experimental results on small experimental scale rhizofiltration systems. This data served as the foundation for developing decision support software for full scale rhizofiltration facility design. The focus of our efforts were to:

- (1) Develop a process model for simulating plant performance within a rhizofiltration system
- (2) Incorporate the process model into a systems model considering the system layout, flow patterns, plant distribution, and operation scheme of the system
- (3) Develop a computerized decision support tool for the full scale facility
- (4) Perform engineering economic analysis on the system

PROCESS MODEL

Data for the process model was supplied from an experiment conducted by Phytotech in conjunction with the Ag/Biotech Center at Rutgers University. Nine 76 liter tanks (collectively called a 'trough') were connected in series, each with six hydroponically grown sunflower plants supported so that their roots were immersed in the water flowing through the tanks. These plants were grown using a specially designed nursery system (Giacomelli et.al., 1995). As contaminated water passed through this hanging root system, the contaminants were adsorbed/absorbed, resulting in a purified effluent. Contaminated water with approximately 300 ppb of cadmium was delivered to the trough at a 11.3 lph (3 gph) flow rate. The concentration in each tank at the end of each day of operation was recorded.

A plot between the tank concentrations versus specific days of operation, called the trough concentration profile, is shown in figure 2. Each curve on this plot represents the concentrations observed in each tank along the rhizofiltration trough at the end of a specific day of operation. The most important items to note from the plot are (1) the increase in the metal concentration 'Cw' with increasing days of operation, suggesting that the plants become less effective in removing metals with time, and (2) that as trough length increases (i.e., as the water passes through more tanks), a cleaner final discharge is observed. Design information on the necessary number of tanks required to meet a specified discharge limit, the amount of biomass needed, and the useable life of the plants in that trough can be inferred from this plot (Fleisher et.al., 1996).

Modeling efforts focused on predicting this trough concentration profile. First, an expression was developed by quantifying the concentration reduction due to plant uptake as a function of tank position within a rhizofiltration trough and day of operation. The strongest correlation was found between the metal uptake observed in each tank and the concentration of metal available ("Ca") to the plants in each tank. This is plotted in figure 3. Each data point represents the metal uptake versus concentration of metal available to plants for each tank and for each day of operation. This dependence was described using the Michaelis-Menton equation, a mathematical expression widely used in biological sciences to quantitate substrate utilization (Thornley, 1976). The equation used was:

$$C_e = \frac{(K_m)(C_a)}{(K_s + C_a)} \quad (1)$$

where:

C_e = concentration reduction or metal uptake observed per tank per day

C_a = concentration of toxin available to plants in tank per day

K_m = maximum substrate utilization rate (or, in this case, maximum concentration reduction per day)

K_s = half the value of the concentration available at which K_m was observed

Determination of the Michaelis-Menton parameters (K_m and K_s) is straight forward. Note that the inverse of the equation can be expressed as:

$$(1 / C_e) = (K_s / K_m)(1 / C_a) + (1 / K_m) \quad (2)$$

A regression on the plot ($1/C_e$) versus ($1/C_a$) (not shown) gave the following results:

$$(1 / C_e) = 0.349(1 / C_a) + 0.0567 \quad (3)$$

Therefore,

$$K_m = 1 / .0567 = .176 \text{ ppm} = 176 \text{ ppb}$$

$$K_s = 0.349 \times K_m = .062 \text{ ppm} = 62 \text{ ppb}$$

and,

$$C_e = \frac{176(C_a)}{(C_a + 62)} \quad (4)$$

Figure 3 shows the results for the predicted concentration reduction on the same plot as the experimental data.

A mass balance performed on the tanks within the rhizofiltration trough incorporated this expression for plant uptake for prediction of tank concentrations at each day of operation (fig. 4). The overall result was:

$$C_w(m+1, n) = \frac{\left[C_w(m, n-1)(q/V) + C_w(m, n) - \frac{(K_m C_a(m, n))}{(K_s + C_a(m, n))} \right]}{[1 + (q/V)]} \quad (5)$$

where:

C_w = tank concentration at day of operation 'm', tank position 'n'
(for example, $C_w(m,n-1)$ would refer to the concentration leaving the previous tank and entering into the current one at day m)

q = flow rate (lph)

V = tank volume (liters)

$$C_a = \text{concentration available} = (q/V)C_w(m, n-1) + C_w(m, n) \quad (6)$$

This equation can be used to predict the trough concentration profile given the following initial conditions:

- (1) Flow rate
- (2) Number of tanks in trough
- (3) Tank volume
- (4) Influent concentration
- (5) Contaminant type and rhizofiltration plant
- (6) Michaelis-Menton parameters for system

Model results are shown in figure 5. In addition, several rhizofiltration field tests conducted by Phytotech on an uranium contaminated DOE site at Ashtabula, Ohio provided an opportunity to extend this model beyond the original data set. These field tests used flow rates ranging from 11.3 to 63 lph (3 to 16.7 gph) and used the following different plant components within the rhizofiltration trough: sunflowers, dried sunflower roots, and live and dried *brassica juncea* seedlings. The Michaelis-Menton parameters changed for each of these tests, and the performance results predicted by the model were similar to the observed results (not shown), suggesting that the model can be extended to different rhizofiltration scenarios provided that a pilot test is run to determine the appropriate Michaelis-Menton parameters for each case.

SYSTEMS MODEL

Two major flow patterns, biomass and water movement, are integrated with the five rhizofiltration facility components identified earlier. Since hundreds or thousands of troughs will be required by a full scale facility, their layout and organization within the controlled environment influences both space utilization efficiency and ease of facility operation. Facility design is therefore centered on the rhizofiltration component.

(1) Organization

Gutter connected greenhouse(s) are used to compartmentalize the rhizofiltration troughs. Each greenhouse consists of a series of gable or arched roofs connected to one another (Aldrich and Bartok Jr., 1992). The floor area covered by each of these roofs is referred to as a 'greenhouse bay'. The troughs are positioned length-wise across each greenhouse bay so that water can flow laterally through the trough in either direction. Typical widths for greenhouse bays are 3.7 (12), 4.8 (16), 6.1 (20), 7.3 (24), and 11 (36) meters (feet) (Giacomelli, 1997); the width used depends on the length of the rhizofiltration troughs.

A small rhizofiltration greenhouse is portrayed in figure 6. This example assumes that only 48 rhizofiltration troughs are needed to treat the volume of contaminated water sent into the facility each day, and each trough consists of 6 tanks (the total length of each trough is therefore approximately 2.7 meters). The closest greenhouse bay width to this distance is 3.7 meters, therefore, the greenhouse is composed of

3.7 meter width greenhouse bays. Troughs are organized so that six are housed per greenhouse bay in this example.

The space required for the nursery component is dependent on the rhizofiltration system area. A standard formula for computing this area multiplies the rhizofiltration area by the age of the plants divided by the number of weeks they are used in the rhizofiltration system.

(2) Rhizofiltration Component Operation

Periodic replacement of biomass in the rhizofiltration troughs presents a problem in terms of operating the facility. If all troughs begin treating water at the same time, they must also all be shut down for plant replacement at the same time. To avoid this situation, two methods for operating the rhizofiltration component were included in the systems model, one based on organizing the timing of water delivery to the troughs, and the other centered on organizing the age distribution of plants in the system.

'Time-staggered' operation refers to operating different groups or sections of troughs on a different time schedule in which each section begins treating water on a different day than the others. Because of this staggering, only one section shuts down each day for plant replacement - inlet valves controlling the contaminated water entering the troughs in this section are closed for a 24 hour period in which spent plants are removed from the troughs and fresh plants enter them. The following day, this section is turned back 'on-line', and another section is shut down for plant replacement.

'Trough-staggered' operation dispenses with the use of a separate nursery component. Plants are grown, in fresh water, within the same section of rhizofiltration troughs in which they will actually be used to treat contaminated water. The rhizofiltration component consists of several of these trough sections, each with different aged plants. When the plants in one section reach the desired age, inlet valves controlling contaminated water to these troughs are opened. When these plants are exhausted, another trough section, now containing the correct age of plants, is turned on-line. Plants in the previous section are replaced; however, instead of receiving fresh full grown plants from a nursery unit, seedlings are transplanted and grown directly on these troughs.

(3) Water movement

Figure 7 shows water movement to the first five greenhouse bays of the greenhouse discussed in figure 6. Contaminated water is sent from the pre-treatment component to the rhizofiltration troughs within each greenhouse bay. Treated water leaving the rhizofiltration troughs enters the post-treatment component where it is further processed before discharged to the environment. Note that the troughs grouped in each greenhouse bay have a separate feed line from the pre-treatment unit, and a separate return line to the post-treatment component from each of the other greenhouse bays. This allows individual operation of each trough section within each greenhouse bay which simplifies rhizofiltration component operation according to the schemes discussed above.

(4) Plant movement

The large amount of biomass required for phytoremediation systems suggests that the facility should be automated as much as possible. Movable units for plant automation are called 'plant benches'. 'Plant benches' contain 'trays' in which the rhizofiltration plants are grown. Plant movement through the facility consists of simultaneously moving plant benches containing exhausted plant material from rhizofiltration troughs to the post harvesting unit while either plant benches from the nursery with fresh

plants ('time-staggered' operation scheme) or with freshly transplanted seedlings from a contracted grower ('trough-staggered' operation) are positioned over the empty rhizofiltration troughs (fig. 8).

Once in the post harvesting unit, plants are removed from the trays for further processing. The trays are cleaned, removed from the benches, and sent to a contracted greenhouse grower for transplanting. The empty benches are cleaned, restocked with fresh seedlings and trays, and sent back to either the nursery or empty rhizofiltration troughs, completing the cycle (fig. 8).

PROCESS & SYSTEMS MODEL INTEGRATION - DECISION SUPPORT SOFTWARE

Microsoft's Visual Basic version 4.0 programming language was used to develop a computerized decision support tool, 'RGS', for designing and operating full scale rhizofiltration systems. RGS, short for Rhizofiltration Greenhouse System, is a user-interactive program which combines user inputs, the rhizofiltration process model, and the rhizofiltration systems model into an integrated series of 'windows', each with specific information about the design and operation of a simulated full scale facility. Greenhouse dimensions, numbers, interior layouts, trough dimensions, a report on system performance, operation, and an engineering economic analysis tool are included in the software.

Figure 9 shows the program's title page. Along the top is a menu bar from which the 'Options' menu has been selected. The 'Options' menu shows a list of windows which simulate various aspects of the full scale facility. The 'Options' menu also includes an economic analysis tool and economic data windows. The 'Data' menu from the menu bar provides access to several windows of input data including physical inputs to the facility, such as flow rate and contaminant concentration, and model parameters (shown in figure 10).

RGS generates a trough concentration profile from these inputs. The useable life of the plants within the rhizofiltration trough, the dimensions of the trough, and the amount of biomass required is determined by the software. Next, RGS processes this information through a series of algorithms integrating it with the systems model as follows.

First, the number of troughs required by the facility is calculated based on the flow rate per trough and the volume of water requiring treatment each day (these are user inputs). Troughs are organized into greenhouses (following the systems model), based on the operation scheme of the rhizofiltration system, and their physical dimensions and quantity. The nursery component (if the 'time-staggered' operation is used) design is based on the area of the rhizofiltration system. Pre and post treatment options are limited to economic estimates for an equalization basin for the pre treatment and a rotary screening operation for the post treatment option. Post harvesting consists of an internal economic model on initial and annual O&M costs including equipment required to remove plants from plant trays, separation of the nonhazardous from hazardous portions of the plants, dewatering of the biomass, packaging the waste in drums for shipment to a permitted hazardous waste landfill, and tipping fees incurred per drum at the landfill.

At this point, a series of options is available to the user, shown in figure 9, some of which are discussed below:

- i) Trough Display. Gives design information for a single rhizofiltration trough, including the option for selecting different orientations to view that trough (fig. 11)
- ii) Rhizofiltration Design. A critical window showing design and layout of one rhizofiltration greenhouse. Options listed on the upper right of the window provide different views of the greenhouse layout (fig. 12)

iii) Simulations. Real-time simulations of rhizofiltration component operation and single trough operation are provided (not shown).

iv) Information Summary. A report on the design and operation of the simulated facility. Information on actual design, layout, and metal removing performance is included. Biomass requirements, including mass of hazardous material requiring disposal, are also determined (fig. 13).

v) Engineering Economic Analysis. A series of windows answer different economic questions about the full scale facility. Each window is based on economic data for each of the five components of the rhizofiltration facility. One window is a 'Cost Comparison' (fig. 14) and serves to compare costs (capital and operating expenses) over the estimated lifetime of the facility with a competing technology. This also provides the RGS user with the amount of money that must be invested at year 0 (at the given interest rate) to pay for the facility's operation over its estimated lifetime (assuming no revenue is earned). A plot of the rhizofiltration facility's and alternative treatment technology's annual cumulative present worth (data comes from economic data) is included.

Another analysis (not shown) finds the flow of money required given an user specified internal rate of return for the facility. This translates into determining the amount of revenue for water treatment that the rhizofiltration facility must earn. This charge, or receipt is expressed on a per 1000 liters (or gallons) treated basis.

RESULTS

The following are results, obtained from the option windows discussed in the previous section, predicted by RGS based on default data using 300 ppb of cadmium at a flow rate of 11.3 lph per trough and a daily volume to be treated of 5,400,000 liters:

(1) Treating the contaminated influent to a discharge level below 25 ppb at a flow rate of 11.3 lph (3 gph) required 7 tank units, or a trough length of 3.2 m (10.5 feet). Each tank used 6 fully grown sunflower plants which could last for fourteen days in the trough (fig. 11).

(2) Based on the daily volume of water treated, the flow rate through the trough, and the organization of those troughs, 21,465 troughs were required by the facility (for the time-staggered operation). These troughs were organized into two large rhizofiltration greenhouses, each with a floor area of 19,982 m² (217,600 ft²) (fig. 12).

(3) Required nursery area was equivalent to four times the size of the rhizofiltration area. Therefore, the total facility area (not including pre and post-treatment, and post harvesting components) was 199,982 m² (2,176,000 ft²). Based on economic data for initial and annual operating expenses for each of the five physical components, the treatment charge that the facility must receive from its customers to reach a 20% internal rate of return for 10 years of operation was \$16.3 / 1000 liters (\$63 / 1000 gallons)¹.

These treatment charges were much larger than a desired maximum of \$3 / 1000 liters treated (Dushenkov, 1997). To improve on facility costs, RGS was utilized to provide insight into efficient rhizofiltration facility design. Specifically, factors leading to a reasonable rate of return while generating a marketable environmental remediation process were analyzed.

¹ Note that similar results were obtained with the trough-staggered operation scheme.

Over 50 input variables in RGS, modifiable by the user, contribute to the final design and operation of the full scale rhizofiltration facility. In order to understand and determine ways to optimize design, the critical variables among these inputs needed to be identified and their impact studied. The largest contributors to the overall facility's costs were determined to be the greenhouses (in terms of square meters (footage)) and post harvesting requirements²; therefore, the effects on system costs observed by increasing / decreasing variables which play a role in the design of these components were studied.

Note that model parameters affecting plant uptake should be developed on a case by case basis. This makes extension of the model to situations which vary in flowrate, concentration, plant life in the trough system, and other technical inputs difficult to validate. Keeping this fact in mind, the following trends were noted:

(1) In terms of physical inputs into the facility, larger flow rates and smaller influent contaminant concentrations decrease the number of troughs and biomass required. This translates into smaller rhizofiltration and nursery area and consequently less costs for the post harvesting operation.

(2) The most economically efficient rhizofiltration design was ultimately dependent upon optimizing plant performance. The ideal rhizofiltration plant component has a high metal/radionuclide accumulating ability, can uptake small amounts of metals quickly (i.e., has a large K_m and small K_s), and will last for a long period of time within a rhizofiltration trough without significant loss in uptake ability. These characteristics reduce trough and, therefore, greenhouse sizes.

(3) Additionally, the plants should be usable at an early age of development, have a small root mass (and not translocate metals from the roots to the shoot), and perform well in small quantities per trough. These characteristics decrease the greenhouse area required for the nursery and decrease the amount of hazardous biomass requiring post harvesting.

A certain minimum level of fixed costs primarily based on greenhouse expenses and post harvesting operations existed for every scenario. Even when the parameters discussed above were set at optimal levels, all rhizofiltration scenarios conducted with RGS produced relatively high facility costs. The lowest estimate for treatment costs was at \$6.3 per 1000 liters (\$24 / 1000 gallons) at an internal rate of return of 20%. If the rhizofiltration system costs only considered the water treatment process using this scenario (i.e., only capital and annual O&M greenhouse costs for a nursery and rhizofiltration component), the cost was \$3.45 per 1000 liters (\$13.2 / 1000 gallons) treated.

DISCUSSION

The development of RGS established the beginnings of an engineering knowledge base for phytoremediation systems. It included: 1) identification, processing, and organization of information required for full scale rhizofiltration systems, 2) development of a process and systems model for the full scale facility, 3) integration of these models via information processing algorithms into a computerized tool which incorporated biological information with engineering design, and 4) provided a platform for parametric modeling.

² Based on the default data, initial charges for the greenhouse modules were estimated at \$61 million, and annual O&M charges at \$9.6 million annually. Similarly, post harvesting set up cost was \$.29 million, and O&M was \$9.7 million annually. Costs for pre and post treatment combined were \$.28 million, and O&M was \$24,000 annually.

The value of RGS lies in its ability to not only provide preliminary guidelines for systems design and operation, but also to provide guidelines for future research directions. Based on the high facility costs predicted by RGS, there are several branches for future study:

- 1) Search for rhizofiltration operation schemes which save on space requirements. The time and trough staggered operation schemes are simple, *initial* ways of looking at a full scale rhizofiltration system. More efficient methods of operating the facility should be devised.
- 2) Research alternative methods for treating large volumes of water by rhizofiltration aside from the semi-continuous flow method. An example could be running large scale batch processes in parallel. This may increase the performance of the rhizofiltration plants.
- 3) Research the post harvesting operation. Based on RGS' internal economic model, a large portion of the cost for this operation was specifically for drying and disposal of the hazardous roots. Alternative methods, such as some type of metal reclamation process, could potentially have a significant impact on reducing post harvesting costs. In addition, methods for separating the root and shoot of the rhizofiltration plants, and inexpensive techniques for dewatering need to be developed.
- 4) Increase efforts on screening for or genetically engineering an ideal rhizofiltration plant. As noted, a plant with enhanced uptake ability and small mass could significantly reduce the expense of the technology.

In terms of developing a more solid phytoremediation knowledge base,

- 5) Methods should be established for determining correlations between different model parameters between different cases. This would provide the ability to predict the outcome for different rhizofiltration scenarios without developing parameters from a pilot study.
- 6) Continued efforts on expanding the process model. Studies should include identifying additional parameters which influence plant uptake. Examples include the impact of root mass, plant age, previous accumulated metals, water velocity, and environmental factors on uptake.
- 7) More specific design of rhizofiltration and nursery components. This includes refining the greenhouse modules with details on environmental control systems and hydroponics growth systems, for example. In addition, automation systems for the plant benches should be developed.

Perhaps the most significant direction from RGS may be towards other phytoremediation technologies, such as phytoextraction processes which use plants to extract contaminants from soil. Methodologies for developing full scale facilities would be similar to the steps outlined in this thesis. Mutual cooperation between engineers and plant scientists would lead to the development of process models which could be incorporated into systems models. The thrust of such an approach could lead to the emergence of several phytoremediation processes from promising experimental stage systems to acceptable, economically efficient commercial remediation technologies.

REFERENCES

- Aldritch, Robert A. and Bartok, John W. Jr. Greenhouse Engineering. The Northeast Regional Agricultural Engineering Service. 1992.
- Dushenkov, V., Kumar, PBA., Motto, H., and Raskin I. Rhizofiltration: The Use of Plants to Remove Heavy Metals from Aqueous Streams. *Environmental Science Technology*, 1995, v29: 1239-1245.
- Dushenkov, S. 1997. Personal Communication. Monmouth Junction, NJ, 11 June.
- Fleisher, D. H., Ting, K.C., and Giacomelli, G.A. Decision Support Software for Phytoremediation Systems. ASAE Paper No. 965042. St. Joseph, Mich.:ASAE. 1996
- Giacomelli, G.A., Kania, S., Ting, K.C., and Raskin, I. Design of a Plant Nursery System for Phytoremediation Techniques of Contaminated Water. ASAE Paper No. 957659. St. Joseph, Mich.:ASAE. 1995.
- Giacomelli, G.A. 1997. Personal communication. New Brunswick, NJ, 16 April.
- Raskin, I., Kumar, PBA., Dushenkov, S., and Salt, D.E. Bioconcentration of Heavy Metals by Plants. *Current Opinion in Biotechnology*, 1994 v5:285-290.
- Salt, D. E., Blaylock, M., Kumar, N., Dushenkov, V., Ensley, B., Chet, I., and Raskin, I. Phytoremediation: A Novel Strategy for the Removal of Toxic Metals from the Environment Using Plants. *Biotechnology*, v13, May 1995: 468-74.
- Thornley, JHM. Mathematical Models in Plant Physiology. Academic Press, 1976.

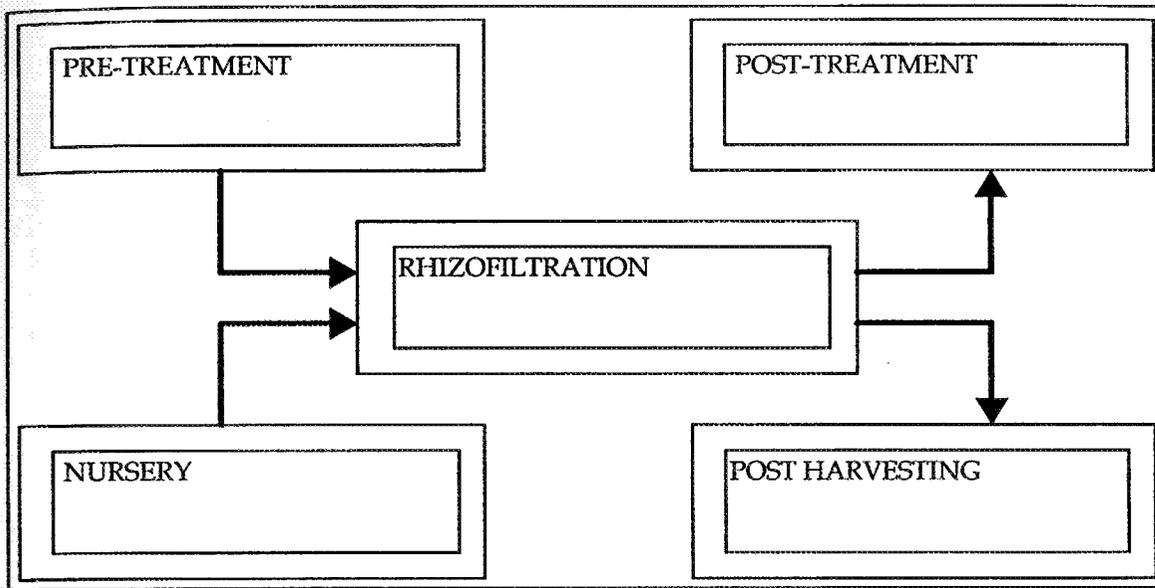


Figure 1: Five components of the full scale rhizofiltration facility. Water movement and treatment involves pre-treatment, rhizofiltration, and post-treatment operations. Plant usage involves the nursery, rhizofiltration, and post harvesting components. The entire facility is linked and coordinated in terms of water and biomass flows.

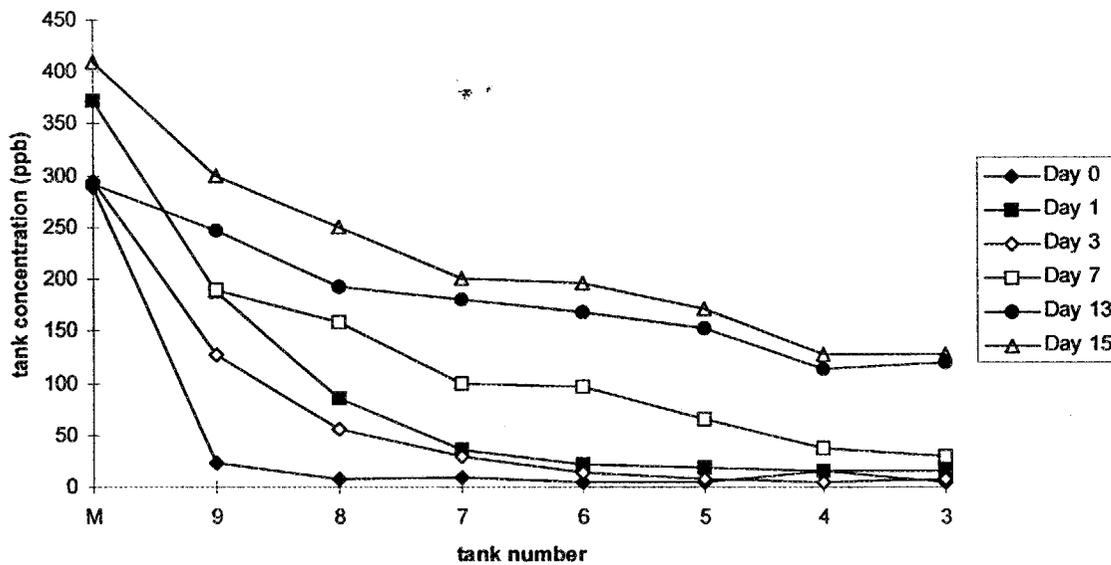


Figure 2: Trough concentration profile plot obtained for cadmium at a 11.3 lph flow rate. Lines connecting tank concentrations are drawn in to distinguish each day of operation in the trough system. 'M' tank represents inlet concentration. Tank order runs from 9 to 1 from the inlet, with the first seven tanks show on this plot.

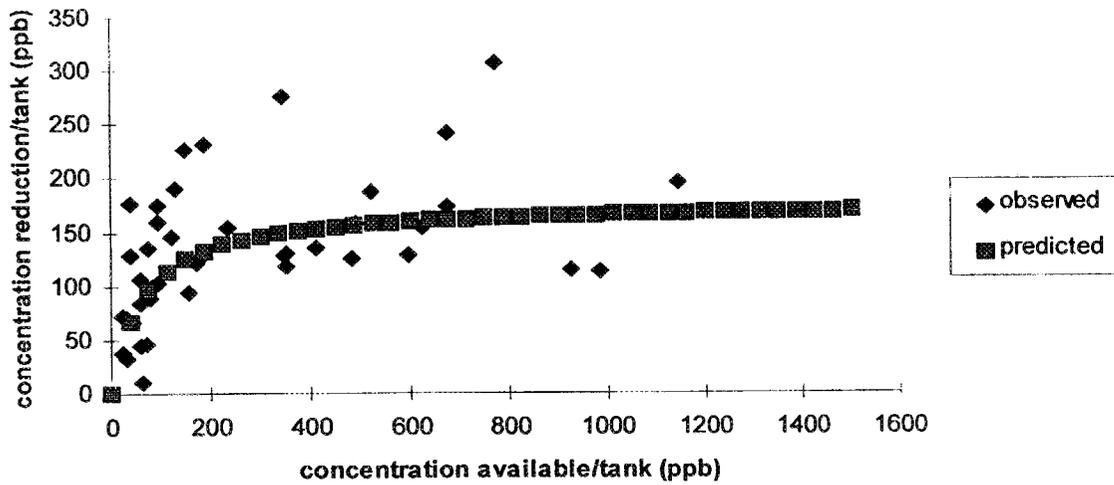


Figure 3: Observed and predicted concentration reduction versus concentration available per tank per day.

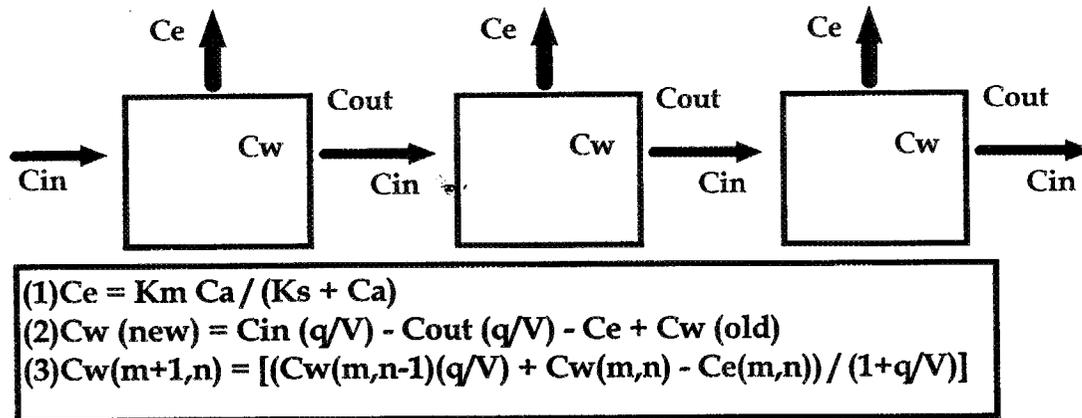


Figure 4: Mass balance example shown for three tanks in a rhizofiltration trough. The process model expression (1) is incorporated into a mass balance for each tank (2). Noting that the concentration leaving each tank is equivalent to the concentration entering the next tank, the final form of the process model (3) is shown with 'm+1' equal to the current day of operation, and 'n' equal to the current tank number.

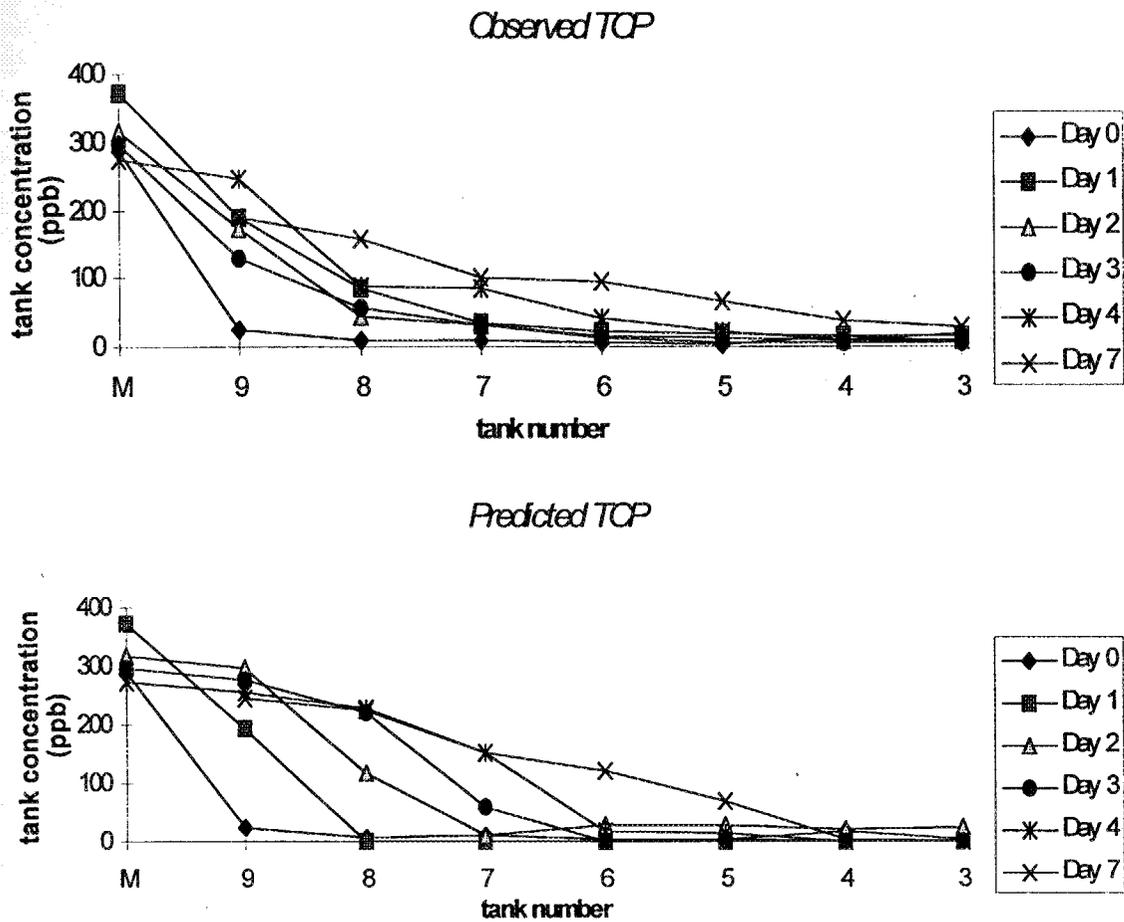


Figure 5: Observed and predicted trough concentration profiles for seven days of operation

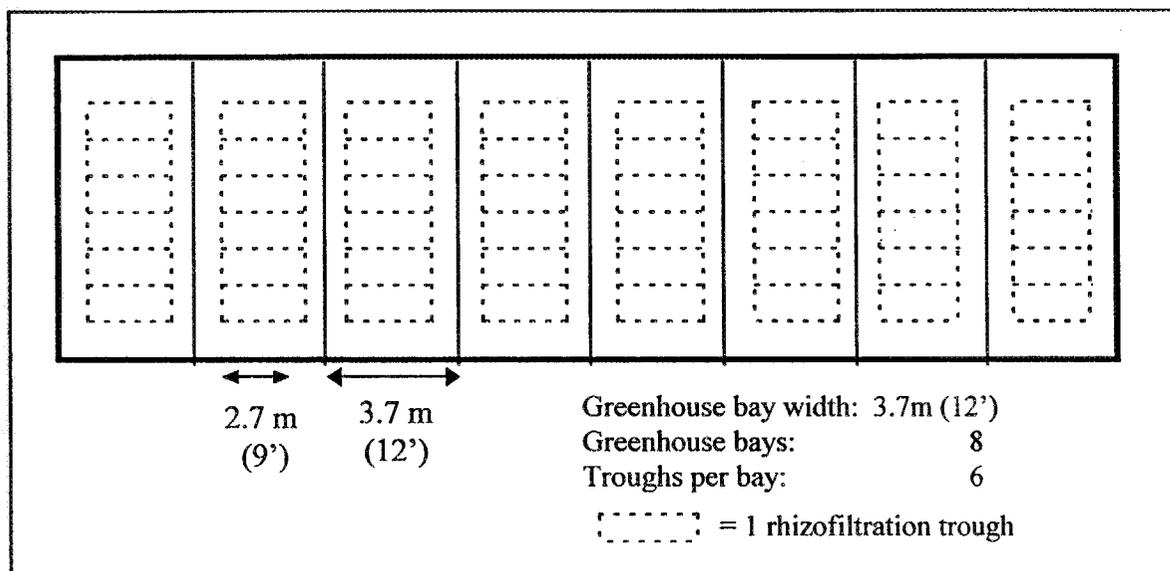


Figure 6: A rhizofiltration greenhouse with 48 rhizofiltration troughs, 6 per greenhouse bay. Each trough is 2.7 meters in length.

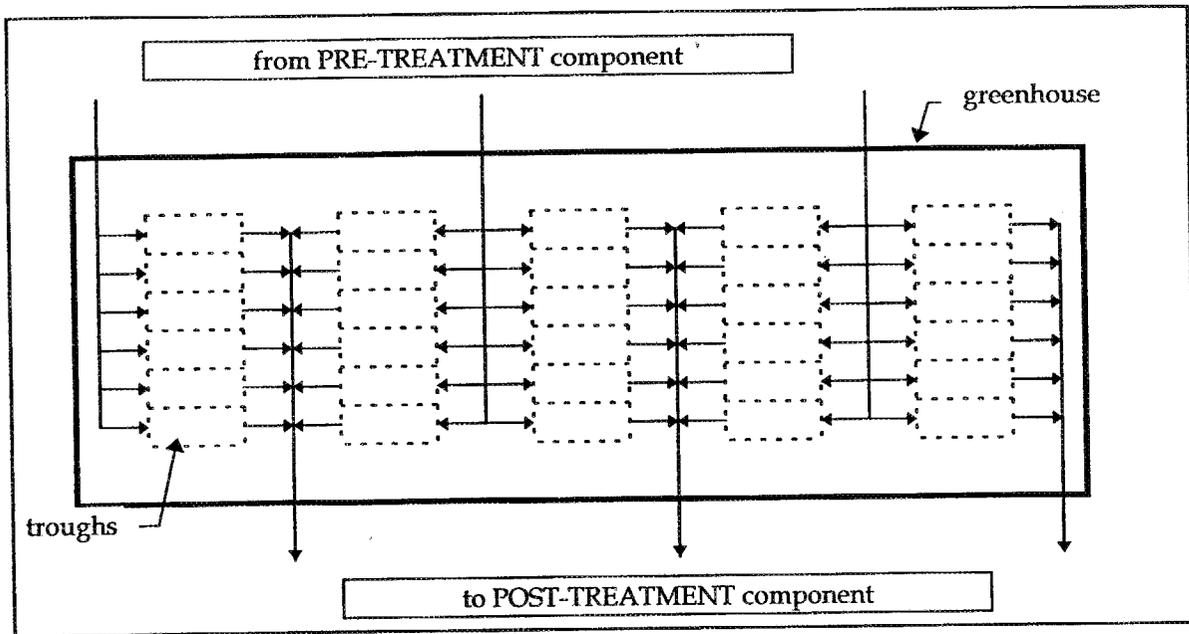


Figure 7: Diagram showing water movement to rhizofiltration troughs. Contaminated water enters each trough from the pre-treatment component while treated water leaving the troughs is sent to the post-treatment component.

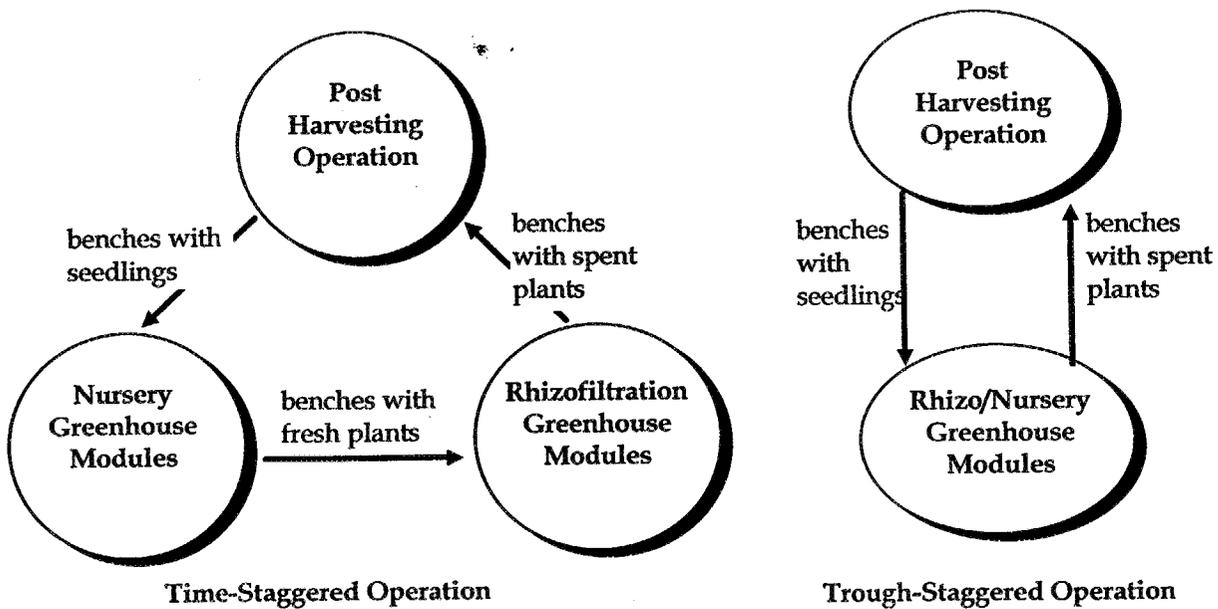


Figure 8: Plant movement throughout a full scale rhizofiltration facility, shown for two different operation schemes.

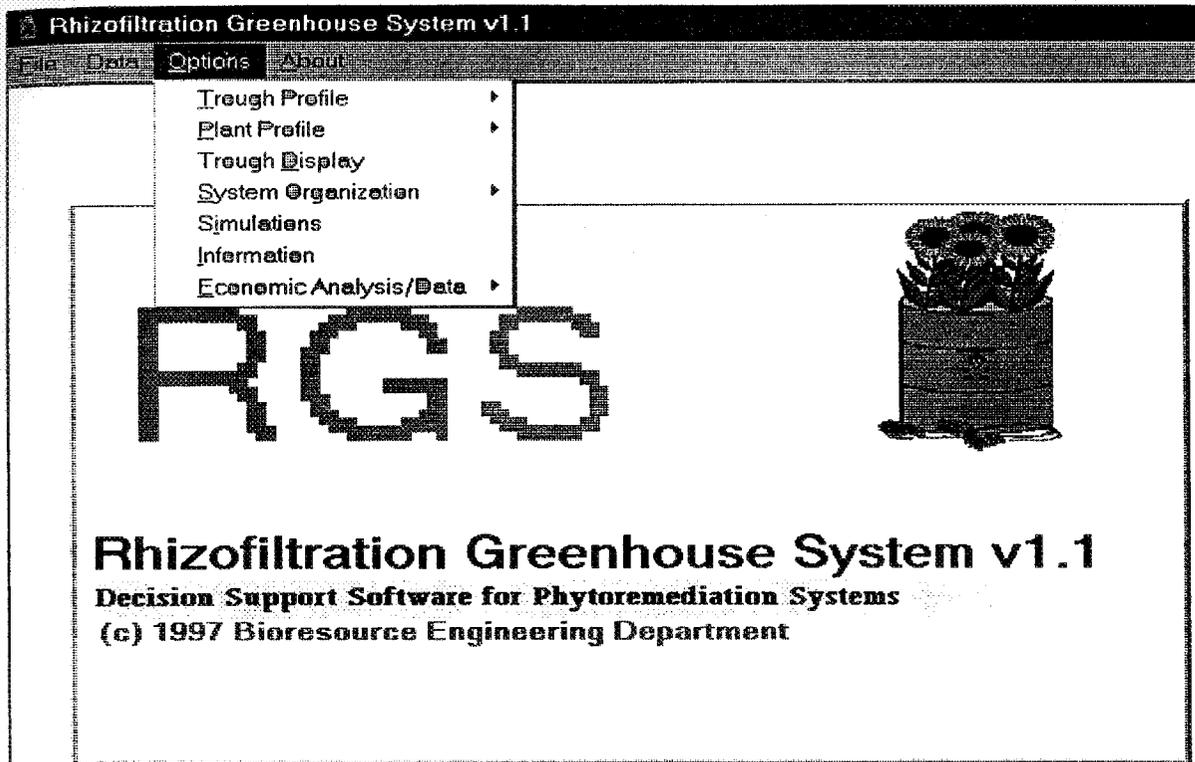


Figure 9: RGS title page. Note the menu bar along the top of the window. The 'options' menu has been selected, revealing a series of selections which call up various aspects of the design and operation of a simulated full scale rhizofiltration facility.

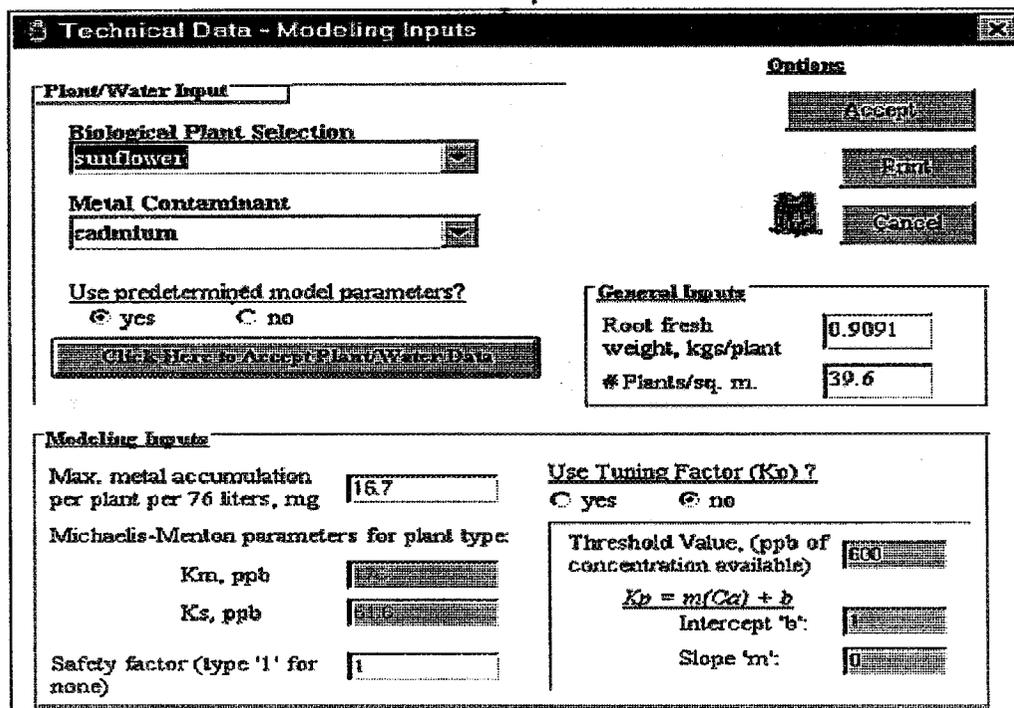


Figure 10: Modeling input window from RGS. The user can select the type of plant and metal contaminant, use model data from a small internal data base, or enter in his/her own information.

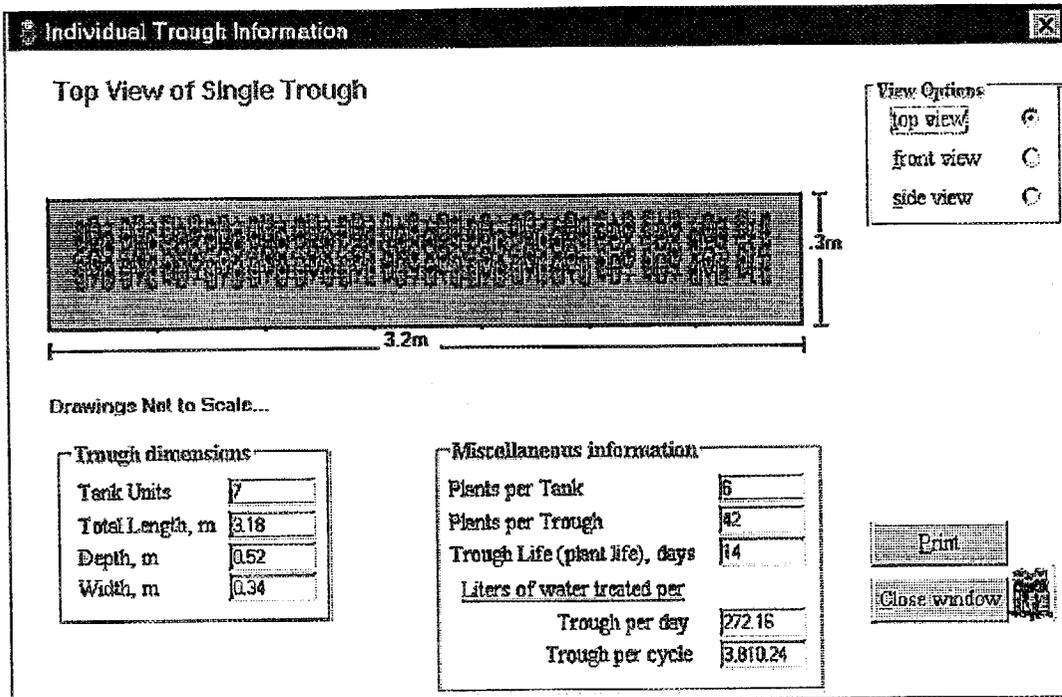


Figure 11: Trough display window from RGS. Dimensions, orientations, and miscellaneous data on a single rhizofiltration trough are provided.

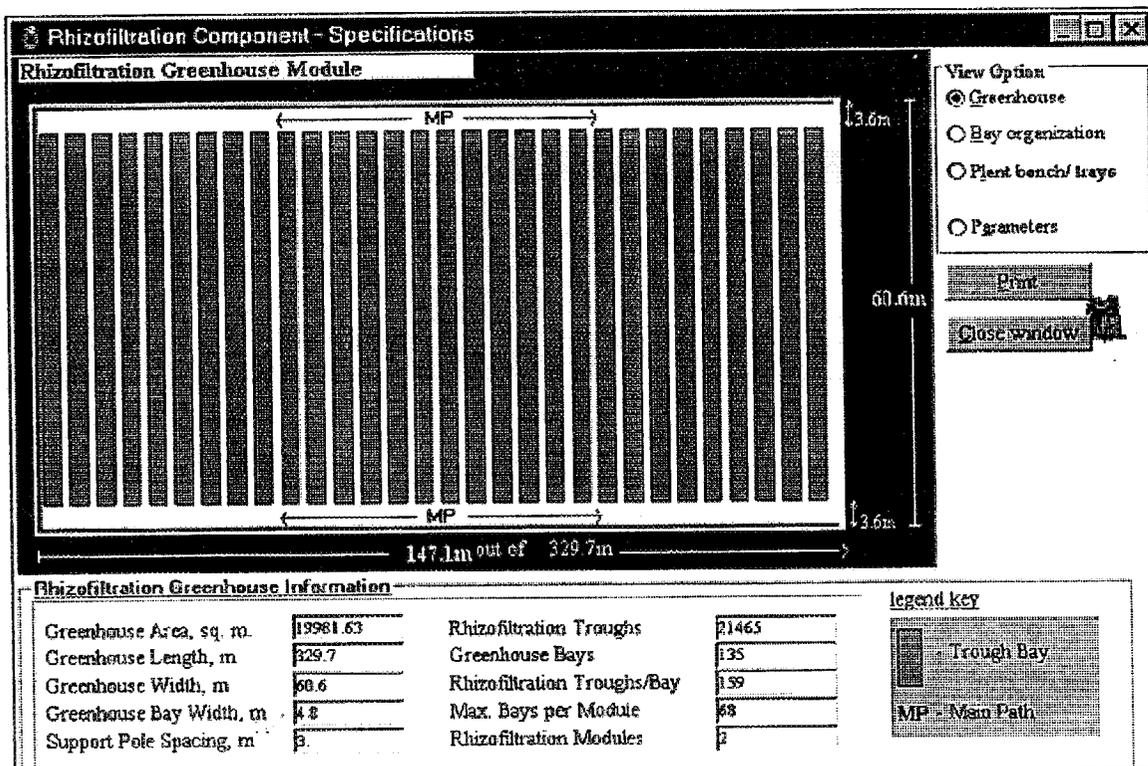


Figure 12: Rhizofiltration component window. Shows interior layout and design of one rhizofiltration greenhouse.

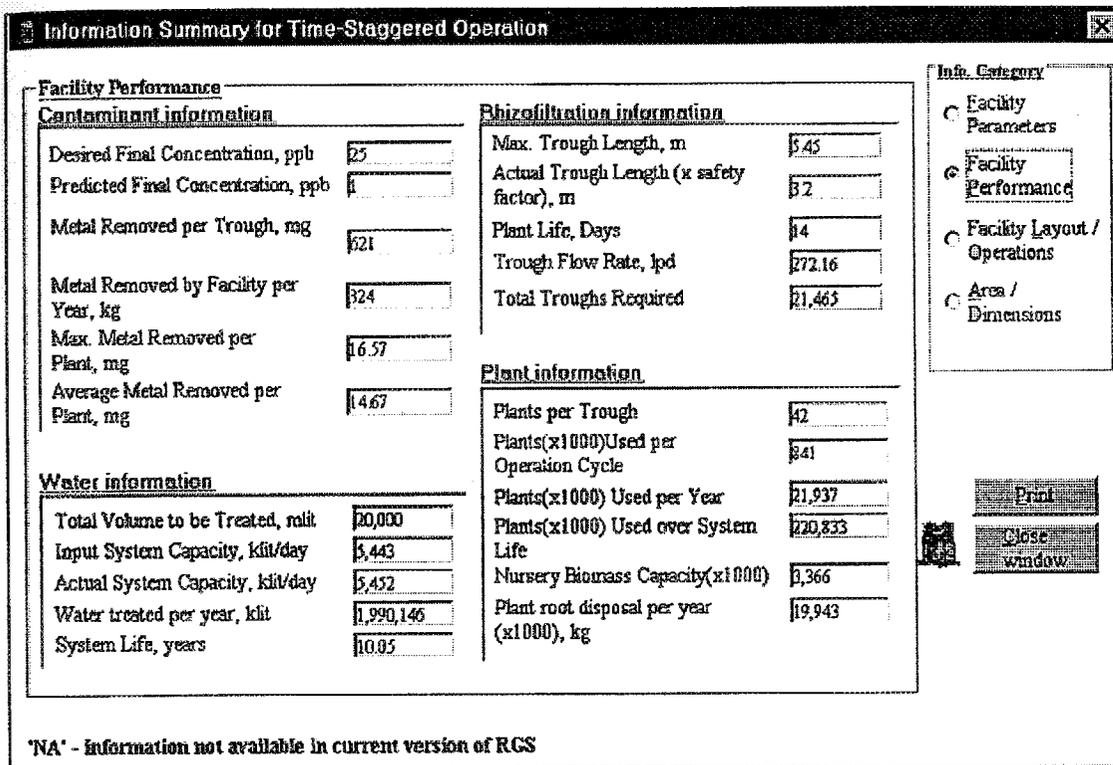


Figure 13: Information summary window. This particular set of information is one of four and summarizes information on contaminant removal, water treatment, and plant usage.

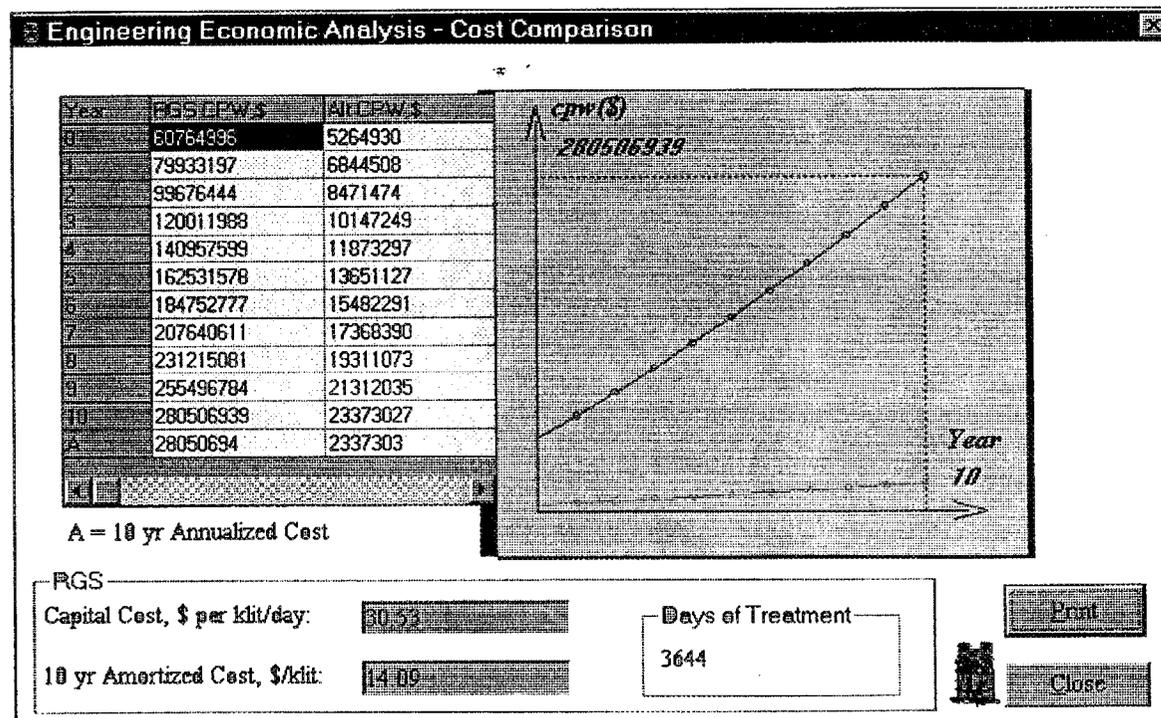


Figure 14: Economic Analysis - Cost Comparison window. This window estimates and compares costs of the rhizofiltration facility in terms of cumulative present worth for each year of system life versus an alternative technology. Revenues earned based on treatment receipts are not included.