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นางสาวภริตา พิมพันธุ์

วิทยานิพนธ์นี้สำหรับการศึกษาตามหลักสูตรปริญญาวิศวกรรมศาสตรดุษฎีบัณฑิต
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ปีการศึกษา 2549

INVESTIGATIONS AND MATHEMATICAL MODELING OF CADMIUM REMOVAL FROM INDUSTRIAL WASTEWATER IN CONSTRUCTED WETLANDS

Parita Pimpan

A Thesis Submitted in Fulfillment of the Requirements for the
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INVESTIGATIONS AND MATHEMATICAL MODELING OF CADMIUM REMOVAL FROM INDUSTRIAL WASTEWATER IN CONSTRUCTED WETLANDS

Suranaree University of Technology has approved this thesis submitted in fulfillment of the requirements for the Degree of Doctor of Philosophy

Thesis Examining Committee

(Asst. Prof. Dr. Sudjit Karuchit)

Chairperson

RJindal

(Asst. Prof. Dr. Ranjna Jindal)

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ภริตา พิมพันธุ์ : การศึกษาแบบจำลองทางคณิตศาสตร์ของการกำจัดแคดเมียมในน้ำเสียอุตสาหกรรมด้วยระบบพื้นที่ชุ่มน้ำเทียม (INVESTIGATIONS AND MATHEMATICAL MODELING OF CADMIUM REMOVAL FROM INDUSTRIAL WASTEWATER IN CONSTRUCTED WETLANDS) อาจารย์ที่ปรึกษา : ผศ. ดร. รันจนา จินดาล, 288 หน้า.

การวิจัยครั้งนี้ เป็นการทดลองเพื่อศึกษาประสิทธิภาพของพื้นที่ชุ่มน้ำเทียมแบบไหลบนพื้นผิวที่ปลูกด้วยพืชชนิดกกกลม ในสภาวะการรับภาระแคดเมียมสูงภายใต้สภาพแวดล้อมที่ต่างกัน น้ำเสียที่เข้าสู่ระบบคือน้ำเสียสังเคราะห์ผสมด้วยแคดเมียมคลอไรด์ที่มีความเข้มข้นคือ 5, 10, 25 และ 50 มิลลิกรัมต่อลิตร โดยแต่ละความเข้มข้นถูกปล่อยเข้าสู่บ่อการทดลอง 4 บ่อในช่วงการทดลองเดียวกันตลอดการทดลอง 3 ช่วงเวลา สมรรถภาพของพื้นที่ชุ่มน้ำเทียมแบบไหลบนพื้นผิวมีการกำจัดแคดเมียมที่ดีมาก มีการสะสมทั้งในดินและพืช โดยการดูดซับในดินและการดูดซึมโดยพืช เกิดกลไกการดูดซับแคดเมียมขึ้นในระบบ การสะสมของแคดเมียมในส่วนต่าง ๆ สามารถคำนวณหาค่าได้จากการทดลอง ช่วงเวลาการทดลองแบ่งเป็นระยะเวลาการเก็บกักที่ 5, 7 และ 10 วัน ผลการทดลองพบว่า ประสิทธิภาพการกำจัด S-COD อยู่ในช่วง 72-91% ตลอดการทดลองทั้ง 3 ช่วงเวลา ค่าเฉลี่ยของประสิทธิภาพการกำจัด S-COD ในการทดลองช่วงที่ 2 มีค่าสูงขึ้น 15.24% เมื่อเปรียบเทียบกับการทดลองช่วงที่ 1 และในการทดลองช่วงที่ 3 มีค่าลดลง 4.95% ค่าเฉลี่ยของแคดเมียมในน้ำออกมีค่าระหว่าง 0.17-12.73 มิลลิกรัมต่อลิตร ประสิทธิภาพในการกำจัดแคดเมียมมีค่าอยู่ระหว่าง 75-97% ประสิทธิภาพในการกำจัดแคดเมียมมีผลต่อภาระแคดเมียมที่สูงขึ้น โดยจะมีประสิทธิภาพลดลงเมื่อภาระแคดเมียมสูงขึ้นในแต่ละการทดลอง อย่างไรก็ตามประสิทธิภาพในการกำจัดจะมีค่าสูงขึ้นเมื่อระยะเวลาเก็บกักสูงขึ้น แคดเมียมมีปริมาณการสะสมมากที่สุดในดิน 56-76% และสะสมในพืชชนิดกกกลม 14-23% ของปริมาณแคดเมียมทั้งหมดที่เข้าสู่ระบบ ปริมาณการสะสมแคดเมียมในดินและพืชมีค่าเพิ่มขึ้นตามปริมาณของแคดเมียมในน้ำเข้าของแต่ละช่วงเวลาของการทดลอง ระยะเวลาการเก็บกักที่เหมาะสมในการกำจัดแคดเมียมคือ 10 วัน

แบบจำลองทางคณิตศาสตร์ของการกำจัดแคดเมียมด้วยระบบพื้นที่ชุ่มน้ำเทียมแบบไหลบนพื้นผิว ได้ถูกพัฒนาขึ้นโดยใช้โปรแกรม STELLA แบบจำลองการปรับเทียบและตรวจสอบความถูกต้องของการสะสมแคดเมียมโดยการดูดซับในดินและการดูดซึมในพืชของการทดลองทั้งหมดพบว่า ค่าที่ได้จากแบบจำลองทางคณิตศาสตร์โดยโปรแกรมคอมพิวเตอร์ มีค่าสอดคล้องกันกับผลการทดลองที่วิเคราะห์ได้ในห้องปฏิบัติการ ค่าเฉลี่ยของประสิทธิภาพในการกำจัดแคดเมียมในพื้นที่ชุ่มน้ำเทียมแบบไหลบนพื้นผิวที่ได้จากแบบจำลองทางคณิตศาสตร์ มีค่าระหว่าง 66.4-83.3%, 73.5-94.2%, และ 83.3-99.6% สำหรับระยะเวลาเก็บกักที่ 5, 7 และ 10 วัน ตามลำดับ

พืชชนิดกกกลมในพื้นที่ชุ่มน้ำเทียมแบบไหลบนพื้นผิวที่มีการดูดซึมและสะสมสารพิษไว้เป็นจำนวนมากแล้วนั้น จะถูกเก็บเกี่ยวและคัดแยกออกจากระบบ หลังจากนั้นจะนำไปเข้าเตาเผาแบบระบบปิด ซึ่งจะได้ขี้เถ้าที่สามารถกำจัดได้ โดยการทิ้งในพื้นที่ทิ้งของเสียโดยเฉพาะ หรือแยกขี้เถ้าที่มีโลหะหนักผสมอยู่กลับมาใช้ใหม่

สาขาวิชาวิศวกรรมสิ่งแวดล้อม
ปีการศึกษา 2549

ลายมือชื่อนักศึกษา ____________
ลายมือชื่ออาจารย์ที่ปรึกษา ____________

PARITA PIMPAN : INVESTIGATIONS AND MATHEMATICAL MODELING OF CADMIUM REMOVAL FROM INDUSTRIAL WASTEWATER IN CONSTRUCTED WETLANDS. THESIS ADVISOR : ASST. PROF. RANJNA JINDAL, Ph. D., 288 PP.

HEAVY METALS/ CADMIUM/ CONSTRUCTED WETLANDS/ FREE WATER SURFACE/ ADSORPTION/ INDUSTRIAL WASTEWATER

This study was conducted to investigate the effect of high cadmium loading on the performance of free water surface constructed wetlands (cultivated bulrush plants) under different environmental conditions. Influents were prepared by mixing the synthetic wastewater with $CdCl_2 \cdot H_2O$ at concentrations of 5, 10, 25, and 50 mg/L for each of the four simultaneous experiments during three runs. The overall performance of the FWS wetlands in terms of Cd removal was very good. Both, the soil and plants were the sinks for the accumulation of cadmium. Cadmium was sorbed by the soil bed and plant uptake. Cadmium adsorption could also have occurred in wetland systems. The total amount of accumulated cadmium in each component of wetlands during the experimental period could be determined. The performance of the wetland system was evaluated for three hydraulic retention times (HRT) 5, 7 and 10 days. Removal efficiencies of the soluble chemical oxygen demand (S-COD) were found to be in the range of 72-91% during the experimental period. With respect to HRT, the S-COD removal increased (15.24% on average) for HRT = 7 days compared to for HRT = 5 days, but slightly decreased (4.95% on average) for HRT = 10 days. The mean effluent cadmium concentrations varied between 0.17-12.73 mg/L. The overall average cadmium removal efficiency during the three runs ranged between 75-97%. Cadmium removal was affected by higher influent loading in each run. Removal decreased with increased loading. However, the removal efficiency for cadmium increased with HRT. Most of the cadmium was accumulated in soil (56-76% of total influent cadmium). Of the total cadmium uptakes, about 14 to 23% of the total cadmium intake was accumulated in bulrush plants. The accumulation in soil and in plants increased with influent loading during each run. The optimum HRT for efficient Cd removal from wastewater was found to be 10 days.

A mathematical model for describing the cadmium removal process in the FWS constructed wetlands was developed using STELLA program. There was good agreement between the simulated and the experimental values of cadmium accumulation in soil and of plants uptake for all experiments used for model calibration and validation. The simulated average Cd removal efficiencies in FWS constructed wetland were in the range of 66.4-83.3%, 73.5-94.2%, and 83.3-99.6% for HRT = 5, 7, and 10 days, respectively.

When the bulrush plants in the FWS constructed wetlands have absorbed and accumulated contaminants, they can be harvested and discarded. Controlled incineration is the most common method used to dispose plants that have absorbed large amounts of contamination. This process produces ashes, which can either be discarded at appropriate waste sites or to recover the original heavy metals from ashes with a high metal content.

School of Environmental Engineering
Student's Signature ____________

Academic Year 2006
Advisor's Signature ____________

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SYMBOLS AND ABBREVIATIONS

FWS	Free water surface constructed wetlands
m^3	Cubic meter
m^2	Square meter
m	Meter
cm	Centimeter
kg	Kilogram
mg	Milligram
g	Gram
kgdw	Kilogram dry weight
L	Liter
mL	Milliliter
d	day
hr	Hour
min	Minute
DO	Dissolved oxygen
S-COD	Soluble chemical oxygen demand
TSS	Total suspended solids
S^{2-}	Sulfide
HCO_3^-	Alkalinity
Cl^-	Chloride

SYMBOLS AND ABBREVIATIONS (Continued)

HRT	Hydraulic retention time
L	basin length, m
W	basin width, m
d_m	media depth, m
d_w	water depth from media surface, m
n	porisity (= void fraction in the media as a decimal fraction)
Q	average flow through the unit, m^3/d
T_{mean}	Actual HRT, d
C_i	Tracer concentration
t_i	Time, min
dt_i	Different time, min
σ^2	Standard deviation
σ_θ^2	Dimensionless standard deviation
d	Dispersion number or dispersion coefficient
D	The longitudinal or axial dispersion coefficient characterizing the degree of back mixing during flow, m^2/d
u	the flow velocity, m/d
BOD	Biochemical oxygen demand
NOD	Dissloved nitrogenous oxygen demand
PAF	Plant aeration flux
SRB	Sulfate reducing bacteria

SYMBOLS AND ABBREVIATIONS (Continued)

Cdp	Cadmium in plants
Cdww	Cadmium in wastewater
Cds	Cadmium in soil
FAAS	Flame atomic adsorption spectrometry
Ms	Dry weight of soil, kgdw
V_{water}	Volume of wastewater of reactor
K	Adsorption coefficient
b	a constant
t	The current simulation time
dt	The time interval between calculations (iteration step)
f	a multiplication factor
mp	The dry weight of plants, kgdw
c	a constant
SPSS	Statistical package for social science
t	Independent samples t-test

CHAPTER I

INTRODUCTION

1.1 Statement of the Problem

Environmental pollution is a consequence of the society we live in. As human population grow in size and density, the magnitude of environmental contamination and pollution problems prow even more rapidly. When human populations were relatively sparse and spread across the landscape, waste products were minor compared to the assimilative capacity of the surrounding natural environment. However, with ever increasing population and the exceeding resources use, the burden of pollution has reached far beyond this capacity.

The major pollutant source categories include municipal, industrial, agricultural, and stormwater. It is evident that industry, being the largest water consumer is also the largest source of water pollution (Kadlec and Knight, 1996). All industrialized and nonindustrialized countries have used and are deliberately using heavy metals for industrial purposes without any consideration in advance of the treatment of the remnant metals. As a consequence, heavy metals are being deposited widespread in the environment and are potential hazards in environmental pollution control (Ernst, 1995; Suschka and Zielonka, 1995). The metals of most immediate concern are: chromium, manganese, iron, cobalt, nickel, copper, zinc, cadmium, mercury, and lead. These metals are widely distributed in materials which make up the earth’s surface (Dean et al., 1972). The wastewater discharged by industrial plants is thought to be the major source of heavy metals discharged to surface water. Electroplating and coating industry, pigments of paint, battery manufacture, plastics manufacture, nonferrous alloys, photocopying, dyeing, and analytical chemistry are some of the leading sources of cadmium in wastewater effluents (Lester, 1987; IARC, 1993; Plachy, 2000; HSDB, 2003). The adverse effects of cadmium on human health are well documented. At extreme levels, it causes an illness called “Itai-Itai” disease, characterized by brittle bones and intense pain. At low levels of exposure over prolonged periods, it causes high blood pressure, sterility among males, kidney damage, and flu-like disorders (Sawyer et al., 1994). The industrial effluent standard for cadmium in Thailand is 0.03 mg/L (Ministry of Science, Technology and Environment, 1996). WHO (2003) has recommended the maximum level of cadmium in drinking water to be 1 µg/L. In the United States, the maximum allowable level of cadmium in drinking water is below 0.005 mg/L (USEPA, 2003).

There are many techniques of heavy metal’ removal from wastewater, such as precipitation, coagulation and complexation, cementation, electrodialysis, reverse osmosis, activated carbon adsorption, ion exchange, and bioremediation; these methods are effective (60-92 % removal) but require high capital, operation and maintenance cost (Drogui et al., 2005; Nomanbhay and Palanisamy, 2005). However, these upgraded treatment systems may not be appropriate for developing countries. Therefore, search for some low cost but reasonable efficiency treatment methods for heavy metals removal from wastewater is needed more than ever before. Among the natural systems of contaminants removal from wastewater, constructed wetlands offer many advantages such as simplicity of design, lower costs of installation, operation, and maintenance, making them an appropriate alternative for both developed and developing countries (Jindal and Samorkhom, 2005). Constructed wetlands are no or low energy requirements. Protection of public health and environment are the fundamental purpose of waste treatment. Wetlands are effective at reducing loads of BOD/COD, nitrogen, phosphorus, suspended solids, metals, and pathogens. Reduction can be up to almost 100% (Dieser, 2006). Heavy metals absorbed by the plants in wetland treatment systems are not returned to the water. There are some limitations to use of constructed wetlands in treating wastewater. They generally require large land areas and the effectiveness will vary with temperature. Metals such as arsenic, chromium, cadmium, copper, mercury, lead, nickel and zinc can accumulate in plants and limit their suitability as fertilizer or feed materials (CEDE, 2001; Chervek, 2005; Dieser, 2006).

1.2 Wetland Treatment System

Wetlands are described as nature’s kidneys because they naturally function as filtering systems in the landscape. Principal processes in wetland systems include: sedimentation, filtration, adsorption, chemical precipitation, decomposition and degradation of material by microorganisms. These ecosystems are being used as templates to design and construct wetlands that have enhanced treatment capabilities for managing domestic, municipal and industrial wastewater (Anonymous, 1994). Constructed wetlands can mimic the filtration processes of natural wetlands, effectively removing contaminants from wastewater (Lorion, 2001). Although constructed wetlands are being developed in many parts of the world for various functions, their wastewater treatment capabilities have attracted research efforts for a wide range of applications (Vigneswaran and Sundaravadivel, 2001).

In the original landscape before economic development, much of the water runoff passed through wetlands which captured the fertile soils and toxic substances. Wetlands all over the world have evolved mechanisms that were mutually reinforcing life in the biosphere. There are now many successful demonstrations that recycling the dilute wastes of cities and industries back through wetlands is a good way to connect the economy to nature. The discovery that many wetlands capture and denature toxic substances raises the possibility that safety for human society can be achieved with little cost by letting nature's ecosystems work for society as they have worked for the biogeosphere in the past (Delfino et al., 2000).

Many researchers have chosen constructed wetlands as an effective method for heavy metals removal from various types of wastewater (Eger, 1994; Goodrich, 1996; Butterworth et al., 1997; Mitsch et al., 1998; Song et al., 2001). The mechanisms of metal removal in wetlands may include adsorption, complexation, precipitation, and plant uptake (Crites et al., 1997; Mungur et al., 1997). Wetlands help to prevent the spread of heavy metal contamination from land to the aquatic environment as there are usually at the ecotone (boundary between land and open surface waters) (Matagi et al., 1998). The ability of a wetland to retain metals is, to a large extent, dependent on the hydrology of the system. In well drained systems, oxidation occurs, and oxides and oxyhydroxides are formed. Iron oxyhydroxides can adsorb metals, forming metal/oxide complexes. In water-saturated soils that are high in organic matter, anoxia develops as microbial oxygen consumption exceeds oxygen replenishment. In anoxic soils, metal ions may precipitate as insoluble, relatively stable sulfide complexes, and may be retained in the sediment (Sinicrope et al., 1992). Many varieties of wetland plant species are tolerant to high concentrations of heavy metals, perhaps because of the protective effect of the iron plaque, which can develop around the roots (Vigneswaran and Sundaravadivel, 2001). Hence, wetlands can be designed and built for heavy metals removal.

1.3 Research Objectives

The overall goal of this study was to investigate the effectiveness of free water surface (FWS) constructed wetlands for removal of cadmium from industrial wastewater under tropical conditions. The specific objectives of this study included:

1. To study the cadmium removal from industrial wastewater in the FWS constructed wetlands by investigating the transport, distribution, and accumulations in the wetland components.
2. To evaluate the effect of cadmium loading and hydraulic retention time (HRT) on the performance of FWS constructed wetlands.
3. To develop a mathematical model for describing the cadmium removal process in the FWS constructed wetlands and verify the model with experimental results.

1.4 Scope of Research

The study was carried out as following:

1. Five laboratory-scale constructed wetland units were constructed near the Equipment building-F5 at Suranaree University of Technology (SUT).
2. The aboveground parts of the bulrush (*Cyperus corymbosus* Rottb.) plants were cultivated in laboratory-scale constructed wetlands.

3. The experimental units were fed with the synthetic industrial wastewater prepared in the laboratory.
4. The experimental runs were carried out with synthetic industrial wastewater mixed with cadmium (Cd) at four concentrations of 5, 10, 25 and 50 mg/L.
5. Wetland systems' performance were evaluated for three hydraulic retention times (HRTs) 5, 7 and 10 days, corresponding to three different influent flow rates of 51.75, 36.96 and 25.88 L/d, respectively.
6. The parameters measured included: pH, dissolved oxygen (DO), temperature, soluble chemical oxygen demand (S-COD), total suspended solids (TSS), Sulfide (S^{2-}), Alkalinity (HCO_3^-), and heavy metals concentrations in influent and effluent, as well as in soil and plants.
7. A mathematical model to describe cadmium removal in the FWS constructed wetlands was developed. The developed model was calibrated and validated with the laboratory-scale experimental results using commercial software "STELLA".

CHAPTER II

LITERATURE REVIEW

2.1 Wastewater Pollutants

The important contaminants of concern in wastewater treatment are listed in Table 2.1. Secondary treatment standards for wastewater are concerned with the removal of biodegradable organics, suspended solids, and pathogens. Many of the more stringent standards have been recently developed to deal with the removal of nutrients and priority pollutants. Diffused pollution may be responsible for the major part of contamination of the environment by toxic pollutants. Toxic chemicals in the environment are either inorganic or organic. Inorganic contaminants are mostly in the category of trace metals, which may be both natural and anthropogenic (man-made). Other inorganic nonmetallic toxic compounds detected in the aquatic environments are unionized ammonia (NH_3), cyanides, asbestos, and hydrogen sulfide (H_2S) (Novotny, 1995).

Heavy Metals

Heavy metals are known for their toxicity. Some heavy metal ions, such as nickel (Ni), lead (Pb), chromium (Cr), cadmium (Cd), zinc (Zn), and mercury (Hg) are particularly toxic with respect to human health and environment. Even if present in extremely low concentrations, the effects of heavy metal ions may be detrimental as a result of steady accumulation in the food chain. Like other persistent environmental pollutants, heavy metals can be transported over long distances

Table 2.1 Important contaminants of concern in wastewater treatment (Metcalf & Eddy, 1991).

Contaminants	**Reason for importance**
Suspended solids	Suspended solids can lead to the development of sludge deposits and anaerobic conditions when untreated wastewater is discharged in the aquatic environment.
Biodegradable organics	Composed principally of proteins, carbohydrates, and fats, biodegradable. Organic are measured most commonly in terms of BOD (biochemical oxygen demand) and COD (chemical oxygen demand). If discharged untreated to the environment, their biological stabilization can lead to the depletion of natural oxygen resources and to development of septic condition.
Pathogens	Communicable diseases can be transmitted by the pathogenic organisms in wastewater.
Nutrients	Both nitrogen and phosphorus, along with carbon, are essential nutrients for growth. When discharged to the aquatic environmental, these nutrients can lead to the growth of undesirable aquatic life. When discharge in excessive amounts on land, they can also lead to the pollution of groundwater.
Priority pollutants	Organic and inorganic compound selected on the basis of their know or suspected carcinogenicity, mutagenicity, teratogenicity, or high acute toxicity. Many of these compounds are found in wastewater.
Refractory organics	These organics tend to resist conventional methods of wastewater treatment. Typical examples include surfactants, phenols, and agricultural pesticides.
Heavy metals	Heavy metals are usually added to wastewater from commercial and industrial activities and may have to be removed if the wastewater is to be reused.
Dissolved inorganics	Inorganic constituents such as calcium, sodium, and sulfate are added to the original domestic water supply as a result of water use and may have to be removed if the wastewater is to be reused.

throughout the environment, far from the original source of pollution, thus potentially causing adverse environmental and public health effects even after long periods of time. On the basis of our growing insight in the risks involved in environmental pollution with heavy metals, it is now obvious that prevention of pollution at the source is the safest option (Salomons et al., 1995).

Since all metals can be found in nature and are part of the earth's crust, distinction must be made whether the metals originate from natural or man-made sources. Both natural and anthropogenic sources contribute to water quality content of surface water bodies, which has two important consequences. First, if the metal content of a water body, in sediment or water, is due to natural causes it is considered as a background (natural) water-sediment quality. Second, only water-sediment contamination from various sources that "impair integrity of the water resource" is pollution. From the many metals in the periodic table, only about a dozen are present in aquatic systems in quantities that can be harmful to aquatic biota and/or human health (Novotny, 1995).

2.2 Techniques for Heavy Metals Removal from Wastewater

Heavy metals exist in wastewaters and environmental waters in many forms, including soluble, insoluble, inorganic, organic, reduced, oxidized, free metal, precipitated, adsorbed, and complexed. As a result of extensive research efforts during the past decade, an impressive array of treatment methods are available to cope with heavy metals today (Dean et al., 1972; Lanouette, 1977; Metzner, 1977; Lanouette and Paulson, 1976). Some of the new techniques developed have been successfully demonstrated in full-scale applications while others are still in the development stage. Recovery of metals from wastewaters and sludges has also received considerable attention and improved methods for the safe disposal (Beszedits and Wei, 1980). Some of the commonly used techniques of heavy metals' removal from wastewater are briefly discussed below.

2.2.1 Precipitation, Coagulation and Complexation

Precipitation is by far the most common technique for removing heavy metals from wastewater. Since metals precipitate at different pH levels, choosing the optimum pH for the treatment of an effluent containing several species requires careful evaluation. The presence of complexing agents can hinder precipitation. Heavy metals in complexed organic form are usually treated to destroy the complex thereby freeing the metal. The freed metal then can be readily removed by precipitation. The resultant precipitate is usually separated from the aqueous phase by sedimentation. However, filtration may be required to remove fine residual solids. Addition of polyelectrolytes can substantially enhance the settling of the precipitate.

Hannah et al. (1977) conducted some studies and carried out the experiments on removal of uncommon trace metals. The treatment plants consisted of chemical clarification, dual media filtration, and granular activated carbon adsorption. Lime, ferric chloride, and alum, alone or in combination, were used as precipitant coagulants. Most metals were readily removed by precipitation and sedimentation. However, there were substantial variations. For, example, ferric chloride was more effective than lime or alum for removing mercury irons. Alum was not very effective for nickel and zinc but gave 91% reduction in the level of lead. All three coagulants attained equally good results with trivalent chromium but most of the hexavalent chromium was removed by activated carbon adsorption. Better than 94% removals were obtained for silver with all three coagulants. Lime treatment followed by activated carbon adsorption appeared to be the most reliable system for removing cadmium while a combination of lime and ferric chloride at pH 10 gave the best results for zinc.

2.2.2 Cementation

Cementation, also referred to as chemical displacement, has a long history in hydrometallurgical applications. The process has been well known and widely used since the time of the ancient Romans. Copper, mercury and silver are the chief metals recovered from solutions by this technique. Moreover, cementation is suitable not only for removal of metals but also for the reduction of hexavalent to the trivalent forms. When a solution containing a dissolved metal is contacted with a more active metal, the less active species is reduced to its metallic form by spontaneous electrochemical reduction and deposits on the more active metal. Some of the more active or sacrificial metal is released into the solution as its ion. The weaker metal is recovered in a very pure from. If required, the solubilized sacrificial metal is removed. A considerable difference in the electromotive force between metals is necessary to produce adequate cementation.

Cementation has also been adopted for the treatment of various metal-contaminated effluents. The process is particularly suitable for small waste flows. It is not advantageous when large flows are involved since effective cementation usually requires long contact times (Beszedits and Wei, 1980).

2.2.3 Electrodialysis

Electrodialysis is a membrane process, which can separate, remove or concentrate ionic species by the imposition of an electric filed. Its use in the production of potable water from brackish and salt waters is well known. Lately, electrodialysis has also found increasing application in the treatment of wastewater.

To achieve good efficiency, electrodialysis cells are made very thin and are assembled in stacks of cell. An electrode flanks each end of the stack. Ion selective membranes are the key to electrodialysis. Two different types of membranes must be employed: an anion-selective membrane and a cation-selective membrane.

Feed is introduced into alternate membrane compartments and under the influent of applied DC voltage, the cations and anions migrate in opposite directions (Mulligan and Fox, 1976). Most membranes used in electrodialysis are based on copolymers of divinyl-benzene-styrene with ion exchange groups. Commercial cation membranes are usually of the sulfonic type. Anion membranes are mainly of the quaternary ammonium type (Beszedits and Wei, 1980).

Trivedi and Prober (1972) investigated the possibility of recovering nickel from plating wastes. Based upon the results generated, they concluded that it is feasible to employ electrodialysis for the recovery and reuse of nickel from such wastes. For a typical application, DC power requirements were estimated to be 1.5 kWhr/kg nickel recovered.

General Motors Research Laboratory developed a process whereby trivalent chromium wastes from plating bath are oxidized to the hexavalent form and then recovered by electrodialysis (Anon, 1976). Electrodialysis has also been adopted for the treatment of waste solutions from copper and nickel plating operations at a number of plants in Japan (Eisenman, 1977).

2.2.4 Reverse Osmosis

Reverse osmosis or hyperfiltration is a separation process, which utilizes high pressures and semi-permeable membranes to remove pollutants from solutions. Reverse osmosis is basically a concentration technique and is most effective if the concentrate can be reused.

Closely related to reverse osmosis is ultrafiltration. Actually there is no sharp distinction between the two. However, ultrafiltration is basically a physical sieving process, which removes solutes on the basis of size and sharp while the operational mechanism in reverse osmosis is generally conceded to be a physical-chemical process in which the nature of the membrane-solution interaction largely determines its effectiveness for the removal or concentration of specific constituents.

Ability of reverse osmosis membranes to reject electrolytes increases with an increase in valency. Because organic compounds vary widely in their molecular weight, steric configuration and ability to form hydrogen bonds, there are considerable variations in the rejection of organics from aqueous solutions (Beszedits and Wei, 1980).

Very high heavy metal removals can be attained by reverse osmosis. Rejection of divalent and trivalent ions for example, can be as high as 97-99% (Kaup, 1977). Due to the relatively large pore sizes of the membranes; ultrafiltration is not suitable for the removal of the heavy metals. However, since it has been suggested that it is possible to separate metal ions by ultrafiltration if the ions could be bound up in large molecular complexes (Beszedits and Wei, 1980).

2.2.5 Activated Carbon Adsorption

Activated carbon adsorption is one of the most popular techniques for the removal of dissolved organics. The carbon may be used in granular or powdered form although granular carbon is preferred type. Carbon in biological treatment plants imparts a number of benefits including improved BOD and COD removals besides removing such toxic chemicals as heavy metals (Flynn and Stadnick, 1979).

Activated carbon has a pronounced affinity for ionic as well as complexed metals. Until recently, however, the use of activated carbon was confined mainly to the removal of mercury. Activated carbon adsorption has also been found to be a very effective polishing step for removing trace heavy metals from secondary effluents (Beszedits and Wei, 1980).

Activated carbon used for metal removal may be regenerated by several techniques including caustic desorption, thermal regeneration and acid washing (Huang and Bowers, 1979). However, if carbon is regenerated thermally at high temperature, an inorganic metal-oxide reside may build up on the carbon surface, necessitating replacement or the application of a suitable washing procedure (Stevens and Kerner, 1975).

2.2.6 Ion Exchange

In ion exchange a solution is passed through a bed of resin, which selectively removes either the cations or the anions. Ion exchange is particularly applicable to wastewaters not amenable to more conventional treatment methods, and is ideally suited for dilute effluents. To prevent fouling and to ensure reasonably long membrane life, a certain degree of pretreatment is essential (Tilsley, 1975). Excellent heavy metal removals can be attained and treated discharge is of very high quality.

However, if the regenerant solution, smaller in volume and higher in pollutant concentration than the original waste stream, cannot be utilized, another waste disposal problem is created.

Ion exchange has been successfully adopted for the treatment of a wide array of effluents, including discharges from pigment works, metal finishing, chlor-alkali plants, and photographic processing (Beszedits and Wei, 1980).

2.2.7 Bioremediation

Bioremediation is the application of biological process principles to the treatment of groundwater, soil, and sludges contaminated with hazardous chemicals (Cookson, 1995). Bioremediation uses microorganisms or microbial processes to detoxify and degrade environmental contaminants. The municipal wastewater treatment industry is based on the exploitation of microorganisms in controlled and engineered systems. Both activated sludge and fixed-film treatment systems depend on the metabolic activities of microorganisms, which degrade the wastes entering the treatment facility. Specialized waste treatment plants containing selected and acclimated populations of microorganisms are often used to treat industrial effluents (Eckenfelder, 1989).

The major ways by which such remediation may be accomplished include: biosorption, bioaccumulation, reduction, solubilization (commonly associated with oxidation of sulfides or ferrous iron), precipitation, and methylation. Biosorption refers to the passive uptake of metals by microbial cells. This sorption is passive in that no energy is required (Alexander, 1999). Some microorganisms can use biomethylation to eliminate heavy metals, such as mercury and tin, and metalloids, such as arsenic and selenium (Wood and Wang, 1983).

Intracellular traps can be biosynthesized as a temporary measure for organisms to remove metal ions (e.g., synthesis of metallothionen and removal of cadmium by this sulfhydryl-containing protein) (Williams, 1981), and to prevent metals from reaching toxic levels (Wood and Wang, 1983). Mutants with intracellular trapping mechanisms tend to bioconcentrate the toxic metals intracellularly to about 200 times over the external concentration. This strategy works well for some organisms but is not as effective as the extracellular binding or precipitation of metals (Riser-Roberts, 1992).

2.2.8 Wetlands

Wetland is an area, which is inundated or saturated by surface or groundwater at a frequency or duration sufficient to maintain saturated conditions and growth of related vegetation (Polprasert, 1996).

Wetlands are defined as lands where the water surface is near the ground surface long enough each year, to maintain saturated soil conditions, along with the related vegetation (Thayalakumaran, 1994).

Wetlands were once regarded as wasted land. It is now clear that they provided irreplaceable benefits to people and the environment in terms of natural flood prevention and pollutant filtering systems and contribute significantly to ground water recharge. Freshwater, brackish, and saltwater wetlands have inadvertently served as natural water treatment systems for centuries. Because of their transitional position in the landscape between terrestrial and aquatic ecosystem, some wetlands have been subjected to wastewater discharges from both municipal and industrial sources. Wetlands have also received agricultural and surface mine runoff, irrigation return flows, urban stormwater discharges, leachates and other sources of water pollution. Wetlands that are dominated by water tolerant woody plants are generally called as swamps; those with soft-stemmed plant species as marshes; and those with mosses as bogs. Swamps and marshes can be of either salt water or freshwater type. Saltwater swamps are popularly known as mangroves.

Wetlands have high rate of biological activity and hence high rate of vegetative growth as well as zooplanktons. Wetlands along the shores of seas, lakes and riverbanks play a valuable role in their stabilization and protection from erosive tides, waves, storms, floods and winds. They also function as groundwater recharge areas and sometimes as discharge areas where the water table touches the surface level. Because of their ability to transform and store organic matter and nutrients, wetlands are often described as the “kidneys of the landscape” (Vigneswaran and Sundaravadivel, 2001). A number of studies have found evidence that wetlands are able to provide a high level of wastewater treatment. However, concern has also been expressed regarding the possible harmful effects of toxic materials and pathogens in wastewater, and the long-term degradation of wetlands due to the additional nutrient hydraulic loadings from wastewater discharges (USEPA, 1987). Due to theses concerns, as well as other factors, there has been considerable interest in using constructed wetlands for wastewater treatment.

Kadlec and Knight (1996) described that wetland treatment systems use rooted, water-tolerant plant species and shallow, flooded, or saturated soil conditions to provide various types of wastewater treatment. The three basic types of wetland treatment systems include natural wetlands, constructed surface flow (SF) wetlands, and constructed subsurface-flow (SSF) wetlands. Constructed wetlands mimic the optimal conditions found in natural wetlands, but provide the flexibility of being construct able at almost any location.

Surface-flow wetlands (natural and constructed) are densely vegetated by a variety of plant species and typically have water depths less than 0.4 m. Open water areas may be incorporated into design to provide for optimization of hydraulics and for wildlife habitat enhancement. According to the WPCF (1990), typical hydraulic loading rates are between 0.4 to 4.0 cm/d (2.5 to 25 ha/1000 m^3/d) in natural wetlands and 0.7 to 5.0 cm/d (2 to 14 ha/1000 m^3/d) in constructed surface-flow wetlands.

Subsurface-flow wetlands use a bed of soil or gravel as a substrate for growth of rooted wetland plants. Pretreated wastewater flows by gravity, horizontally through the bed substrate where it contacts a mixture of facultative microbes living in association with the substrate and plant roots. Bed depth in SSF flow wetlands is typically less than 0.6 m, and the bottom of the bed is sloped to minimize that water flow overland.

Wetlands have been found to be effective in treating biochemical oxygen demand, suspended solids, nitrogen, and phosphorus, as well as for reducing metals, organics, and pathogens. Effective wetlands performance depends on adequate pretreatment, conservative constitute and hydraulic loading rates, collection of monitoring information to assess system performance, and knowledge of success operation strategies.

2.3 Constructed Wetlands

2.3.1 Description

Constructed wetlands are defined as those systems specially designed for wastewater treatment and located at a site where natural wetlands do not exist at least at the time of construction (Thayalakumaran, 1994).

Hammer (1989) defined constructed wetlands as a designed and man-made complex of saturated substrates, emergent and submergent vegetation, animal life, and water that simulate natural wetlands for human use and benefits.

Constructed wetlands are engineered systems that have been designed to employ wetland type vegetation to assist treating wastewater in a more controlled environment than occurs in natural wetlands. Constructed wetlands, as the term suggests, are man-made wetlands artificially developed in areas where they do not occur naturally. Although constructed wetlands are being developed in many parts of the world for various functions, their wastewater treatment capabilities have attracted research efforts for a wide range of applications including domestic wastewater, urban stormwater, industrial/agricultural flows, landfill leachates, acid mine draining, etc (Vigneswaran and Sundaravadivel, 2001).

Constructed wetlands may be developed for one or more of the following reasons: (1) to compensate or help offset the rate of conversion of natural wetlands resulting from agricultural and urban development (constructed habitat wetlands); (2) to act as a flood control facility (constructed flood control wetlands); (3) to be used for production of food and fiber (constructed aquaculture wetlands); and (4) to be a wastewater treatment system and to improve water quality (constructed treatment wetlands) (Kadlec and Knight, 1996).

Constructed wetlands have been used as wastewater treatment system: it is generally found that this system may act as efficient water purification system and nutrient sinks. The pollutants in these systems are removed through a combination of physical, chemical and biological processes including sedimentation, precipitation, adsorption to soil particles, assimilation by the plant tissue, and microbial transformation (Maw, 1996). The advantages of this system are its simplicity, low construction cost, absence of special high-tech equipment, low energy consumption and minimum maintenance. These systems are usually more flexible and less susceptible to variations in loading rate than conventional treatment systems (Maw, 1996; Salek et al., 1996). Other beneficial features include: insensitivity to fluctuating hydrologic and contaminant loading rates, effective and reliable wastewater treatment systems, and provision of green space, wildlife habitats and recreational and educational areas (Hilton, 1993; Wrigley and Toerien, 1988).

2.3.2 Components of Constructed Wetlands

The basic mechanism of organic matter degradation in constructed wetlands is plant-bacteria symbiotic reactions. Major influential components in the treatment process of constructed wetlands include aquatic plants, substratum, water column, and microorganisms (Reed et al., 1995).

1) Aquatic Plants

The basis for employing constructed wetlands for wastewater treatment is the ability of aquatic plants to translocation oxygen to their roots, and the surrounding water (wastewater, in case of treatment wetlands) environment. Although a number of other pollution removal processes have been identified, the wetland plants play a major role in the occurrence of most of these processes. Within the water column, the stems and leaves of the wetland plants significantly increase surface area for biofilm development. Plant tissues, moreover, are colonized by photosynthetic algae as well as by bacteria and protozoa. Likewise, the roots and rhizomes that are buried in the wetland substrate provide for attached growth microorganisms (Brix, 1997). Major roles of vegetation in constructed wetlands are summarized in Table 2.2.

Table 2.2 Major roles of macrophytes in constructed wetlands (Brix, 1997).

Wetland plant part	**Role**
Aerial plant tissue	• Light attenuation → reduced growth of phytoplanktons • Influence on microclimate → insulation during winter • Reduced wind velocity → reduced risk of resuspension of solids • Aesthetic appearance • Nutrient storage
Plant tissue in water	• Filtering effect → filter out large debris • Reduced current velocity → increased rate of sedimentation, reduced risk of resuspension • Surface area for attached microorganisms • Excretion of photosynthetic oxygen → increased aerobic degradation • Nutrient uptake
Roots and rhizomes	• Stabilizing the sediment surface → less soil erosion • Prevents the medium from clogging in vertical flow systems • Release of oxygen increase organic degradation and nitrification • Nutrient uptake • Secretion of antibiotics for detoxification of root zone → pathogen removal

Wetland Plant Species

A wide variety of aquatic plants can be used in constructed wetland systems designed for wastewater treatment. The emergent macrophytes (rooted plants that anchor to the substrate media) that are most commonly used planted in constructed wetlands, are cattails (*Typha* spp.), common reeds (*Phragmitis* spp.), bulrushes (*Scirpus* spp.), and sedges (*Carex* spp.) shown in Figure 2.1 (Lim and Polprasert, 1996; Reed et al., 1988). These plants can grow in a wide range of substrates and in a wide variety of wastewater (Reed et al., 1995). Macrophytes have several intrinsic properties, which influence the treatment of wastewater in constructed wetlands (Brix, 1994).

Oxygen Supply

Oxygen can be considered to cycle within wetlands. Oxygen enters via inflows or by diffusion at the water surface when the surface is turbulent (for example, due to wind mixing). Oxygen is also produced within the water column during photosynthesis. It is well documented that aquatic macrophytes release oxygen from roots which influences the biogeochemical cycles in the sediments due to the effects on the redox status of the sediments (Barko et al., 1991; Sorrel and Boon, 1992).

In anaerobic soils, oxygen is transferred to the roots primarily for plant respiration (Kadlec, 1995) and only excess oxygen is leaked to the micro-zone around the root (rizhosphere). Oxygen release is primarily at the root tip to detoxify and oxidize potentially harmful substances in the rhizosphere (Armstrong and Armstrong, 1990). In this zone, oxidation reaction can take place, while anaerobic reactions can occurrence only microns away (Figure 2.2).

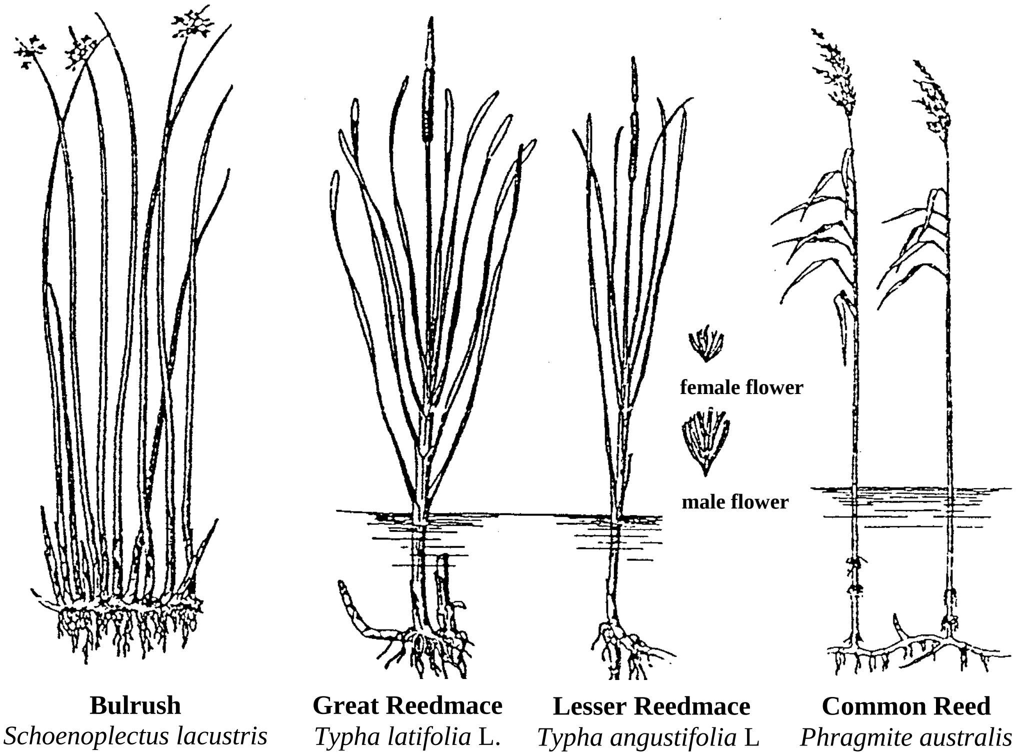


Figure 2.1 Common emergent plants. (Source: Koottatep, 1999)

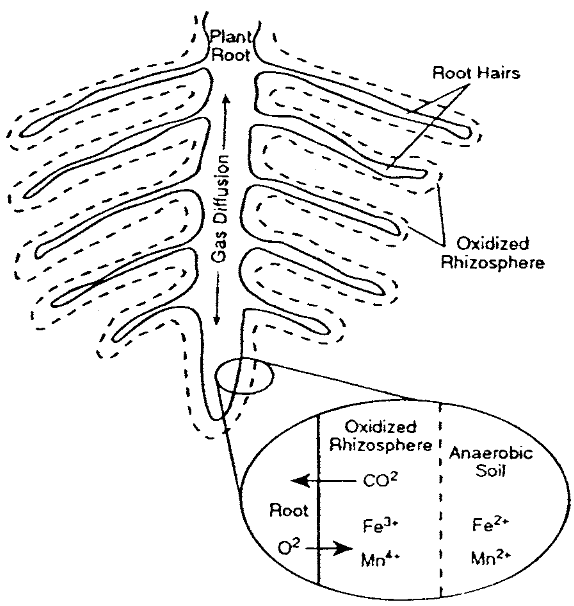


Figure 2.2 Oxygen transfer through root zone. (Source: Kadlec and Knight, 1996)

Physical Effects

The physical presence of vegetation in wetlands distributes and reduces the current velocities of the water, which creates better conditions for sedimentation of suspended solids. Light attenuation by the wetland plants hinders the production of algae in the water below the vegetation cover. The vegetation cover in a wetland can be regarded as a thick biofilm located between the atmosphere and the wetland soil or water surface in which significant gradients in different environmental parameters occur. Wind velocities are reduced near the soil or water surface compared to the velocities above the vegetation, which reduced resuspension of settled material and thereby improves the removal of suspended solids by sedimentation. In temperature areas, the plant cover provides insulation during winter and helps keep the substrate free of frost (Smith et al., 1997).

Hydraulic Conductivity

In treatment wetlands, wastewater flow is largely intended to be below the surface through channels created by living and dead roots as well as through the pore space of the substrate medium. As roots and rhizomes grow, they disturb and loosen the soil. Further more, when the roots and rhizomes die and decay, they may leave behind tubular pores and channel, which can improve the hydraulic conductivity of the substrate. This may be largely true with gravel medium based substrate. On the contrary, the hydraulic conductivity of soil-based systems often decreases (Marsteiner et al., 1996). Data on hydraulic conductivity in soil-based reeds in Australia, Denmark, and in the UK also do not support the increase in hydraulic conductivity due to wetland plants in soil-based system (Conely et al., 1991; Haberl and Perfler, 1990).

Nutrient Uptake

Nutrient requirement for growth of wetland macrophytes, mainly the nitrogen and phosphorus, are taken up primarily through their root systems. Marginal uptake occurs also through immersed stems and leaves from the surrounding water (Gumbricht, 1993). Thus, the vegetation may be helpful in removal of nutrients from wastewater. Shaver and Mellio (1984) have shown that nutrient uptake is maximum during the initial period of establishment of the plants in constructed wetlands, and the efficiency tends to decreases an available nutrient input rise, that is, when the nutrient loading rates increases, the uptake of nutrient by plants decreases.

Organic and Antibiotic Excretion

Root systems of wetland plants also release substances other than oxygen. Early experiments of the Max Planck Institute in Germany showed that the bulrush *Schoenoplectus* released antibiotics from its roots. It is also known that a range of submerged macrophytes release compounds that that affects the growth of other species. However, the role of these compounds in wetland treatment processes has not yet been experimentally verified. Plants also release a wide range of organic compounds through their roots (Rovira, 1969; Barber and Martin, 1976). Reported values of these organic compounds are in the range of 5 to 25% of the photosynthetically fixed carbon (Brix, 1997). The organic carbon so excreted may be act as a carbon source for denitrification process, and hence enhance the nutrient removal process in constructed wetlands (Platzer, 1996).

2) Substratum

Substratum is needed to support vegetation. It may be soil, sand, gravel, rock or combination of these components. Apart from supporting vegetation, the substrates also act as the principal storage of all biotic and abiotic components that exist in a wetland. In addition, coarse sand and gravel substrates provide surface area for attached growth microorganisms and promote filtration and setting of suspended solids (Vigneswaran and Sundaravadivel, 2001). The rate of soil accretion in wetland treatment systems affects the potential removal of conservation elements such as phosphorus and heavy metals and also is an important consideration during design of term height above the wetland substrate. Surface soil/subsurface layer with slow permeability (<0.5 cm/h ~ 0.2 inch/h) are most suitable for the constructed wetland system (Metcalf & Eddy, 1991). Soil may be selected as the bed media when phosphorus removal is a requirement. However, soils with high phosphorus removal potential tend to be finer in texture, with low to moderate permeability, and this may limit the hydraulic capacity of a wetland soil bed (Mattaraj, 1995).

A common problem in constructed wetland operation is clogging. Several studies with soil based treatment wetlands have reported problems of clogging and causing overflows of wastewater resulting in bed erosion and poor plant growth (Cooper and Hobson, 1990). Infilling and occlusion of interstitial spaces by solids will reduce the effective volume available within the substratum, leading to increasing flow velocities, decreasing hydraulic retention times, and short-circuiting. Many cases of surface flow problems investigated by USEPA (1993) were attributed to inadequate hydraulic design or introduction of fine inorganic sediments during construction and planting, which clogged void space in the bed.

Therefore, soil is usually not recommended as substrate for wastewater treatment wetlands, and gravel has been used in reed bed systems in several countries. In the longer term, factors such as the degradable fraction of the suspended solids and their rate of microbial and chemical degradation under the wetland environment will determine the solids accumulation and hence the clogging rate (Vigneswaran and Sundaravadivel, 2001).

3) Water Column

Maintaining the water column is an important requirement of constructed wetlands since the water level governs the major ecological functions occurring in the system. Water provides the environment for biochemical reactions to occur and acts as a transport medium to carry the end-products such as gases, organic acids etc., from one reaction site to another reaction site (Vigneswaran and Sundaravadivel, 2001).

4) Microorganisms

The presence of vertebrates and invertebrates (higher level animals) may not be essential for the functioning of constructed wetlands; microbial forms of organisms play a critical role. Microorganisms are typically responsible for degradation of organic content and are naturally found in water and wastewater, such as bacterial, fungi, protozoa, etc., thrive in wetlands, which provide suitable environmental conditions for their survival and proliferation (Vigneswaran and Sundaravadivel, 2001). Bacteria in the constructed wetland systems can be divided into two main types; suspended and attached-growth bacteria. The suspended bacteria generally live in the surface water of constructed wetlands, while the attached-growth bacteria grow on the surfaces of submerged parts at the emergent plants (roots, stems), peat, rock, sand or sediment at the bottom layer (Rogers et al., 1985). Polprasert and Khatiwada (1998) reported that suspended bacteria are much less active than those of attached-growth bacteria in the constructed wetlands.

2.3.3 Types of Constructed Wetlands

Municipal wastewater treatment systems using constructed treatment wetlands have been categorized as either free water surface (FWS) or subsurface flow (SF) types.

1) Free Water Surface System (FWS)

In FWS wetlands (Figure 2.3), the substrate bed is densely vegetated, and the water column will be above the surface of the bed. The FWS systems are flooded and expose water surface in the system to the atmosphere. These systems consist of parallel basins or channels with relatively impermeable bottom (subsurface barrier) and soil or rock layer to support the emergent vegetation and shallow water depth is maintained at 0.1-0.6 m above the soil surface. Emergent vegetation is grown and wastewater is treated as it flows through the vegetation and plant litter. The FWS wetlands are typically long and narrow to minimize short-circuiting (Polprasert, 1996; USEPA, 1988; Vigneswaran and Sundaravadivel, 2001).

2) Subsurface Flow System (SF)

In SF wetlands, the water level is maintained below the surface of the substrate bed. These systems are variously known as vegetate submerged bed (VSB), root zone system, rock reed filter, or microbial rock filter (Figure 2.4). SF wetlands basically consist of channels or trenches with impermeable bottoms filled with sand, rock, crushed stone or gravel media. The substrate medium in SF wetlands is usually made of gravel to provide high void space to enable wastewater loaded on the bed to quickly seep through the bed. Wastewater flows horizontally through the root zone of the wetland plants about 100 to 150 mm below the gravel surface. The bed depth of horizontal SF wetlands is typically less than 0.6 m, and the bottom of

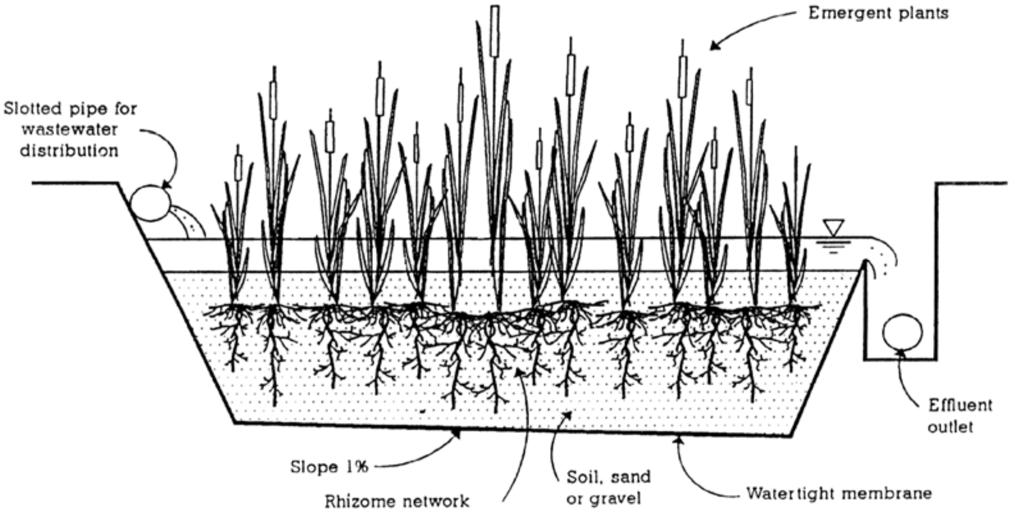


Figure 2.3 Free water surface constructed wetland system (FWS)

(Source: Lim and Polprasert, 1996).

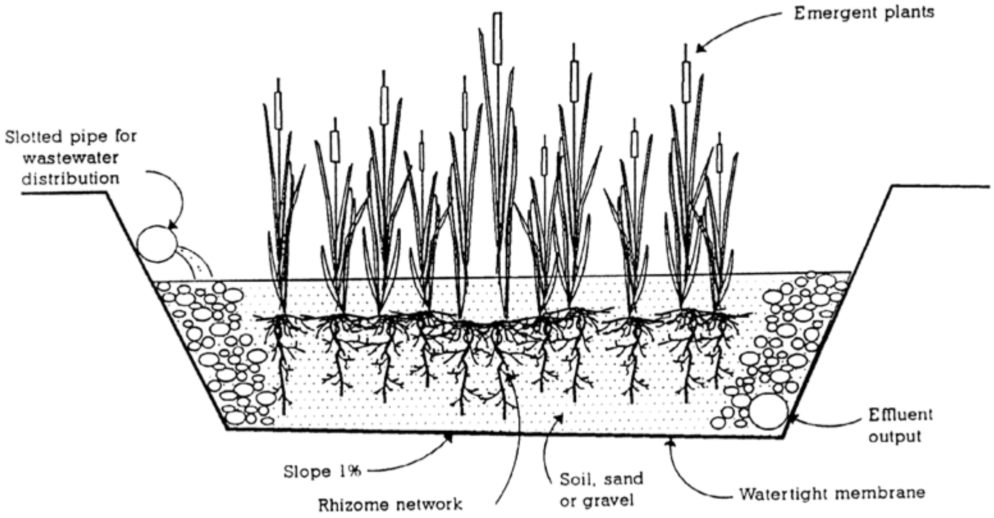


Figure 2.4 Subsurface flow constructed wetland system (SF)

(Source: Lim and Polprasert, 1996).

bed is sloped to minimize flow above the surface (Kadlec, 1995; Mattaraj 1995; Reed et al., 1988; Lim and Polprasert, 1996; Vigneswaran and Sundaravadivel, 2001).

There are limited data available on the metal removal capability of FWS wetlands; because the removal mechanisms are similar to those described above for phosphorus, the response is not very effective (USEPA, 1987). The SF constructed wetlands could be subjected to frequent clogging problem, the FWS system, which has less operating problems (Koottatep, 1999). There is greater opportunity for contact and sorption in SF systems and metals removal can be very effective. Phosphorus removal and metals removal will likely be finite due to exhaustion of exchange sites (USEPA, 1988).

Constructed wetlands can be classified according to the life form of the dominating macrophyte in the wetland as follows (Brix, 1993; Polprasert, 1996):

1) Free-Floating Macrophyte-Based Systems are highly diverse in form and habit, ranging from type of plants, leaves and submerged roots, e.g. water hyacinth (*Eichhornia crassipes*), duckweeds (*Lemma*, *Spirodella, Wolfia arrhiga*), water lettuce (*Pistia stratiotes*), and salvinia (*Salvinia* spp.).

2) Emergent Macrophyte-Based Systems are the common reeds (*Phragmites communis*), cattails (*Typha* spp.), and bulrushes (*Scirpus* spp.). All species of these plants grow in water-logged sediment by air transportation of oxygen from leaves and stems to the root and rhizomes, creating oxidizing conditions in the otherwise anoxic sediment. All of this can promote decomposition of organic matter and growth of nitrifying bacteria. Emergent macrophyte-based wastewater treatment systems can be divided in three groups:

a) Emergent Macrophyte-Based Systems with Surface Flow

b) Emergent Macrophyte-Based Systems with Horizontal Subsurface Flow

c) Emergent Macrophyte-Based Systems with Vertical Subsurface Flow

3) Submerged Macrophyte-Based Systems: Such aquatic macrophyte lives under the water. They have low productivity and grow only in oligotrophic water (e.g. *Isoetes lacustris* and *Lobelia dortmana*), and to high-productivity in eutrophic water (e.g. *Elodea Canadensis*). Subsurface aquatic plants are able to assimilate nutrients from polluted water but cannot grow in high concentration of organic matter because of anoxic condition development. Inorganic carbon reduction and DO increase occur during photosynthesis of submerged plants.

2.3.4 Treatment Mechanisms

Wetland systems reduce many contaminants, including biochemical oxygen demand (BOD), suspended solids (SS), nitrogen, phosphorus, heavy metals, trace organics, and pathogens. This reduction is accomplished by diverse treatment mechanisms: sedimentation, filtration, chemical precipitation, adsorption, microbial interaction, and uptake by vegetation. These are summarized in Table 2.3 and discussed in below for major constituents.

BOD Removal

The removal of settleable organics is very rapid in all wetland system and is due to the quiescent condition in the FWS types and to deposition and filtration in the VSB systems. In the VSB systems, the major oxygen source is the amount of $O_{2,}$ which is transmitted by emergent plants through the root zone. In most cases, the

Table 2.3 Summary of removal mechanisms in wetlands for the pollutants in wastewater (USEPA, 1988).

Mechanism	**Pollutant affected** [a]								**Description**
	Settleable solids	Colloidal solids	BOD	N	P	Heavy metals	Refractory organics	Bacteria & virus	
Physical									
sedimentation	P	S	I	I	I	I	I	I	Gravitational settling of solids (and constituent pollutants) in wetland settings.
filtration	S	S							Particulates filtered mechanically as water passes through substrate, and root masses.
adsorption		S							Interparticle attractive forces.
volatilization				S					Volatilization of NH_3 from the wastewater.
Chemical									
precipitation					P	P			Formation of or coprecipitation with insoluble compounds.
adsorption					P	P	S		Adsorption on substrate and plant surfaces.
decomposition							P	P	Decomposition or alteration of less stable compounds by phenomena such as UV irradiation, oxidation and reduction.
Biological									
bacteria metabolism[b]		P	P	P			P		Removal of colloidal solids and soluble organics by suspended and plant-supported bacteria. Nitrification / denitrification.
plant metabolism[b]							S	S	Uptake and metabolism of organics by plants. Root excretion may be toxic to organisms of enteric origin.
plant absorption				S	S	S	S		Under proper conditions, these pollutants will be taken up by plants.
natural die-off								P	Natural decay of organisms in an unfavorable environmental.

Notes : [a] P = primary effects; S = secondary effect; I = incidental effect (effect occurring incidental to removal of another pollutant)

[b] The term metabolism includes both biosynthesis and catabolic reactions

system is designed to maintain flow below the surface of the bed, so that there can be very little direct atmospheric reaeration.

The city of Arcata’ s pilot project showed that lower hydraulic loading rates applied to wetland beds produced higher BOD removal efficiencies. Seasonal variations in effluent concentration were affected by vegetation type, density, and distribution (Gearheart, 1992a).

SS Removal

SS are removed very effectively in most wetland systems due to long HRT, shallow depth and quiescent conditions. Most settlement of solids occurs within the first few meters beyond the inlet (Reed et al., 1988). In addition, the plants tend to slow the incoming velocity and disperse the influent, so further enhances the settling process (Gray, 1989). Colloidal solids/unsettleable solids are removed at least partially by attachment of bacteria, collision, aggregation and absorption to other materials such as stems of plants, and sides and bottom of trench (Kessomboon, 1990). SS removal and biomass decomposition result in the build up of sludge layer at the bottom (Hammer and Kadlec, 1983).

Nitrogen Removal

Nitrogen is removed in wetland systems by 5 main mechanisms: 1) plant uptake and subsequent harvesting of plants, 2) nitrification and denitrification, 3) ammonia (NH_3) volatilization, 4) sedimentation of particulate N, and 5) N adsorption onto substrata (Koottatep, 1999; Rogers et al., 1985). Bacteria (Nitrosomonas and Nitrobacter) convert ammonia (NH_3) to nitrate (NO_3^-) in aerobic conditions (Nitrification), which exist at wastewater surface or in the root zone where oxygen is transferred by emergent plants. Under anoxic conditions, NO_3^- is converted to N_2 and released to atmosphere. In many cases, nitrogen can be lost in the form of ammonia (NH_3) by volatilization from the water surface, especially at high temperature and high pH conditions. Normally, large surface area and shallow depth in wetland systems contribute to ammonia volatilization (Rogers et al., 1985; Sawyer et al., 1994).

Phosphorus Removal

The principal phosphorus removal mechanisms are precipitation and adsorption to sedimentation, with secondary mechanisms including plant uptake and sedimentation (Tchobanoglous, 1987). Harvesting of plants, dredging of sediments, or resolubilizing of phosphorus stored in sediments and released to receiving water, when it would have the least environmental impact, could achieve ultimate removal of phosphorus from wetland systems (Stowel et al., 1981). Substratum adsorption is suggested as a significant mechanism in phosphorous removal in constructed wetland systems (Mann, 1990; Wood, 1990; Steiner and Freeman, 1989; Swindle and Jackson, 1990).

Heavy Metals Removal

Heavy metals are removed by plant uptake, chemical precipitation, and ion exchange and adsorption to settled clay and inorganic compounds (Gearheart, 1992b). As wastewater moves to plant roots for uptake and transportation, the solute metals ions move with it to the surface of the roots, thus a mass flow occurs. The amount of metal ions transported will depend on: (a) the concentration of metal ions in soil solution, (b) the amount of wastewater moving to roots for plant needs of metabolism, and evaporative cooling by evapotranspiration, and (c) plant response to metal ions. Predominant factors for metal ions concentration in soil solution and transport to roots are: pH of soil, chelating agent, and transpiration rate. Total metal accumulation depends on the nature of plants, which includes: species, growth rate, root size and depth, transpiration rate, and nutritional requirements (Allaway, 1968; Chaney, 1973; Leeper, 1972; Lisk, 1972; Page et al., 1973; Tiffin et al., 1973).

Refractory Organics Removal

Refractory organic compounds, which include surfactants, phenols, benzene and agricultural pesticides, are toxic and very slow in biological decomposition. The key methods for refractory organics removal in wetlands are volatilization, adsorption and then biodegradation (Rogers et al., 1985). Volatilization can occur at the water surface of wetlands. Adsorption occurs primarily on the organic matter in the treatment system that contacts with the wastewater (Reed et al., 1988). Polprasert (1996) documented that refractory organic compounds in aquatic systems are removed by absorption to intra system surfaces and are altered by physical, chemical and biological decay processes. The adsorption to the bottom sediments, detrital layer, and submerged parts of the plant also partially reduce refractory organic (Polprasert, 1996). In the wetland systems, refractory organics accumulated in the sediments will be gradually decomposed by microbial activity (Kadlec, 1987). The rate of biodegradation of refractory organics increases with increasing bacterial numbers. In addition, pH, water temperature, natural of substrate and HRT affect the biodegradation rate.

Pathogens Removal

Major mechanisms of pathogens removal in wetlands are natural die-off and decomposition (Sintumongkolchai, 1996). There are many factors involved, such as long HRT, exposure to sunlight (UV radiation), sedimentation, oxidation, and exposure to toxic chemicals (Polprasert, 1996). Gersberg et al. (1987) documented that, bacteria were absorbed to particles in the water and were removed when the particles settled down. In addition, they might also become absorbed onto the surfaces of aquatic plants. Numerous studies have demonstrated that the removal of pathogen bacteria and virus in wetland systems depend on hydraulic retention time (HRT) and temperature (Reed et al., 1988). Bavor et al. (1987) reported that the removal of indicator bacteria by wetland systems with HRTs of 3 to 7 days was equivalent to or greater than removal obtained in conventional oxidation ponds operating at much longer HRTs.

2.4 Heavy Metals in Wastewater

2.4.1 Sources of Heavy Metals and Possible Pathway

Sources of metals that can eventually reach wastewater treatment works can be considered as five types: domestic and industrial effluents, runoff, atmosphere, and lithosphere. Domestic and industrial discharges are probably the two most important anthropogenic sources. Anthropogenic metals may also come from the atmosphere and runoff, depending on whether the sewage system is separate or combined with storm drainage. The interrelationship between the major sources of heavy metals and the possible pathway to wastewater treatment processes are shown in Figure 2.5 (Lester, 1987).

2.4.2 Heavy Metals Removal in Constructed Wetlands

The main heavy metals of concern in water quality management are lead, copper, zinc, chromium, mercury, cadmium, and arsenic. These metals may be highly toxic when present in higher concentrations in water. However, some metals

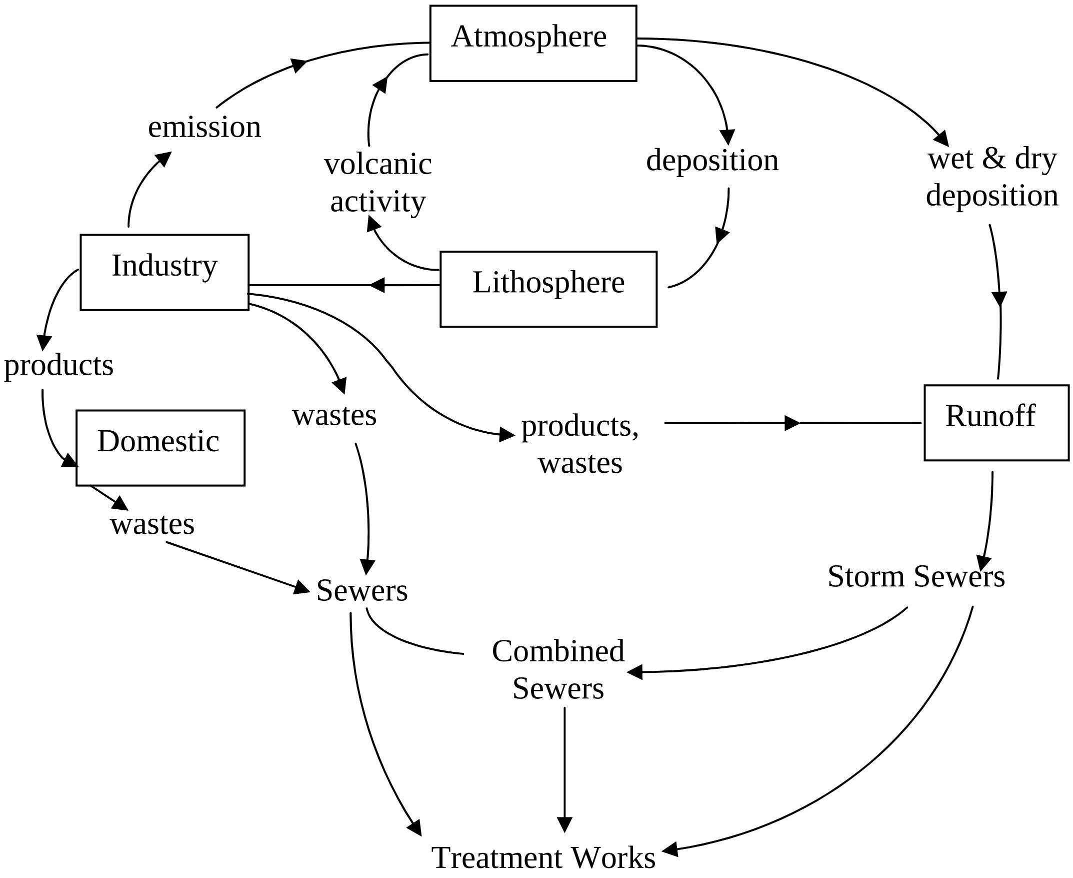


Figure 2.5 Sources and pathways of heavy metals entering wastewater treatment processes (Source: Lester, 1987).

such as copper and zinc are also essential micronutrients for plants and microorganism. Heavy metals in wastewater derive from many sources including corrosion of metal pipes, and paints (Vigneswaran and Sundaravadivel, 2001).

Many varieties of wetland plant species are tolerant of high concentrations of heavy metals, perhaps because of the protective effect of the iron plaque, which can develop around the roots (Vigneswaran and Sundaravadivel, 2001). Hence, wetlands can be designed and built for heavy metals removals. In fact, many constructed wetlands specifically built for heavy metals are in operation in Australia

(Morey, 1996). The three main wetland processes, which remove heavy metals from wastewater in constructed wetlands, are (Kadle and Knight, 1996):

1) binding to soils, sediments and particulate matter
2) precipitation as insoluble salts; and
3) uptake by bacteria, algae, and plants

Major proportion of heavy metal removal is accounted to binding process within wetlands (Kadlec and Keoleian, 1986). Because of their positive charge, the heavy metals are readily adsorbed, complexed and bound with suspended particles, which subsequently settle on the substrate. Precipitation of heavy metals as insoluble salts such as carbonates, bicarbonates, sulfides, and hydroxides is another process that leads to their long-term removal. These salts formed by reaction of heavy metals with other chemicals present in water column are insoluble, and hence precipitate to bottom to become fixed within the wetlands substrate (Vigneswaran and Sundaravadivel, 2001).

During the initial period of establishment of treatment wetlands, the binding processes are limited and the uptake by the biota is dominant. Algae and microorganisms take up heavy metals available in the dissolved from, whereas macrophytes can take up also from the sediments. However, the uptake by plants, bacteria, and algae accounts for less than 1% of the total heavy metals removal in constructed treatment wetlands (Hiley, 1995).

Accumulation of heavy metals in wetland substrates may also have long-term implications. The sedimented heavy metals may be released into the system if the substrates are disturbed or oxidized. To avoid such as an eventuality, substrates have to be permanently maintained in anoxic conditions (DLWC, 1998).

2.5 Cadmium in Wastewater

2.5.1 Physical and Chemical Properties

Cadmium (Cd) is the second member of the Group IIb triad (Zn, Cd, and Hg) in the periodic classification of elements. It has an atomic number of 48 and an atomic weight of 112.40. The stable state of cadmium in the natural environment is Cd (+2), oxidation state as d^{10} ions. Cadmium metal is silvery white in color, malleable and ductile and very resistant to corrosion. It is this latter property for which cadmium is valued and which has given rise to its major industrial use-to make corrosion-resistant metallic surface. Cadmium metal is not usually found in environment in its pure form, occurs naturally in the Earth’s crust in association with zinc ores. It has a medium class b character compared to zinc and mercury (Fulkerson and Goeller, 1973; Lake et al., 1979).

2.5.2 Cadmium Compounds

Cadmium sulfide (CdS), cadmium carbonate ($CdCO_3$), and cadmium oxide (CdO) are all insoluble compounds and all are found naturally in low concentrations. Cadmium sulfide is to be found in freshwater and marine sediments where anoxic conditions may occur. Cadmium hydroxide ($Cd(OH)_2$) is also insoluble. The fluoride, chloride, bromide, iodide, nitrate and sulfate of cadmium are all relatively soluble compounds (Dobson, 1992; Stumm and Morgan, 1970; Stumm and Brauner, 1975).

2.5.3 Production, Uses, and Discharges

Cadmium is most commonly found associated with zinc in carbonate and sulfide ores. Cadmium is also obtained as a by-product in the refining of other metals. Thus humans, through their production of metals like copper, lead, and zinc for several centuries, were unknowingly polluting the environment with cadmium.

Most of the virgin cadmium currently being recovered around the world is a byproduct of zinc smelting and refining. The cadmium is associated with the zinc in concentrations of sphalerite (ZnS) and related sulfide ore minerals. It is also recovered during the beneficiation and refining of some lead ores and complex copper-zinc ores (Plachy, 2000).

Cadmium is used extensively in the manufacture of nickel-cadmium storage batteries, stabilizers, power transmission wires, paints, plastics, selenium rectifiers, brazing alloys, pigments, metal coating, fire protection systems, and photoelectric cells. In addition, it is used to plate iron products, such as nuts and bolts, for corrosion prevention. It is from plating operations that most of the cadmium reaches the water environment. The largest source of environmental cadmium is from the disposal of rechargeable nickel-cadmium batteries. Cadmium can enters water via waste effluents, fertilizer, and spills or leaks from hazardous waste sites (Ratanachoo, 1995; Sawyer et al., 1994; Metcalf & Eddy, 1991).

2.5.4 Harmful Effects of Cadmium

The target organs for acute toxicity to cadmium are the lungs, while the kidneys and bones are main target organ for chronic exposures. The physicochemical properties of the given cadmium compounds, like most of the inorganic metals, are important determinants of toxic. The rank order of solubility is: cadmium chloride $CdCl_2$ > cadmium sulfate ($CdSO_4$) > cadmium oxide (CdO) > cadmium sulfide (CdS). These compounds can be absorbed through the skin, intestinal tract, or respiratory tract and transported in the blood throughout the body. At extreme levels, it causes an illness called “Itai-Itai” disease, characterized by brittle bones and intense pain. At low levels of exposure over prolonged periods, it causes high blood pressure, sterility among males, kidney damage, and flu-like disorders. It has also recently been discovered that significant amounts are contained in cigarette smoke. As mentioned above, the Cd^{+2} sequestering protein metallothionen provides protection until its capacity is exceeded. Since metallothionen is concentrated in the kidney, this organ is damaged first by excessive cadmium. The downside of metallothionen protection is that cadmium is stored in the body and accumulates with age, so that damage from long-time exposure becomes irreversible (Sawyer et al.,1994; Spiro and Stigliani, 1996; Zelikoff and Thomas, 1998).

2.5.5 Cadmium in Natural Waters

Binding to Inorganic Ligands

Cadmium is an oxyphilic and sulfophilic element. It undergoes multiple hydrolysis at pH values encountered in the environment. Furthermore, within the triad Zn, Cd and Hg, marked differences in binding to ligands exist. Cadmium (+2) is present totally as divalent species up to pH 8, in the absence of any precipitating anions such as phosphate and sulfide. Cadmium begins to hydrolyse at pH 9, forming $Cd(OH)^+$ species. Higher hydroxyl species of cadmium are not relevant at the pH values commonly found in the environment (Moore and Ramamoorthy, 1984).

Binding to Organic Ligands

Cadmium forms moderately stable complexes with a variety of organic compounds. Being a soft acid acceptor in co-ordination reactions, it prefers soft donor atoms such as sulfur, selenium and nitrogen. Cadmium interacts strongly with sulfydryl groups such as in cysteine. The organic matter found in natural water, including amino acids, aminosugars, polysaccharides, hydroxyl and carboxylic acids of aliphatic and aromatic nature also contains suitable donor atoms for complex formation with cadmium.

Binding of cadmium to humic substances from sea, river and lake waters was studied by Mantoura et al. (1978). In general, stabilities of humic complexes of various metals followed the Irving-Williams order of stabilities of chelates:

$$\mathrm{Mg} < \mathrm{Ca} < \mathrm{Cd} \sim \mathrm{Mn} < \mathrm{Co} < \mathrm{Zn} \sim \mathrm{Ni} < \mathrm{Cu} < \mathrm{Hg}.$$

2.5.6 Cadmium in Soils and Plants

Based on one study (Davis and Coker, 1980), the concentration of Cd in most soils is in the range 0.5-1.0 mg/kg, although concentrations of > 20 mg/kg also occur naturally in some places in England. Raised concentrations result from smelting and mining activities and from the use of sewage sludge on land. Reclaimed surface soils at Shipham in Somerset contain up to 800 mg Cd/kg. The median concentration of Cd in sewage sludge used in agriculture in England and Wales is about 20 mg/kg dry solids, but the maximum recommended increase in soil concentration of Cd where sludge is used on land is 2.3 mg/kg to be achieved gradually over a long period e.g. 30 years. Background concentrations of Cd in plant tissue are normally in the range 0.1-1.0 mg/kg dry weight. A sample of fifty background concentrations from the literature showed a range of < 0.02-1.0 mg/kg with a median value of 0.29 mg/kg; lowest concentration were seen in refined plant material e.g. wheat flour. Concentrations of Cd in plants vary according to season and according to which part of the plant is sampled. Highest concentrations of Cd in plants occur in the winter.

In general, Cd concentrations in plant tissue decrease in the order fibrous roots > leaves > seeds = storage organs. The concentration of Cd in plant tops above which phytotoxicity occurs is about 8 mg/kg dry weight.

Aery and Tiagi (1988) reported that several plants of the Zawar Zinc Deposits of Rajasthan (India) accumulate very high levels of cadmium. The maximum concentration namely 420 µg/g was found in the stems of Crotalaria linifolia. Some other cadmium accumulators with the concentration of the metal in µg/g are Impatients balsamina (380), Dyerophytum indicum (282) and Melhania futteyporensis (245). Stout and Nusslein (2005) reported *L. minor* has been shown to accumulate as much as 1,300 time more Cd than concentrations present in the surrounding water or as much as 14,000 mg/kg Cd. The hyperaccumulator *Thlaspi caerulescens* can take in 1,500 ppm of cadmium without displaying serious effects, while a normal plants would be poisoned at 20 to 50 ppm (Hank, 2000). A stunning example of this is found to contain the toxic and non-essential metal cadmium (Cd) between 1,000 and 3,000 mg/kg dry biomass (Kramer, 2000). Cadmium could have been chelated by organic acids and amino acids present in higher concentration in the roots (Thayalakumaran, 1994). Since the cattails were able to accumulate up to 3,200 ppm in the FWS and 2,800 ppm in the SF, these plants can be classified as cadmium hyperaccumulators (Jindal and Samorkhom, 2005).

Cadmium toxicity in plants

The toxic effects of cadmium on biological systems have been reported by several authors (Bingham et al., 1976; Mukherjee et al., 1984; Obata and Umebayashi, 1997; Das et al., 1997; Sanita di Toppi and Gabbrielli, 1999). However, the mechanisms of Cd toxicity are not completely understood yet (Benavides et al., 2005). Cadmium can alter the uptake of minerals by plants through its effects on the availability of minerals from the soil, or through a reduction in the population of soil microbes (Moreno et al., 1999). The degree to which higher plants are able to take up Cd depends on its concentration in the soil and its bioavailability, modulated by the presence of organic matter, pH, redox potential, temperature and concentrations of other elements (Maria et al., 2005). Normally, Cd ions are mainly retained in the roots, and only small amounts are transported to the shoots (Cataldo et al., 1983). In general, the content of Cd in plants decreases in the order: roots > stems > leaves > fruits > seeds (Blum, 1997).

2.5.7 Mechanism of Cadmium Removal in Constructed Wetlands

Cadmium removal mechanisms in FWS constructed wetlands can be described with first order plug-flow kinetics. The main mechanisms will be occurring after wastewater containing cadmium through the substratum and plants of constructed wetlands. The mechanisms are discussed below:

Plant Uptake

Cadmium is very toxic substance to plants and can change the permeability of the cell membrane (Alloway, 1990). Uptake can occur passively as well as metabolically. Within plants, it is very mobile. In the soil, it occurs in divalent state and form complex ions and organic chelates. It is easily absorbed by clay and organic matter. Its uptake is promoted by pH values below 6 and restrained by pH values above 7. Zn, Cu, and Se seem to reduce cadmium uptake or toxicity. It is easily transported to different plants parts; highest concentrations are found in roots and in the parts of the leaves. In acidic soils with pH < 6, Cd is very mobile and therefore does not accumulate. However, Cd does accumulate in some soils as has been demonstrated. At pH > 6, Cd attaches to hydroxides of iron, aluminium and manganese after the protons have been eliminated from the OH groups. While such a fixing is reversible if the pH decreases, Cd and other heavy metals can enter irreversibly into the crystal grid of oxides and lime minerals. Compounds of Cd with humic acids are less stable than those of lead. Accordingly, Cd accumulations in the upper humus are clearly less than corresponding lead accumulations. CdS has been found in specific compounds in the soil; it forms under reductive conditions in the presence of sulfate ions. $CdCO_3$ is found only at pH > 8, and such conditions occur only rarely (Fellenberg, 2000).

Microorganisms

Microorganisms operating in soil systems and around the roots of the plants play important role in Cd removal from wastewater in the wetlands. Microorganisms remove heavy metals directly from wetlands by two major mechanisms; the first is a metabolism dependent uptake of metals into their cells at low concentrations (some toxic metal ions are micronutrients for the micro-organism); the second is bio-sorption which is a non-active adsorption process binding metal ions to the extracellular charged materials or the cell walls (Matagi et al. 1998). Many papers find lower species diversity with increasing heavy metals. There is toxic action, but also an effect of helping those species that are adapted to the heavy metals to prevail and dominate (Delfino et al., 2000).

Adsorption

Cadmium can be adsorbed in constructed wetlands bed media such as rock, gravel, sand and soil. There are two major factors involved in adsorption: pH and type of media. Adsorption can occur in the pH range of 4-7.7 (Sintumongkolchai, 1996). Adsorption to sediments increases with pH and beyond a threshold point (pH ≥ 7 for Cd); virtually all the metal ion is sorbed. In the presence of sorbents, the pH values required for precipitation of Cd species are greatly reduced. Addition of ligands which yield cationic complexes suppresses precipitation of Cd-hydroxide, yet the sorption increase with increasing pH. This suggests that formation of Cd-monohydroxide is not a prerequisite for sorption by clays. Formation of an anionic complex results in zero uptake of cadmium over a wide pH range. This observation is consistent with cadmium sorption sites on clays being negative in sign (Moore and Ramamoorthy, 1984).

Ramamoorthy and Rust (1978) similarly studies the sorption-desorption of cadmium in sand, silt and organic-rich sediments from river. The sorption for all sediment samples were fitted to the linear form of the Langmuir equation;

$$\frac{C}{x/m} = \frac{1}{kb} + \frac{C}{b}$$

Where, C = the equilibrium concentration of sorbate (Cd (+2) ion);

x/m = the amount of Cd (+2) per unit mass of sorbent;

k = the bonding energy constant;

b = the sorption maximum.

Precipitation

Precipitation plays a major role in cadmium immobility under two conditions, pH > 8 and under reducing environment. Formation of $Cd(OH)_2$ controls the equilibrium concentration at high values (pH > 12). Precipitation of cadmium with carbonates ($CdCO_3$) and phospoates ($(Cd_3(PO_4))_2$) regulate cadmium concentration at the pH range of 8-12. Under reducing conditions, such as in poorly drained soils, the precipitation of CdS will occur. It should be noted that adsorption, ion-exchange reactions are generally faster than many of the precipitation-dissolution reactions (Bhuvendralingam, 1987; Sintumongkolchai, 1996).

Complexation

Cadmium can from complex ions with organic or inorganic substances. The complexes formed with inorganic substance, like carbonate, hydroxo complexes are called inorganic complexes; these organic matters are from decaying plant materials. Cadmium complexation with humic and fulvic acid fractions is reported to be an important process affecting cadmium bio-availability. Fulvic acid can form complexes with cadmium over a wide pH range thus increasing the solubility and mobility of heavy metals. Humic acids are insoluble in acid medium but dissolve gradually as pH increases. Hence at high pH values, humic complexes are formed. These properties: at alkaline pH all elements are practically bound as soluble humates or precipitated as hydroxides (Bhuvendralingam, 1987; Sintumongkolchai, 1996).

2.5.8 Cadmium Speciation

Cadmium can be sunk by a) precipitation by sulfides, b) adsorption by various adsorbents present in sediments, and c) organic concentration by living organisms. Cadmium associated with sediment solids may be present in several chemical forms, depending on the sediment composition and physicochemical properties of the sediments, and can be classified in to following groups (Nriagu, 1980).

Exchangeable Phase

Cadmium may be adsorbed by electrostatic attraction to negatively charged ion exchange site on mineral colloids (clays), organic particulates, and hydrous oxides. This phase is in equilibrium with interstitial water phase and can be readily adsorbed or desorbed as a consequence of changes in the physicochemical parameters or concentration gradient. The high concentration of cadmium present in this phase in sediments may have an adverse impact on water quality during dredging and disposal operations because of mixing.

Carbonate Phase

Carbonate precipitation may be an important sink for cadmium in sediments high in bicarbonate and alkaline in reaction. Under slightly reduced to oxidized conditions, solid $CdCO_3$ is major control mechanism for cadmium solubility and is a potentially bioavailable fraction.

Reducible Phase

This phase consists of cadmium adsorbed or coprecipitated with oxides, hydroxides, and hydrous oxides of Fe, Mn, and possibly Al present as coating on clay minerals or as discrete particles. However, cadmium is a weak competitor for adsorption on hydrous metal oxides in the environment and suggest that adsorption by colloidal hydrous oxides may not be a major control mechanism for cadmium in sediments.

Organic Phase

This phase contains complexes that vary in stability from immediately mobile, easily decomposable, and moderately decomposable to resistant to decomposition. Cadmium complexed with the organic fraction may be divided in to chelated and organic bound. Chelated cadmium is the fraction that is loosely attached to immediately mobile. It is an easily decomposable organic material and is a good indicator of the easily bioavailable cadmium form. Organic-bound cadmium, on the other hand, is the fraction incorporated in to the insoluble organic material and can be solubilized only after in tense oxidation of the organic matter.

Sulfide Phase

Sulfide phase represents highly in soluble and stable complexes of cadmium sulfides and exists in reduced sediments. Oxidation of reduced sediments results in the transformation of sulfide-bound cadmium into more mobile. The potentially available carbonate, exchangeable, and organic-complexed fractions are in equilibrium with the soluble cadmium fraction.

Mineral Crystalline Lattices Phase

This phase consists of cadmium bound within the crystalline lattices of mineral particles and is essentially unavailable in the sedimentary environment. This phase is called lithogenic or residual fraction. A significant part of sediment-bound cadmium is generally present in this unavailable fraction. In polluted sediments, however, the fraction of cadmium present in the clay lattices and silicate minerals may be rather small.

2.6 Past Studies

Richter et al. (2002) conducted a study on baseline hydraulic performance of the constructed wetlands subsurface flow system at Heathrow Airport in UK. A constructed wetland treatment system was commissioned by BAA (formerly the British Airports Authority) in order to attenuate airfield runoff contaminated with deicant and other potentially polluting materials from Heathrow Airport. Airfield runoff containing de-icants has the potential to impose significant oxygen demands on water bodies. The site consists of a number of integrated treatment systems, including a 1 ha rafted reed bed canal system and a 2 ha subsurface flow gravel reed bed. This research project was concerned with the performance of the subsurface flow reed bed, though attention would be paid in this paper to the operation of the whole system. Prior to the planting of the subsurface flow reed beds, flow-tracing experiments were carried out on the three different types of subsurface beds, so that the baseline performance of the system could be quantified. In association, data regarding the soil organic matter content was also collected prior to the planting of the beds. As expected, soil organic matter content was observed to be negligible within the bed, though a small amount of build up was observed in localized areas on the surface of the beds. This was attributed to the growth of algae in depressions where standing water persisted during the construction phase.

In a similar study, hydraulics of sub-superficial flow constructed wetlands in semi arid climate conditions were investigated in Italy by Ranieri (2002). He reported the evaluation of the hydraulics of two constructed wetland (CWs) plants located in Apulia (South Eastern Italy region characterized by semi arid climate conditions). These fields were planted with *phragmites australis* hydrophytes and were supplied with local secondary wastewater municipal treatment plant effluent. Each plant-Kickuth Root-Zone method based-covers an area of approx. 2,000 m^2. Evapotranspiration phenomena were evaluated with in perforated tubes fixed to the filed bottom and very high values-up to 40 mm/d were found. Hydraulic conductivity was evaluated by in situ measurements in different field points. Hydraulic gradient and the piezometric curve within the field are also reported.

There have been few more reported research works on application of constructed wetlands for wastewater treatment conducted in various parts of the world. Meutia (2002) evaluated the application of subsurface constructed wetland to treat dormitory wastewater in Rural Indonesia. The aim of his research was to examine the capability of constructed wetland to treat dormitory wastewater and to investigate the efficiency of wetland use system in which fish rearing and agriculture were integrated. Dormitory wastewater from bathroom and septic tank flew into the first bed containing gravel and sand planted with mix population of aquatic plants such as *Typha spp*., Water Spinach (*Pomenus*), Water Hyacinth (*Eichornia crassipes*), etc. Water flew from the bottom of the bed. The outflow was located near the top of the bed. After the first bed, wastewater flew into second bed containing the same substrate with floating plant *Lemna minor* and *Hydrilla*. Treated water then flew into clarifier with three chambers intended to separate the fine sediment and water. Finally, treated water was kept in a pond containing several kinds of fishes such as *Tilapia spp*., and *Clarias batrachus*. Water from fishpond was used for watering several kinds of vegetables. During first year of operation, several parameters were monitored in order to evaluate the efficiency of the system. The results showed that removal efficiencies based on concentration were found to be BOD_5 15-95%, COD 15-75%, and TOC 34-95%. Total nitrogen (T-N) and phosphorus (T-P) removal varied between 10-73% and 10-40%, respectively. Bacterial pathogen such as total coli and E.coli decreased 14-100% and 68-100%. The results showed that the constructed wetland is capable enough to treat the dormitory wastewater in the integrated system.

Lund (2002) presented the results his research in designing constructed wetlands for removal of filterable reactive P from storm/groundwater in a Mediterranean climate in the Western Australian city of Perth. Three replicate experimental periods (15 × 5 m), were constructed to present at a 1:1 scale a single cell form a repeating 16 cell design proposed in 1997. Three 5 m zones of each pond were sampled, shallow (0.3 m) vegetated (*Schoenoplectus validus*) inflow and outflow zones and a deeper (1 m), V-shaped central zone. The V-shape was designed to increase hydraulic residence time, control the spread of plants and provide a pool of water to support the plant communities in summer. In 1998/99, inflows and outflow water were intensively sampled and analyzed for FRP. In addition, all major pools of P (plants, interstitial water, and sediment) within the ponds, and important P removal processes (benthic flux, uptake by biofilm and *S. validus*) were quantified. A removal efficiency of 5% (1998) and 10% (1999) was obtained for FRP. When this scaled to operational size indicates a removal rate of approximately 40-60% for FRP. Initial uptake was mainly in plant biomass, although the sediment became an increasing important sink. The highly colored wasters (DOC concentrations of 50 mg/L) were believed responsible for the very low biofilm biomasss recorded (< 1 g/m^2). This project has demonstrated that constructed wetlands can be effective in this type of the environment, although the high water table does pose particular design challenges.

A full-scale surface flow landfill-leachate treatment wetland installed in Mobile Country, Alabama, USA, indicated high removal rates of lead and nickel (Sanford, 1999). The reported removal efficiencies of these metals were 94% and 88%, respectively. Another similar system with 3 days retention operated at Isanti Chisago sanitary landfill site in Minnessota, USA, reported removal efficiencies of iron, zinc, manganese, arsenic, and mercury as 97%, 93%, 91%, 89%, and 75%, respectively (Loer et al., 1999).

The U.S. Bureau of Mines, Pittsburgh Research Center, reported that iron concentration of 33 mg/L were reduced to less than 1.2 mg/L, and pH rose from 4.9-6.0 after a mine water passed through the constructed wetlands with a mean flow rate of 1.3 L/s, and water depth of 0.3 m (Kleinmann and Girts, 1987) In addition to mine wastewater treatment, Noller et al. (1994) showed that very high reduction of metal concentrations (75-99%) in the effluent form constructed wetlands did occur to below levels of concern at several mine sites in tropical Australia. Chromium concentration reduction in wetlands varied from zero at low influent concentrations to 87.5% or greater at an influent concentration of 160 μg/L (Kadle and Knight, 1996).

Thayalakumaran (1994) investigated the effectiveness of vegetated submerged bed (VSB) constructed wetlands by cattails for treating an electroplating wastewater for Cr and Ni removal. The removal efficiencies of more than 99% were observed in the constructed wetlands even when the influent heavy metal concentration was 25 mg/L. The ambient temperature range of 22-31^{o}C and pH range of 7.6-9.0 observed in the wetland beds were suitable for cattail growth. The heavy metals were removed mainly by precipitation and adsorption. The soil adsorbed more Cr and Ni than the plants. About 15% of these heavy metals were found to be removed by soil adsorption; the extents of heavy metal adsorption decreased along the bed length of the wetland units. Heavy metal accumulation was more in the roots than in the leaves and stem of the cattail plants. The Cr was more strongly chelated in the roots than Ni. The removal efficiencies of soluble chemical oxygen demand (SCOD), total suspended solids (TSS) and total kjeldahl nitrogen (TKN) were approximately 64%, 89%, and 85%, respectively.

Mungur et al. (1995) conducted a study at the Urban Pollution Research Center, Middlesex University, London, UK, for the assessment of some metals' removal by a natural wetland receiving highway runoff. They compared their results with the levels found in an adjacent stream, which also received runoff from the same major road. Both subsequently discharged effluent at proximal locations into the Brent Reservoir, a site of special scientific interest in NW London. The concentrations and temporal trends of Cd, Cu, Pb and Zn in the water, sediment, and emergent macrophytes of the wetland and stream, were discussed with respect to the treatment efficiency of the wetland. Although there was evidence of active metals' uptake by the sediment and macrophytes, aqueous metal concentrations generally remained unchanged. The results supported the proposal to construct a wetland planted with selected species of macrophyte to treat highway runoff on approximately half the area of the current site.

Debusk et al. (1996) reported the results of a 14 months study of the fate of trace-metals contaminants in wetland microcosms. Duplicated wetland microcosms contained cattail, *Typha domingebsis* or duckweed, *Lemma minor*, as the dominant macrophyte. Each wetland microcosm received 14.6 cm/day of dilute landfill leachate amended with lead (measured average: 396 µg/L) and cadmium (measured average: 105 µg/L). Differences between measured trace-metal concentrations in inflow and outflow samples indicated that approximately half of the added lead and cadmium were retained in wetland microcosms. Of the fraction removed from the water, less than half could be accounted for in calculated sediment and plant tissue concentrations, based on analysis. Measurement of sediment acid volatile sulfides (AVS), and comparisons of these concentrations to those of added lead and cadmium, showed that nearly all of these trace metals were present in the sediments as sulfides, limiting bioavailability and toxicity of these elements. Comparison of heavy metals uptake by cattails and duckweed showed that duckweed, on a whole plant basis, accumulates lead and cadmium more effectively than cattails. Potential metal removal rates by duckweed were 3-8 mg Pb/m^2 day and 2-4 mg Cd/m^2 day.

Kananidhinan (1996) studied the efficiency of constructed wetlands to remove chromium in electroplating wastewater with four emergent plants, *Cyperus corymbosus* (bulrush), *Typha angustifolia* (cattail), *Phragmites australias* (reed), and *Eleocharis dulcis* (spikerushes). During experimental period, influent chromium concentrations were in the range of 2.82-20.93 mg/L and the average was 7.61 mg/L. The best efficiency was found in Cyperus, as high as 98.21%, while the efficiencies of Eleocharis, Typha and Phragmites were 95.96%, 95.90%, and 94.87%, respectively. And the lowest efficiency was found in control unit (no plants), 89.13%, which was 9.1% lower than the highest efficiency, Cyperus. Accumulation of chromium in soil and plants were also studied and were found to tend to increase with passage of time. Average accumulation of chromium in soil in each pilot unit was slightly different and the highest mean was 29.16 µg/g dry weight. In plants, Eleocharis dulcis showed the maximum chromium concentration, 397.15 µg/g dry weight, at the end of the experiments, but had the lowest weight per unit. Mass balance showed that more than 90% of total chromium, which disappeared from the water, was found in the soil.

Polprasert et al. (1996) studied the application of a free water surface (FWS) constructed wetland system to treat some toxic wastewater under tropical conditions at the Asian Institute of Technology, Thailand. In a temperature range of 22-30^{o}C, the constructed wetland units whose hydraulic retention times (HRTs) were 5-7 days, could remove more than 99% of the input phenol when they were operated at or below the organic loading rates (OLR) of 270 kg COD/(ha.d) and influent phenol concentrations at 400 mg/L. The effluent dissolved oxygen (DO) levels were 4-7 mg/L at OLR of 40-140 kg COD/(ha.d). However, these DO levels decreased to 0.2-0.3 mg/L when the OLR were increased to 165-270 kg COD/(ha.d). Under similar operating conditions, the constructed wetland units could remove more than 99% of the applied chromium (Cr) and nickel (Ni), when either the Cr or Ni influent concentrations were 1-50 mg/L. The phenolic and heavy metal compounds were found to accumulate mostly at the roots of *Typha*, followed by the stems and leaves.

Mungur et al. (1997) conducted a study for the assessment of metal removal by a laboratory scale wetland at the Urban Pollution Research Center, Middlesex University, London, UK. They carried out experiments in laboratory scale gravel-substrate subsurface-flow (SF) wetlands in a continuous recirculating mode regarding the removal of Cu, Pb and Zn from contaminated water. After establishing the flow characteristics, the wetland was planted with *Typha latifolia, Phragmites australis, Schoenoplectus lacustris* and *Iris pseudacorus*. The wetland system was dosed with increasing concentrations (1, 5 and 10 mg/L) of Cu, Pb and Zn. Finally, a shock load of metals (concentration 20 mg/L) was introduced to simulate a storm event. In each experiment, water samples collected from the outlet at timed intervals were analyzed and loadings were calculated in order to assess the metal removal efficiency of the system. The removal efficiencies and rates for these different doses ranged from 81.7% to 91.8% and 36.6 to 372.7 mg/m^2/d for Cu, 75.8% to 95.3% and 30.8 to 387 mg/m^2/d for Pb, and 82.8% to 90.4% and 33.6 to 362.1 mg/m^2/d for Zn, respectively. Results for the storm simulation showed that in the time taken for the water level to subside to its original level (just below the substrate surface) at established outlet flow rates, the metal loadings leaving the system remained very low with the wetlands retaining over 99% of the metals. These results indicated the ability of the system to act as an efficient sink for heavy metals. The macrophytes were collected and segregated by species and subsurface tissue type (rhizomes, roots and root tips) and analyzed for Cu, Pb and Zn. The results were discussed with respect to the surrounding peat substrate, biomass accumulation and the overall removal performance of the laboratory scale wetland. *Typha* and *Schoenoplectus* in the middle row of the wetland accumulate the highest metal loads per species. Metal loads decrease in the order of Zn > Cu > Pb in the peat and subsurface tissue of *Phragmites*, *Typha*, and *Iris*. The metal loads in *Schoenoplectus* decrease in the order of Zn over Cu and Pb by the peat and subsurface tissue.

In another study, Sakadevan et al. (1999) evaluated the impact of heavy metals on denitrification in surface wetland sediments receiving wastewater. Results from the study showed that application of 100 mg Cd/kg sediment had no effect ($P < 0.05$) on denitrification (161±2.7 mg N/kg sediment) compared to the control (162±2.4 mg N/kg sediment), which did not receive Cd, Cu or Zn. However, addition of 100 mg Cu or Zn/kg sediment significantly increased denitrification (170±0.8 and 168±2.7 mg N_2O-N/kg sediment for Cu and Zn, respectively) compared to the control treatment. Addition of Cd, Cu or Zn at 500 or 1,000 mg/kg sediment significantly decreased ($P < 0.05$) total denitrification compared to the control and treatments, which received 100 mg Cd, Cu or Zn/kg sediment. For a given heavy metal concentration (in the range of 500-1,000 mg/kg), the largest denitrification inhibition occurred with Cd (30.9%) followed by Zn (24.9%) and Cu (18.9%) over a period of seven days. The amount of ammonium in the sediment water increased in all treatments receiving Cd, Cu or Zn, and increased with the increased concentration of Cd, Cu or Zn. For a given heavy metal concentration, the largest increase in ammonium occurred in treatments receiving Cd (31.1±0.9 mg N/kg sediment) followed by Zn (24.8±0.5 mg N/kg sediment) and Cu (17.0±0.3 mg N/kg sediment). Denitrification inhibition was linearly related to the concentration of ammonium in sediment water ($R^2 = 0.928$). In general, the study showed that the addition of Cd, Cu or Zn inhibited denitrification and increased the concentration of ammonium in the sediment-water environment.

Scholes et al. (1999) reported the removal of urban pollutants during wet weather by constructed wetlands developed by the Environment Agency for England and Wales. The systems were monitored for a range of determinands including heavy metals, suspended solids and BOD. Initial analysis of the data indicated that during dry weather, removal efficiencies vary greatly. However, during storm events removal efficiencies were higher with mean values of 71% for Zn, 72% for Cd, 69% for Pb, 66% for Cu, 34% for Ni, and 81% for Cr at Dagenham wetland. Mean removal efficiencies of 20% for Cd, 40% for Pb, 36% for Cu, 34% for Ni, and 38% for Cr were observed during storm conditions at the Brentwood wetland, but an overall increase in Zn was measured. Removal of BOD was greater at both sites during storm events with mean removal efficiencies of 24% and 29% at Dagenham and Brentwood, respectively. Suspended solids were reduced on passing through both wetlands during dry weather, but during storm events there was an overall increase.

Treerattanaporn (1999) evaluated efficiency of cadmium removal from wastewater using subsurface flow constructed wetland and cadmium accumulation in wetland at Chulalongkorn University, Bangkok. In addition, cadmium in various parts of the systems, which consisted of varied mediums-sand, sand and soil, and soil, respectively, and also in the plants (*Typha* spp.) was studied. Cd concentration in wastewater was varied at 1, 5, 10, and 20 mg/L. Retention time (HRT) was 5 days, and flow rates were varied at 4, 4.4, and 5 L/d for wetlands with sand, sand and soil, and soil medium, respectively. Constructed wetlands could remove cadmium from wastewater according to industrial effluent standards in Thailand (< 0.03 mg/L), when $[Cd]_{inf}$ was not more than 5 mg/L. When $[Cd]_{inf}$ increased (10 and 20 mg/L), efficiency in cadmium removal was still more than 99%. Cadmium removal occurred when wastewater passed through medium layer in horizontal flow direction. Soil was able to adsorb cadmium better than sand. Most of the cadmium in influent was adsorbed on medium (95.56% on sand, 95.53% on sand and soil, 94.07% on soil). In plants, accumulated cadmium was only 0.08%, 0.06%, and 0.08% for wetlands with sand, sand and soil, and soil medium, respectively. Cadmium adsorption on soil was tighter than sand, since cadmium leaching from medium was 5.37%, 11.15%, and 54.25% for soil, sand and soil, and sand, respectively. In conclusion, only cadmium in leachate from soil, and sand and soil met standard (not more than 1 mg/L), so both of the mediums were not hazardous waste and could be used for landfill.

CHAPTER III

METHODOLOGY

Part I: Experimental System

3.1 Experimental Setup

Laboratory-scale units of constructed wetlands were setup near Equipment building-F5 at Suranaree University of Technology (SUT) in Thailand. The schematic layout of the experimental setup is shown in Figure 3.1.

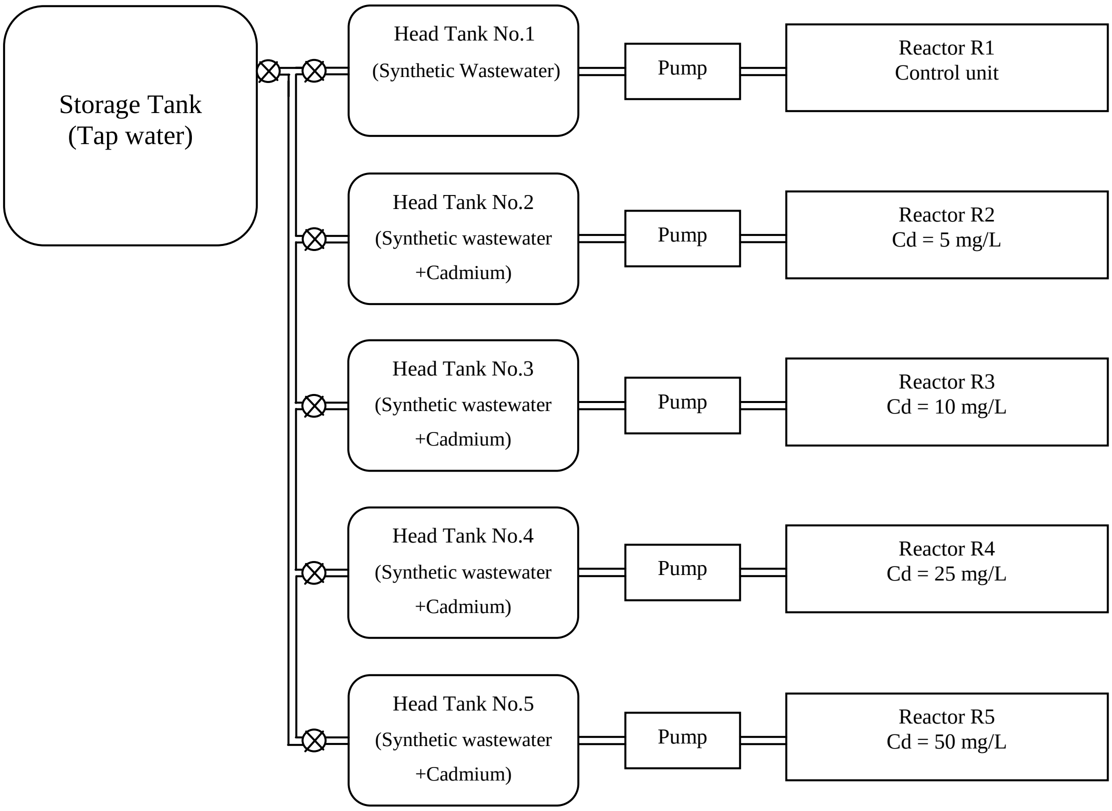


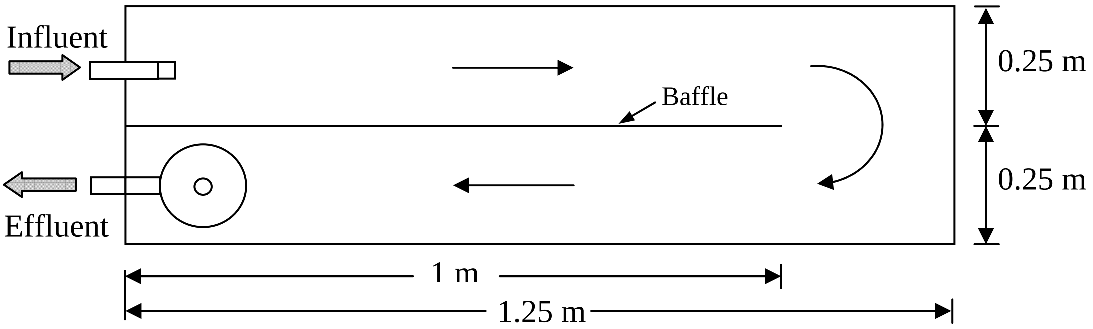
Figure 3.1 The schematic layout of the experimental setup.

3.1.1 Laboratory-scale Constructed Wetland Units

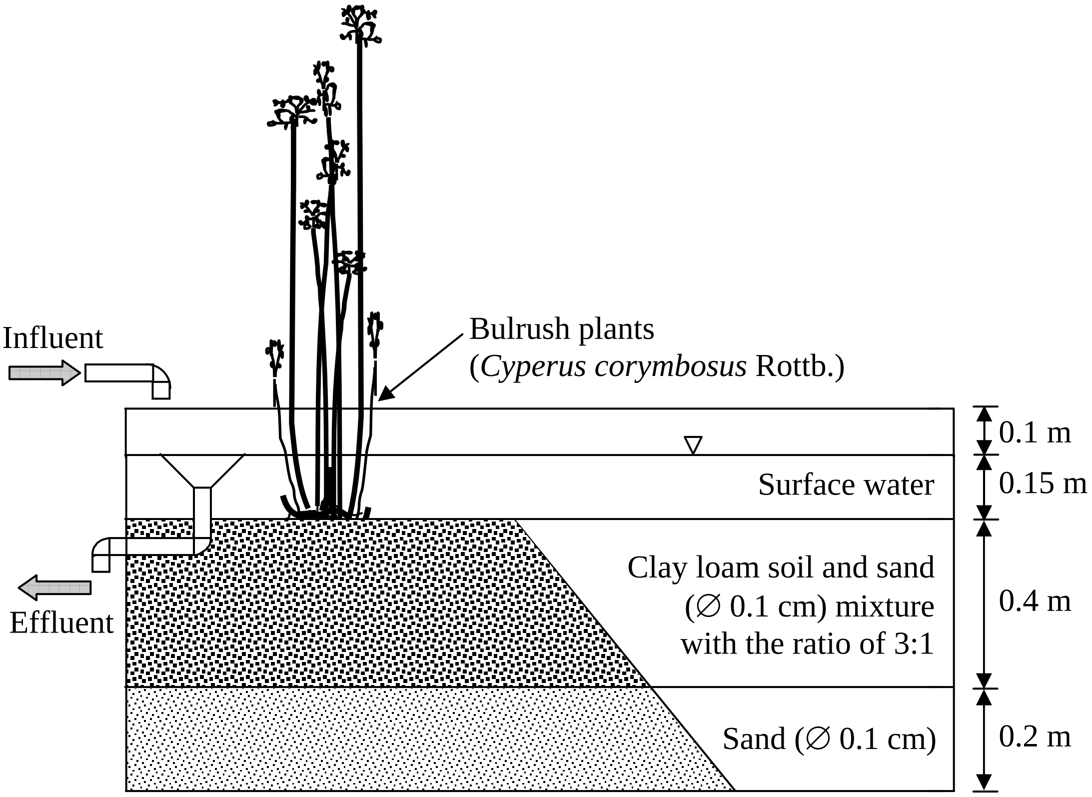
The experimental setup consisted of five laboratory-scale FWS constructed wetland units (designated as R1, R2, R3, R4, and R5) made of zinc plate, with the dimensions (length × width × depth = 2.5 × 0.25 × 0.85 m) and length-to-width ratio of 10:1. The recommended length to width ratio in FWS constructed wetlands is in the range of 2:1-10:1 (Reed et al., 1988; Hammer, 1993; Crites, 1994; Wood, 1995; Debusk et al., 1996; Vigneswaran and Sundaravadivel 2001). Each unit had a 20 cm thick layer of sand with 0.1 cm particle diameter at the bottom and a 40 cm layer of clay loam soil (Korat series) and sand mixture in 3:1 ratio at the top. Bulrush (*Cyperus corymbosus* Rottb.) plants were cultivated in the wetland units at approximately 0.15 m intervals, corresponding to 23 rhizomes/m^2, with a planting depth of 0.10 m. A water level of 0.15 m above the substratum surface was maintained in the FWS constructed wetlands. The schematic diagram of lab-scale FWS constructed wetland is shown in Figure 3.2.

3.1.2 Head-tank Unit

Five head tanks (200 L each) were used for feeding the wastewater to the five constructed wetland units. Head tank no. 1 was used for control reactor R1. Head tank Nos. 2-5 were used for feeding the synthetic wastewater to reactors R2-R5 after mixing with known concentrations of cadmium (Cd). Five peristaltic pumps (505S, Watson Marlow) were used to feed wastewater to the constructed wetland units. The five FWS constructed wetland units and head tanks are shown in Figure 3.3.



(a) Top view of FWS constructed wetland



(b) Side view of FWS constructed wetland

Figure 3.2 The schematic diagram of lab-scale FWS constructed wetland.

Figure 3.3 The five FWS constructed wetland units and head tanks.

3.1.3 Influent

A synthetic wastewater was prepared for this study in the laboratory, having a 600-900 mg/L of soluble chemical oxygen demand. A 10 ml solution having 15 g/L $MgSO_4{\cdot}7H_2O$, 0.5 g/L $FeSO_4{\cdot}7H_2O$, 0.5 g/L $ZnSO_4{\cdot}7H_2O$, 0.5 g/L $MnSO_4{\cdot}3H_2O$ and 2 g/L $CaCl_2$ was mixed with another solution having 93.8 g/L of glucose, 120 g/L NH_4Cl, 160 g/L KH_2PO_4, and 320 g/L K_2HPO_4 (Laboratory Instruction Sheet No.ED082313, 2001). The idea of choosing the COD of synthetic wastewater in the range of 600-900 mg/L, was taken from some similar studies reported in literature (Oviedo et al., 2002). Influents were prepared by mixing the synthetic wastewater with $CdCl_2{\cdot}H_2O$ at concentrations of 5, 10, 25, and 50 mg/L for each of the four simultaneous experiments during three runs designated as Runs I-III, respectively. The characteristics of the prepared synthetic wastewater are shown in Table 3.1.

Table 3.1 The characteristics of the synthetic wastewater.

Parameters	Range (mg/L)
pH	4.22-5.45
DO	0.0-0.3
S-COD	600-847
TSS	84-229
S^{2-}	2.2-6.2
HCO_3^-	32-112

3.2 Experimental Plan-Operating Conditions

The performance of the wetland system was evaluated over three hydraulic retention times (HRTs) 5, 7 and 10 days. The recommended HRT for FWS constructed wetlands has been reported to be 5-14 days (USEPA, 1988; Breen, 1990; Crites, 1994; Wood, 1995). The four simultaneous experiments in the wetland units during the three runs (Runs I-III) were designated as R11, R12, R13, R14, R15; R21, R22, R23, R24, R25; and R31, R32, R33, R34, R35, respectively. The three runs were conducted consecutively by changing the HRTs to 5, 7 and 10 days, respectively. The experimental period was from December 2003 to May 2005 and covered mild cooler weather during December-February, summer and dry seasons (March-July) and rainy season during August-November, typical in Thailand. Each experiment was run for 2 months and 22 days. Table 3.2 summarizes the plan of operating conditions for three experimental runs.

3.3 Sampling and Analytical Methods

During the experiments, synthetic wastewater was prepared every other day in five units. Temperature and flow rate were measured daily. Wastewater samples were collected daily from the influent and effluent points and analyzed for soluble chemical oxygen demand (S-COD) concentration until quasi-steady-state conditions were reached at 46-53 days. When the S-COD concentration was steady, seven parameters were analyzed twice a week in the influent and effluent streams including: pH, dissolved oxygen (DO), S-COD, total suspended solids (TSS), Sulfide (S^{2-}), Alkalinity (HCO_3^-), and cadmium, following the procedures of Standard Methods (APHA et al., 1995). Samples from soils and plants were also analyzed for cadmium accumulations at 2 week intervals and at the end of each run, following the procedures described in Chemical Analysis of Ecological Materials (Allen, 1974) and Soil Testing and Plant Analysis (Westerman, 1990).

At the beginning of the experiments (November 2003), the average height of the cultivated bulrush plants was about 1.5 m above the water level with an average diameter of 1 cm. After achieving quasi-steady-state conditions in 53 days, the first run with four simultaneous experiments was started, with four different cadmium

Table 3.2 Plan of operating conditions for three experimental runs.

Run	Unit No.	Cadmium Concentration (mg/L)
Run 1 (HRT 5 days)	R11	Control unit
	R12	5
	R13	10
	R14	25
	R15	50
Run 2 (HRT 7 days)	R21	Control unit
	R22	5
	R23	10
	R24	25
	R25	50
Run 3 (HRT 10 days)	R31	Control unit
	R32	5
	R33	10
	R34	25
	R35	50

concentrations in influent. During the run, no complete plant harvesting was done. Samples of plants, as well as of soil, were analyzed for Cd concentrations twice a month (only stems and top soil) and at the end of each run (roots and stems at the distances of 0.05-0.625 (zone 1), 0.625-1.25 (zone 2), 1.25-1.875 (zone 3), and 1.875-2.45 m (zone 4) from the inlet; and soil at the distances of 0.05, 0.625, 1.25, 1.875 and 2.45 m from the inlet, and the depths of 0, 15, 30 and 45 cm from the top of the soil bed). At the end of Run I (82 days), the average plant height and diameter had reached 1.9 m and 1.5 cm, respectively. At this time, plants were harvested. Subsequently, all the wetland units were cleared of soil and plants.

All the wetland units were again refilled with soil (in May 2004), and plants were recultivated to prepare for the second run. It took about 45 days for plants to grow to the same height (1.5 m), as at the beginning of Run I. After achieving the quasi-steady-state condition in 46 days, Run II was started in August 2004 that also lasted for 82 days (until November 2004). The last experimental run was conducted from February to May 2005 (82 days) after quasi-steady-state conditions were reached in 46 days. The details of the analyses are shown in Table 3.3.

3.4 Harvest and Disposal of Plants and Soil

Cadmium accumulated in soil can be removed by harvesting the plant's shoots and extracting the metals from them (Kochian, 2000). The plants would take up the toxic metals or isotopes through their roots and transport them to stems or leaves where they could be easily removed by harvesting. The cost of using plants to clean polluted soil could be less than one-tenth the price tag for either digging up and trucking the soil to a hazardous waste landfill or making it into concrete. The cost

Table 3.3 Sampling plan and methods of analysis.

Parameters	Frequency	Method of Analysis
Cl^-	Beginning of the experiments (Tracer Study)	Argentometric method
pH	2/week	pH meter (pH301/HANNA)
DO	2/week	Azide modification of idometric method
S-COD	2/week	Closed reflux
TSS	2/week	Filtered and dried at 103 °C
S^{2-}	2/week	Idometric method
HCO_3^-	2/week	Indicator method
Cadmium in wastewater	2/month and end of the run	Digestion with HNO_3 and measurement of Cd by atomic adsorption spectrometer (AAS-Analyst-10/Perguine Elmer)
Cadmium in plants	2/month and end of the run	Digestion with HNO_3, $HClO_4$ and measurement of Cd by atomic adsorption spectrometer (AAS-Analyst-10/Perguine Elmer)
Cadmium in soil	2/month and end of the run	Digestion with HNO_3, HCl, H_2O_2 and measurement of Cd by atomic adsorption spectrometer (AAS-Analyst-10/Perguine Elmer)

could be further offset by recovering heavy metals from the plants and selling them. The metal-scavenging plants, called hyperaccumulators, would be grown and harvested like hay. Burning the hay allows recovery and recycling of the metals. The ash is similar to commercial ore (Chaney, 1995).

Part II: Mathematical Modeling

3.5 Introduction

Mathematical modeling techniques can be used to aid in predicting the quality and sequence of relationships between interdependent components and processes in a system. A mathematical model is an idealization of a real situation, in which the most important components are identified and their interactions described and used as a tool to solve problems (Jorgensen, 1986; Daigger and Grady, 1982). A model can be regarded as an assembly of concepts in the form of one or more mathematical equations that approximate the behavior of a nature system or phenomena. Simulation models address the formulation of a mathematical model that simulates a specific situation, with the development of mathematical relationships and solution through a structured and valid process (Tantrakarnapa, 2003).

3.6 Mathematical Model Development

A logical approach to the model development process includes structuring of several steps, and identifying the various tasks involved in each of the steps as shown in Figure 3.4 (Nirmalakhandan, 2002).

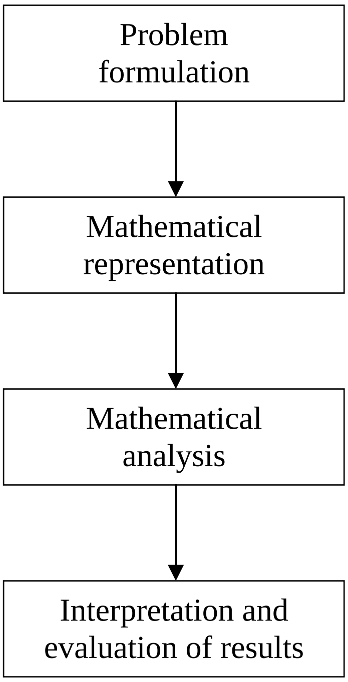


Figure 3.4 Overall approach to mathematical modeling.

3.6.1 Problem Formulation

As in any other filed of scientific study, formulation of the problem is the first step in the mathematical model development process. This step involves the following tasks:

Task 1: Establishing the goal of the modeling efforts

Modeling projects may be launched for various reasons. The scope of the modeling effort will be dictated by the objectives and the expectations. Because the premise of the effort is for the model to be simpler than the real system and at the same time be similar to it, one of the objectives should be to establish the extent of correlation expected between model predictions and performance of the real system, which is often referred to as performance criteria.

Task 2: Characterizing the system

Characterizing the system implies identifying and defining the system, its boundaries, and the significant and relevant variables and parameters. The modeler should be able to establish how, when, where, and at what rate the system interacts with its surrounding; namely, provide data about the inflow rates and the outflow rates. Processes and reaction occurring inside the system boundary should also be identified and quantified.

Task 3: Simplifying and idealizing the system

Based on the goals of the modeling efforts, the system characteristics, and available resources, appropriate assumptions and approximations have to be made to simplify the system, making it amenable to modeling within the available resources.

3.6.2 Mathematical Representation

This is the most crucial step in the process, requiring in-depth subject mater expertise. This step involves the following tasks:

Task 1: Identifying fundamental theories

Fundamental theories and principles that are known to be applicable to the system and that can help achieve the goal have to be identified.

Task 2: Deriving relationships

The next step is to apply and integrate the theories and principles to derive relationships between the variables of significance and relevance. This essentially transforms the real system into a mathematical representation.

Task 3: Standardizing relationships

Once the relationships are derived, the next step is to reduce them to standard mathematical forms to take advantage of existing mathematical analyses for the standard mathematical formulations. This is normally done through standard mathematical manipulations, such as simplifying, transforming, normalizing, or forming dimensionless groups.

3.6.3 Mathematical Analysis

The next step of analysis involves application of standard mathematical techniques and procedures to "solve" the model to obtain the desired results. The convenience of the mathematical representation is that the resulting model can be analyzed on its own, completely disregarding the real system, temporarily. The analysis is done according to the rules of mathematics, and the system has nothing to do with that process.

3.6.4 Interpretation and Evaluation of Results

This process consists of two main tasks-calibration and validation.

Task 1: Calibrating the model

Even if the fundamental theorems and principles used to build the model described the system truthfully, its performance might deviate from the real system. These deviations can be minimized by calibrating the model to more closely match the real system. In the calibration process, previously observed data from real system are used as a "training" set. The model is run repeatedly, adjust the model parameters by trial and error (within reasonable range) until its predictions under similar condition match the training data set as per goals and performance criteria established in problem formulation.

Task 2: Validating the model

Preliminary, informal validation of model performance can be conducted relatively easily and cost effectively. For formal validation, a “testing” data set from the real system can be used as a benchmark. The calibrated model run under conditions similar to those of the testing set, and the results are compared against the testing set. An important point to note is that the testing set should be completely independent of, and different from, the training set (Nirmalakhandan, 2002).

3.7 Software for Developing Mathematical Models

The low cost availability of high-performance desktop computer hardware and equally powerful software applications in recent years has fostered expensive use of computer-based simulation models in all fields of science and engineering. The benefits of computer-based simulation models in understanding, analyzing, and predicting the behavior of complex and large scale natural and engineered systems in a safe, timely, and cost effective manner have been well recognized. A large number of professionally developed, special purpose modeling and simulation programs are available commercially and also as shareware/freeware. Most such programs in use today have been developed using traditional computer programming languages such as Pascal, FORTRAN, C, BASIC, etc (Nirmalakhandan, 2002).

3.7.1 Dynamic Simulation-Based Software

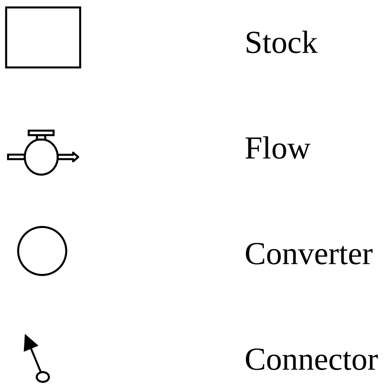
System dynamics is a subset of the large filed of simulation modeling and was developed at Massachusetts Institute of Technology (MIT) during the 1950s, by Jay W. Forrester who brought together the ideas from new-control engineering, cybernetics and organizational theory (Keerativiriyaporn, 1998).

Commonly available dynamic simulation software are Extend, ithink, STELLA, Simulink, etc. STELLA software was employed for this study.

STELLA Software

STELLA is a graphical programming language developed by High Performance System, Inc. (HPS) specifically for system dynamics study. As a graphical programming language, it allows a modeler using the program's graphical tools and functions to build dynamic models. Models can be configured to run independently with set inputs (either numerically or graphically specified) or in an interactive "flight simulator" mode. Model output can be observed via numerical readouts, tables, and graphs. Graphic output possibilities are excellent. The STELLA software also provides a variety of tools that facilitate documentation and presentation of the model as a structured "learning environment" (Dunn et al., 1988; HPS, 2001).

STELLA features a flow diagram interface; only four basic building blocks are used: stocks, flows, converters, and connectors as shown below.



Stock blocks, represented by rectangles in the flow diagram and functioning as reservoirs, are accumulators that keep track of the state values at any instant in times. Flow blocks, represented by a pipeline with a spigot, let material flow into or out of the stocks at rates specified at the spigots. Converters, represented by circles, function as modifiers of flows or containers for model parameters. The connector, represented by arrows, link the other three blocks according to the system logic, serving to transmit information (not material) between them. The converters can receive one or more inputs and generate an output by performing a calculation. The calculation is entered into the dialog box for the converter in the form of an algebraic equation, just as is done in the cell in the spreadsheet-based programs. Once the blocks are connected according to the program logic, and the program is run, STELLA performs a "material balance" across each stock at every time step to update all the state values (Nirmalakhandan, 2002).

3.7.2 Application of STELLA

Martin and Reddy (1997) studied the interaction and spatial distribution of wetland nitrogen processes by means of simulation analysis. Most processes were represented by first-order kinetics, except vegetative uptake, which was represented by Michaelis-Menten kinetics. A spatially explicit, two dimensional model was developed to evaluate the processes which determine the fate and transport of nitrogen (N) in wetland system. STELLA software was used to simulate processes regulating N removal from wetlands. Duplisea (1998) used STELLA software to study the feedbacks between benthic carbon mineralization and community structure by constructing an ecological simulation model. Model simulations generated reasonable results and compared with the empirical data from benthic systems.

Krivtsov et al. (2000) employed system dynamics approach to study the indirect regulation rule for consecutive stage of ecosystems, management of natural resources, environmental assessment and auditing. Woodwell (1998) used STELLA to study a simulation model to illustrate feedbacks among resource consumption, production, and factors of production in ecological-economic systems. Dynamic models in chemical and biological engineering are usually non-liner, and the resulting differential equations require numerical solution. In order to simulate the result, the graphical capabilities are limited. Tantrakarnapa (2003) studied the modeling of an upflow anaerobic sludge blanket process treating dairy wastewater by using STELLA software. The sensitivity of this model was also performed. It was observed that, the model was more sensitive to K_s value than μ_m, and increasing both parameters gave the good performance of the model than the decreasing or increasing only single parameter.

CHAPTER IV

EXPERIMENTAL RESULTS AND DISCUSSION

4.1 Tracer Study

At the outset of this research, a tracer study was carried out to evaluate the flow pattern in three of the five experimental wetland units. A sodium chloride (NaCl) solution was prepared with tap water at a concentration of 5 g/L and fed into the constructed wetlands. The effluent was analyzed for chloride concentration for the three flow rates.

Chloride (Cl^-) concentration in the effluent was analyzed at sampling intervals of 12 hrs during the three HRTs. The flow rate for the FWS constructed wetland units were calculated by Lim and Polprasert (1996) as in Eq. (4.1) below.

$$\mathrm{HRT} = \frac{L\mathrm{W}\left(\mathrm{d_m n} + \mathrm{d_w}\right)}{\mathrm{Q}} \tag{4.1}$$

Where, HRT = hydraulic retention time, d

L = basin length, m

W = basin width, m

d_m = media depth, m

d_w = water depth from media surface, m

n = porisity (= void fraction in the media as a decimal fraction)

Q = average flow through the unit, m^3/d

The properties of the media bed are given in Tables D.1-D.2 (Appendix D). Porosity of the two media components were determined in the laboratory following the ASTM method (ASTM, 1992) and were found to be 0.49 for sand and 0.41 for mixture of clay loam soil (Korat series) and sand, respectively. The overall porosity of the media was calculated as follows:

$$n = \frac{n_1 d_1 + n_2 d_2}{d_1 + d_2} \tag{4.2}$$

$$n = \frac{(0.49 \text{ x } 0.2) + (0.41 \text{ x } 0.4)}{(0.2 + 0.4)}$$

$$n = 0.44$$

Values of the parameters used in this study are given below:

L = 2.50 m

W = 0.25 m; (L/W ratio = 10:1)

d_m = 0.6 m

d_w = 0.15 m

n = 0.44

For HRT = 5 d, Q can be obtained from Eq. (4.1)

$$5 \text{ d} = \frac{2.50 \text{ x } 0.25 \text{ x } [(0.6 \text{ x } 0.44) + 0.15] \text{ m}^3}{Q}$$

$$Q = 51.75 \text{ L/d}$$

For HRT = 7 d, Q can be obtained from Eq. (4.1)

$$7 \text{ d} = \frac{2.50 \text{ x } 0.25 \text{ x } [(0.6 \text{ x } 0.44) + 0.15] \text{ m}^3}{Q}$$

$$Q = 36.96 \text{ L/d}$$

For HRT = 7 d, Q can be obtained from Eq. (4.1)

$$10 \text{ d} = \frac{2.50 \text{ x } 0.25 \text{ x } [(0.6 \text{ x } 0.44) + 0.15] \text{ m}^3}{Q}$$

$$Q = 25.88 \text{ L/d}$$

Thus, the three calculated flow rates for the 3 HRTs used were: 51.75 L/d (HRT = 5 d), 36.96 L/d (HRT = 7 d) and 25.88 L/d (HRT = 10 d), respectively. The raw data of tracer study and calculations of dispersion numbers are shown in Tables A.1-A.3 in Appendix A. The results of tracer experiments are shown in Figures 4.1-4.3.

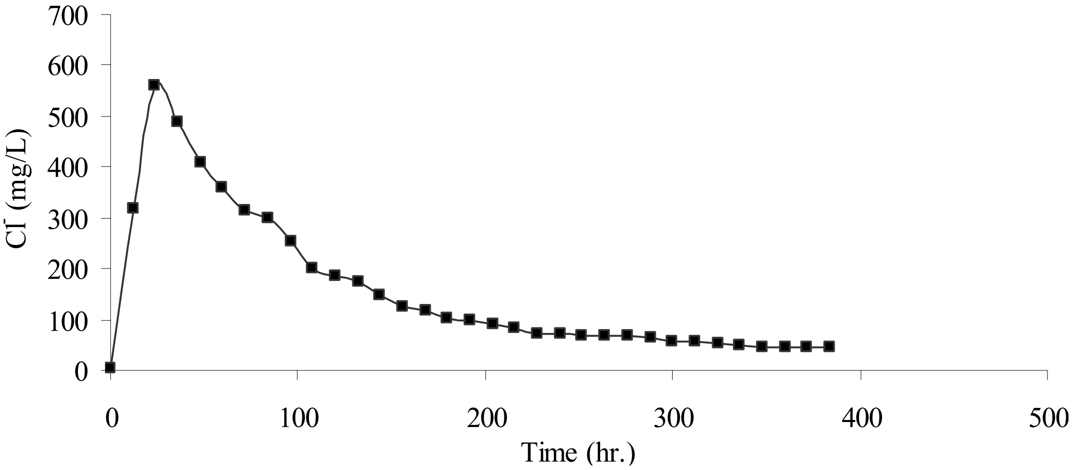


Figure 4.1 The effluent sodium chloride concentration versus time for HRT of 5 d.

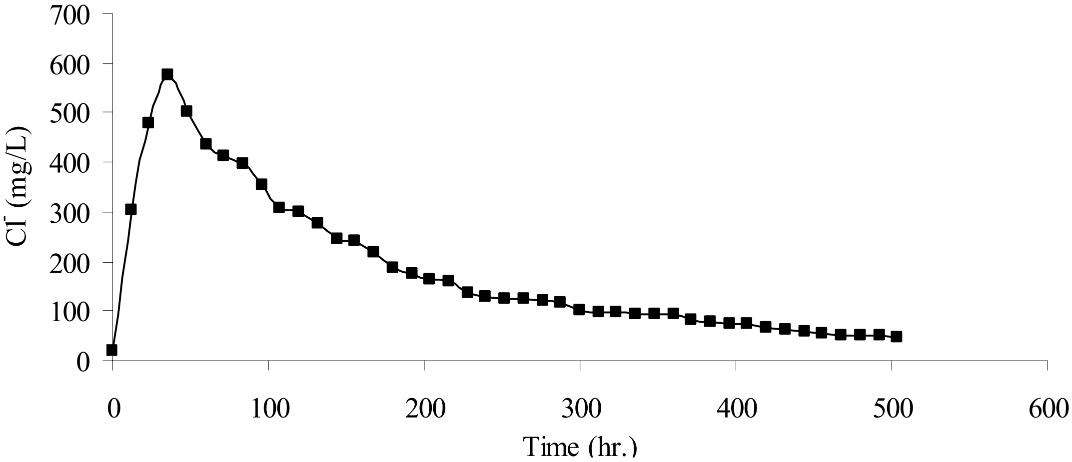


Figure 4.2 The effluent sodium chloride concentration versus time for HRT of 7 d.

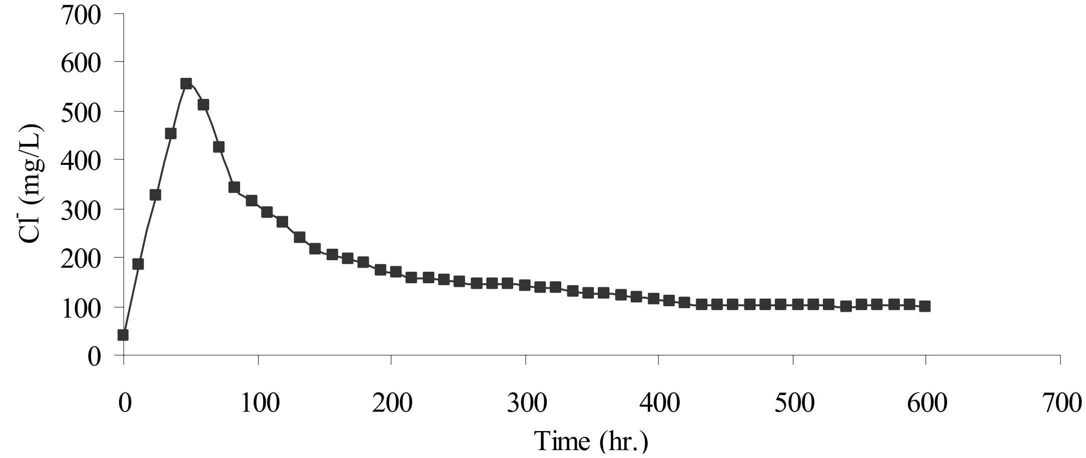


Figure 4.3 The effluent sodium chloride concentration versus time for HRT of 10 d.

The dispersion number was determined by the following equations (Levenspiel, 1972; Mattaraj, 1995).

$$T_{mean} = \frac{\sum_{i=0}^{t} C_i t_i dt_i}{\sum_{i=0}^{t} C_i dt_i} \tag{4.3}$$

$$\sigma^2 = \frac{\sum_{i=0}^{t} C_i t_i^2 dt_i}{\sum_{i=0}^{t} C_i dt_i} - T_{meann}^{\ \ 2} \tag{4.4}$$

$$\sigma_\theta^{\ 2} = \frac{\sigma^2}{T_{mean}^{\ \ 2}} = 2d + 8d^2 \tag{4.5}$$

$$d = \frac{D}{uL} \tag{4.6}$$

$$u = \frac{L}{\text{HRT}} \tag{4.7}$$

$$\text{D} = \frac{dL^2}{\text{HRT}} \tag{4.8}$$

Where, T_{mean} = actual HRT, d

C_i = tracer concentration

t_i = time, min

dt_i = different time, min

σ^2 = standard deviation

σ_θ^2 = dimensionless standard deviation

d = dispersion number or dispersion coefficient

D = the longitudinal or axial dispersion coefficient characterizing the degree of back mixing during flow, m^2/d

u = the flow velocity, m/d

L = the length of fluid travel path from influent to effluent, m.

The flow condition was characterized according to the following ranges: $D/uL = 0$, is plug flow condition (negligible dispersion); $D/uL = 0.002$, is small amount of dispersion; $D/uL = 0.0025$, is intermediate amount of dispersion; $D/uL = 0.2$, is large amount of dispersion; and $D/uL = \propto$, is mixed flow condition (large dispersion). The values of dispersion numbers indicated the intermediate amount of dispersion according to the Levenspiel's classfication as shown in Figure 4.4.

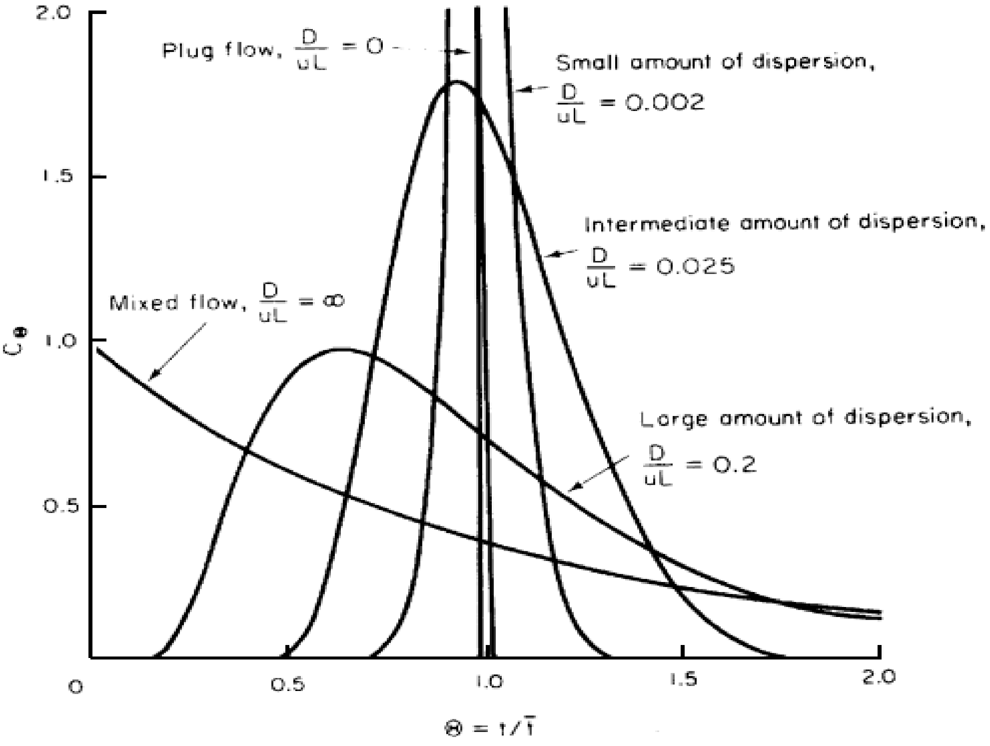


Figure 4.4 Effects of dispersion on the effluent tracer concentration.

The values of the actual HRT, dispersion number, *d* and dispersion coefficient, D are shown in Table 4.1.

Table 4.1 Actual hydraulic retention time (HRT) and dispersion numbers of constructed wetlands by tracer study.

HRT (d)	**Actual HRT (d)**	**Dispersion Number, *d***	**Dispersion Coefficient, D (m^2/d)**
5	4.78	0.1951	0.244
7	6.61	0.1833	0.164
10	9.27	0.1742	0.109

Kadle and Knight (1996) characterised the single parameter, plug flow with dispersion model using the dimensionless, wetland dispersion number, *d* and quoted typical values ranging from 0.07 to 0.33 for FWS and SF wetlands. Thus, a dispersion number of 0.17-0.20 implies the flow characteristics to follow the plug-flow pattern.

4.2 Influent and Effluent Concentrations of Monitored Parameters

The four simultaneous experiments in the wetland units during the three runs (Runs I-III) were designated as R11, R12, R13, R14, R15; R21, R22, R23, R24, R25; and R31, R32, R33, R34, R35, respectively (Table 3.2). The overall average influent and effluent for DO, pH, temperature, S-COD, TSS, S^{2-} and HCO_3^-, and cadmium removal efficiencies during three experimental runs are shown in Table 4.2.

4.2.1 DO

Dissolved oxygen (DO) is depleted to meet wetland oxygen demands in four major categories: sediment/litter oxygen demand, respiration demands, dissolved carbonaceous BOD, and dissolved nitrogenous oxygen demand NOD. Plant roots also require oxygen, which is normally transported downward through passages (aerenchyma) in stems and roots. Some surplus of oxygen may be released from small roots into their immediate environs, but it is quickly consumed by the local oxygen demand (Brix, 1994). Wetland soils are typically anoxic or anaerobic (Reddy and D’Angelo, 1994).

Wetland free water surface (FWS) areas may get aerated via oxygen transfer from the atmosphere at the air-water interface. In un-shaded open water areas, photosynthesis by algae within the water column also produces oxygen, sometimes creating dissolved oxygen concentrations in excess of the saturation limit

Table 4.2 The overall average influent and effluent for DO, pH, temperature, S-COD, TSS, S^{2-} and HCO_3^-, and cadmium removal efficiencies during three experimental runs.

Experiments	**DO**		**pH**		**Temperature**		**S-COD**		**TSS**		**S^{2-}**		**HCO_3^-**		**Cd Removal (%)**
	Influent (mg/L)	**Effluent (mg/L)**	**Influent**	**Effluent**	**Influent (°C)**	**Effluent (°C)**	**Influent (mg/L)**	**Effluent (mg/L)**	**Influent (mg/L)**	**Effluent (mg/L)**	**Influent (mg/L)**	**Effluent (mg/L)**	**Influent (mg/L)**	**Effluent (mg/L)**	
R11	0.00	0.79	4.74	5.87	27.77	27.11	687	162	109	14	3.8	0.6	49	151	control
R12	0.00	0.76	4.72	5.76	27.83	27.37	691	169	102	18	4.0	0.5	50	153	81.97
R13	0.00	0.76	4.66	5.78	27.71	27.35	688	182	112	23	3.8	0.5	48	150	80.79
R14	0.00	0.75	4.71	5.83	27.75	27.41	705	195	106	21	3.8	0.6	50	120	79.29
R15	0.00	0.74	4.65	5.85	27.68	27.42	698	198	104	21	3.8	0.5	48	130	74.55
R21	0.14	1.25	4.90	6.83	26.83	26.33	652	75	160	20	3.9	0.4	66	173	control
R22	0.09	1.23	4.94	6.91	26.62	26.25	644	59	159	18	4.1	0.4	65	190	90.96
R23	0.08	1.25	4.93	6.93	26.32	26.12	674	66	162	21	3.8	0.3	67	197	89.06
R24	0.08	1.25	4.92	6.94	26.15	26.20	725	95	158	19	3.9	0.5	68	185	87.77
R25	0.07	1.23	4.95	6.77	26.25	26.08	762	108	160	21	4.0	0.3	68	180	87.19
R31	0.16	1.84	4.79	7.36	27.93	26.97	710	115	169	24	4.1	0.2	94	244	control
R32	0.15	1.82	4.87	7.23	27.68	27.01	712	105	167	21	4.1	0.2	93	246	96.47
R33	0.14	1.92	4.89	7.54	27.85	27.07	713	111	168	20	4.2	0.2	95	246	95.71
R34	0.11	1.84	4.84	7.58	27.94	27.19	723	125	173	28	4.2	0.3	95	248	95.41
R35	0.12	1.88	4.88	7.56	27.89	27.48	727	128	155	18	4.0	0.2	93	250	95.18

(Schwegler, 1978). However, photosynthesis stops at night, and respiration, which consumes oxygen, then dominates. The result is strong diurnal variations in water column DO for lighty loaded, algae-rich, open water wetlands. In vegetated regions of the wetland, shading prevents high algal concentrations and DO levels are typically low near the surface. Anoxic or anaerobic conditions persist throughout the remainder of the water column (USEPA, 1999).

The DO levels in influent and effluent on average during the experimental period (1 year and 6 months) are shown in Table 4.2. Tables B.1-B.3 in Appendix B show details of the experimental data. The DO in the influent was in the range of 0-0.3 mg/L. The effluent DO concentrations in the five reactors during the three experimental runs varied between 1.6-6.1 mg/L. The effluent DO levels in FWS constructed wetland units were higher than in influent.

Oxygen is produced by photosynthesis and consumed by respiration. When photosynthesis takes place below the water surface, as in the case of periphyton and plankton, oxygen is added to the water internally. Oxygen transfers from air and generation with in the wetland supplement any resisdual DO that may have been present in the incoming water. This may explain the higher effluent DO levels than in influent. Three routes have been documented for transfer from air: direct mass tranfer to the water surface, convective transport down dead stems and leaves, and convective transport down live stems and leaves. The latter two combine to form the plant aeration flux (PAF). These transfers are largely balanced by root respiration, but may contribute to other oxidative processes in the root zone (Kadlec and Knight, 1996).

The average effluent DO concentrations were in the range of 0.74-1.92 mg/L during three experimental runs. It can be seen that the near-surface layer of water is aerobic while the deeper waters and the substrate are usually anerobic (USDA, 1995; ITRC, 2003).

4.2.2 pH

Wetland water chemistry and biology are affected by hydrogen ion concentration ($pH = -\log_{10}C_{H+}$). Hydrogen ion concentration, measured as pH, influences many biochemical transformations. Hydrogen ions form part of the total cation content of wetland waters and are active in cation exchange processes with wetland sediments and soils. Open water zones within wetlands can develop high levels of algal activiy, which in turn create a high pH environment (Kadlec and Knight, 1996). Table 4.2 shows the average influent and effluent pH in the five reactors during the three experimental runs. The details of the experimental data are shown in Appendix B (Tables B.4-B.6).

The pH of the prepared synthetic wastewater was in the range of 4.2-5.45, whereas the pH of synthetic wastewater mixed with different cadmium concentrations varied between 4.04-5.72. The mean effluent pH during the three experimental runs varied between 5.76 and 7.58. Bulrush plants are found to be growing well in a pH range of 4-9 (Reed et al., 1988; USEPA, 1988). At this pH range, precipitation seems to be the predominant mechanism for cadmium removal in wetlands. Also, adsorption can occur in the pH range of 4-7.7. The effluent pH was higher than the influent pH, an effect that could have been a result of plant metabolic activitie sand cycling of organic substrates associated with the wetland (Haraguchi 1996; Sintumongkolchai, 1996; Hutchins and Merrick 2004).

Based on the results of a study (Bavor et al., 1988) data on an open water, unvegetated treatment "wetland" displayed high pH during some summer periods ($pH > 9$) with circumneutral influent ($7.0 < pH < 7.4$). Photosynthesis utilizes carbon dioxide and produces oxygen, thereby shifting the carbonate-bicarbonate-carbon dioxide equilibriato a higher pH (Kadlec and Knight, 1996). Algal photosynthetic processes peak during the daytime hours, reducing dissloved CO_2 concentrations, creating high pH during the day, followed by a night-time sag with low pH as respiration replaces photosynthesis (USEPA, 1999).

4.2.3 Temperature

Table 4.2 shows the average influent and effluent temperature of wastewater during the experimental period. Tables B.7-B.9 (Appendix B) show the raw data. The ambient, as well as influent and effluent temperatures during the experimental period, varied between 20 and 32°C. Desirable temperatures for growth of bulrush are 16-27°C (Reed et al., 1988; USEPA, 1988).

The temperature of wetland waters influences both the physical and biological processes within a FWS constructed wetland. Temperature is highly variable over daily, seasonal, and latitudinal gradients; however, it is affected very little by biology. Decreased temperatures are known to reduce the rates of biological reactions, the extent of which, however, varies with the constituent (USEPA, 1999).

A shallow, FWS wetland strongly mimics the air temperature swing, with perhaps a slight delay in timing due to the thermal inertia of the surface soils and vegetation (Kadlec and Knight, 1996). The important gains and losses in the energy balance will vary seasonally. At mininium, a winter and summer energy balance will be needed to predict the range of operating water temperatures, and thus the corresponding range in temperature dependent pollutant removal rates. In summer, large amounts of energy are supplied by solar radiation. A small portion of this recharges the soil energy storage, but most is lost vai evaporation and transpiration.

In winter, energy gains are from soil storage, and loss is to the cold ambient air (USEPA, 1999).

4.2.4 S-COD

The chemical oxygen demand (COD) measures the concentration of oxidizable compounds using a strong chemical oxidant. Thus, the COD test measures the sum concentration of two distinct fractions of oxidizable compounds: easily biodegradable compounds and oxidizable but not easily biodegradable compounds (USEPA, 1999). This measure is larger than BOD because the strong oxidant attacks a large group of compound (Kadlec and Knight, 1996).

In wetland systems, microbial degradation plays a dominant role in the removal of soluble/colloidal biodegradable organic matter [biochemical oxygen demand (BOD) or COD] present in wastewater. Settable organics are rapidly removed in wetland systems by quiescent conditions, deposition, and filtration. Figures 4.5-4.7 show the influent and effluent S-COD concentations during three experimantal runs. The influent and effluent S-COD on average and experimental data of S-COD are shown in Table 4.2 and Appendix B (Tables B.10-B.12), respectively. Mean S-COD removal efficiencies in the FWS wetland systems were in the range of 71.58-90.89% during the experimental period (Figure 4.8). The main mechanism of S-COD removal was biodegradation by the attached and suspended microorganisms (Sintumongkolchai, 1996).

It can be seen in Figure 4.8 that S-COD removal in the control units and experimental units were not significantly different. Thus, different concentrations of cadmium (5, 10, 25, and 50 mg/L) were not affecting the mechanism of microorganisms in the removal organics from wastewater. The S-COD removal in the

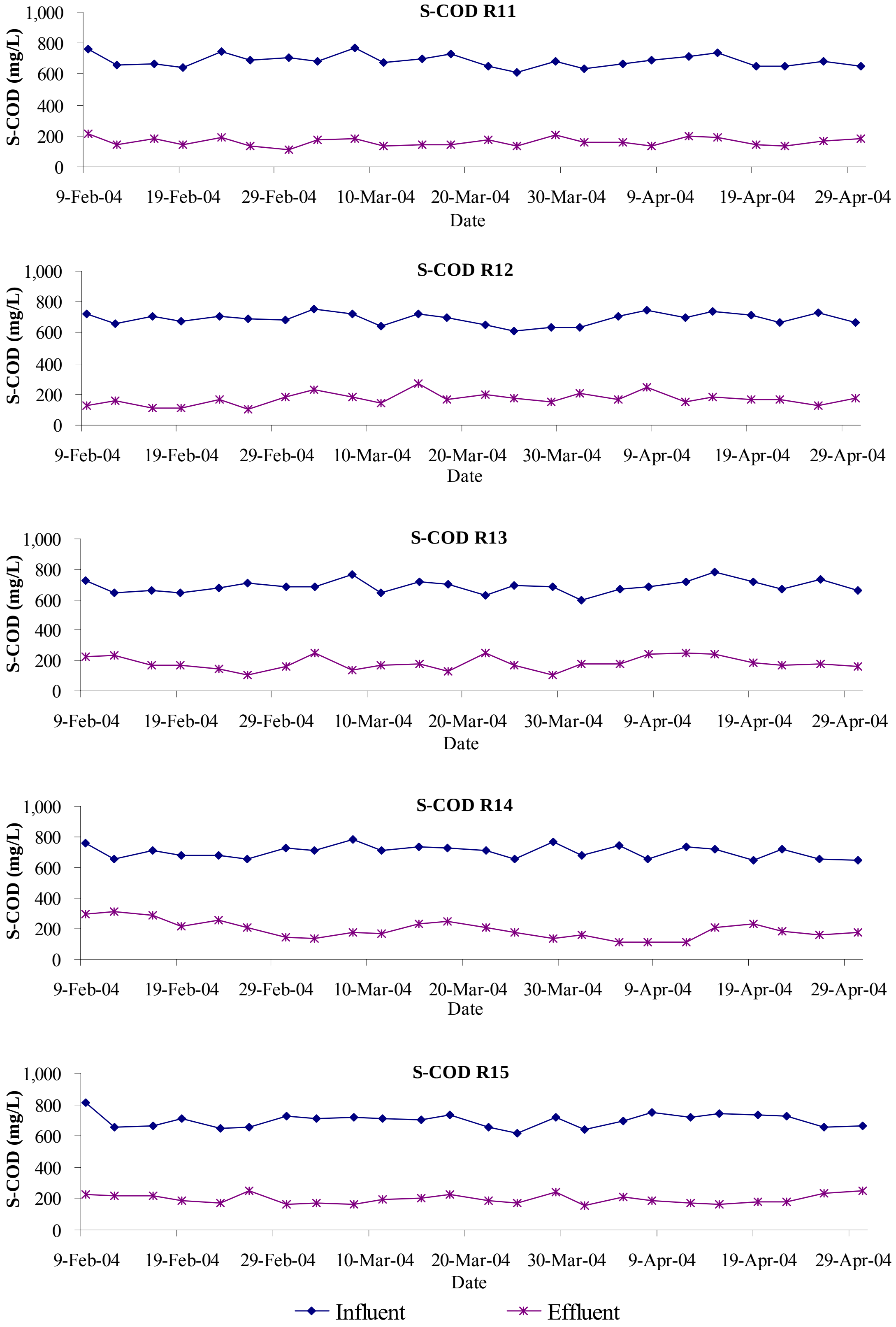


Figure 4.5 The influent and effluent S-COD concentrations during Run I.

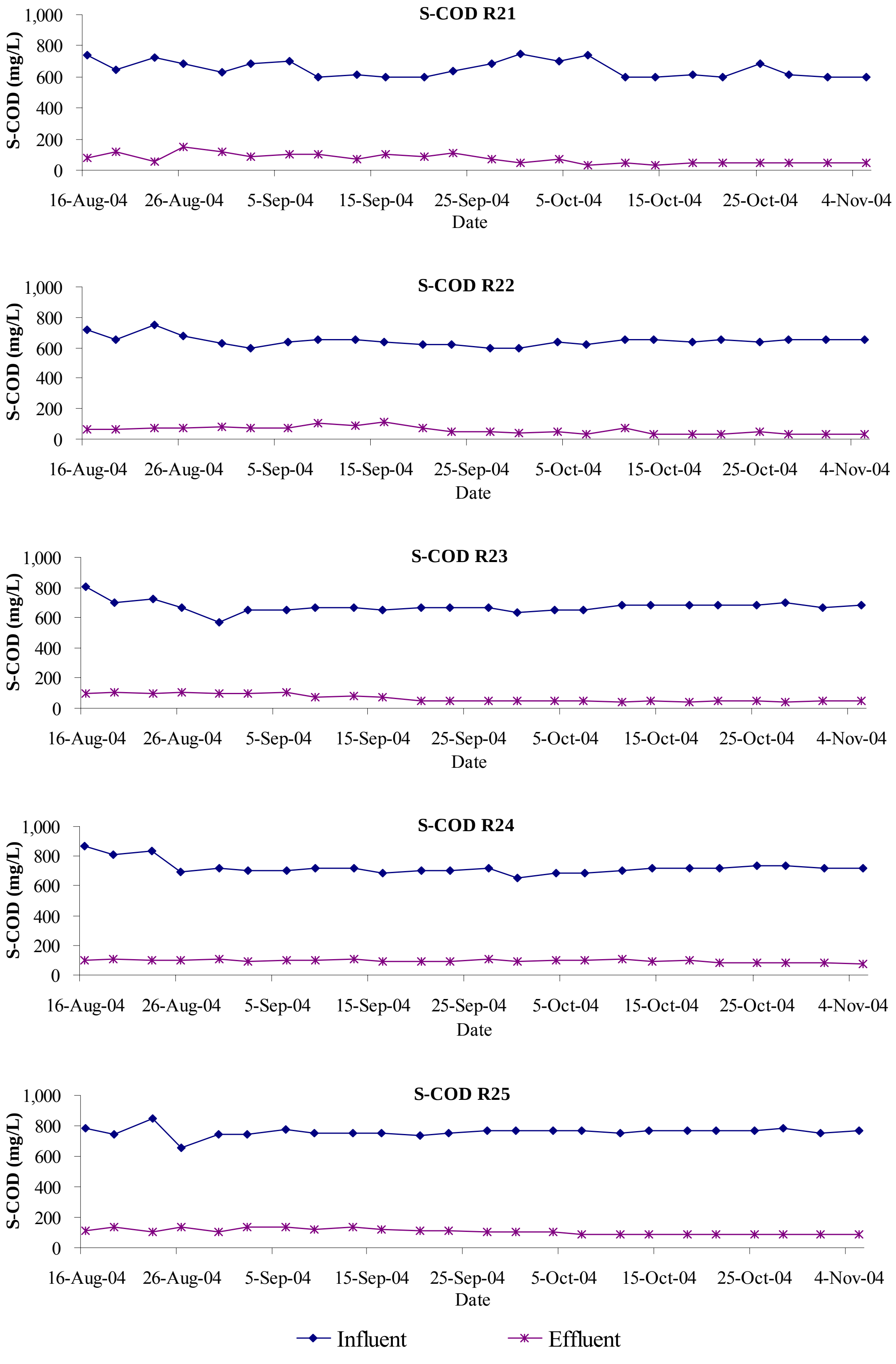


Figure 4.6 The influent and effluent S-COD concentrations during Run II.

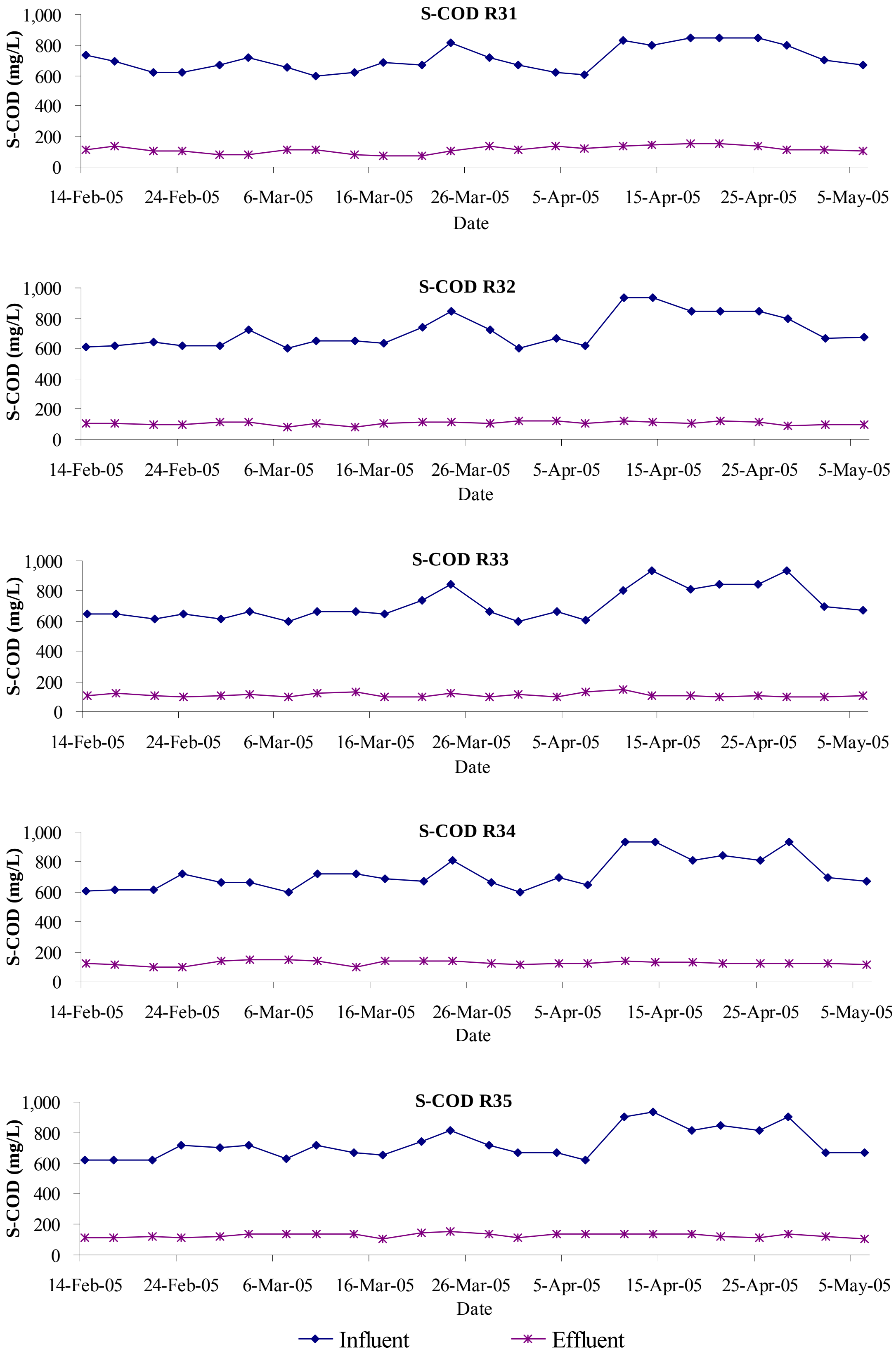


Figure 4.7 The influent and effluent S-COD concentrations during Run III.

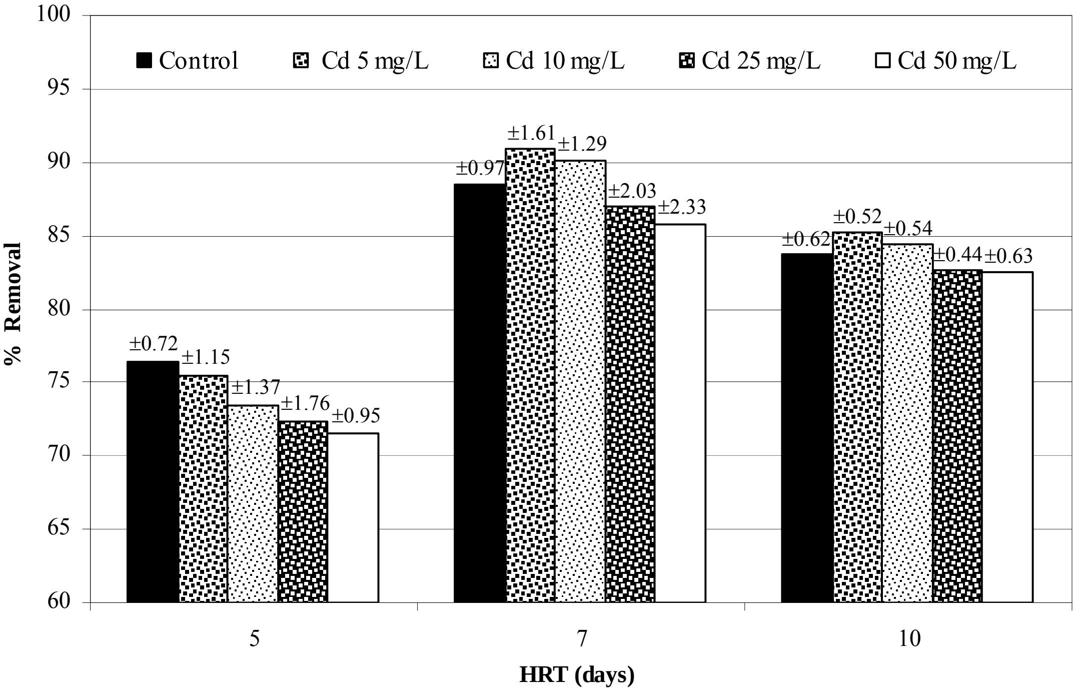


Figure 4.8 Average removal efficiencies of S-COD during the experimental period.

wetland units was only slightly affected by the influent Cd concentrations. There was a reduction in S-COD removal with increased influent Cd loading during each run (3.92% in Run I, 5.12% in Run II, and 2.76% in Run III, respectively). Thus, the performance of free water surface constructed wetlands in terms of S-COD removal was adversely affected by high Cd loading. With respect to HRT, the removal increased (15.24% on average) in Run II (HRT = 7 d) compared to in Run I (HRT = 5 d), but slightly decreased (4.95% on average) in Run III (HRT = 10 d). Therefore, 7 d seems to be the optimum HRT for S-COD removal in the FWS wetland systems with bulrush plants in this study. The decrease in performance of S-COD removal during the last run (increased HRT to 10 d) could be due to the problems of more bulrush plants dying (plant decomposition) compared to the previous run.

4.2.5 TSS

Total suspended solids (TSS) are both removed and produced by natural wetland processes. During treatment, settleable incoming particulate matter usually has ample time to settle and become trapped in litter or dead zones. Once there, soluble organic constituents are reduced to carbon dioxide and low molecular weight organic acids and inorganic constituents can become bound as sulfide complexes or become buried through sediment accretion. Wetland scientists generally refer to the combination of removal processes as filtration, although stem densities are not typically high enough to act as a filter mat. A number of wetland processes produce particulate matter including: death of invertebrates, fragmentation of detritus from plants and algae, and the formation of chemical precipitates such as iron sulfide. Bacteria and fungi can colonize these materials and add to their mass.

The average influent and effluent TSS concentrations during the three experimental runs are presented in Table 4.2 with details of raw data shown in Appendix B (Tables B.13-B.15). The average removal efficiencies of TSS were in the range 79.39-82.49%, 87.04-88.71%, and 84.01-88.59% in Runs I, II, and III, respectively. The FWS constructed wetlands, TSS concentrations were mainly removed by plants which physically retard the pathways of wastewater enchancing sedimentation of suspended soilds (Samorkhom, 2002).

4.2.6 S^{2-}

Table 4.2 shows the average influent and effluent S^{2-} concentrations in all runs during the experimental period. The details are shown in Appendix B (Tables B.16-18). From the basic physical chemistry, it is known that heavy metals precipitate as the result of changes in pH, oxidation state, and other changes of their chemical composition (Novotny, 1995). Under reducing conditions, such as in poorly drained soils, the precipitation of CdS will occur (Sintumongkolchai, 1996). The average S^{2-} removal efficiencies during the experimental period were in the range of 42.63-68.93% in Run I, 80.60-83.81% in Run II, and 93.19-96.62% in Run III. The removal efficiencies of sulfide in control units were not different than the other units (with Cd) in all experimental runs. Therefore, CdS precipitation was not a significant removal mechanism. In view of low DO concentrations in effluents of this study seem to be anaerobic conditions at organic substrate in FWS constructed wetlands. Wetlands provide anaerobic conditions that promote the growth of sulfate reducing bacteria (SRB) (ITRC, 2003). SRB reduce sulfate to hydrogen sulfide by using organic compounds or hydrogen as electron donor (Kaksonen, 2006):

$$SO_4^{2-} + 2CH_2O \longrightarrow H_2S + 2HCO_3^- \qquad (4.9)$$

Hydrogen sulfide precipitates metals as sulfides:

$$H_2S + M^{2+} \longrightarrow MS(s) + 2H^+ \qquad (4.10)$$

Where, M^{2+} = Metal, such as Zn^{2+}, Cd^{2+}

The oxidation of electron donors produces alkalinity (e.g. HCO_3^-) which neutralizes acidic water:

$$HCO_3^- + H^+ \longrightarrow CO_2(g) + H_2O \qquad (4.11)$$

Sulfate reducing bacteria remove metals and add alkalinity. These bacteria convert sulfate into both sulfide and bicarbonate. In this study, the increase bicarbonate alkalinities from wastewater correspond with the research of Kaksonen.

4.2.7 HCO_3^-

Alkalinity is a measure of the buffering capacity of water, or the capacity of bases to neutralize acids. Measuring alkalinity is important in determining a stream's ability to neutralize acidic pollution from wastewater. These buffering materials are primarily the bases: bicarbonate (HCO_3^-), and carbonate (CO_3^{2-}), and occasionally hydroxide (OH^-), borates, silicates, phosphates, ammonium, sulfides, and organic ligands. If natural buffering materials are present, pH will drop slowly to around 6; then a rapid pH drop occurs as the bicarbonate buffering capacity (CO_3^{2-} and HCO_3^-) is used up. At pH 5.5, only very weak buffering ability remains, and the pH drops further with additional acid. A solution having a pH below 4.5 contains no alkalinity, because there are no CO_3^{2-} or HCO_3^- ions left. Alkalinity not only helps regulate the pH of a water body, but also the metal content. Bicarbonate and carbonate ions in water can remove toxic metals (such as lead, arsenic, and cadmium) by precipitating the metals out of solution (Murphy, 2005).

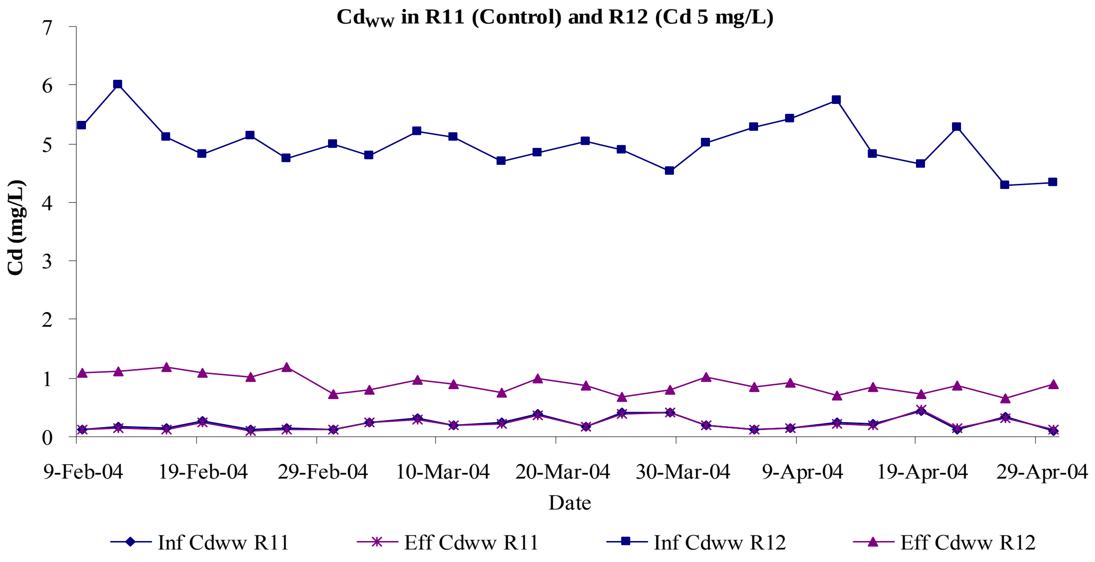
The average influent and effluent HCO_3^- concentrations during the three experimental runs are illustrated in Table 4.2. The experimental data are shown in Tables B.19-B.21 in Appendix B. The mean influent and effluent HCO_3^- were in the range of 40-157 and 122-368 mg $CaCO_3$/L, 32-89 and 64-211 mg $CaCO_3$/L, and 36-116 and 143-235 mg $CaCO_3$/L in Runs I, II, and III, respectively.

As can be seen in the results of this study, the FWS constructed wetlands are able to increase alkalinity and also they allow the metals to precipitate after they have passed through the system (NCCD, 2006). Constructed wetlands are ecological systems designed to optimize a variety of natural physical, chemical, microbial and plant-mediated processes. In a constructed wetland, metals are removed by precipitation, chelation and exchange reactions, while neutralization is primarily achieved by the activity of sulfate reducing bacteria (SRB), or the increase in alkalinity from the chemical and microbial reactions. SRB use organic carbon from residues within the wetland as an energy source to reduce sulfates to sulfides, and, in the process, increase bicarbonate alkalinity, precipitate out heavy metals, and neutralize the acidity (reduce acidity) in the system. (USEPA, 1997; MEND, 1999).

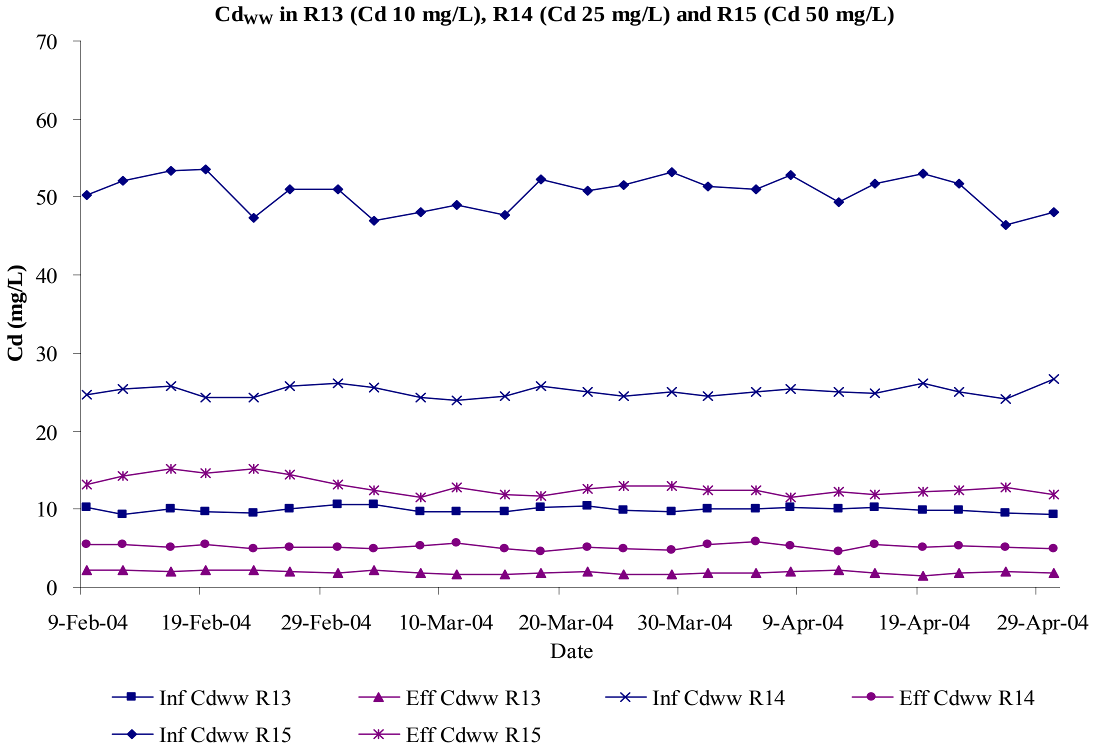
4.2.8 Cadmium Removal in Wastewater

Removal of cadmium in wetlands may occur through a number of processes, including plant uptake and soil adsorption (binding to soil particles) (Samorkhom, 2002). Tables C.1-C.3 in Appendix C and Figures 4.9-4.11 present the experimental results of Cd removal in wastewater in Runs I, II, and III. Table 4.2 and Figure 4.12 show cadmium removal efficiency of wetland units with four different Cd concentrations in influen during the three experimental runs. The overall average cadmium removal efficiency during the three runs ranged between 75-97% (74.6-81.9% in Run I at HRT = 5 d, 82.6-90.8% in Run II at HRT = 7 d, and 92.7-96.5% in Run III at HRT = 10 d, respectively).

For HRT of 5 d (Run I), influent and effluent cadmium loadings were 258.8, 517.5, 1,293.8, 2,587.5 mg/d, and 46.6, 99.4, 267.9, 658.5 mg/d, for reactors R2, R3, R4, and R5, respectively. In Run II (HRT = 7 d), influent and effluent cadmium loadings were 184.8, 369.6, 924.0, 1,848.0 mg/d, and 16.7, 38.9, 113.4, 322.3 mg/d, for R2, R3, R4, and R5, respectively. For HRT of 10 d (Run III), cadmium loadings were 129.4, 258.8, 647.0, 1,294.0 mg/d in the influent and 4.5, 10.9, 37.3, 93.9 mg/d in the

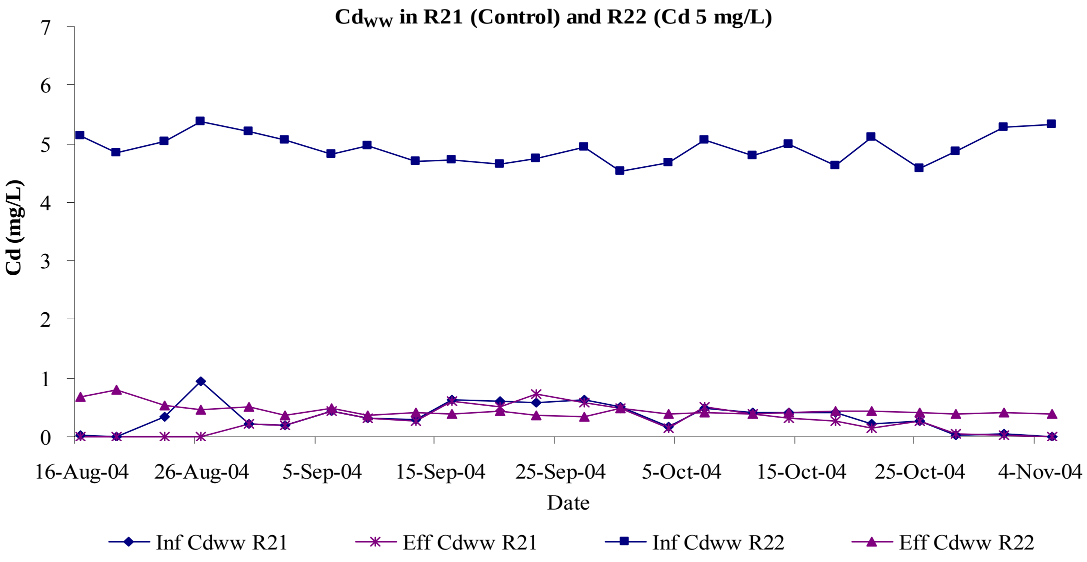


(a) Cadmium in wastewater for R11 and R12

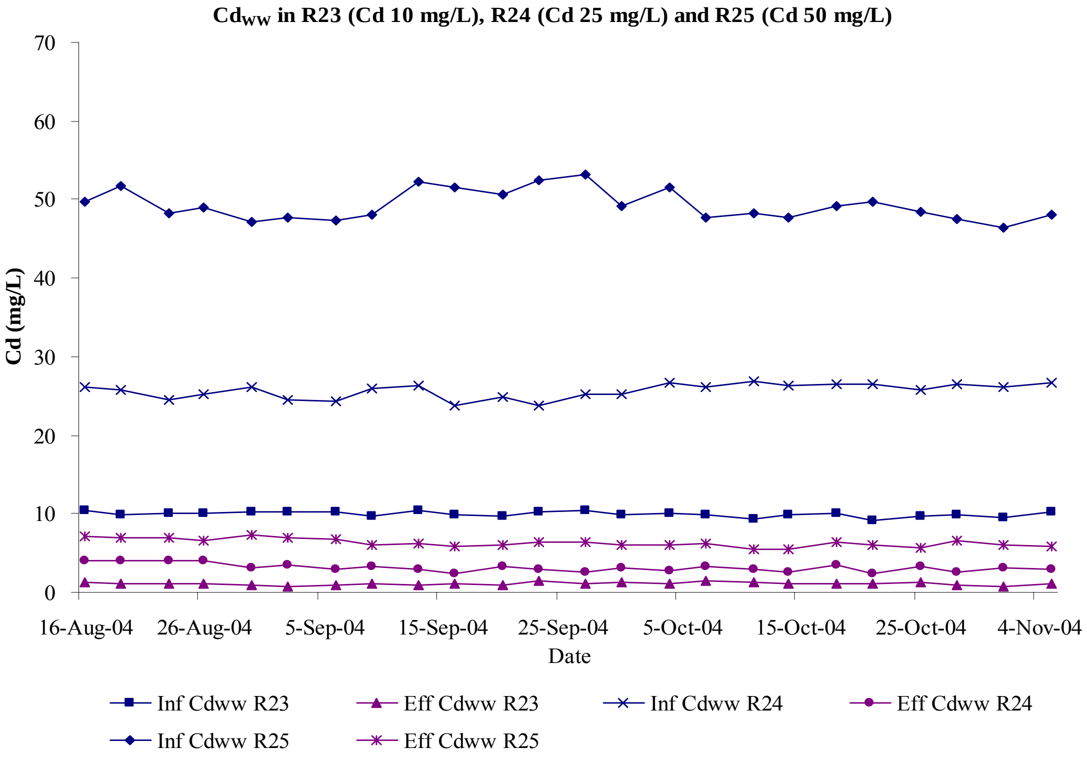


(b) Cadmium in wastewater for R13, R14 and R15

Figure 4.9 The influent and effluent Cd concentrations during Run I.

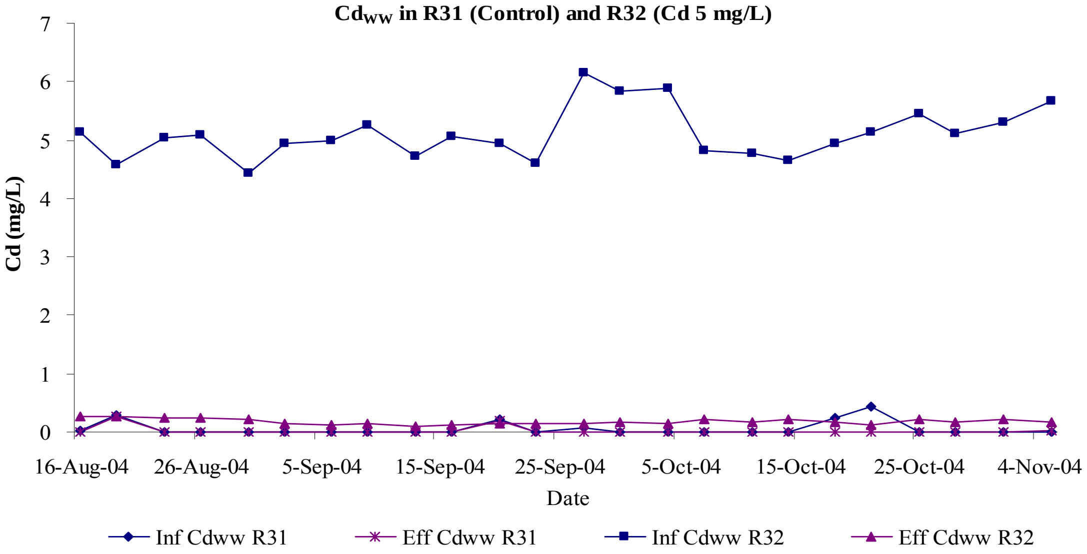


(a) Cadmium in wastewater for R21 and R22

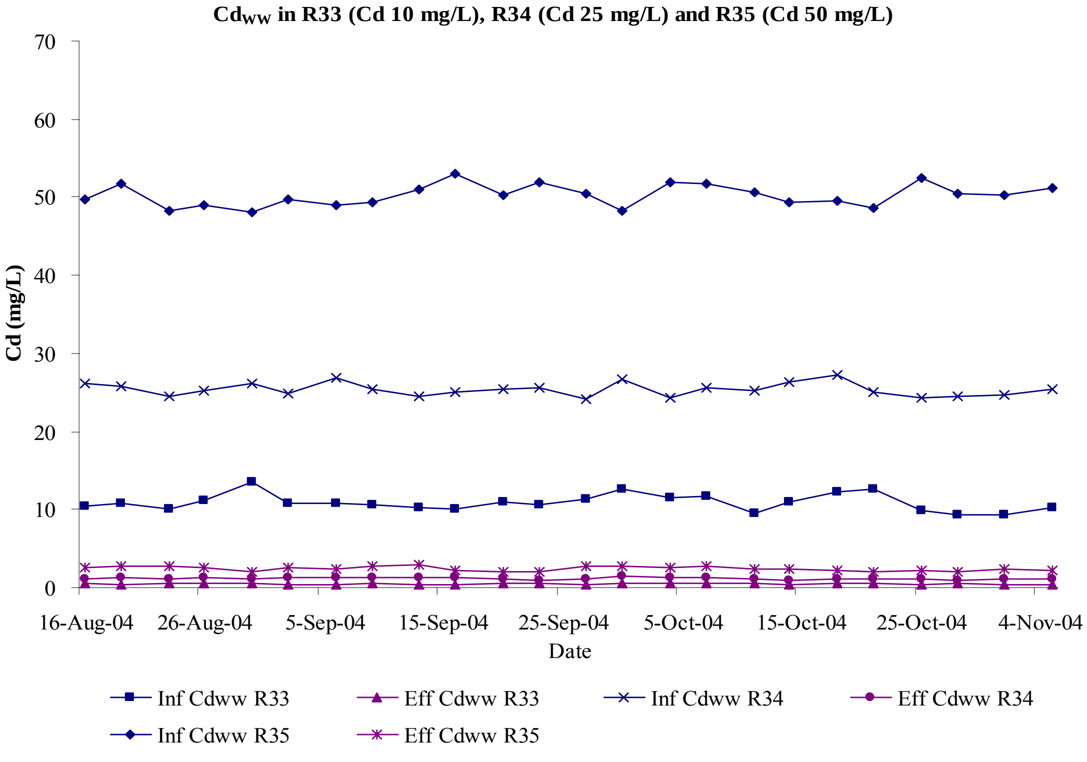


(b) Cadmium in wastewater for R23, R24 and R25

Figure 4.10 The influent and effluent Cd concentrations during Run II.



(a) Cadmium in wastewater for R31 and R32



(b) Cadmium in wastewater for R33, R34 and R35

Figure 4.11 The influent and effluent Cd concentrations during Run III.

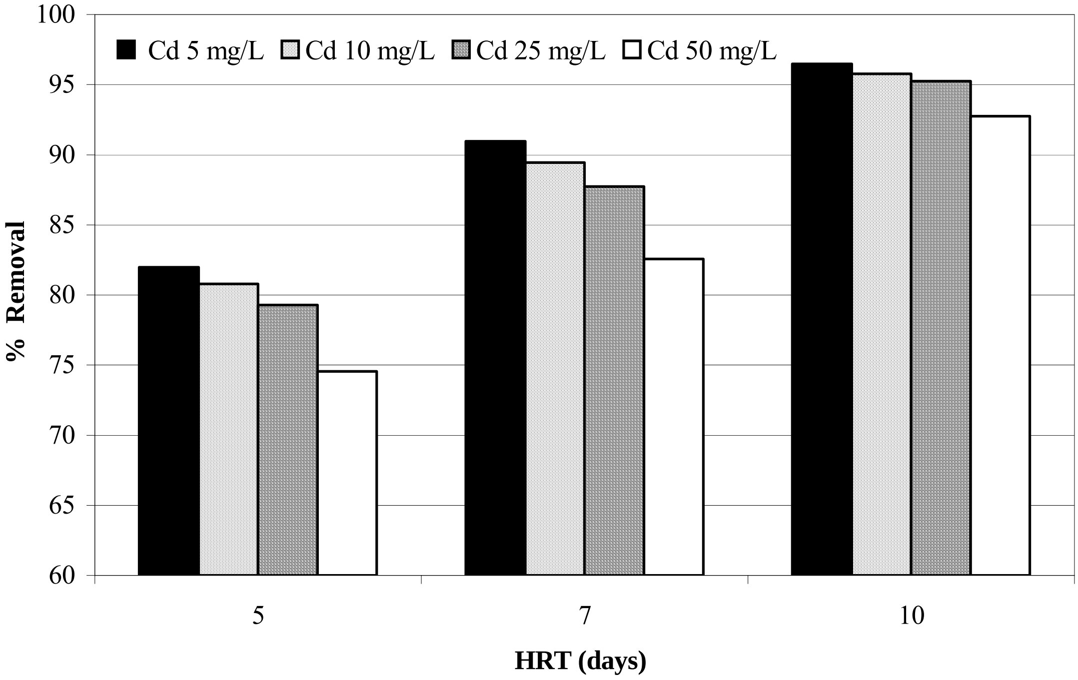


Figure 4.12 Average cadmium removal efficiencies during three runs.

effluent for R2, R3, R4, and R5, respectively. Table 4.3 shows comparison of total Cd loading and % removal efficiencies at the same Cd concentration for all experimental runs.

As reported by Hedin et al. (1994) and Sobolewski (1997, 1999), metal removal processes occurring in wetlands involve a series of mechanism: filtration of metals suspended on solids, including adsorbed metals, are easily filtered and retained in wetlands. Sorption of metals, which includes adsorption and precipitation reactions, is the transfer of ions from the solution phase (water) to the solid phase (soil) (Halverson, 2004). Adsorption can occur in the pH range of 4-7.7 (Sintumongkolchai, 1996). Adsorption to sediments increases with pH and beyond a threshold point ($pH \geq 7$ for Cd); virtually all the metal ion is sorbed (Moore and Ramamoorthy, 1984). Metal adsorption at low total metal concentration was suppressed, as could be shown

Table 4.3 Comparison of total Cd loading and % removal efficiencies for all experimental runs.

Cd concentration (mg/L)	**Run I**		**Run II**		**Run III**	
	Loading (mg/d)	**% Removal**	**Loading (mg/d)**	**% Removal**	**Loading (mg/d)**	**% Removal**
5	258.8	81.97	184.8	90.96	129.4	96.47
10	517.5	80.79	369.6	89.06	258.8	95.71
25	1,293.8	79.29	924.0	87.77	647.0	95.41
50	2,587.5	74.55	1,848.0	87.19	1,294.0	95.18

by adsorption isotherms at pH 7.35 (Weirich, 2000). The results of pH from Table 4.2 show that cadmium adsorption could be observed in FWS constructed wetlands.

Also, it can be seen in Figure 4.12, that cadmium removal was affected by higher influent loading in each run. Removal decreased with increased loading. However, the removal efficiency for cadmium increased with HRT. This could be explained by the fact that the longer HRT would be more effective in sedimentation, adsorption, cation exchange, complexation, microbial activity and plant uptake. Maximum removal occurred at HRT of 10 d. Thus, in terms of Cd removal from wastewater in FWS constructed wetlands with bulrush plants, HRT of 10 d was found to be optimum for this study. The longer HRTs (> 10 d) may be have a problem in constructed wetland operation (clogging). The comparison of S-COD and

Cd removal efficiencies were slightly different in Runs I and II. The removal efficiencies of S-COD were slightly decreased in Run III compared to Run II but increased in term of Cd removal.

4.2.9 Cadmium Removal in Soil

Soil samples were analyzed for Cd concentrations twice a month (only top soil at the distances of 0.05, 0.625, 1.25, 1.875 and 2.45 m from the inlet). At the end of each run, soil samples were analysed at the five locations along the lengths and at the depths of 0, 15, 30 and 45 cm from the top of the soil bed. Figures 4.13-4.15 and Tables C.4-C.6 in Appendix C show the cadmium accumulation in top soil along the reactor lengths during the experimental run. The results showed that the concentrations were very high near the inlet and decreased with the distances along the reactor lengths for all experimental runs.

At the end of each run, the Cd accumulation in soil were determined at the different depths along the reactor lengths (Figures 4.16-4.18, and Tables C.7-C.9 in Appendix C). Vertical profiles of Cd accumulation in the soil indicated that, Cd tends to be present at higher concentrations in the surface horizons and remain in the top 15 cm as a result of cycling through vegetation and adsorption by soil organic matter. The relatively high humus content also contributes to adsorptive capacity of surface horizon. However, the accumulation in top soil decreased with the depths because pedogenic (soil formation) processes have not been operating long enough to effect a redistribution within the profile (Alloway, 1990).

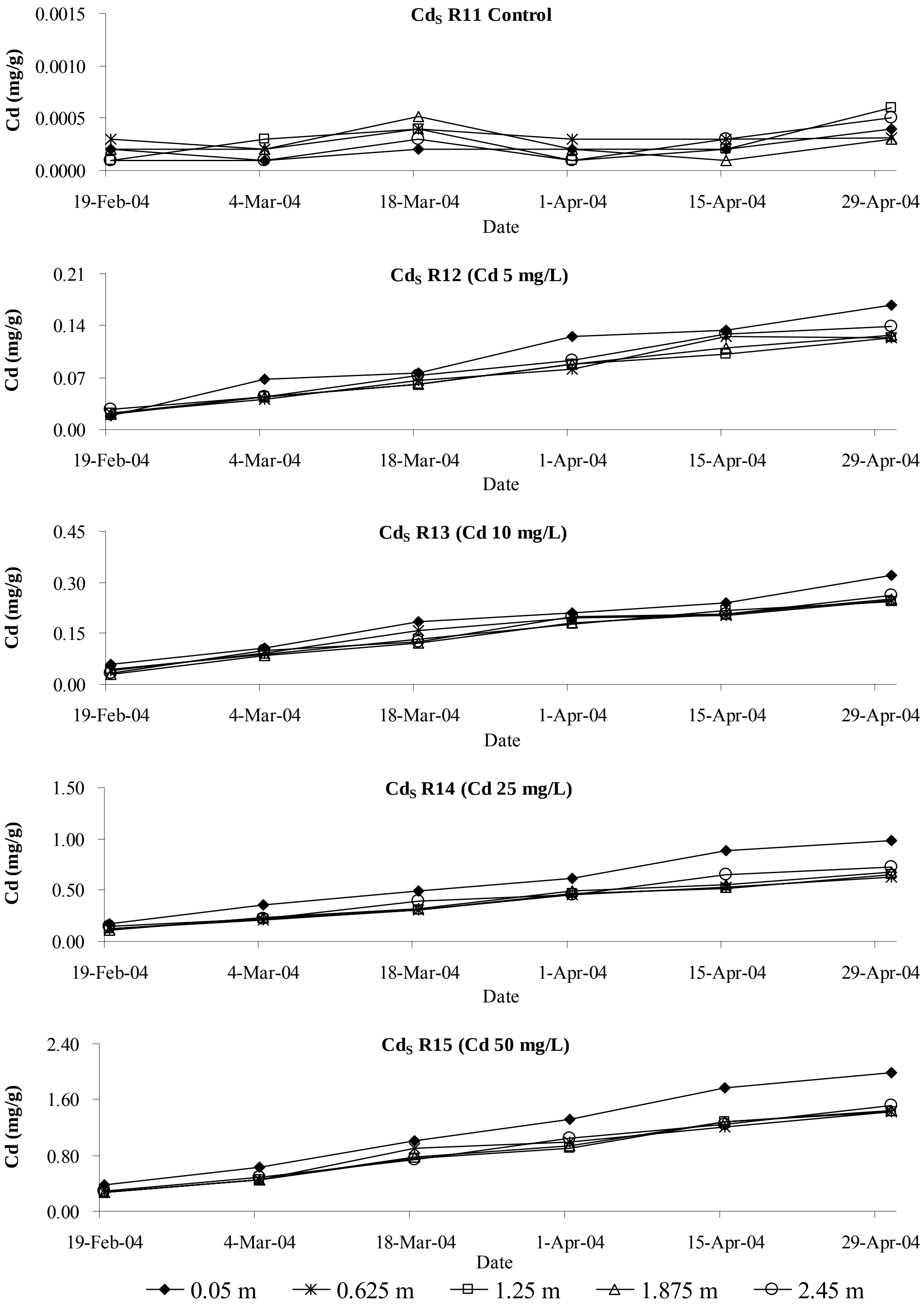


Figure 4.13 The Cd accumulation in top soil along the reactor lengths during Run I.

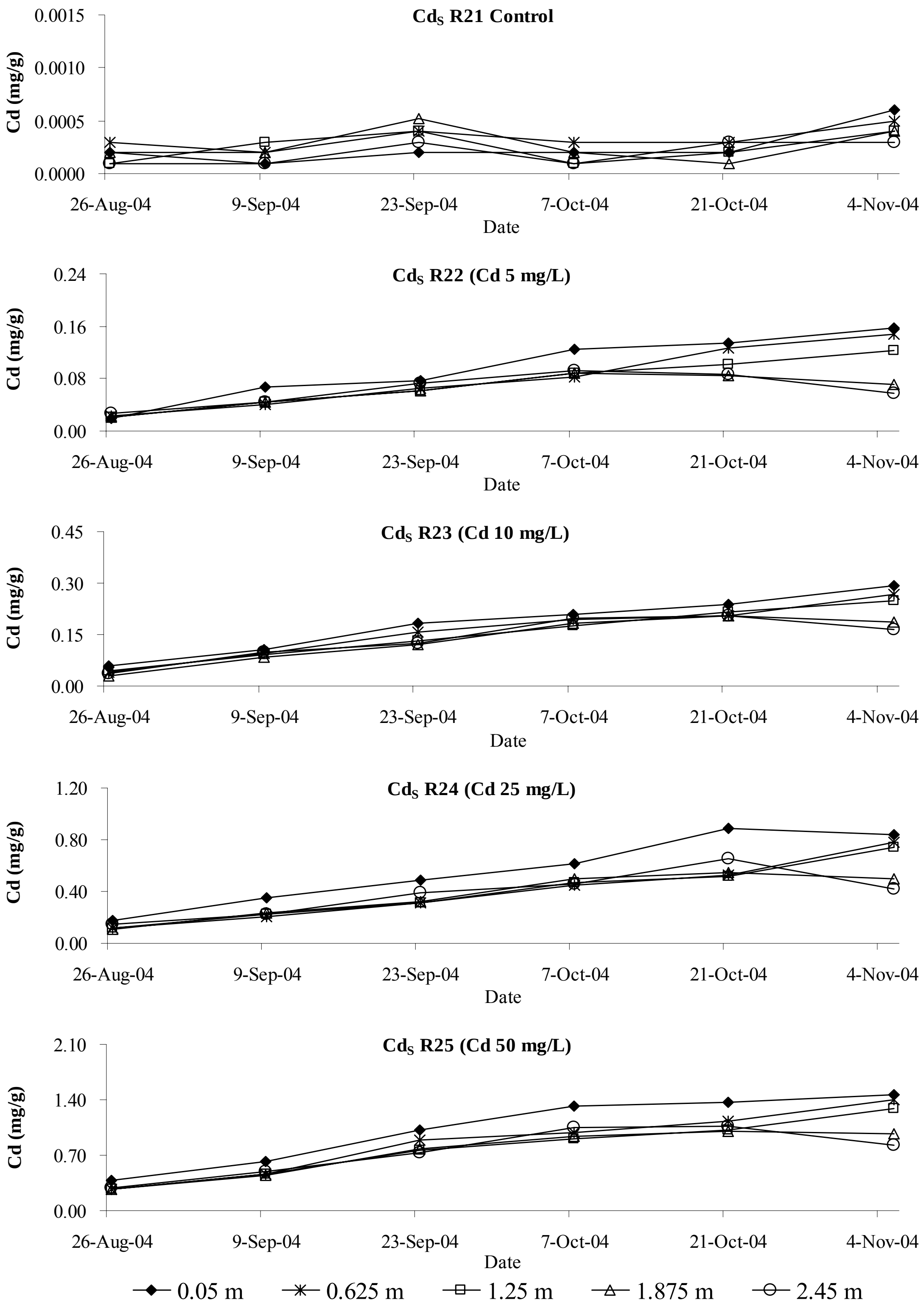


Figure 4.14 The Cd accumulation in top soil along the reactor lengths during Run II.

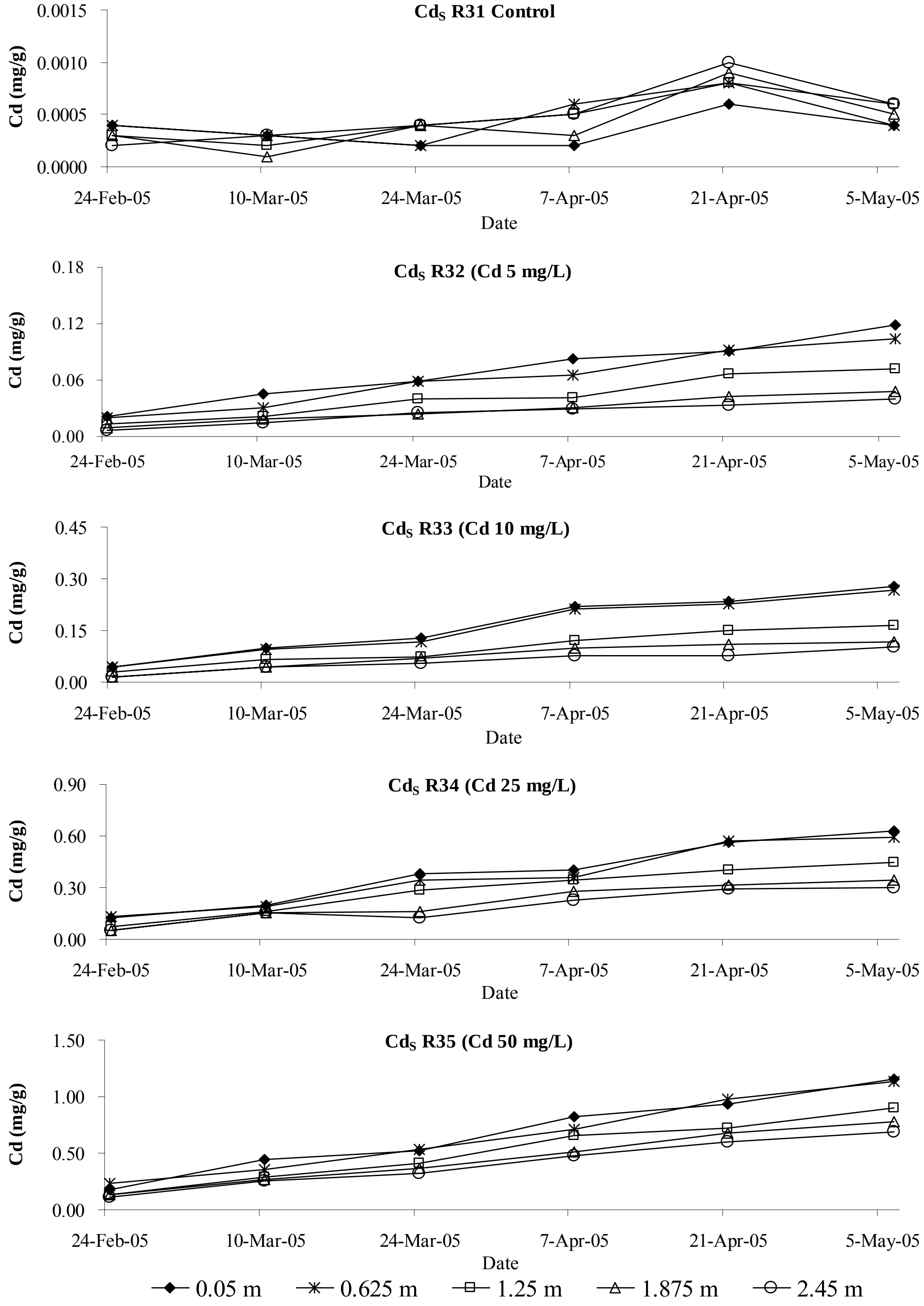


Figure 4.15 The Cd accumulation in top soil along the reactor lengths during Run III.

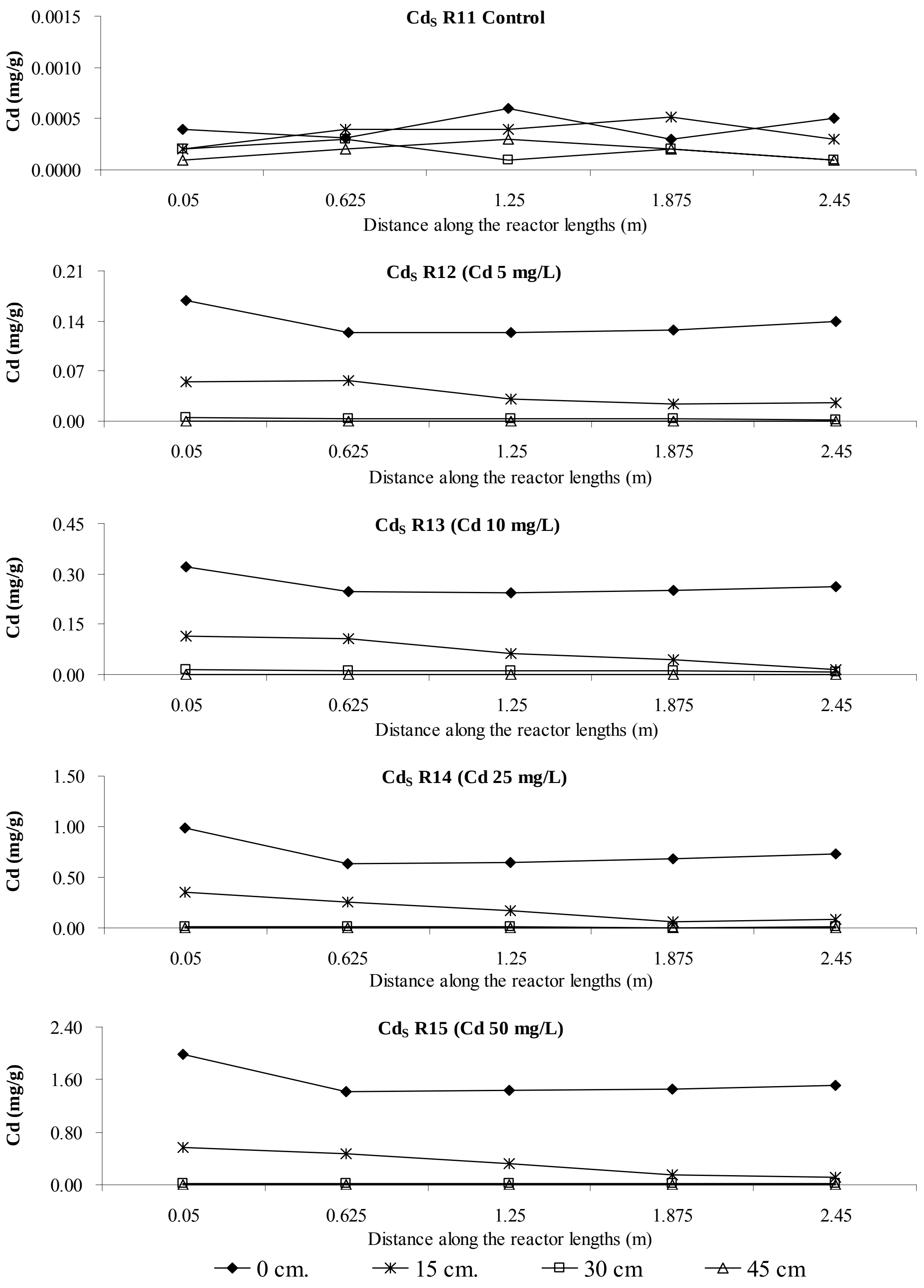


Figure 4.16 Profiles of Cd accumulation in soil along reactor lengths at different depths during Run I.

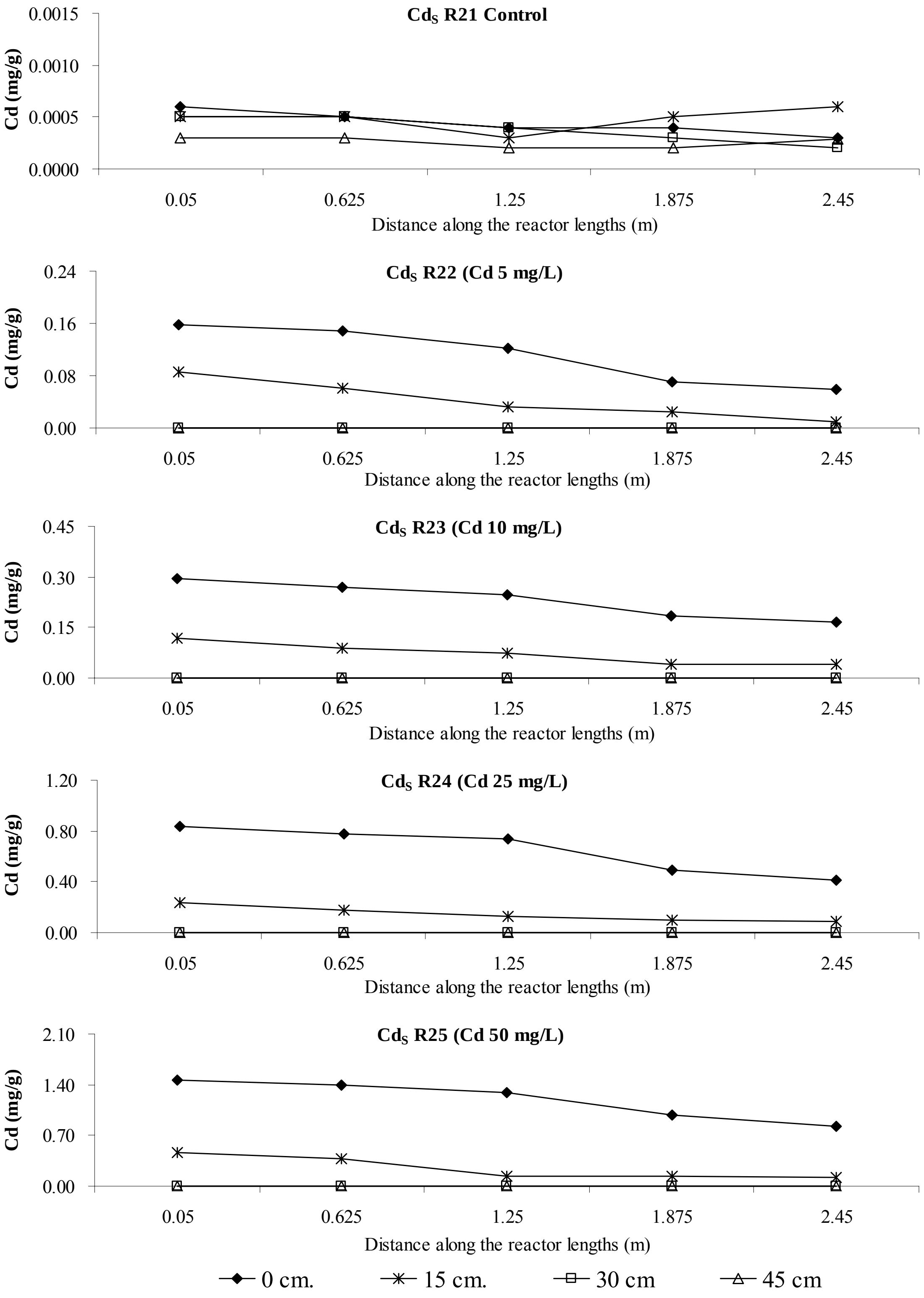


Figure 4.17 Profiles of Cd accumulation in soil along reactor lengths at different depths during Run II.

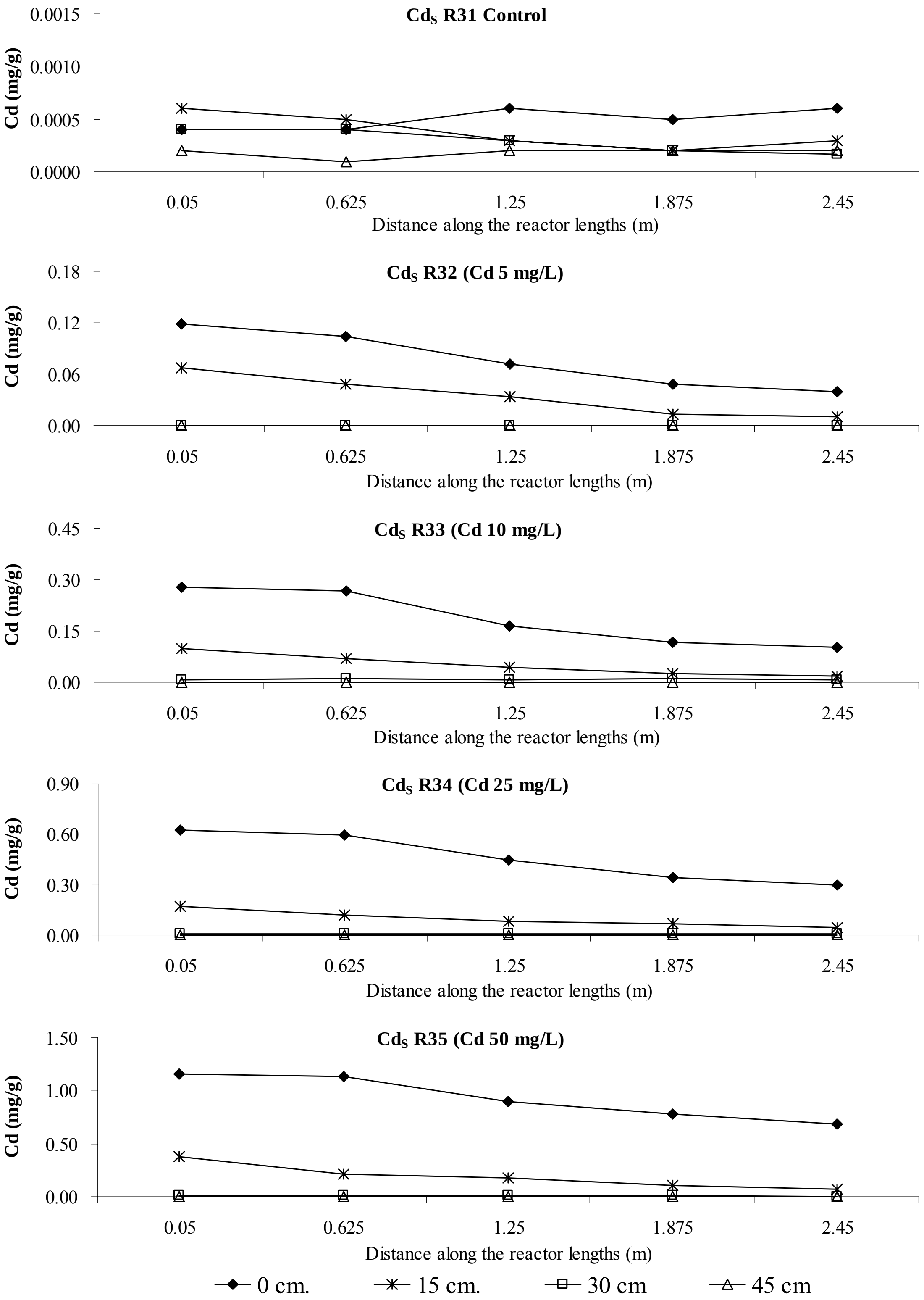


Figure 4.18 Profiles of Cd accumulation in soil along reactor lengths at different depths during Run III.

The profiles of Cd along the soil bed of the wetlands in the three experimental runs are illustrated in Figure 4.19 (Table C.10 in Appendix C), indicating a high concentration of cadmium at the inlet. Concentrations at the top were higher than at the depths of 15, 30 and 45 cm. The porosity of sand (0.49), being higher than that of the mixture of clay loam soil and sand (0.41), could have been the cause of a higher adsorption of cadmium at the top of the soil bed. Clays are soil with very fine particles packed closely together. Clays typically have the highest adsorption potential of any soils because of their high surface area to volume ratio, resulting from their small particle size distribution. Loamy soils have excellent plant growth characteristics because of adequate nutrient holding capacity and higher hydraulic conductivities and gaseous diffusion rates (Kadlec and Knight, 1996).

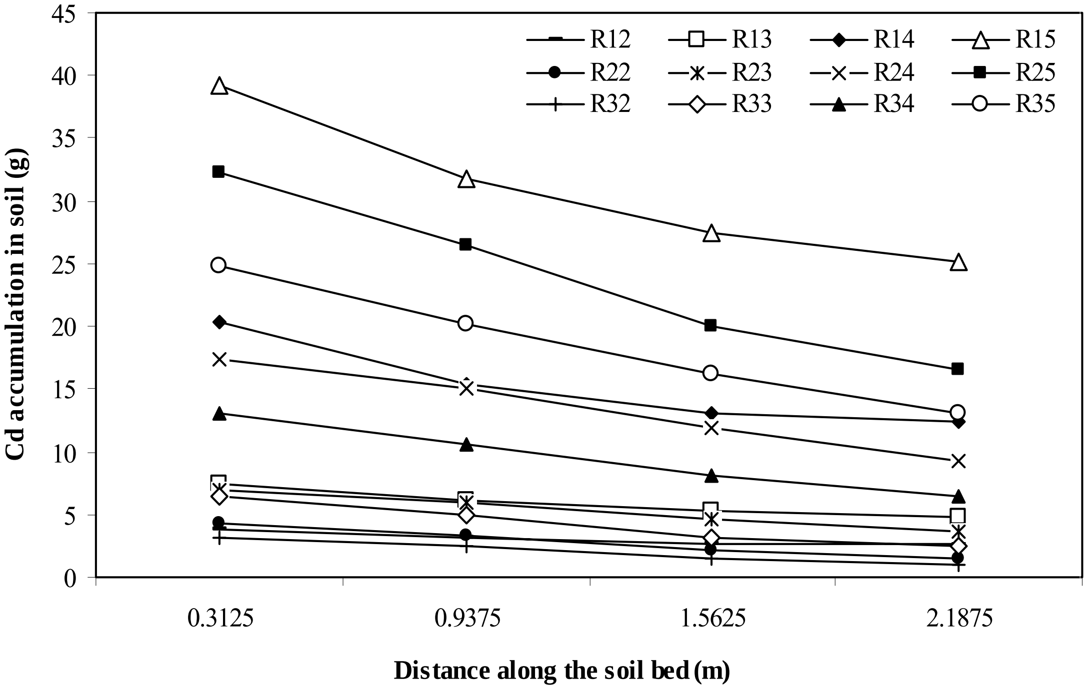


Figure 4.19 The profiles of cadmium accumulation in soil along the soil bed of the FWS wetland system.

The total accumulation of cadmium in the soil, during the three experimental runs, was obtained at the end of each run as shown in Figure 4.20. Cadmium accumulation in soil was determined as follows:

1. The reactor volume was divided into 16 zones along the length and depth.
2. Concentration of Cd in each zone was calculated by:

$$\text{Cd(g)} = \text{Avg.Cd in soil zone(mg/g)} \times \text{Volume of soil in the zone}(\text{m}^3) \times \text{Bulk density of soil(g/mL)}$$

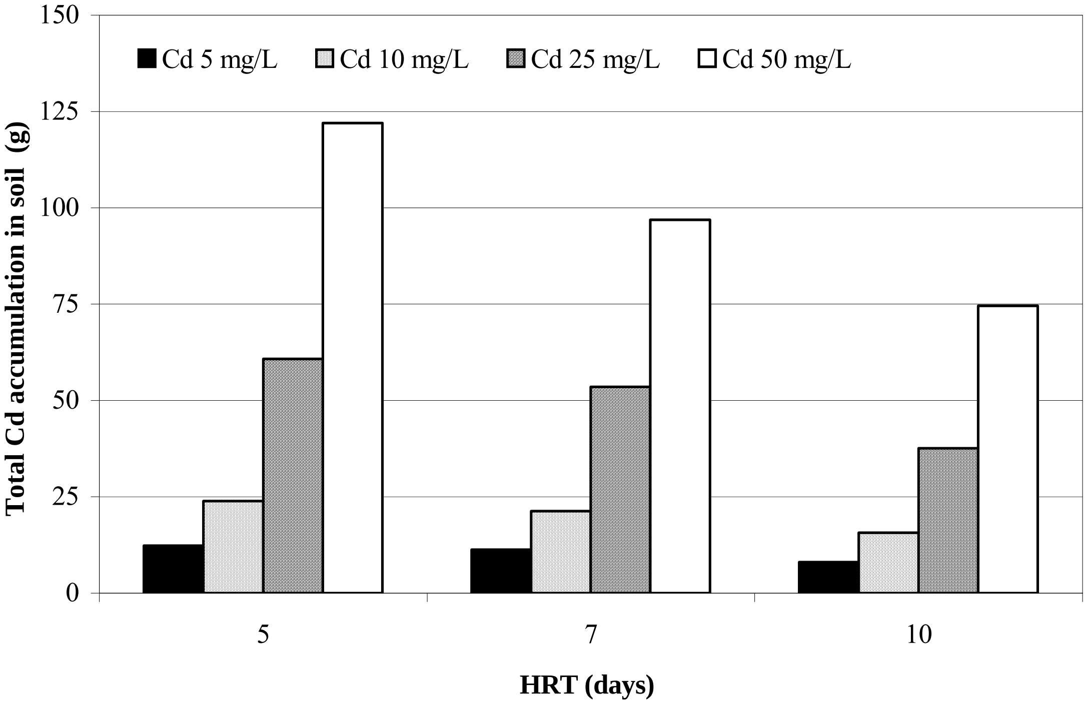


Figure 4.20 Total cadmium accumulation in soil bed.

It can be seen in Figure 4.20, that total cadmium accumulation in the soil bed increased with influent loading during each run. Also, the accumulation decreased with HRT for all influent concentrations. At higher HRT, the loading of Cd might have decreased, which would have decreased the availability of Cd for accumulation. The most of cadmium (56.3-75.5%) could be adsorbed by soil. In the organic substrate, adsorption (the attachment of ions to soil particles) seems to be the dominant mechanism for metals removal (Fitch and Burken, 2004).

4.2.10 Cadmium Removal by Plant Uptake

Wetland plants perform a number of important functions in wetlands. They serve to stabilize wetland soil and sediment and enhance the accretion of new sediments by the filtering action of their leaves and stems, causing settleable metal suspended on solids to fall out of the water column (ITRC, 2003).

The factors affecting the amount of metal absorbed by a plant are those controlling: (i) the concentrations and speciation of the metal in the soil solution, (ii) the movement of the metal from the bulk soil to the root surface, (iii) the transport of the metal from the root surface into the root, and (iv) its translocation from the root to the shoot. Plant uptake of mobile ions present in the soil solution is largely determined by the total quantity of this ion in the soil, but in the case of strong adsorbed ions, absorption is more dependent upon the amount of root produced (Alloway, 1990).

Plant uptake rates and tolerance of metals vary considerably among plant species. Some terrestrial plant species are known to be capable of storing high concentrations of metals in roots and other tissues. Metals may also tend to accumulate on the root surfaces, rather than being taken up into the plant (Vigneswaran and Sundaravadivel, 2001).

Samples of plants were analyzed for Cd concentrations twice a month (only stems at the distances of 0.05-0.625 (zone 1), 0.625-1.25 (zone 2), 1.25-1.875 (zone 3), and 1.875-2.45 m (zone 4) from the inlet). At the end of each run, both roots and stems samples were analysed in the four zones along the reactor lengths. The cadmium uptake in bulrush' stems during the experimental period is illustrated in Figures 4.21-4.23 (Tables C.11-C.13 in Appendix C). The details of the harvested bulrush plants at the end of each run are presented in Appendix E (Tables E.1-E.3).

Table 4.4 shows the cadmium uptake in bulrush (*Cyperus corymbosus* Rottb.) plants at the end of each run. The results of this study, bulrush plants can uptake cadmium in the range of 1,533-15,974 mg/kg for 82 days without displaying serious effects. Also, cadmium in normal bulrush plants (control units) were in the range of 38-54 mg/kg. Stout and Nusslein (2005) reported *L. minor* has been shown to accumulate as much as 1,300 time more Cd than concentrations present in the surrounding water or as much as 14,000 mg/kg Cd. The hyperaccumulator *Thlaspi caerulescens* can take in 1,500 ppm of cadmium, while a normal plants would be poisoned at 20 to 50 ppm (Hank, 2000). The leaves *Thlaspi caerulescens* in the Cevennes (southern France) have been found to contain the toxic and non-essential metal cadmium (Cd) between 1,000 and 3,000 mg/kg dry biomass (Kramer, 2000). Cadmium could have been chelated by organic acids and amino acids present in higher concentration in the roots (Thayalakumaran, 1994). Since the cattails were able to accumulate up to 3,200 ppm in the FWS and 2,800 ppm in the SF, these plants can be classified as cadmium hyperaccumulators (Jindal and Samorkhom, 2005).

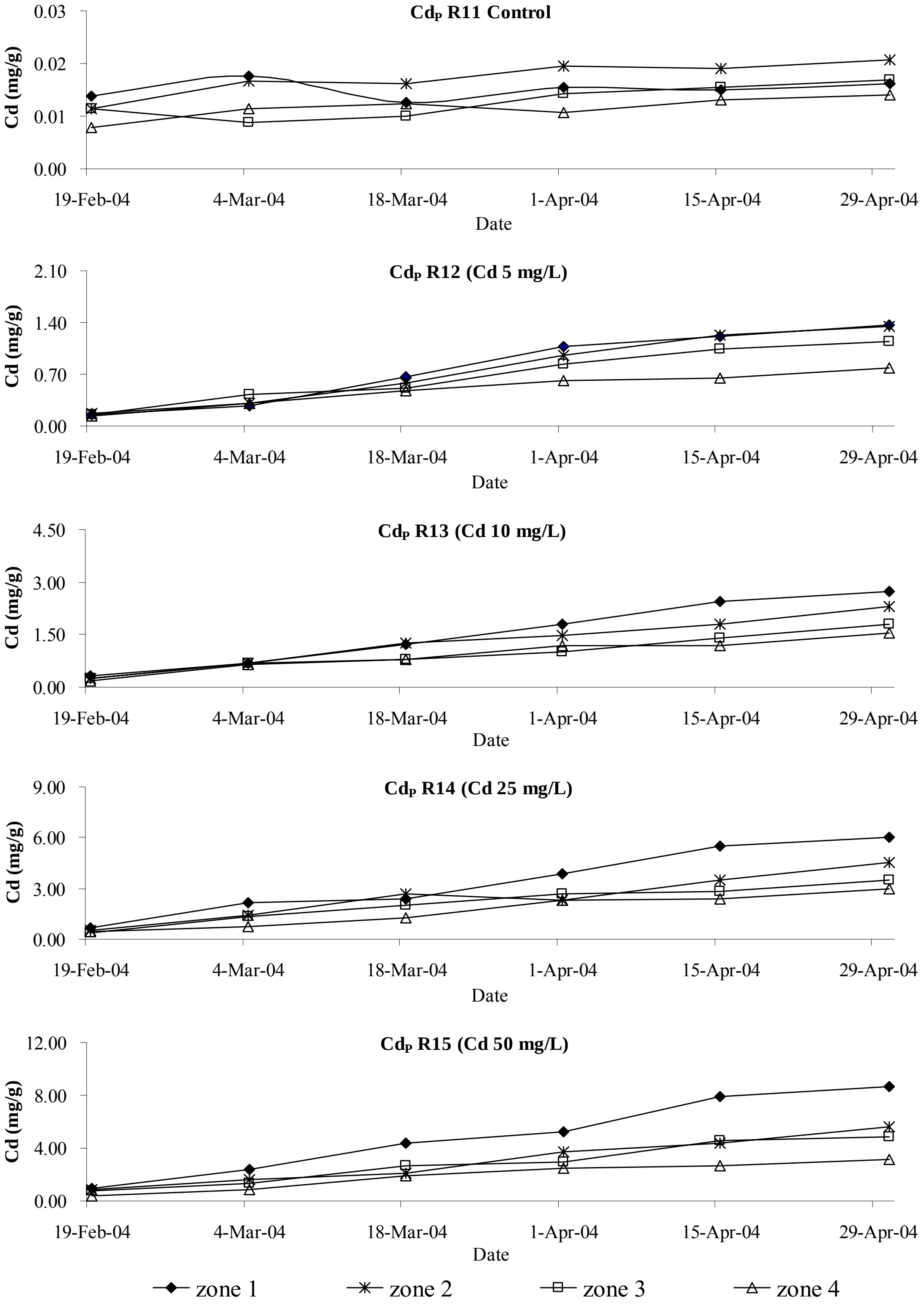


Figure 4.21 The accumulation of Cd in stems during Run I.

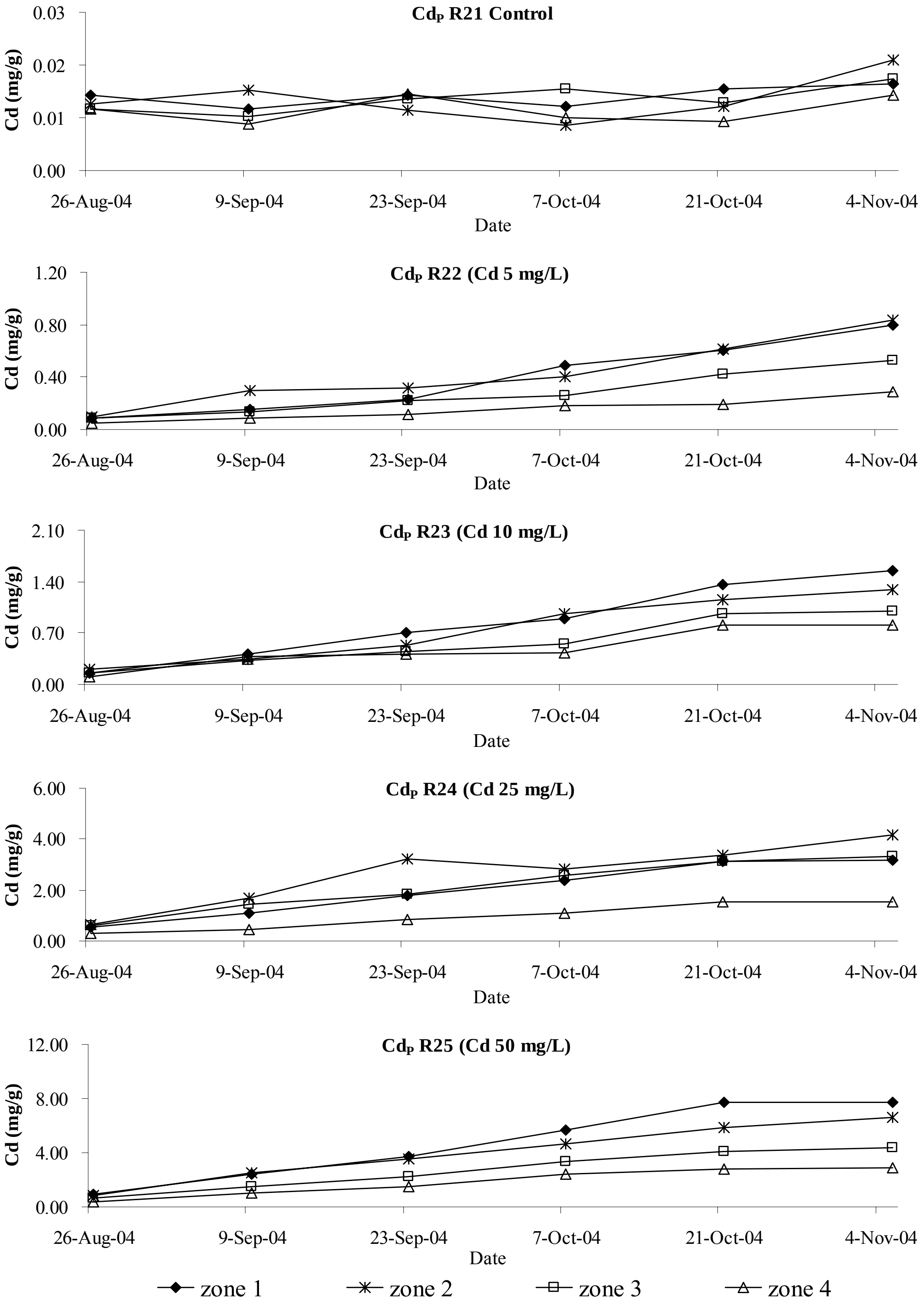


Figure 4.22 The accumulation of Cd in stems during Run II.

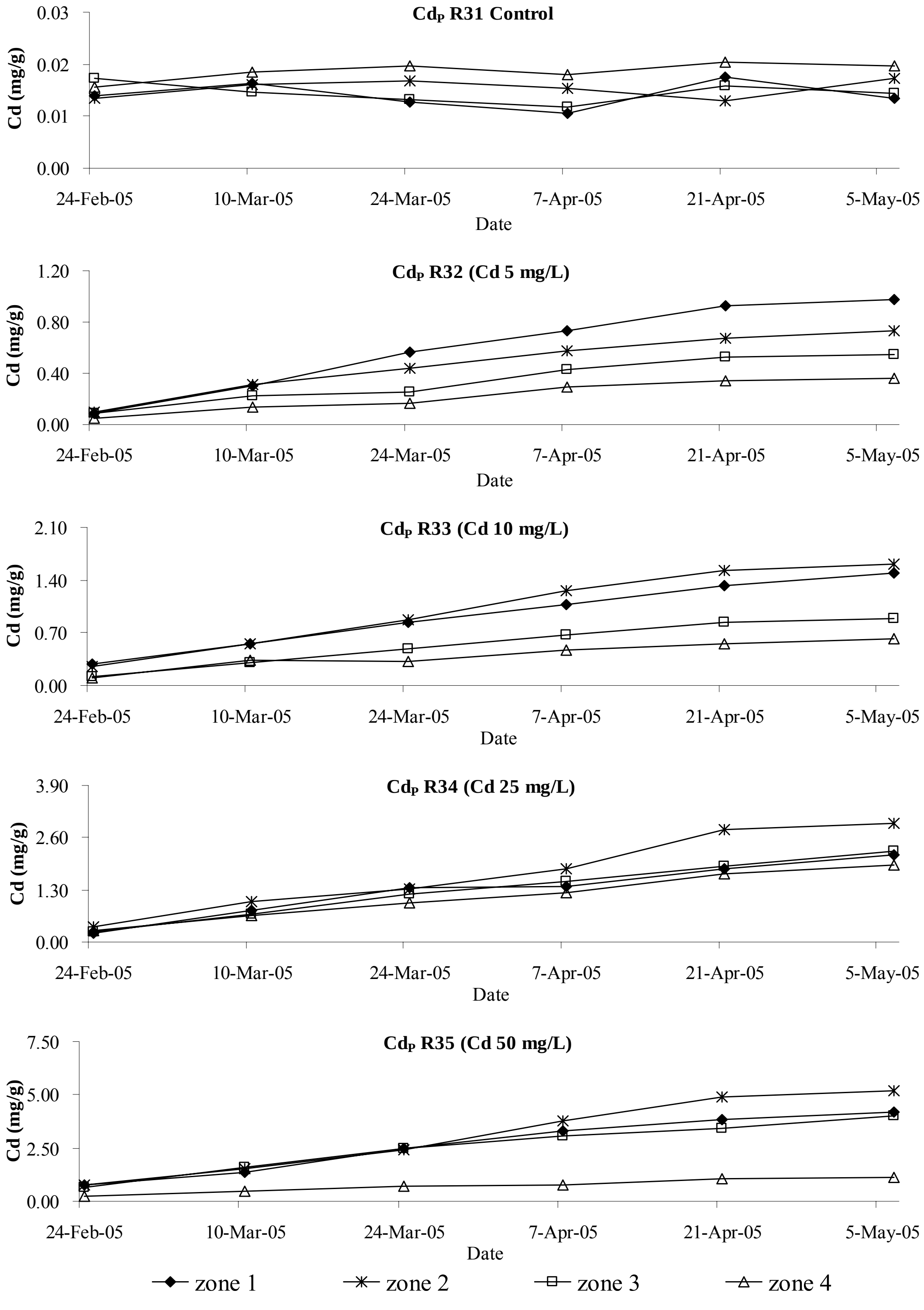


Figure 4.23 The accumulation of Cd in stems during Run III.

Table 4.4 The cadmium uptake in bulrush (*Cyperus corymbosus* Rottb.) plants at the end of each run.

Run	Reactors	Roots (mg/kg)	Stems (mg/kg)	Total (mg/kg)
I	R1	21.00	17.00	38.00
	R2	1,795.25	1,162.00	2,957.25
	R3	4,207.75	2,096.25	6,304.00
	R4	7,868.50	4,232.75	12,101.25
	R5	10,380.50	5,594.25	15,974.75
II	R1	36.50	17.00	53.50
	R2	1,274.25	611.50	1,885.75
	R3	1,422.00	1,158.25	2,580.25
	R4	5,223.00	3,065.50	8,288.50
	R5	8,225.75	5,383.50	13,609.25
III	R1	33.25	16.00	49.25
	R2	881.00	652.25	1,533.25
	R3	1,496.75	1,154.75	2,651.50
	R4	4,102.50	2,331.00	6,433.50
	R5	5,787.25	3,627.00	9,414.25

In general heavy metals are toxic, therefore the uptake and storage is very well regulated. However, the uptake mechanism is not very selective for each metal species. As a consequence, plants will take up substantial amounts of very toxic heavy metals when growing on soil containing elevated concentrations of these metals (Mortal, 2006).

Table 4.5 shows the mass density and moisture content of bulrush plants in the three experimental runs. It can be seen that the yield for bulrush plants in FWS wetland increased with cadmium concentration during the three experimental runs.

Table 4.5 Mass density and moisture content of bulrush (*Cyperus corymbosus* Rottb.) plants in three experimental runs.

Run	Reactors	Wet Weight (kg/m^2)	Dry Weight (kg/m^2)	Moisture (%)
I	R2	45.93	7.36	83.97
	R3	47.44	8.23	82.66
	R4	53.86	8.21	84.75
	R5	71.58	10.82	84.88
II	R2	48.15	6.14	87.25
	R3	45.29	6.64	85.34
	R4	51.72	7.05	86.37
	R5	74.54	10.17	86.36
III	R2	40.03	4.93	87.69
	R3	50.97	6.51	87.23
	R4	50.86	7.29	85.66
	R5	73.05	9.75	86.66

Cadmium accumulations in roots and stems of the bulrush plants until the end of each experimental run are shown in Figure 4.24 (Tables C.14-C.16 in Appendix C). It can be seen that total Cd accumulation in the stems was higher than in the roots for all four wetland units. It should also be noted that the cadmium concentration in the roots (mg/g) was found to be higher than in the stems. However, as the dry weight of the roots of bulrushes was only 25% of the stems, the actual mass accumulation of Cd in stems was higher than in the roots.

It can be seen in Figure 4.24 that, during all the runs, cadmium accumulations in stems and roots were higher at high influent loadings. However, the cadmium accumulations in stems and roots at higher HRT (lower loading for each concentration) decreased, as compared to those at lower HRT (higher loadings). This could be explained as follows:

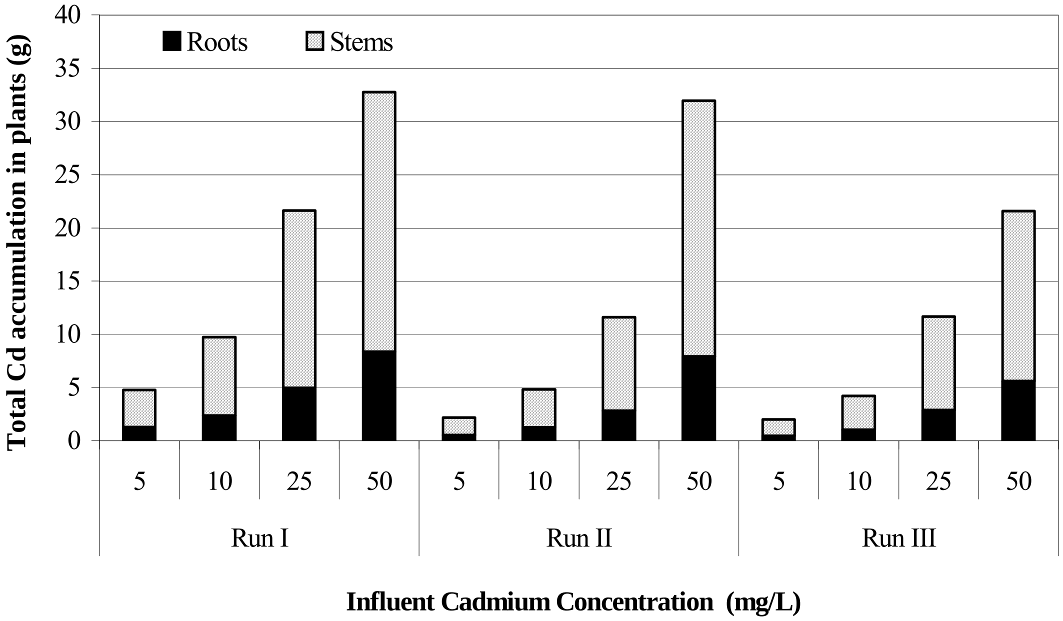


Figure 4.24 Total cadmium accumulation in roots and stems of plants in FWS wetland system at the end of each experimental run.

$$\text{Cd Loading (mg/d)} = \text{Flow rate, Q (m}^3\text{/d)} \times \text{Cd Conc.(mg/L)}$$

$$= \frac{\text{Volume (m}^3\text{)} \times \text{Cd Conc.(mg/L)}}{\text{HRT (d)}}$$

Thus, for the same Cd concentration, at higher HRT, the Cd loading should have decreased and so decreasing the availability of Cd for accumulation.

4.2.11 Cadmium Mass Balance

The overall performance of the FWS wetlands in terms of Cd removal was very good. Most of the cadmium was accumulated in soil (56-76% of total influent cadmium). Of the total cadmium uptakes, about 14 to 23% of the total cadmium intake was accumulated in bulrush plants. Both, the soil and plants were the sinks for the accumulation of cadmium. Cadmium was sorbed by the soil bed and plant uptake. Cadmium adsorption could also have occurred in wetland systems. The total amount of accumulated cadmium in each component of wetlands during the experimental period could be determined. The mass balance of cadmium for 82 days in the FWS constructed wetland can be shown by equation below.

$$\mathrm{Cd}_{\mathrm{inf}} = \mathrm{Cd}_{\mathrm{eff}} + \mathrm{Cd}_{\mathrm{soil}} + \mathrm{Cd}_{\mathrm{plants}} + \mathrm{Cd}_{\mathrm{others}}$$

The mass balance of cadmium in FWS constructed wetland shows some of cadmium lost in the system. This loss could be accounted by the remaining wastewater within the wetlands that had cadmium. Some of the cadmium was precipitated and settled down at the bottom of reactor, as well as some stuck to the reactor walls. The decayed plants could be the other sink of cadmium removed from wastewater.

The mass balance of cadmium in percent fraction during each experimental run shown in Figure 4.25. Table C.17 in Appendix C shows the cadmium mass balance in mass fraction and percent fraction during each experimental run. Relative to the total intake, the cadmium present in the effluents was in the range of 18.1-25.5%, 9.1-13.2%, and 3.5-7.4% in Runs I, II, and III, respectively. The maximum cadmium removal occurred through the accumulation in the soil with mass fraction values of 56.3-57.9%, 63.9-74.8%, and 69.9-75.5% for HRT = 5, 7, and 10 d, respectively. The Cd lost via other sinks ranged between 1.5-1.6%, 1.7-1.9%, and 2.1-2.3% of total cadmium uptake in Runs I, II, and III, respectively. Mass fraction of cadmium, accumulated in plants, ranged between 15.4 and 22.9, 14.4 and 21.1, and 18.9 and 21.9%, during Run I, Run II, and Run III, respectively.

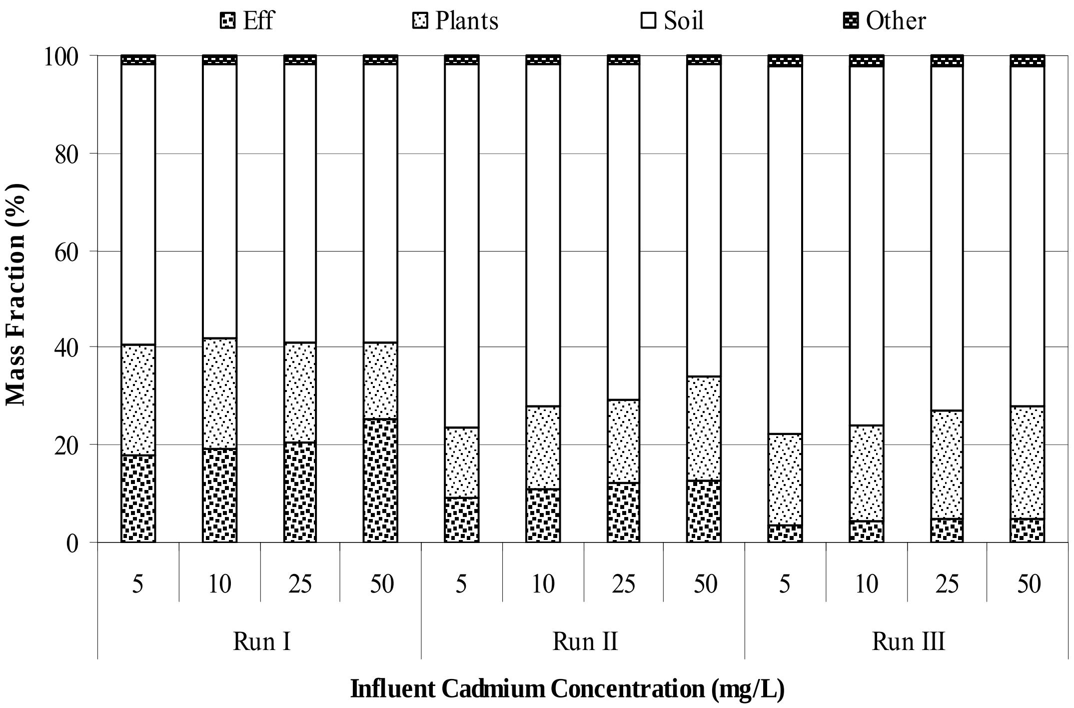


Figure 4.25 Cadmium mass balance in percent fraction during each experimental run.

The mass concentration was maximum in soil because cadmium must have been transported from water to sediments or biota or suspended solids. In sediments heavy metals are adsorbed to clay and organic matter by electrostatic attraction (Patrick et al., 1990). For chemicals such as heavy metals, more than 50% can easily be adsorbed onto particulate matter in the wetland and thus be removed from the water component by sedimentation (Muller, 1988). In permanently anoxic water conditions, decomposition of organic matter is by reduction and organic matter accumulates on the sediment surface. The resulting organic sediment surface is also responsible for scavenging heavy metals from influent wastewater (Matagi et al., 1998). Plants also intercept and uptake metals, mostly in the roots, but also in the stems, leaves and rhizomes. Upon roots death, some portion of the metals may be permanently buried in the sediments (Kadlec and Knight, 1996).

CHAPTER V

MATHEMATICAL MODELING OF CADMIUM REMOVAL IN WETLANDS

5.1 Model Development for Cadmium Removal in FWS Constructed Wetland

5.1.1 Conceptual Model

The conceptual model for cadmium removal in FWS constructed wetland is shown in Figure 5.1. The wetland is divided into four compartments along the reactor length; 1, 2, 3 and 4. Each compartment representing 1/4 of the reactor had Cd removal in three components of wetlands: plants, wastewater, and soil. The Cd present in the three components of wetland was expressed by three variables; cadmium in plants (Cdp), cadmium in wastewater (Cdww), and cadmium in soil (Cds).

5.1.2 Operating Conditions

The flow rate was adjusted daily to secure the correct flow. Wastewater samples were collected twice a week from the inlet and outlet. At every two weeks intervals, the samples of wastewater and top soil at 5 sampling points (including inlet and outlet) along the reactor length of the wetland, and four samples of stems, one each from four compartments were taken. At the end of each run, soil samples were taken at the five locations along the lengths and at the depths of 0, 15,

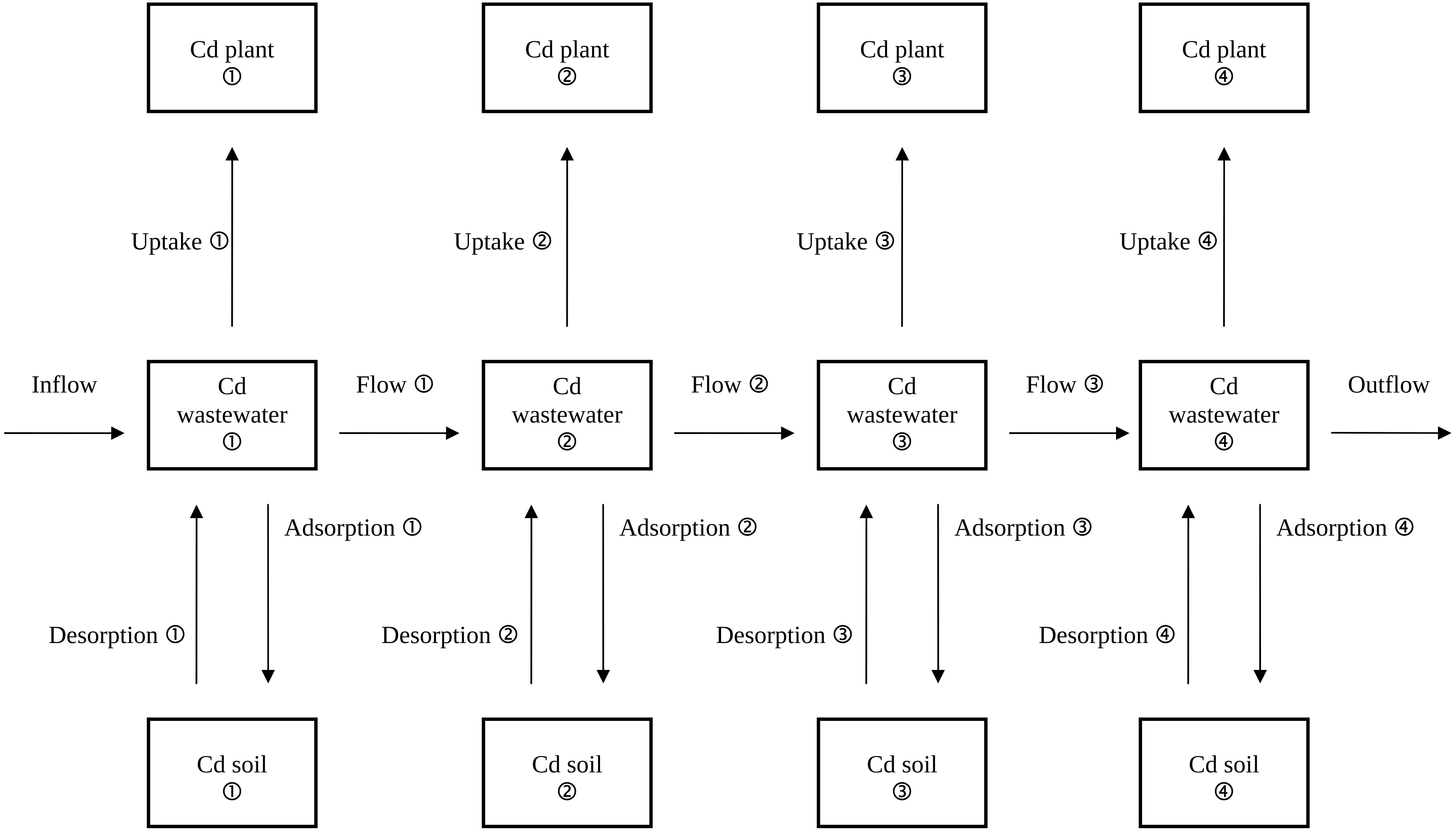


Figure 5.1 General conceptual model of cadmium removal in FWS constructed wetland.

30 and 45 cm from the top of the soil bed. The plants' samples, both roots and stems, one each from the four compartments were also collected. All samples were analyzed for Cd concentration by flame atomic adsorption spectrometry (FAAS).

The concentrations of cadmium initially present in the soil bed were measured in the four compartments. These initial values were multiplied by the volume of soil in the compartment (one-fourth of the wetland) to obtain the amount of Cd accumulation in milligrams (mg). Similar approach was applied to obtain the mass concentrations of cadmium in plants and wastewater.

5.1.3 General Parameters for Cadmium Removal Model

Flow diagram of cadmium removal in FWS constructed wetland using STELLA simulation program is presented in Figure 5.2. The details of model equation and explanation to names used in cadmium removal model are shown in Appendix G (Tables G.1-G.2). For these parameters, the suffix 1, 2, 3, and 4 were used for the first, second, third, and fourth compartment, respectively. The parameters used in cadmium removal model in this study are shown in Table 5.1.

Table 5.1 General parameters for cadmium removal model in FWS constructed wetlands.

Parameter	Value	Source
Bulk density of soil	1210 kgdw/m^3	Measured
Total volume of soil in each reactor	0.375 m^3	Measured
Dry weight of soil per one-fourth of reactor (Ms)	113.44 kgdw	Calculated
Volume of wastewater per one-fourth of reactor (V_{water})	64.69 L	Calculated

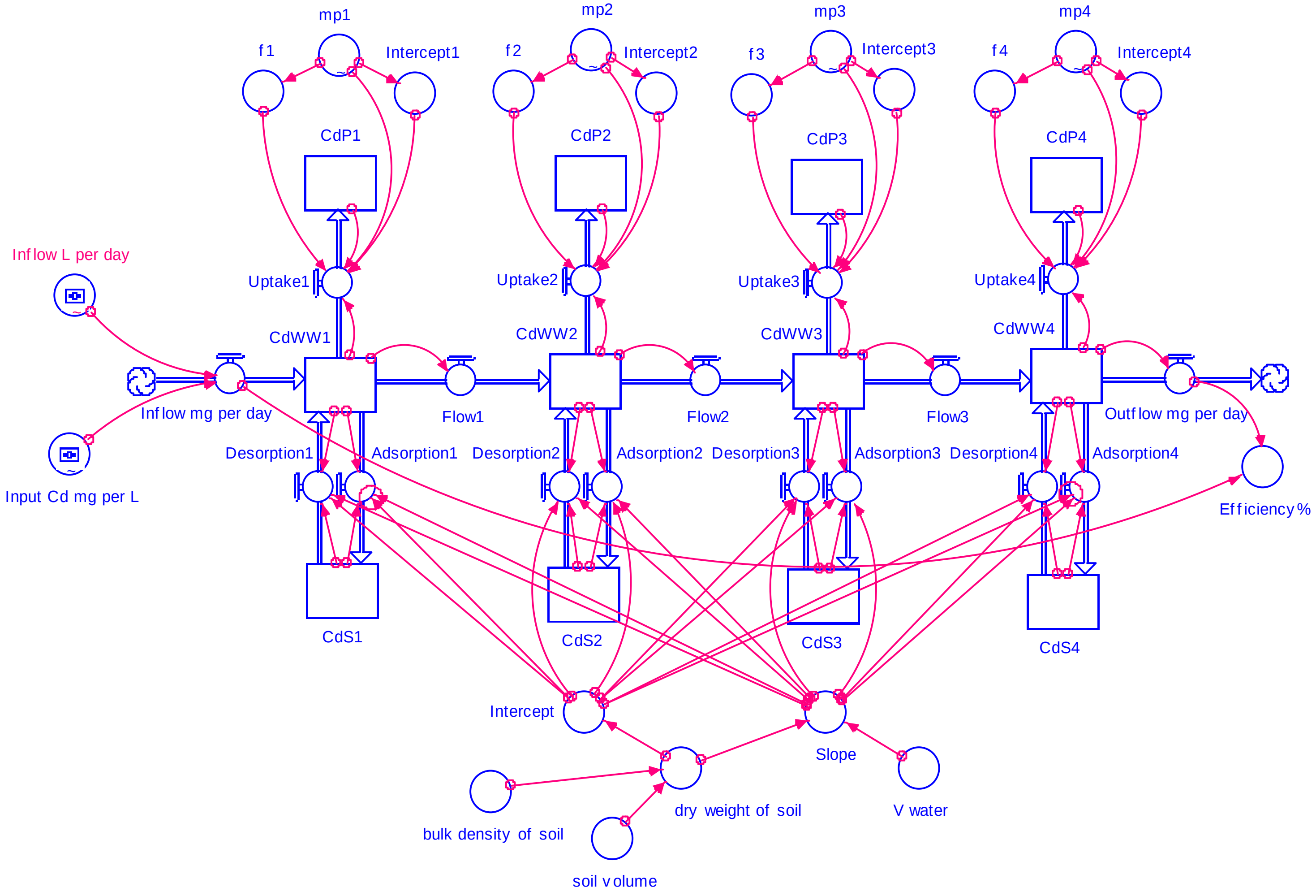


Figure 5.2 Flow diagram of cadmium removal in FWS constructed wetland using STELLA simulation program.

5.2 Model Equations of Cadmium Removal in FWS Constructed Wetlands

Mathematical models describe the relationship between the model components, using specific mathematical expressions. The mathematical equations are used to present the biological, chemical and physical processes occurring in the system of interest. The relation between the state variables and forcing functions can readily be depicted by using mathematical equations.

5.2.1 Equations of Cadmium Removal in Soil

Adsorption Equation in Soil

A simplified Freundlich equation, shown in Eq. 5.1, had a better correlation than both the Freundlich and Langmuir isotherms used individually. This equation was chosen to describe the adsorption process in the FWS constructed wetland.

$$\mathrm{Cds} = K\,\mathrm{Cdww} + \mathrm{b} \qquad (5.1)$$

Where, K = Adsorption coefficient (slope)

b = a constant (intercept)

From Eq. 5.1, the relationship between Cd accumulation in soil (Cds) and Cd concentration in wastewater (Cdww) in four reactors during three runs were obtained as shown in Figure 5.3 and Appendix F (Table F.1).

From the results of regression analysis, the following equation was obtained to express the correlation between Cds (mg/kgdw) and Cdww (mg/L):

$$\text{Cds(mg/kgdw)} = 3.678\text{(L/kgdw) Cdww(mg/L)} + 17.621\text{(mg/kgdw)}, \qquad R^2 = 0.5324 \qquad (5.2)$$

Eq. 5.2 may be multiplied by Ms (kgdw), which is dry weight of soil (bulk density of soil, kgdw/m^3 × soil volume, m^3), as follows:

$$\text{Cds(mg)} = \frac{3.678\text{(L/kgdw) Ms(kgdw)}}{\text{Vwater(L)}}\text{Cdww(mg)} + 17.621\text{(mg/kgdw) Ms(kgdw)} \qquad (5.3)$$

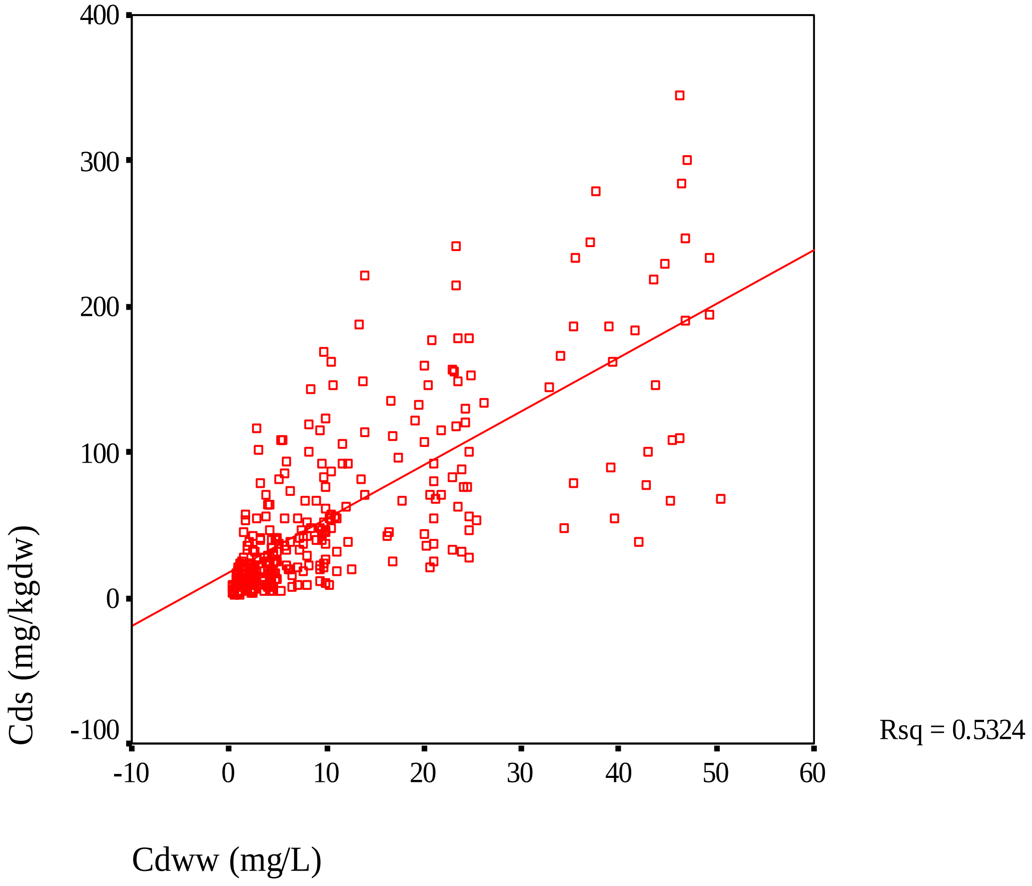


Figure 5.3 Relationship between Cds and Cdww in FWS constructed wetlands during three experimental runs.

The resulting equation for each compartment is shown as below:

$$\text{Cds(mg)} = \frac{3.678\text{(L/kgdw) Ms/4 (kgdw)}}{\text{Vwater/4 (L)}}\ \text{Cdww(mg)} + \frac{17.621\text{(mg/kgdw) Ms(kgdw)}}{4} \tag{5.4}$$

$$\text{Slope} = \frac{3.678\text{(L/kgdw) Ms(kgdw)}}{\text{Vwater(L)}} \tag{5.5}$$

$$\text{Intercept} = \frac{17.621\text{(mg/kgdw) Ms(kgdw)}}{4} \tag{5.6}$$

Model Equations used in STELLA Simulation Program

After setting up the model in a flow diagram form (Figure 5.2), STELLA program automatically converted the graphical representation to the basic equations. Subsequently, the input data were filled up in the basic equations to obtain model equations. Finally, the simulation could be started.

Details of model equations used in STELLA program are shown in Appendix G (Tables G.1-G.2). The basic model equation for cadmium in soil was transformed from flow diagram as follows:

$$\text{CdS(t)} = \text{CdS(t – dt)} + \text{(Adsorption – Desorption)*dt}$$

$$\text{INIT CdS} = \frac{0.32\text{mg/kgdw} \times \text{dry weight of soil } (1{,}210\text{kgdw/m}^3 \times 0.375\text{m}^3)}{4}$$

Where, t = the current simulation time

dt = the time interval between calculations (iteration step)

The adsorption is in equilibrium with the desorption; thus, the above expression can be used to describe both processes. The adsorption is described by the following expression:

INFLOWS:

Adsorption = IF(Cds < slope × Cdww + intercept)
THEN(slope × Cdww + intercept – Cds) ELSE(0)

The term Cds subtracted represents the Cd already present in soil upto that time and a difference is being added to the soil. The expression states that if the concentration in soil is less than the equilibrium concentration, adsorption will occur. Using the same expression, desorption is described as:

OUTFLOWS:

Desorption = IF(Cds > slope × Cdww + intercept)
THEN((Cds – intercept) / slope – Cdww) ELSE(0)

The term Cdww subtracted represents the Cd already present in wastewater upto that time and a difference is being added to the wastewater. The concentration in soil has to be larger than the equilibrium concentration for desorption to occur.

5.2.2 Equations of Cadmium Removal by Plants

Uptake by Plants

Initial plant biomass was measured at the beginning of each run. The average value of initial plant biomass was found to be 0.563 kgdw/m^2. Thus, each compartment of the reactor (1/4 of wetland) had an initial plant biomass of 0.1408 kgdw. The mean growth rate (average of three runs) of the bulrush (*Cyperus corymbosus* Rottb.) in the wetlands were observed to be 0.00294 kgdw/d in the first compartment, 0.00586 kgdw/d in the second compartment, 0.00710 kgdw/d in the third compartment and 0.00588 kgdw/d in the last compartment. Assuming a linear growth, these growth rate values were added to the mass of plants each day, with the resulting values inserted into the model.

The plants uptake is described by the following equation (Kayombo et. al, 2004):

$$Cdp = f \times Cdww \times mp + c \tag{5.7}$$

Where, f = a multiplication factor (slope)

mp = the dry weight of plants, kgdw

c = a constant (intercept)

The relationship between Cd uptake by plants (Cdp) and Cd concentration in wastewater (Cdww) were obtained by regression analysis after multiplying Eq. (5.7) with dry weight of plants (mp) in four reactors during three runs, as shown in Figure 5.4 and Appendix F (Table F.2).

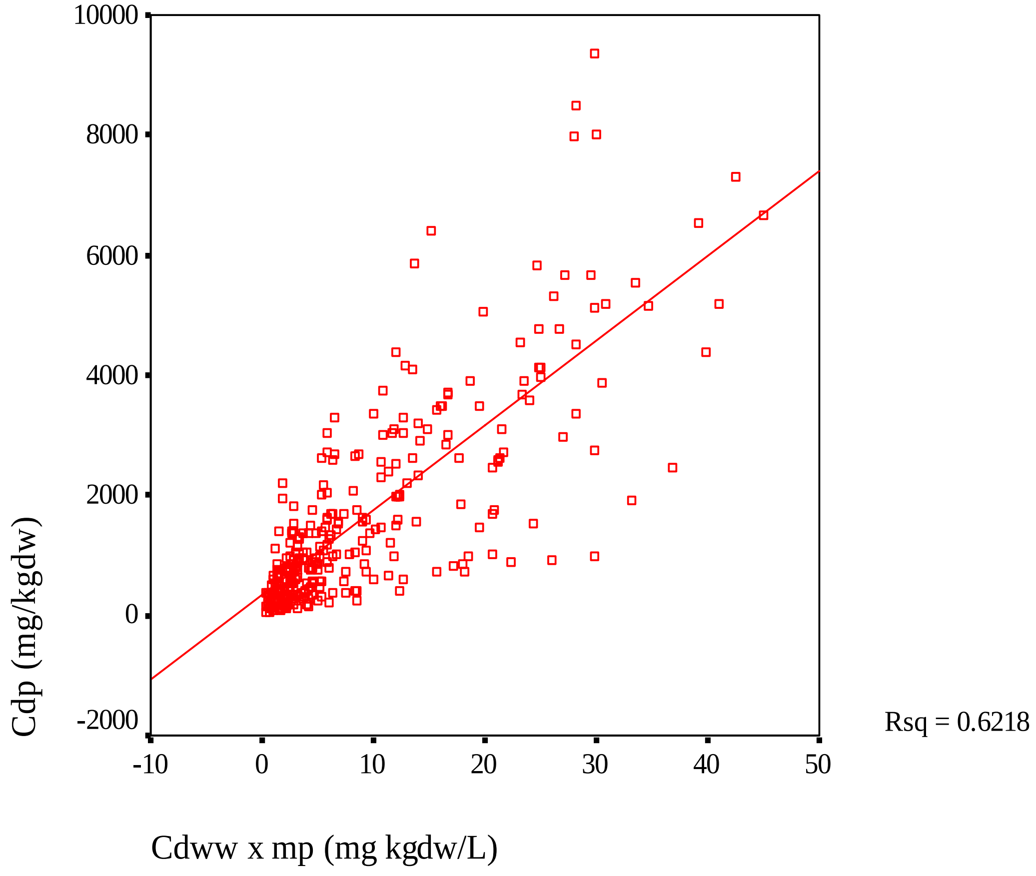


Figure 5.4 Relationship between Cdp and Cdww × mp in FWS constructed wetlands during three experimental runs.

Value of “f” was determined from the correlation between Cdp (mg/kgdw) and Cdww × mp (mg×kgdw/L) as follows:

$$\text{Cdp(mg/kgdw)} = 140.801(\text{L/kgdw}^2)\ \text{Cdww} \times \text{mp(mg}\times\text{kgdw/L)} + 346.813(\text{mg/kgdw}), \qquad R^2 = 0.6218 \tag{5.8}$$

Eq. 5.8 may be multiplied by mp (kgdw) to obtain the equation for each compartment as shown below:

$$\text{Cdp}_{1\text{-}4}(\text{mg}) = \frac{140.801(\text{L/kgdw}^2)\,[\text{mp}_{1\text{-}4}(\text{kgdw})]^2}{\text{Vwater(L)}}\ \text{Cdww(mg)} + 346.813(\text{mg/kgdw})\ \text{mp}_{1\text{-}4}(\text{kgdw}) \qquad (5.9)$$

$$f_{1\text{-}4} = \frac{140.801(\text{L/kgdw}^2)\ \text{mp}_{1\text{-}4}(\text{kgdw})}{\text{Vwater(L)}} \qquad (5.10)$$

$$\text{Intercept} = 346.813(\text{mg/kgdw})\ \text{mp}_{1\text{-}4}(\text{kgdw}) \qquad (5.11)$$

Where, $p_{1\text{-}4}$, $f_{1\text{-}4}$, and $mp_{1\text{-}4}$ represent the values for the four compartments (1-4).

Model Equations used in STELLA Simulation Program

Details of model equations used in STELLA program are shown in Appendix G (Tables G.1-G.2). The basic equation of the model for cadmium removal by plants uptake was transformed from flow diagram as follows:

Cdp(t) = Cdp(t – dt) + (Uptake1)*dt

INIT Cdp = 16.988(mg/kg dw) × mp(kgdw)

INFLOWS:

Uptake = ((f × mp × Cdww) + Intercept – Cdp)

The term Cdp subtracted represents the Cd already present in plants upto that time and a difference is being added to the plants.

5.2.3 Model Equations of Outflow

The initial values for Cd in wastewater in 4 compartments ($Cdww_{1-4}$) were measured at five sampling points in the wetlands, and were multiplied by the volume of water in the compartment (one-fourth of the wetland).

Model Equations used in STELLA Simulation Program

The basic equation of the model for instantaneous cadmium concentration in wastewater at time “t” for each compartment was transformed from flow diagram as follows (mass balance):

$$\text{Cdww}(t) = \text{Cdww}(t - dt) + (\text{Inflow, mg/d} + \text{Desorption} - \text{Uptake} - \text{Adsorption} - \text{Outflow, mg/d}) * dt$$

$$\text{INIT Cdww} = 0.2 \times V_{water}$$

INFLOWS:

$$\text{Inflow, mg/d} = (\text{Inflow, L/d}) \times (\text{Input Cd, mg/L})$$

$$\text{Desorption} = \text{IF}(\text{Cds} > \text{slope} \times \text{Cdww} + \text{intercept}) \; \text{THEN}((\text{Cds} - \text{intercept}) / \text{slope} - \text{Cdww}) \; \text{ELSE}(0)$$

OUTFLOWS:

$$\text{Uptake} = ((f \times mp \times \text{Cdww}) + \text{Intercept} - \text{Cdp})$$

Adsorption = IF(Cds < slope × Cdww + intercept)

THEN(slope × Cdww + intercept – Cds) ELSE(0)

Outflow, mg/d = Cdww

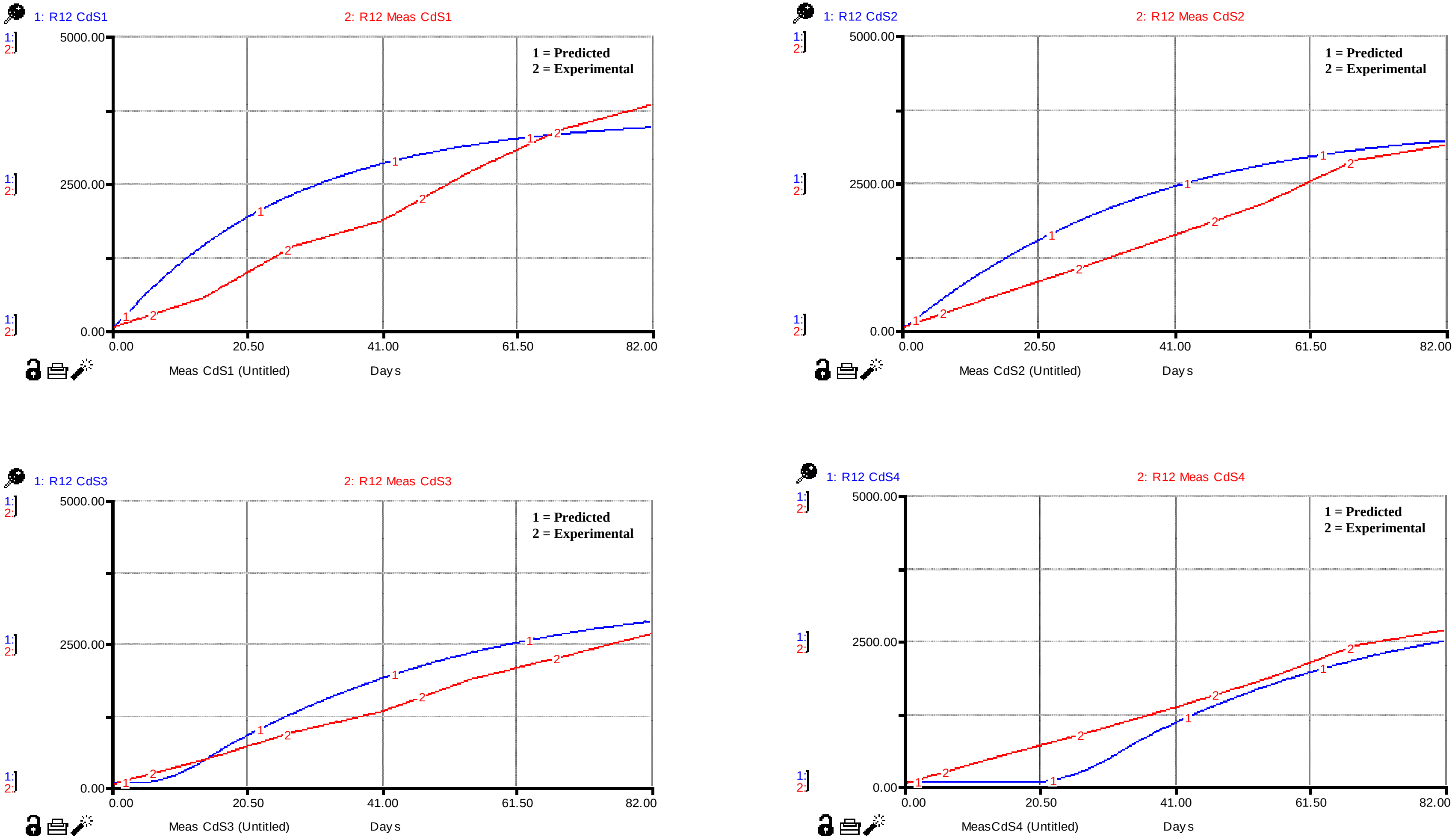
5.3 Model Calibration for Cadmium Removal in FWS Constructed Wetlands

The four simultaneous experiments in the wetland units during the three runs (Runs I-III) were designated as R11 (control), R12, R13, R14, R15; R21 (control), R22, R23, R24, R25; and R31 (control), R32, R33, R34, R35, respectively (Table 3.2).

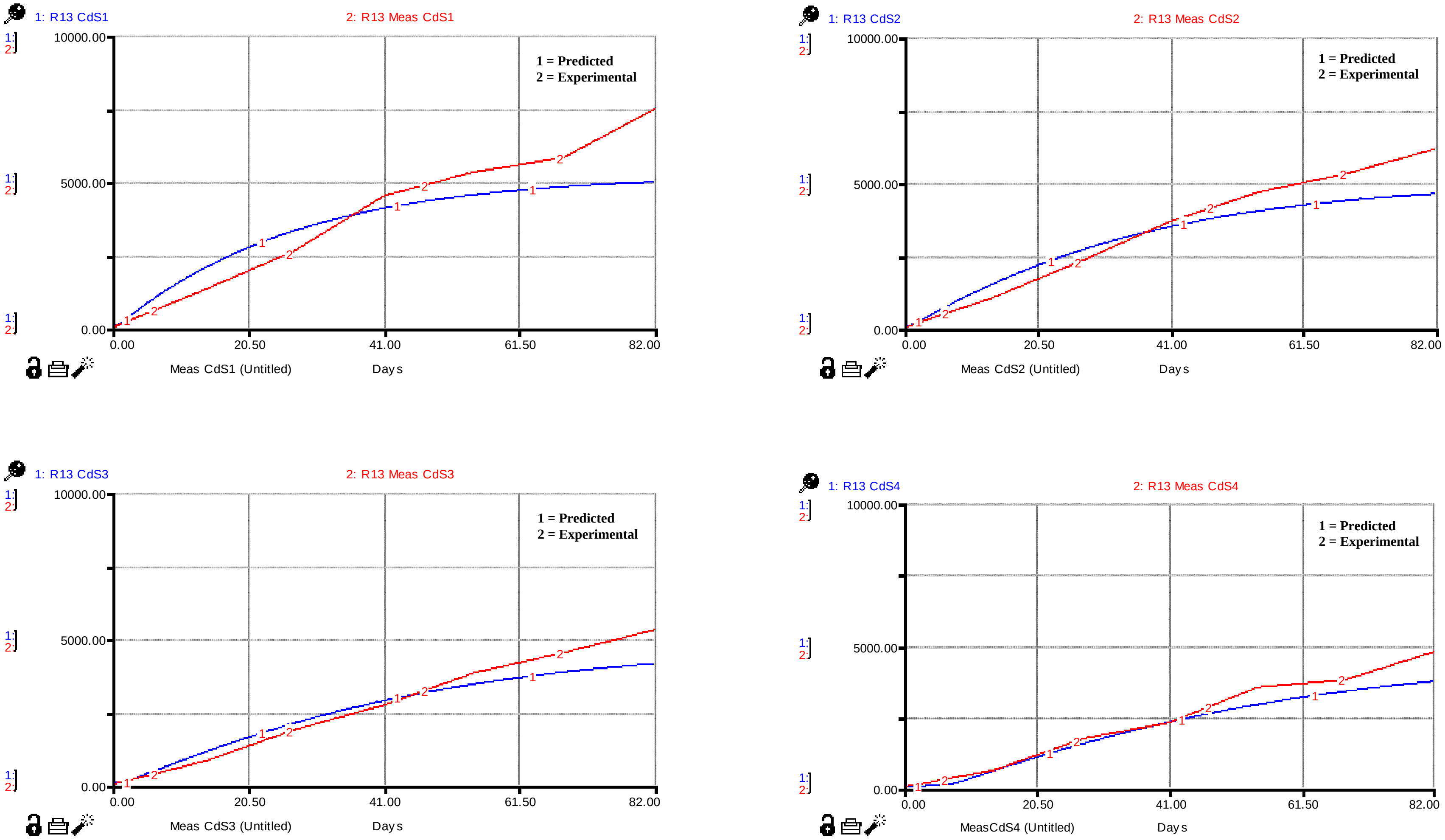
For the calibration of the developed mathematical model, the simulation program was run repeatedly, adjusting the model parameters by trial and error (within reasonable range) until its predictions under similar conditions had good agreement with the experimental data. A calibration sequence was selected, starting with the cadmium removal in soil and then uptake by plants. The model was calibrated by using the equations for Cd accumulation in soil and for plant uptake for six experiments (R12, R13, R22, R23, R32, and R33) by adjusting the parameters until a very good agreement between the predicted and the experimental values was obtained.

5.3.1 Model Calibration for Cadmium Removal by Adsorption in Soil in FWS Constructed Wetlands

Model calibrations, using the data form experiments R12 (Cd = 5 mg/L) and R13 (Cd = 10 mg/L) of the first run, are illustrated in Figures 5.5 and 5.6,



Figures 5.5 Model calibration for adsorption of Cd in the soil in four compartments of reactor R12 (mg/d).



Figures 5.6 Model calibration for adsorption of Cd in the soil in four compartments of reactor R13 (mg/d).

respectively. Calibrations for other four experiments (R22, R23, R32 and R33) are shown in Figures H.1-H.4 (Appendix H). For adsorption process, a multiplication factor of 0.05 was used in calibration as shown below:

INFLOWS:

$$Cds < 3.678 \times Cdww + 17.621$$

$$Adsorption = (3.678 \times Cdww + 17.621 - Cds)*0.05$$

The correlations between measured and simulated values of cadmium accumulation in soil for R12 and R13 are shown in Figures 5.7 and 5.8, respectively. The regression analyses of other four experiments are shown in Appendix I (Figures I.1-I.4). The slopes of the regression lines for R12 and R13 were close to 1 and 0.7, respectively, and correlations (R^2) for both were close to 0.9, which supported a good model calibration.

5.3.2 Model Calibration for Cadmium Removal by Plants Uptake in FWS Constructed Wetlands

Model calibrations, using the data form experiments R12 (Cd = 5 mg/L) and R13 (Cd = 10 mg/L) of the first run, are illustrated in Figures 5.9 and 5.10, respectively. Calibrations for other four experiments are shown in Figures H.5-H.8 (Appendix H). For plants uptake, a multiplication factor of 0.09 was used in calibration as shown below:

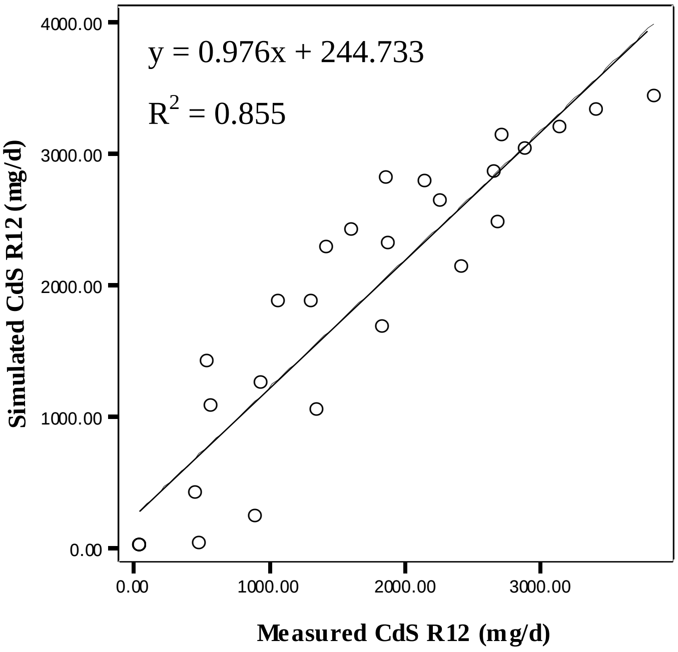


Figure 5.7 Correlation between simulated and measured cadmium accumulation in soil for R12.

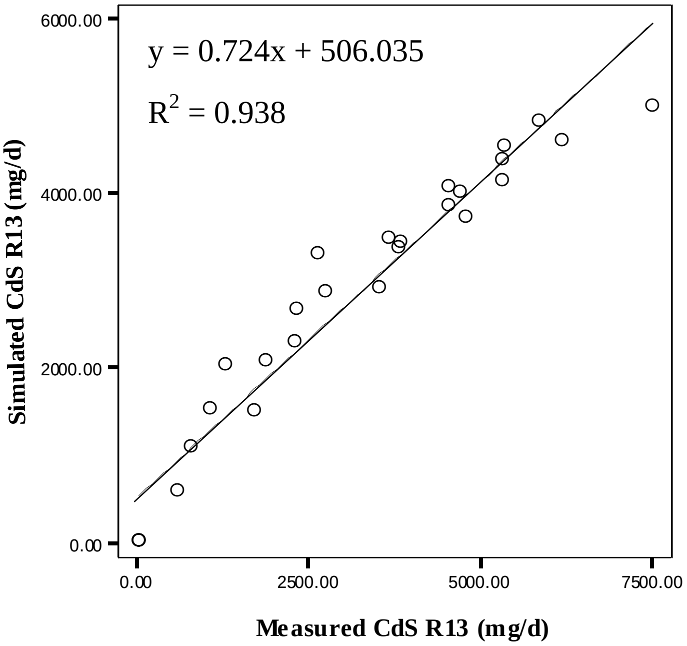
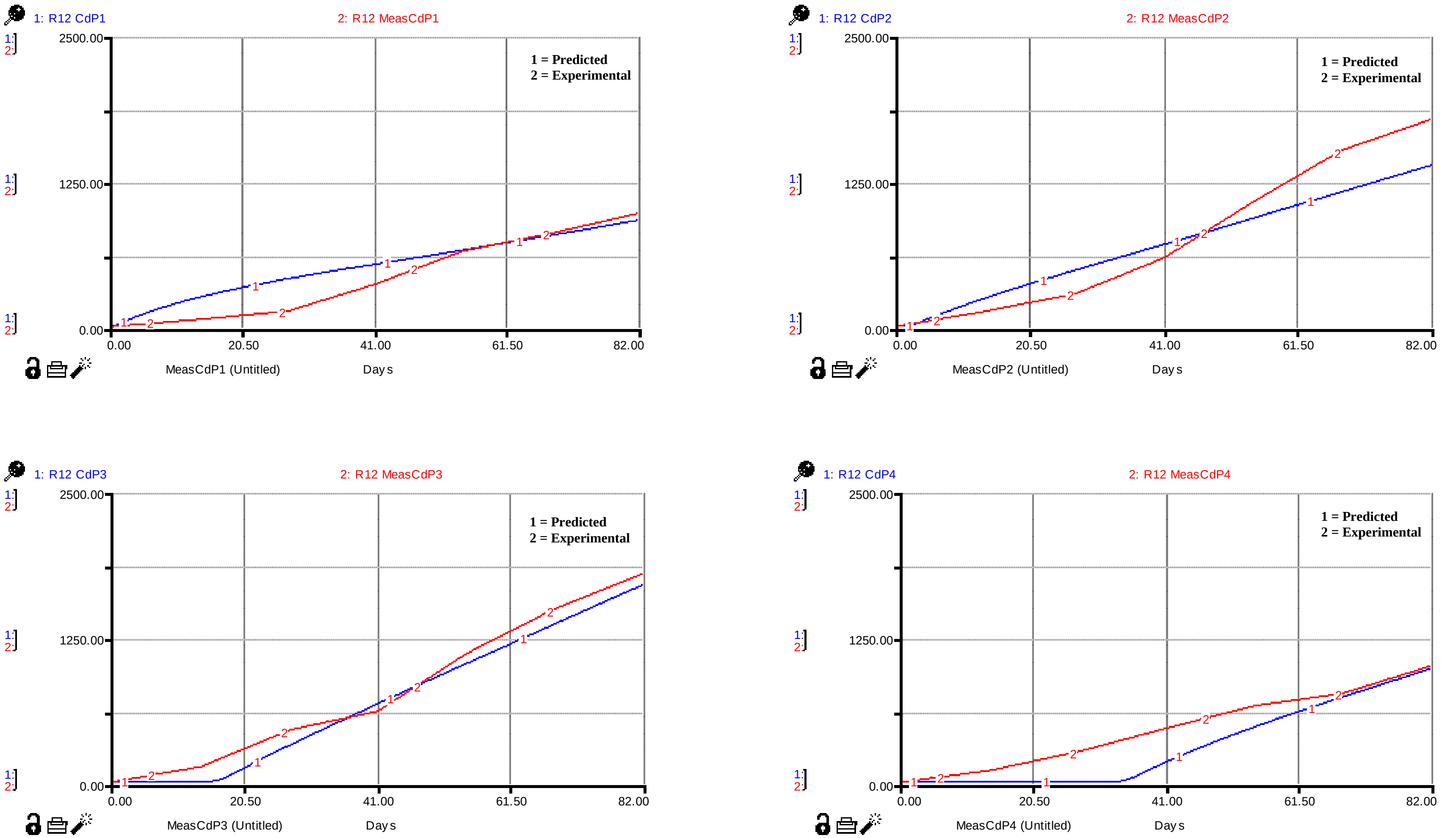
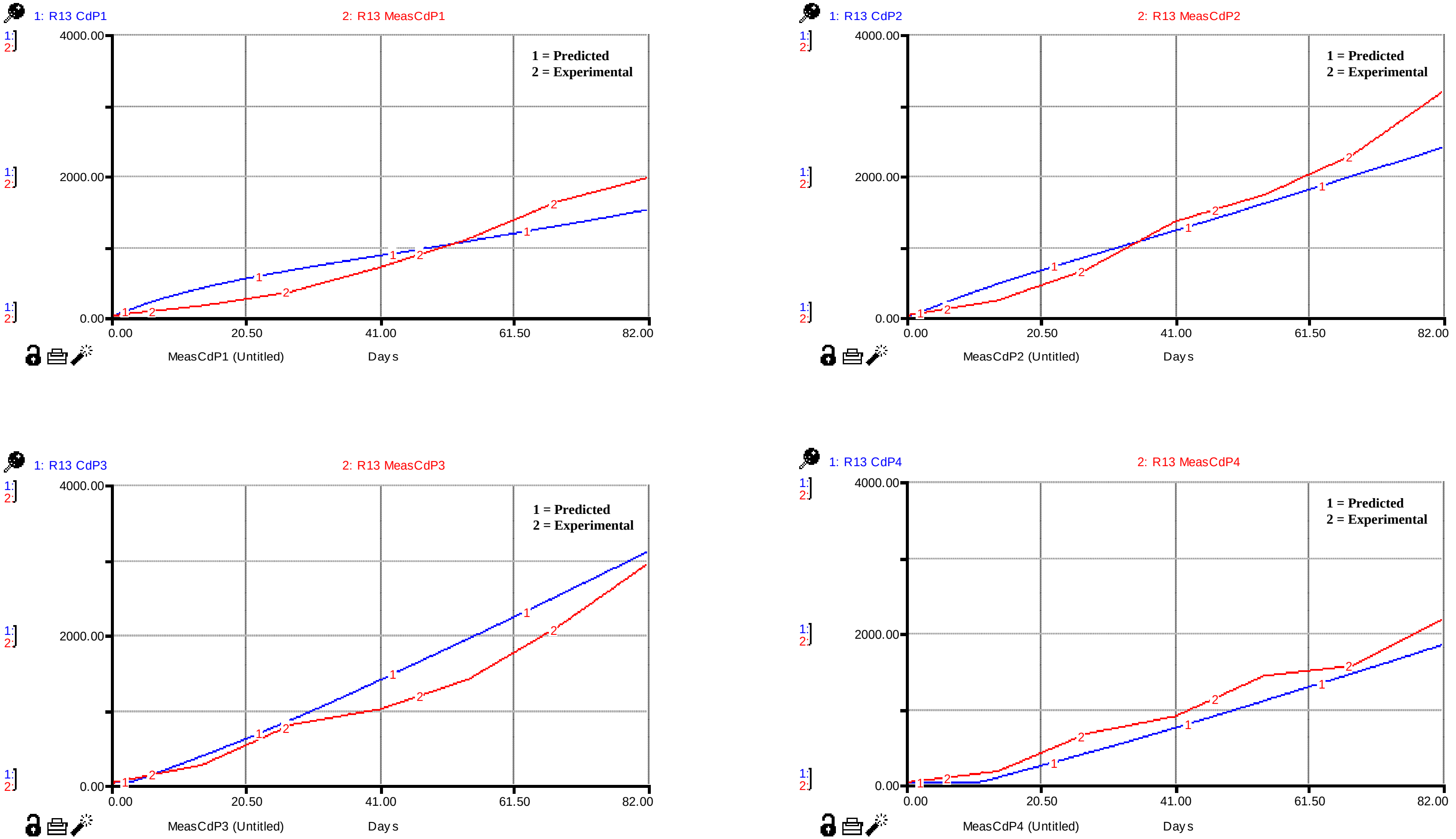


Figure 5.8 Correlation between simulated and measured cadmium accumulation in soil for R13.



Figures 5.9 Model calibration for plants uptake of Cd in four compartments of reactor R12 (mg/d).



Figures 5.10 Model calibration for plants uptake of Cd in four compartments of reactor R13 (mg/d).

INFLOWS:

$$\text{Uptake} = \left(\frac{(140.801\ \text{mp}^2 \times \text{Cdww})}{(64.6875\ \text{L})} + 346.813 - \text{Cdp}\right)*0.09$$

The correlation between measured and simulated values of cadmium removal by plants uptake for R12 is shown in Figure 5.11. The slope of the regression line for R12 was close to 0.8 and the correlation (R^2) was close to 0.9, which also supported a good model calibration.

Figure 5.12 presents the regression analysis of plants uptake for R13. The slope of the regression line and R^2 for R13 were both close to 0.9, which again supported a good model calibration. Figures I.5-I.8 in Appendix I show the regression analyses of other four experiments.

There was good agreement between the simulated and the experimental values of cadmium accumulation in soil and of plants uptake for six experiments (HRTs of 5, 7 and 10 d at cadmium concentrations of 5 and 10 mg/L) used for model calibration.

5.3.3 Comparison of Predicted and Experimental Values of Outflow (Effluent) in Model Calibration

The comparison of predicted and experimental values of outflow in model calibration for R12 and R13 are shown in Figures 5.13 and 5.14, respectively. Similar comparisons for other four experiments are shown in Figures H.9-H.12 (Appendix H).

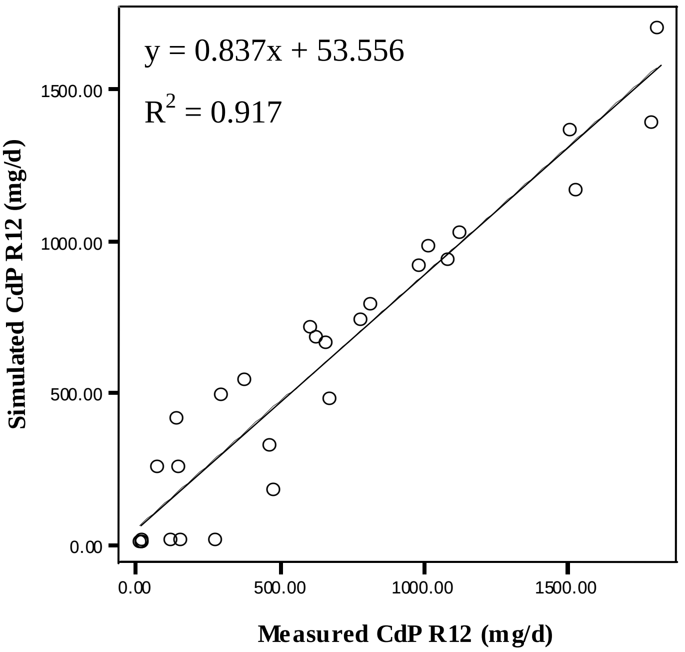


Figure 5.11 Correlation between simulated and measured cadmium removal by plants uptake for R12.

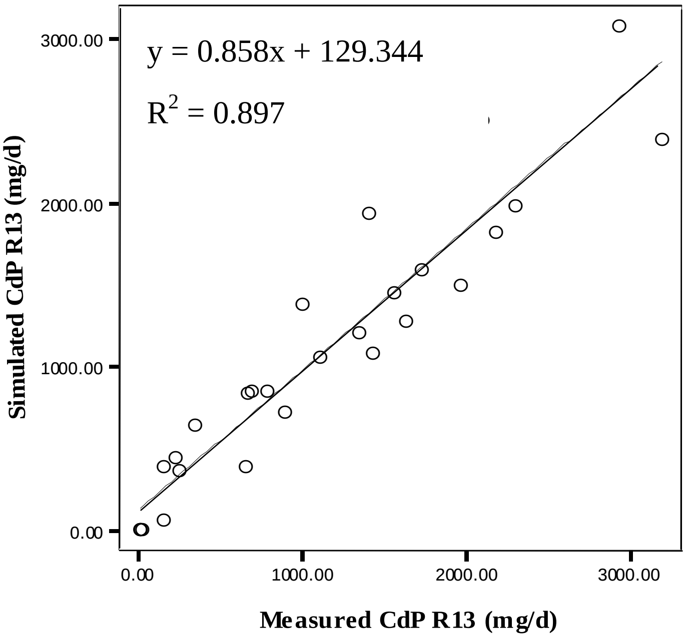


Figure 5.12 Correlation between simulated and measured cadmium removal by plants uptake for R13.

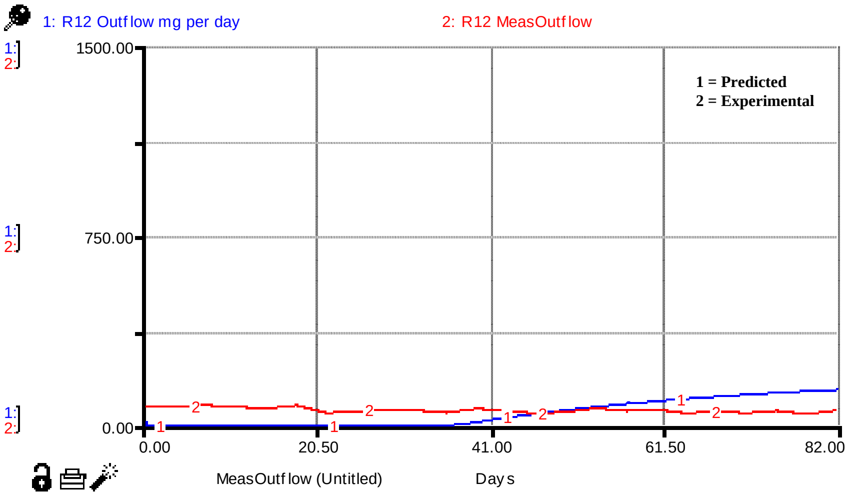


Figure 5.13 Comparison of predicted and experimental value of outflow in model calibration for R12 (mg/d).

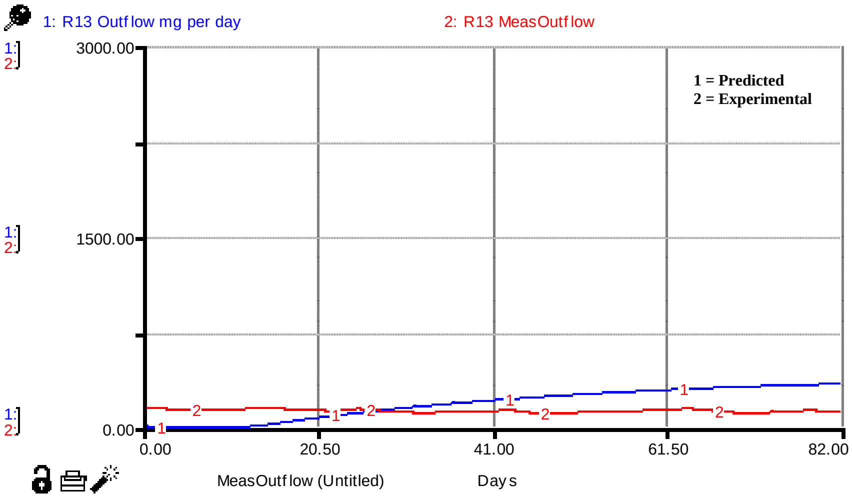


Figure 5.14 Comparison of predicted and experimental value of outflow in model calibration for R13 (mg/d).

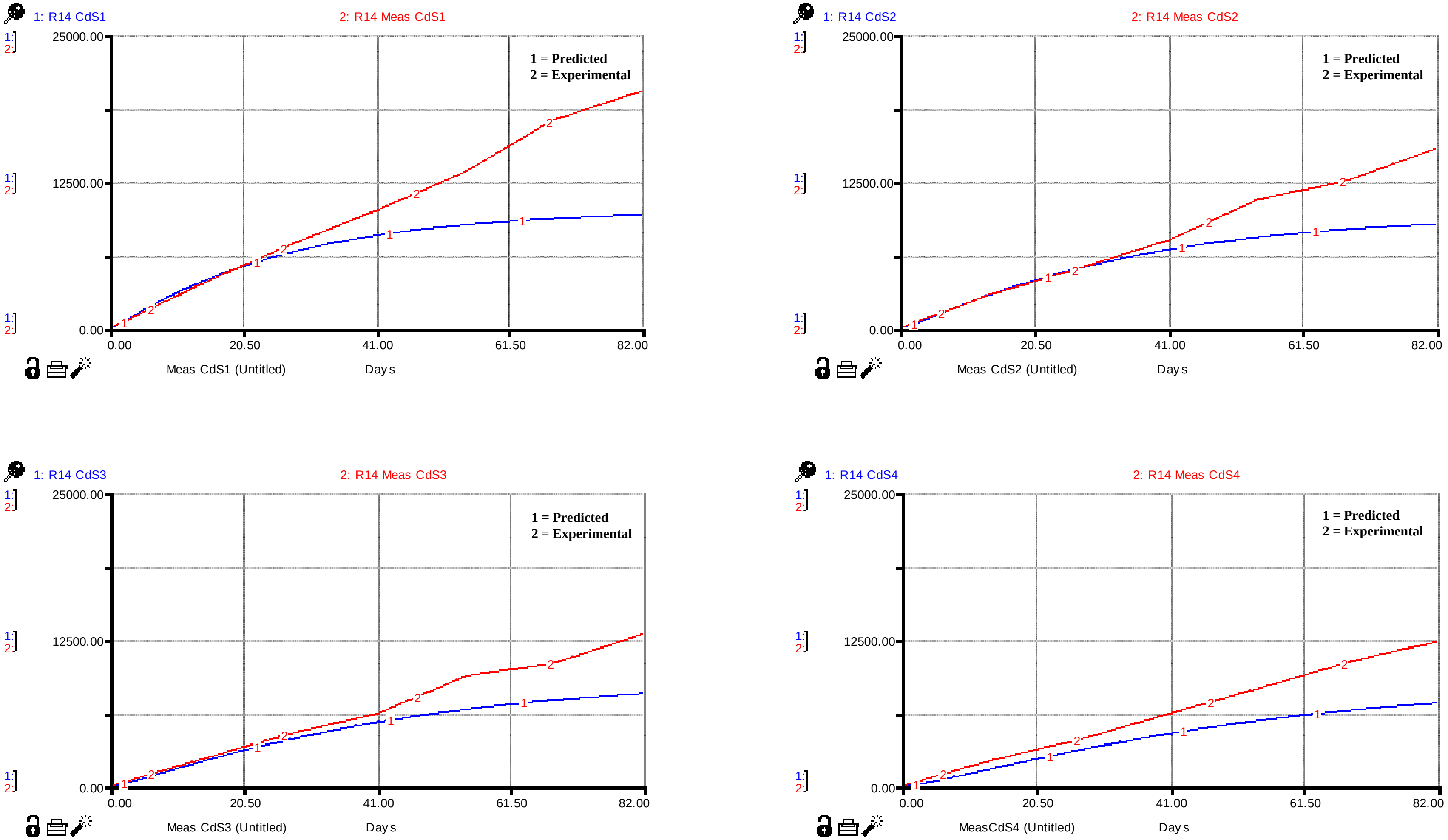
5.4 Model Validation for Cadmium Removal in FWS Constructed Wetlands

A model is used to predict (forecast) the system behavior, and then comparisons are made between the system's behavior and the model's forecast to determine if they are the same. The data may come from an operational system or from experiments performed on the system.

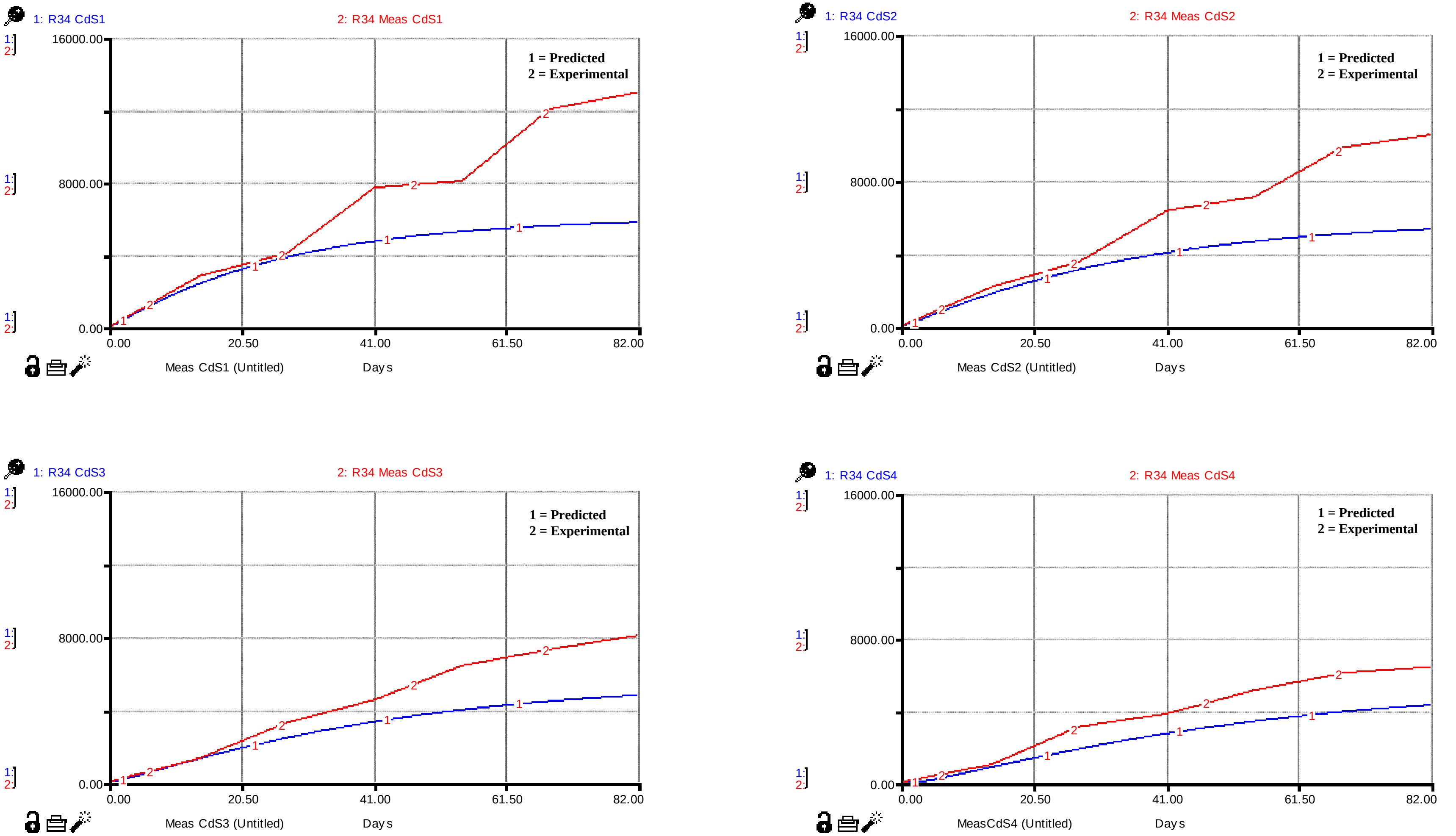
Model validation is done by running the calibrated model with a new set of data, with physical parameters and forcing functions to reflect new conditions. The Cd concentration in the inlet wastewater is an advantage for the validation process, as it puts the model to a true test of its applicability outside the range of Cd concentrations for which it was calibrated. The influent loading of Cd was also different in six experiments, which depend on influent concentration and HRT. The model is revised each time, until it is verifiably and consistently accurate. When the new model is validated, it becomes an effective predictive tool for the range of conditions defined by the original calibration and validation data set. If there is no match between predicted and real data, the model often can be analysed to determine the possible reasons for the discrepancy. The model was validated using the data from the remaining six experiments (R14, R15, R24, R25, R34 and R35) of the first, second, and third runs.

5.4.1 Model Validation for Cadmium Removal by Adsorption in Soil in FWS Constructed Wetlands

Model validations, by using the data form experiments R14 (Cd = 25 mg/L) and R34 (Cd = 25 mg/L) of the second and third run, are illustrated in Figures 5.15 and 5.16, respectively. Validations for other four experiments (R15, R24, R25,



Figures 5.15 Model validation for adsorption of Cd in the soil in four compartments of reactor R14 (mg/d).



Figures 5.16 Model validation for adsorption of Cd in the soil in four compartments of reactor R34 (mg/d).

and R35) are shown in Figures H.13-H.16 (Appendix H).

The correlations between measured and simulated values of cadmium accumulation in soil for R14 and R34 are shown in Figures 5.17 and 5.18, respectively. The regression analyses of other four experiments are shown in Appendix I (Figures I.9-I.12). The slopes of the regression lines for R14 and R34 were close to 0.5 and correlation (R^2) for both were close to 0.9, indicating a good agreement between predicted and observed values.

5.4.2 Model Validation for Cadmium Removal by Plants Uptake in FWS Constructed Wetlands

Model validations for cadmium removal by plants uptake for R14 and R34 are shown in Figures 5.19 and 5.20, respectively. Validations for other four experiments are shown in Figures H.17-H.20 (Appendix H).

The correlations between measured and simulated values of cadmium removal by plants uptake for R14 and R34 are shown in Figures 5.21 and 5.22, respectively. The regression analyses of other four experiments are shown in Appendix I (Figures I.13-I.16). For R14 and R34, the slopes of the regression lines were close to 1 and 0.8, respectively, and the correlation (R^2) for both were close 0.9, which supports a good model validation.

5.4.3 Comparison of Predicted and Experimental Values of Outflow (Effluent) in Model Validation

The comparison of predicted and experimental values of outflow in model validation for R14 and R34 are shown in Figures 5.23 and 5.24, respectively. Similar comparisons for other four experiments are shown in Figures H.21-H.24 (Appendix H).

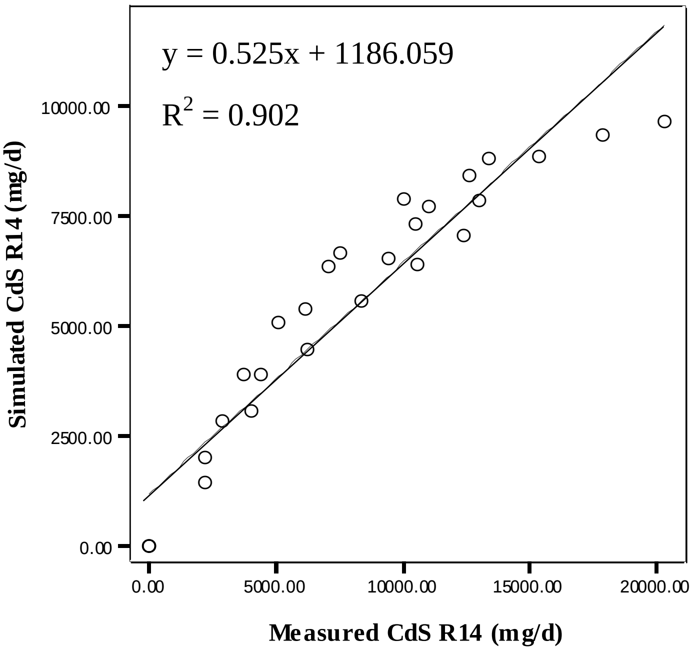


Figure 5.17 Correlation between simulated and measured cadmium accumulation in soil for R14.

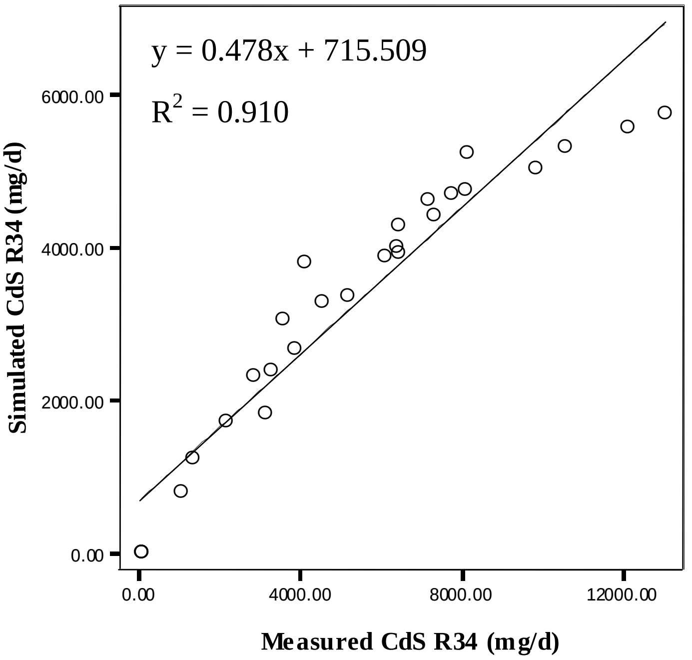
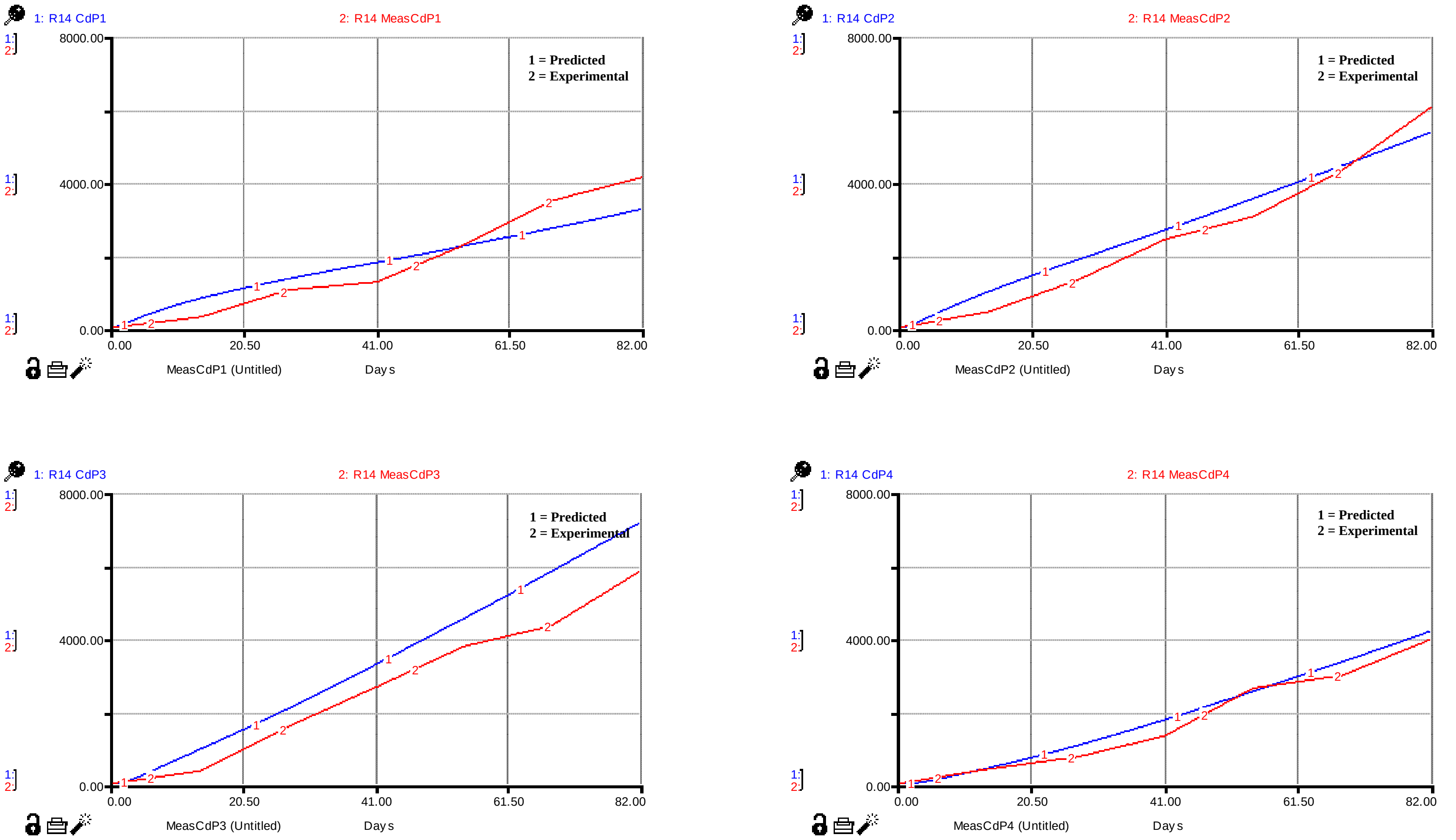
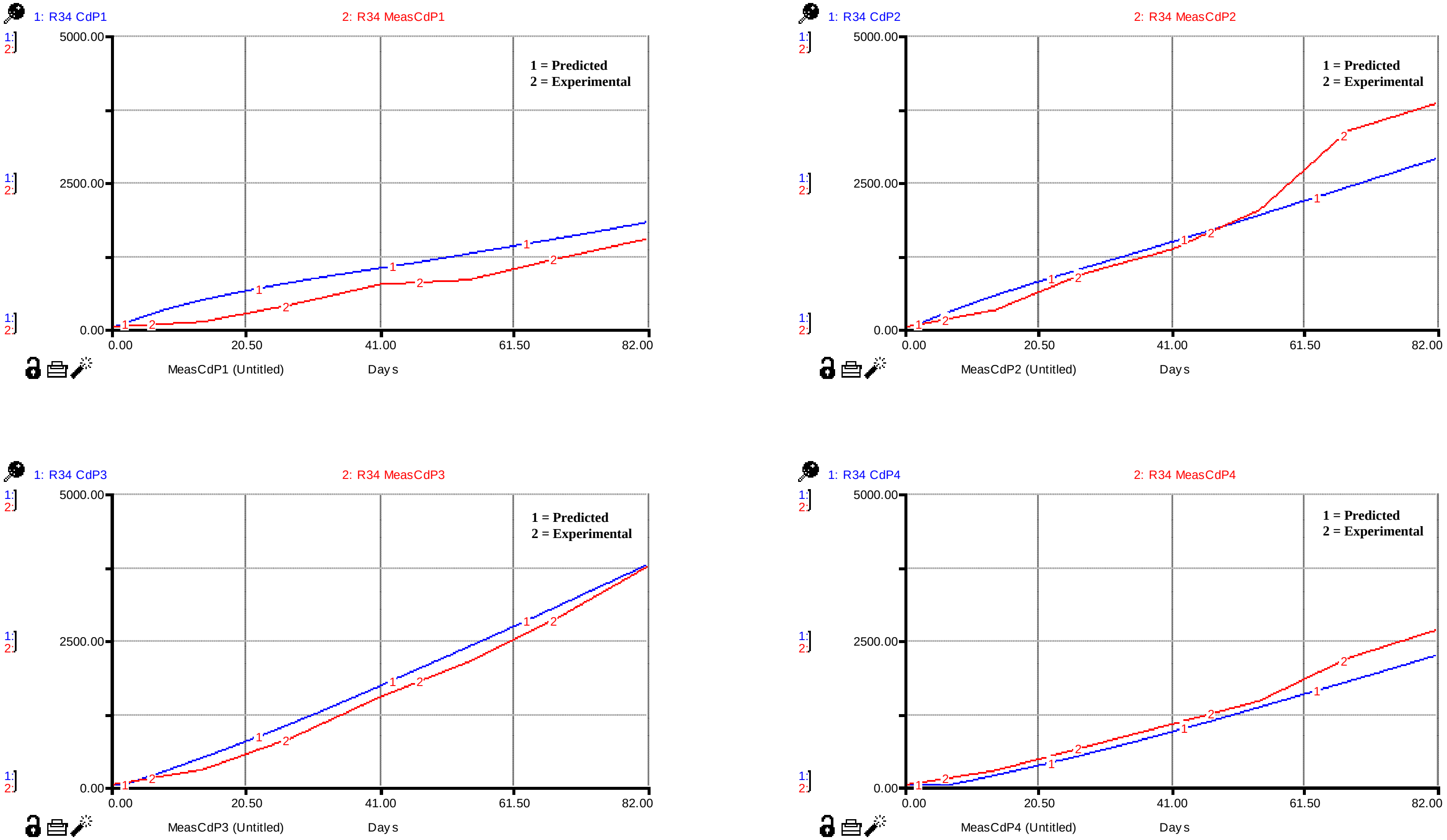


Figure 5.18 Correlation between simulated and measured cadmium accumulation in soil for R34.



Figures 5.19 Model validation for plants uptake of Cd in four compartments of reactor R14 (mg/d).



Figures 5.20 Model validation for plants uptake of Cd in four compartments of reactor R34 (mg/d).

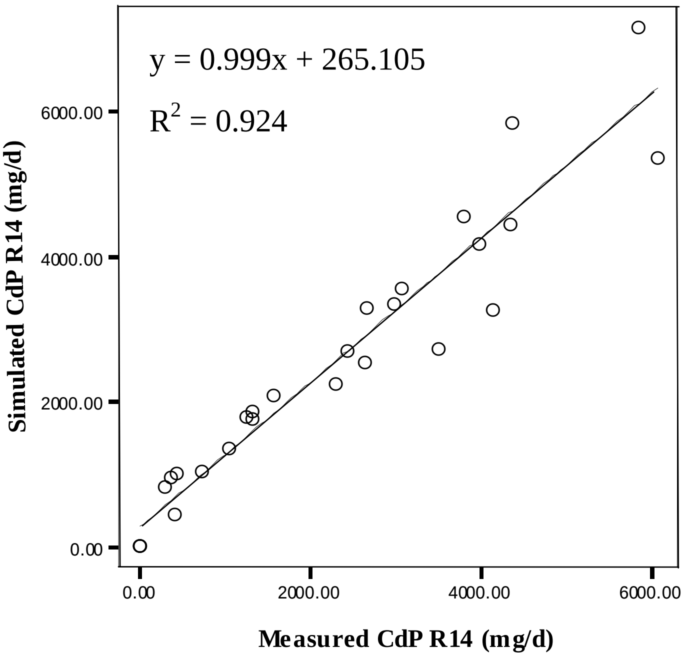


Figure 5.21 Correlation between simulated and measured cadmium removal by plants uptake for R14.

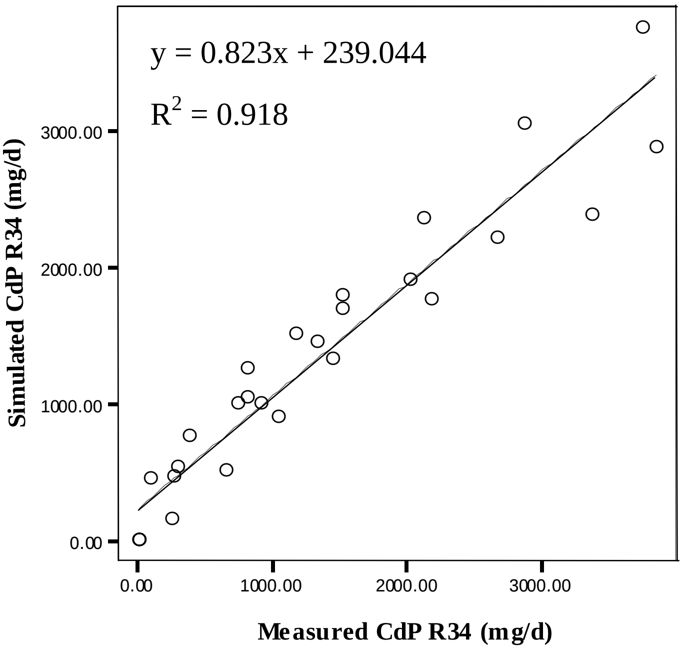


Figure 5.22 Correlation between simulated and measured cadmium removal by plants uptake for R34.

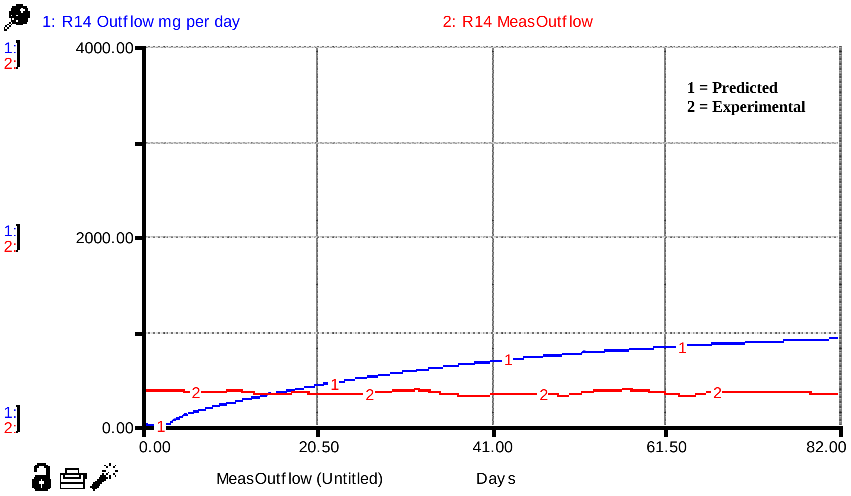


Figure 5.23 Comparison of predicted and experimental value of outflow in model validation for R14 (mg/d).

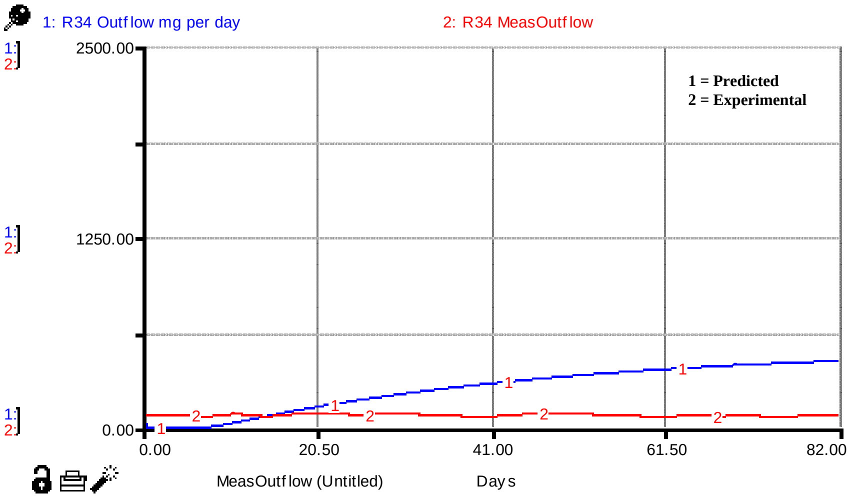


Figure 5.24 Comparison of predicted and experimental value of outflow in model validation for R34 (mg/d).

5.5 Mass Balance

The cadmium flows (Cd loading) through all the compartments (state variables), expressed in mg/d, were simulated by the model. The Cd in wastewater was transported to the soil by adsorption process and returned back to wastewater by desorption process. Cadmium in the roots and stems accumulated by plants uptake could be used for their growth, although there is some possibility that decomposed plants mass returned to wastewater. Thus, the quantity of Cd can be removed from the constructed wetlands system permanently by harvesting the plants. Mass balance obtained from the models is presented in Table 5.2.

Table 5.2 Mass balance of simulated and measured cadmium flows during three experimental runs.

Experiments	Simulated Cd mass fraction (%)					Measured Cd mass fraction (%)				
	Eff	**Plants**	**Soil**	**Other**	**R.E.**	**Eff**	**Plants**	**Soil**	**Other**	**R.E.**
R12	16.71	23.46	56.29	3.54	83.29	18.03	22.50	57.93	1.54	81.97
R13	33.63	20.63	41.05	4.70	66.37	19.21	22.91	56.31	1.56	80.79
R22	5.79	24.91	66.90	2.40	94.21	9.04	14.43	74.84	1.69	90.96
R23	26.49	21.85	47.42	4.24	73.51	10.94	16.90	70.37	1.79	89.06
R32	0.43	22.71	76.58	0.28	99.57	3.53	18.90	75.45	2.12	96.47
R33	16.71	23.46	56.29	3.54	83.29	4.29	19.91	73.61	2.19	95.71

The simulated values of cadmium mass fraction present in the effluents relative to the total intake were in the range of 16.7-33.6%, 5.8-26.5%, and 0.43-16.7% in Runs I, II, and III, respectively. The maximum cadmium removal predicted by the model occurred through the accumulation in the soil with mass fraction values of

41.1-56.3%, 47.4-66.9%, and 56.3-76.6% for HRTs = 5 d, 7 d, and 10 d, respectively. The mass fraction of the Cd lost via other sinks ranged between 3.5-4.7%, 2.4-4.2%, and 0.3-3.5% of total cadmium intake in Runs I, II, and III, respectively. Predicted mass fractions of cadmium, accumulated in plants, ranged between 20.6 and 23.5%, 21.9 and 24.9%, and 22.7 and 23.5%, during Run I, Run II, and Run III, respectively.

Figure 5.25 show comparison of simulated and measured average Cd removal efficiencies during three experimental runs. The simulated and measured average Cd removal efficiencies in FWS constructed wetland were in the range of 66.4-83.3 and 80.8-82.0%, 73.5-94.2 and 89.1-91.0%, and 83.3-99.6 and 95.7-96.5% for HRTs = 5 d, 7 d, and 10 d, respectively.

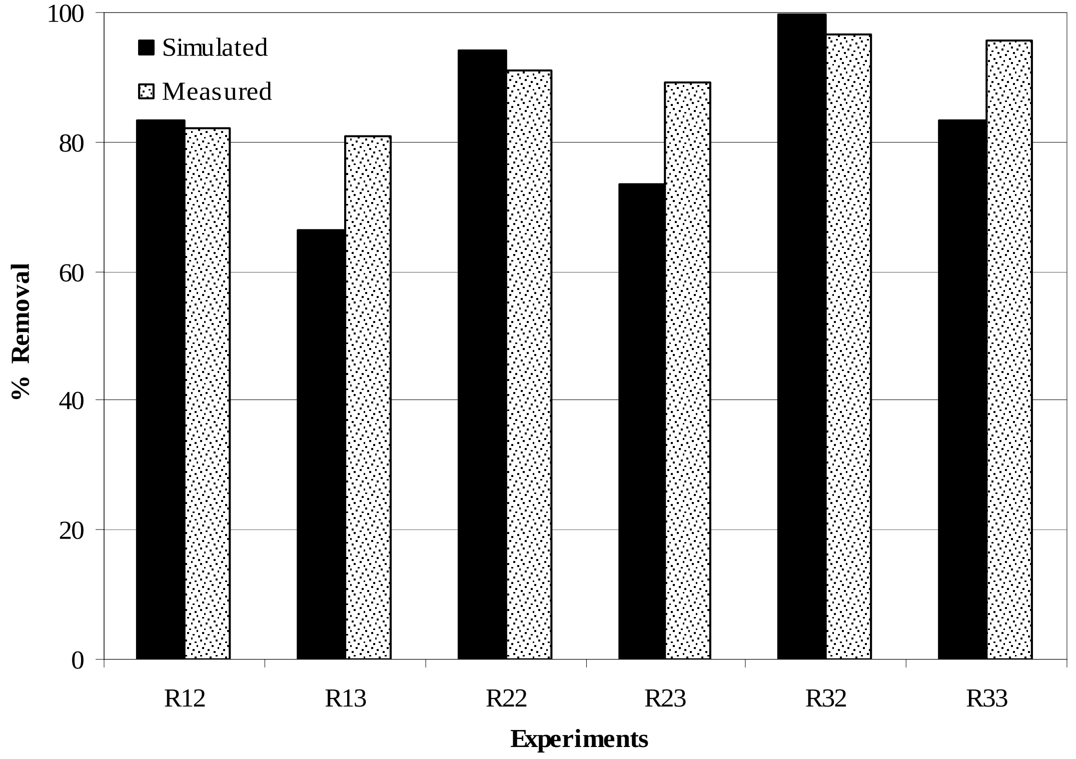


Figure 5.25 Comparison of simulated and measured average Cd removal efficiencies during three experimental runs.

The average cadmium removal efficiencies of simulated and measured were statistically compared for three experimental runs. All statistical analyses were conducted using statistical package for social science (SPSS) version 11.5 for Windows. *T* test used to compare two independent groups (independent samples *t* test). The hypothesis for this study was follow, H_0: The average Cd removal efficiencies of simulated and measured were not different for three experimental runs and H_1: The average Cd removal efficiencies of simulated and measured were different for three experimental runs. Table 5.3 shows the group statistics and independent samples *t* test of measured and simulated average Cd removal efficiencies.

The first output table, labeled group statistics, displays descriptive statistics. The second output table, labeled independent samples test, contains the statistics that were critical to evaluating the current research question. This table contains two sets of analyses: the first assumes equal variances and the second does not. In this study, the value $0.284 > 0.05$ in the column labeled sig. indicates that the variance of the two groups, simulated and measured, was equal (difference with no significance level of 0.05). Thus, *t*-test statistics in the row labeled equal variances assumed was used. The SPSS output reports a *t* statistic and degrees of freedom for all *t* test procedures. The hypothesis was not different in measured and simulated average Cd removal efficiencies, the *t* statistic under the assumption of equal variances has a value of 1.009, and the degrees of freedom has a value of 10 with an associated significance level of 0.337. The lower and upper bounds of 95% confidence interval of the difference includes zero that there was no significant difference between the means of the simulated and measured (accept H_0). Therefore, the mathematical model of this study can be used to explain the cadmium removal process in the FWS constructed wetlands.

Table 5.3 The group statistics and independent samples *t* test of measured and simulated average Cd removal efficiencies.

Group Statistics

	GROUP	N	Mean	Std. Deviation	Std. Error Mean
Cd Removal	Measured	6	89.1600	6.65344	2.71626
	Simulated	6	83.3733	12.37884	5.05364

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
									Lower	Upper
Cd Removal	Equal variances assumed	1.280	0.284	1.009	10	0.337	5.7867	5.73736	-6.99697	18.57030
	Equal variances not assumed			1.009	7.666	0.344	5.7867	5.73736	-7.54460	19.11794

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

6.1.1 Experimental Results

The three FWS constructed wetlands with bulrush plants were used to treat synthetic industrial wastewater with 600-900 mg/L of S-COD. Influents were prepared by mixing the synthetic wastewater with $CdCl_2 \cdot H_2O$ at concentrations of 5, 10, 25, and 50 mg/L for each of the four simultaneous experiments during three runs designated as Runs I-III. The performance of the wetland system was evaluated over three hydraulic retention times (HRT) to 5, 7 and 10 days. The flow characteristics of these constructed wetlands could be classified as approaching a plug-flow pattern. The overall average cadmium removal efficiency during the three runs ranged between 75-97% (74.6-81.9% in Run I at HRT = 5 days, 82.6-90.8% in Run II at HRT = 7 days, and 92.7-96.5% in Run III at HRT = 10 days, respectively). Most of the cadmium was accumulated in soil (56-76% of total influent cadmium). Total accumulation of Cd in the soil bed was found to be higher in Run I (HRT of 5 days) and decreased with HRT for all influent concentrations. Also, the accumulation increased with influent loading during each run. The cadmium accumulation in soil decreased along the reactor lengths. Cadmium accumulations at the top of the soil bed were higher than those at depths of 15, 30 and 45 cm. The porosity of sand (0.49), being higher than that of the mixture of clay loam soil (Korat series) and sand

(0.41), could have been the cause of a higher adsorption of cadmium at the top of the soil bed. The amount of total Cd uptake by the stems of bulrush plants was higher than roots for all four wetland units fed with synthetic wastewater at different influent loadings during the three runs. Of the total cadmium uptakes, about 14 to 23% of the total cadmium intake was accumulated in bulrush plants. During all the runs, cadmium accumulations in stems and roots were higher at high influent loadings. However, the cadmium accumulations in stems and roots at higher HRT (lower loading for each concentration) decreased as compared to those at lower HRT (higher loadings). Cadmium was removed from wastewater and accumulates in wetlands, primarily in the soil and sediment layers. Plants serve to stabilize wetland soil and sediment and enhance the accretion of new sediments by the filtering action of their leaves and stems, causing settleable metal suspended on solids to fall out of the water column. Plants also have the ability to remove cadmium from the wastewater through biological uptake and surface adsorption.

Based on the results of this study, it could be concluded that FWS constructed wetland system with bulrush plants may be effective in cadmium removal from industrial wastewater, even at high influent loadings. The optimum HRT for efficient Cd removal from wastewater was found to be 10 days. Thus, wetland systems can be used to improve the quality of final effluents from industrial wastewater treatment plants, before their disposal into receiving water bodies.

When the plants have absorbed and accumulated contaminants, they can be harvested and discarded. If organic chemical contaminants are degraded into molecules like water and carbon dioxide, the plants may not require any special method of disposal. Controlled incineration is the most common method used to dispose of plants that have absorbed large amounts of contamination. This process produces ashes, which can either be discarded at appropriate waste sites or to recover the original metals from ashes with a high metal content.

6.1.2 Mathematical Modeling of Cadmium Removal in Wetlands

A mathematical model for describing the cadmium removal process in the FWS constructed wetlands was developed using STELLA program. There was good agreement between the simulated and the experimental values of cadmium accumulation in soil and of plants uptake for all experiments used for model calibration and validation. The Cd in wastewater was transported to the soil by adsorption process and returned back to wastewater by desorption process. Cadmium in the roots and stems accumulated by plants uptake could be used for their growth, although there is some possibility that decomposed plants mass returned to wastewater. Thus, the quantity of Cd can be removed from the constructed wetlands system permanently by harvesting the plants.

The simulated and measured average Cd removal efficiencies for 6 runs were in the range between 66.4-99.6% and 80.8-96.5%, respectively. The average cadmium removal efficiencies of simulated and measured were statistically compared for three experimental runs. *T* test used to compare two independent groups (independent samples *t* test). The hypothesis was not different in measured and simulated average Cd removal efficiencies, the *t* statistic under the assumption of equal variances has a value of 1.009, and the degrees of freedom has a value of 10 with an associated significance level of 0.337. The lower and upper bounds of 95% confidence interval of the difference includes zero that there was no significant difference between the means of the simulated and measured (accept H_0). Therefore, the mathematical model of this study can be used to explain the cadmium removal process in the FWS constructed wetlands.

6.2 Recommendations

Based on the results of this study, some recommendations for further research are suggested as follows:

6.2.1 To study the cadmium removal from real industrial wastewater in the FWS constructed wetlands.

6.2.2 The evaluation of plant uptake behaviour with decreasing heavy metal concentrations in soils.

6.2.3 To study the growth rate of plants and determine the effects of plant harvesting on Cd removal in FWS constructed wetlands.

6.2.4 The feasibility study on the reuse or remediation of plants and soil after the treatment runs in the wetlands should be conducted in order to avoid public health problems resulting from toxicity of accumulated cadmium in them.

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APPENDIX A

EXPERIMENTAL DATA OF TRACER STUDY

Table A.1 The experimental data of tracer study at HRT = 5 days.

D/M/Y	t_i (hrs)	dt_i	C (mg/L)	C/Co=Ci	$C_i t_i$	$C_i t_i dt_i$	$C_i dt_i$	Ci t_i^2 dti
9-Dec-02	0	0	5.21	0.00	0.00	0.00	0.00	0.00
10-Dec-02	12	12	317.84	0.06	0.76	9.15	0.76	109.85
10-Dec-02	24	12	561.53	0.11	2.70	32.34	1.35	776.26
11-Dec-02	36	12	489.00	0.10	3.52	42.25	1.17	1,520.99
11-Dec-02	48	12	410.16	0.08	3.94	47.25	0.98	2,268.02
12-Dec-02	60	12	361.15	0.07	4.33	52.01	0.87	3,120.34
12-Dec-02	72	12	315.86	0.06	4.55	54.58	0.76	3,929.80
13-Dec-02	84	12	297.20	0.06	4.99	59.92	0.71	5,032.90
13-Dec-02	96	12	254.39	0.05	4.88	58.61	0.61	5,626.70
14-Dec-02	108	12	198.81	0.04	4.29	51.53	0.48	5,565.41
14-Dec-02	120	12	186.64	0.04	4.48	53.75	0.45	6,450.28
15-Dec-02	132	12	173.14	0.03	4.57	54.85	0.42	7,240.30
15-Dec-02	144	12	148.45	0.03	4.28	51.30	0.36	7,387.82
16-Dec-02	156	12	125.76	0.03	3.92	47.08	0.30	7,345.19
16-Dec-02	168	12	118.46	0.02	3.98	47.76	0.28	8,024.20
17-Dec-02	180	12	101.78	0.02	3.66	43.97	0.24	7,914.41
17-Dec-02	192	12	96.51	0.02	3.71	44.47	0.23	8,538.59
18-Dec-02	204	12	92.65	0.02	3.78	45.36	0.22	9,253.73
18-Dec-02	216	12	82.31	0.02	3.56	42.67	0.20	9,216.61
19-Dec-02	228	12	71.25	0.01	3.25	38.99	0.17	8,889.26
19-Dec-02	240	12	70.05	0.01	3.36	40.35	0.17	9,683.71
20-Dec-02	252	12	69.59	0.01	3.51	42.09	0.17	10,606.18
20-Dec-02	264	12	67.74	0.01	3.58	42.92	0.16	11,330.90
21-Dec-02	276	12	66.82	0.01	3.69	44.26	0.16	12,216.19
21-Dec-02	288	12	64.52	0.01	3.72	44.60	0.15	12,843.71
21-Dec-02	300	12	57.61	0.01	3.46	41.48	0.14	12,443.76
22-Dec-02	312	12	55.76	0.01	3.48	41.75	0.13	13,026.96
22-Dec-02	324	12	53.46	0.01	3.46	41.57	0.13	13,468.84
23-Dec-02	336	12	47.93	0.01	3.22	38.65	0.12	12,986.65
23-Dec-02	348	12	46.54	0.01	3.24	38.87	0.11	13,526.83
24-Dec-02	360	12	45.62	0.01	3.28	39.42	0.11	14,189.64
24-Dec-02	372	12	44.70	0.01	3.33	39.91	0.11	14,845.84
25-Dec-02	384	12	44.24	0.01	3.40	40.77	0.11	15,656.29
		SUM	5,142.68	1.03	117.87	1,414.49	12.33	275,036.17

$$\mathrm{T}_{\mathrm{mean}} = \frac{\sum_{i=0}^{t} \mathrm{C}_i \mathrm{t}_i \mathrm{dt}_i}{\sum_{i=0}^{t} \mathrm{C}_i \mathrm{dt}_i}$$

$$= \frac{1{,}414.49}{12.33} \qquad = 114.72 \text{ hrs} \qquad = 4.78 \text{ days}$$

$$\sigma^2 = \frac{\sum_{i=0}^{t} \mathrm{C}_i \mathrm{t}_i{}^2 \mathrm{dt}_i}{\sum_{i=0}^{t} \mathrm{C}_i \mathrm{dt}_i} - \mathrm{T}_{\mathrm{meann}}{}^2$$

$$= \frac{275{,}036.17}{12.33} - 114.72^2 \qquad = 9{,}145.58 \text{ hrs}^2$$

$$\sigma_\theta{}^2 = \frac{\sigma^2}{\mathrm{T}_{\mathrm{mean}}{}^2} = 2d + 8d^2$$

$$= \frac{9{,}145.58}{114.72^2} \qquad = 0.6949$$

$$2d + 8d^2 = 0.6949$$

Therefore, $d = 0.1951$

From: $d = \frac{\mathrm{D}}{uL}$, $u = \frac{L}{\mathrm{HRT}}$

$$\mathrm{D} = \frac{dL^2}{\mathrm{HRT}}$$

$$= \frac{(0.1951)(2.5)^2}{5} \qquad = 0.244 \text{ m}^2/\text{d}$$

Table A.2 The experimental data of tracer study at HRT = 7 days.

D/M/Y	t_i (hrs)	dt_i	C (mg/L)	C/Co=Ci	$C_i t_i$	$C_i t_i dt_i$	$C_i dt_i$	Ci t_i^2 dti
09-Dec-02	0	0	19.54	0.00	0.00	0.00	0.00	0.00
10-Dec-02	12	12	302.85	0.06	0.73	8.72	0.73	104.66
10-Dec-02	24	12	477.52	0.10	2.29	27.51	1.15	660.12
11-Dec-02	36	12	575.67	0.12	4.14	49.74	1.38	1,790.56
11-Dec-02	48	12	500.02	0.10	4.80	57.60	1.20	2,764.91
12-Dec-02	60	12	436.48	0.09	5.24	62.85	1.05	3,771.19
12-Dec-02	72	12	411.57	0.08	5.93	71.12	0.99	5,120.59
13-Dec-02	84	12	396.26	0.08	6.66	79.89	0.95	6,710.43
13-Dec-02	96	12	352.23	0.07	6.76	81.15	0.85	7,790.76
14-Dec-02	108	12	306.67	0.06	6.62	79.49	0.74	8,584.80
14-Dec-02	120	12	297.51	0.06	7.14	85.68	0.71	10,281.95
15-Dec-02	132	12	276.51	0.06	7.30	87.60	0.66	11,562.98
15-Dec-02	144	12	246.42	0.05	7.10	85.16	0.59	12,263.44
16-Dec-02	156	12	241.80	0.05	7.54	90.53	0.58	14,122.67
16-Dec-02	168	12	216.29	0.04	7.27	87.21	0.52	14,650.97
17-Dec-02	180	12	188.35	0.04	6.78	81.37	0.45	14,646.10
17-Dec-02	192	12	174.89	0.03	6.72	80.59	0.42	15,473.15
18-Dec-02	204	12	165.18	0.03	6.74	80.87	0.40	16,497.91
18-Dec-02	216	12	159.14	0.03	6.87	82.50	0.38	17,819.61
19-Dec-02	228	12	134.43	0.03	6.13	73.56	0.32	16,771.70
19-Dec-02	240	12	129.04	0.03	6.19	74.33	0.31	17,838.49
20-Dec-02	252	12	122.59	0.02	6.18	74.14	0.29	18,683.89
20-Dec-02	264	12	123.51	0.02	6.52	78.26	0.30	20,659.57
21-Dec-02	276	12	120.74	0.02	6.66	79.98	0.29	22,073.98
21-Dec-02	288	12	116.13	0.02	6.69	80.27	0.28	23,117.49
21-Dec-02	300	12	102.77	0.02	6.17	73.99	0.25	22,198.32
22-Dec-02	312	12	98.62	0.02	6.15	73.85	0.24	23,040.16
22-Dec-02	324	12	96.32	0.02	6.24	74.90	0.23	24,267.09
23-Dec-02	336	12	95.26	0.02	6.40	76.82	0.23	25,810.74
23-Dec-02	348	12	94.94	0.02	6.61	79.29	0.23	27,594.27
24-Dec-02	360	12	92.17	0.02	6.64	79.63	0.22	28,668.56
24-Dec-02	372	12	81.11	0.02	6.03	72.42	0.19	26,938.38
25-Dec-02	384	12	78.34	0.02	6.02	72.20	0.19	27,724.09
26-Dec-02	408	12	73.28	0.01	5.98	71.76	0.18	29,276.36

Table A.2 The experimental data of tracer study at HRT = 7 days (Continued).

D/M/Y	t_i (hrs)	dt_i	C (mg/L)	C/Co=Ci	$C_i\,t_i$	$C_i\,t_i\,dt_i$	$C_i\,dt_i$	Ci t_i^2 dti
26-Dec-02	420	12	65.44	0.01	5.50	65.96	0.16	27,704.68
27-Dec-02	432	12	61.29	0.01	5.30	63.55	0.15	27,451.64
27-Dec-02	444	12	59.45	0.01	5.28	63.35	0.14	28,127.36
28-Dec-02	456	12	55.76	0.01	5.09	61.02	0.13	27,826.83
28-Dec-02	468	12	49.31	0.01	4.62	55.38	0.12	25,920.18
29-Dec-02	480	12	51.62	0.01	4.96	59.47	0.12	28,543.80
29-Dec-02	492	12	49.77	0.01	4.90	58.77	0.12	28,914.06
30-Dec-02	504	12	48.39	0.01	4.88	58.53	0.12	29,500.40
		SUM	7,817.530	1.56	247.48	2,969.76	18.72	770,498.35

$$T_{mean} = \frac{\sum_{i=0}^{t} C_i t_i dt_i}{\sum_{i=0}^{t} C_i dt_i}$$

$$= \frac{2,969.76}{18.72} \qquad = 158.64 \text{ hrs} \qquad = 6.61 \text{ days}$$

$$\sigma^2 = \frac{\sum_{i=0}^{t} C_i t_i^{\,2} dt_i}{\sum_{i=0}^{t} C_i dt_i} - T_{meann}^{\quad 2}$$

$$= \frac{770,498.35}{18.72} - 158.64^2 \qquad = 15,992.45 \text{ hrs}^2$$

$$\sigma_\theta^{\ 2} = \frac{\sigma^2}{T_{mean}^{\quad 2}} = 2d + 8d^2$$

$$= \frac{15,992.45}{158.64^2} \qquad = 0.6355$$

$$2d + 8d^2 = 0.6355$$

Therefore, $d = 0.1833$

From: $d = \frac{\mathrm{D}}{uL}$, $u = \frac{L}{\mathrm{HRT}}$

$$\mathrm{D} = \frac{dL^2}{\mathrm{HRT}}$$

$$= \frac{(0.1833)(2.5)^2}{7} \qquad = 0.164 \text{ m}^2/\text{d}$$

Table A.3 The experimental data of tracer study at HRT = 10 days.

D/M/Y	t_i (hrs)	dt_i	C (mg/L)	C/Co=Ci	$C_i t_i$	$C_i t_i dt_i$	$C_i dt_i$	Ci t_i^2 dti
09-Dec-02	0	0	40.34	0.01	0.00	0.00	0.00	0.00
10-Dec-02	12	12	185.22	0.04	0.44	5.33	0.44	64.01
10-Dec-02	24	12	325.39	0.07	1.56	18.74	0.78	449.82
11-Dec-02	36	12	454.17	0.09	3.27	39.24	1.09	1,412.65
11-Dec-02	48	12	555.12	0.11	5.33	63.95	1.33	3,069.59
12-Dec-02	60	12	509.74	0.10	6.12	73.40	1.22	4,404.15
12-Dec-02	72	12	425.10	0.09	6.12	73.46	1.02	5,288.92
13-Dec-02	84	12	342.01	0.07	5.75	68.95	0.82	5,791.73
13-Dec-02	96	12	314.87	0.06	6.05	72.55	0.76	6,964.42
14-Dec-02	108	12	290.12	0.06	6.27	75.20	0.70	8,121.50
14-Dec-02	120	12	271.50	0.05	6.52	78.19	0.65	9,383.04
15-Dec-02	132	12	237.95	0.05	6.28	75.38	0.57	9,950.50
15-Dec-02	144	12	214.44	0.04	6.18	74.11	0.51	10,671.91
16-Dec-02	156	12	206.23	0.04	6.43	77.21	0.49	12,045.15
16-Dec-02	168	12	195.51	0.04	6.57	78.83	0.47	13,243.38
17-Dec-02	180	12	188.75	0.04	6.80	81.54	0.45	14,677.20
17-Dec-02	192	12	172.81	0.03	6.64	79.63	0.41	15,289.12
18-Dec-02	204	12	170.63	0.03	6.96	83.54	0.41	17,042.25
18-Dec-02	216	12	159.11	0.03	6.87	82.48	0.38	17,816.25
19-Dec-02	228	12	155.81	0.03	7.10	85.26	0.37	19,439.10
19-Dec-02	240	12	152.14	0.03	7.30	87.63	0.37	21,031.83
20-Dec-02	252	12	148.67	0.03	7.49	89.92	0.36	22,658.74
20-Dec-02	264	12	146.91	0.03	7.76	93.08	0.35	24,573.69
21-Dec-02	276	12	146.29	0.03	8.08	96.90	0.35	26,745.09
21-Dec-02	288	12	145.15	0.03	8.36	100.33	0.35	28,894.37
22-Dec-02	300	12	140.95	0.03	8.46	101.48	0.34	30,445.20
22-Dec-02	312	12	138.32	0.03	8.63	103.57	0.33	32,315.09
23-Dec-02	324	12	137.67	0.03	8.92	107.05	0.33	34,684.91
23-Dec-02	336	12	128.12	0.03	8.61	103.32	0.31	34,714.17
24-Dec-02	348	12	127.58	0.03	8.88	106.55	0.31	37,081.08
24-Dec-02	360	12	124.29	0.02	8.95	107.39	0.30	38,659.16
25-Dec-02	372	12	120.08	0.02	8.93	107.21	0.29	39,881.16
25-Dec-02	384	12	118.12	0.02	9.07	108.86	0.28	41,802.01
26-Dec-02	396	12	115.26	0.02	9.13	109.54	0.28	43,379.07

Table A.3 The experimental data of tracer study at HRT = 10 days (Continued).

D/M/Y	t_i (hrs)	dt_i	C (mg/L)	C/Co=Ci	$C_i t_i$	$C_i t_i dt_i$	$C_i dt_i$	Ci t_i^2 dti
26-Dec-02	408	12	110.45	0.02	9.01	108.15	0.27	44,126.28
27-Dec-02	420	12	105.02	0.02	8.82	105.86	0.25	44,461.27
27-Dec-02	432	12	102.04	0.02	8.82	105.80	0.24	45,703.47
28-Dec-02	444	12	101.94	0.02	9.05	108.63	0.24	48,230.51
28-Dec-02	456	12	101.55	0.02	9.26	111.14	0.24	50,678.16
29-Dec-02	468	12	100.37	0.02	9.39	112.74	0.24	52,760.25
29-Dec-02	480	12	102.39	0.02	9.83	117.95	0.25	56,617.57
30-Dec-02	492	12	102.11	0.02	10.05	120.57	0.25	59,321.17
30-Dec-02	504	12	101.50	0.02	10.23	122.77	0.24	61,878.30
31-Dec-02	516	12	101.05	0.02	10.43	125.14	0.24	64,572.41
31-Dec-02	528	12	102.47	0.02	10.82	129.85	0.25	68,560.79
01-Jan-03	540	12	100.22	0.02	10.82	129.89	0.24	70,137.96
01-Jan-03	552	12	100.96	0.02	11.15	133.75	0.24	73,831.00
02-Jan-03	564	12	102.54	0.02	11.57	138.80	0.25	78,282.15
02-Jan-03	576	12	102.12	0.02	11.76	141.17	0.25	81,314.32
03-Jan-03	588	12	101.54	0.02	11.94	143.29	0.24	84,256.43
03-Jan-03	600	12	100.04	0.02	12.00	144.06	0.24	86,434.56
		SUM	9,042.68	1.81	400.78	4,809.39	21.61	1,703,156.88

$$T_{mean} = \frac{\sum_{i=0}^{t} C_i t_i dt_i}{\sum_{i=0}^{t} C_i dt_i}$$

$$= \frac{4,809.39}{21.61} \qquad = 222.55 \text{ hrs} \qquad = 9.27 \text{ days}$$

$$\sigma^2 = \frac{\sum_{i=0}^{t} C_i t_i{}^2 dt_i}{\sum_{i=0}^{t} C_i dt_i} - T_{meann}{}^2$$

$$= \frac{1{,}703{,}156.88}{21.61} - 222.55^2 \qquad = 29{,}284.87 \text{ hrs}^2$$

$$\sigma_\theta{}^2 = \frac{\sigma^2}{\mathrm{T_{mean}}{}^2} = 2d + 8d^2$$

$$= \frac{29{,}284.87}{222.55^2} \qquad = 0.5913$$

$$2d + 8d^2 = 0.5913$$

Therefore, $d = 0.1742$

From: $d = \frac{\mathrm{D}}{uL}$, $u = \frac{L}{\mathrm{HRT}}$

$$\mathrm{D} = \frac{dL^2}{\mathrm{HRT}}$$

$$= \frac{(0.1742)(2.5)^2}{10} \qquad = 0.109 \text{ m}^2/\text{d}$$

APPENDIX B

EXPERIMENTAL DATA OF MONITORED WATER QUALITY PARAMETERS

Table B.1 The influent and effluent DO concentrations of Run I.

D/M/Y	R11		R12		R13		R14		R15	
	Influent (mg/L)	**Effluent (mg/L)**	**Influent (mg/L)**	**Effluent (mg/L)**	**Influent (mg/L)**	**Effluent (mg/L)**	**Influent (mg/L)**	**Effluent (mg/L)**	**Influent (mg/L)**	**Effluent (mg/L)**
9-Feb-04	0.00	1.10	0.00	1.00	0.00	1.00	0.00	0.80	0.00	0.80
12-Feb-04	0.00	0.70	0.00	0.80	0.00	0.70	0.00	0.70	0.00	0.70
16-Feb-04	0.00	0.70	0.00	0.70	0.00	0.70	0.00	0.70	0.00	0.70
19-Feb-04	0.00	0.80	0.00	0.80	0.00	0.80	0.00	0.70	0.00	0.60
23-Feb-04	0.00	0.70	0.00	0.60	0.00	0.70	0.00	0.70	0.00	0.60
26-Feb-04	0.00	0.60	0.00	0.70	0.00	0.60	0.00	0.60	0.00	0.60
1-Mar-04	0.00	0.80	0.00	0.80	0.00	0.60	0.00	0.80	0.00	0.70
4-Mar-04	0.00	0.80	0.00	0.70	0.00	0.70	0.00	0.80	0.00	0.70
8-Mar-04	0.00	0.60	0.00	0.60	0.00	0.60	0.00	0.60	0.00	0.80
11-Mar-04	0.00	0.80	0.00	0.60	0.00	0.80	0.00	0.80	0.00	0.80
15-Mar-04	0.00	0.90	0.00	0.70	0.00	0.90	0.00	0.90	0.00	0.90
18-Mar-04	0.00	0.70	0.00	0.70	0.00	0.70	0.00	0.70	0.00	0.80
22-Mar-04	0.00	0.70	0.00	0.80	0.00	0.70	0.00	0.70	0.00	0.70
25-Mar-04	0.00	0.90	0.00	0.90	0.00	0.80	0.00	0.90	0.00	0.70
29-Mar-04	0.00	0.80	0.00	0.80	0.00	0.80	0.00	0.80	0.00	0.60
1-Apr-04	0.00	1.00	0.00	0.80	0.00	1.00	0.00	0.80	0.00	0.70
5-Apr-04	0.00	0.90	0.00	0.80	0.00	0.90	0.00	0.90	0.00	0.90
8-Apr-04	0.00	0.90	0.00	0.70	0.00	0.80	0.00	0.90	0.00	0.80
12-Apr-04	0.00	0.70	0.00	0.70	0.00	0.70	0.00	0.70	0.00	0.80
15-Apr-04	0.00	0.80	0.00	0.80	0.00	0.70	0.00	0.80	0.00	0.80
19-Apr-04	0.00	0.80	0.00	0.80	0.00	0.80	0.00	0.70	0.00	0.80
22-Apr-04	0.00	0.80	0.00	0.90	0.00	0.80	0.00	0.60	0.00	0.80
26-Apr-04	0.00	0.80	0.00	0.80	0.00	0.80	0.00	0.60	0.00	0.80
30-Apr-04	0.00	0.70	0.00	0.80	0.00	0.70	0.00	0.70	0.00	0.70
Mean	0.00	0.79	0.00	0.76	0.00	0.76	0.00	0.75	0.00	0.74
SD	0.00	0.12	0.00	0.10	0.00	0.11	0.00	0.10	0.00	0.09

Table B.2 The influent and effluent DO concentrations of Run II.

D/M/Y	**R21**		**R22**		**R23**		**R24**		**R25**	
	Influent (mg/L)	**Effluent (mg/L)**	**Influent (mg/L)**	**Effluent (mg/L)**	**Influent (mg/L)**	**Effluent (mg/L)**	**Influent (mg/L)**	**Effluent (mg/L)**	**Influent (mg/L)**	**Effluent (mg/L)**
16-Aug-04	0.00	1.00	0.00	1.10	0.00	1.00	0.00	0.90	0.00	1.00
19-Aug-04	0.00	0.90	0.00	0.90	0.00	0.90	0.00	0.80	0.00	1.00
23-Aug-04	0.00	1.00	0.00	1.20	0.00	1.10	0.00	1.20	0.00	1.10
26-Aug-04	0.00	1.10	0.00	1.30	0.00	0.90	0.00	1.00	0.00	1.20
30-Aug-04	0.00	1.20	0.00	1.20	0.00	1.20	0.00	1.10	0.00	1.20
2-Sep-04	0.00	1.40	0.00	1.30	0.00	1.50	0.00	1.50	0.00	1.40
6-Sep-04	0.00	1.30	0.00	1.50	0.00	1.40	0.00	1.60	0.00	1.60
9-Sep-04	0.00	1.20	0.00	1.40	0.00	1.50	0.00	1.50	0.00	1.30
13-Sep-04	0.00	1.20	0.00	1.30	0.00	1.30	0.00	1.30	0.00	1.20
16-Sep-04	0.00	1.10	0.00	1.00	0.00	1.20	0.00	1.20	0.00	1.20
20-Sep-04	0.20	1.50	0.20	1.20	0.20	1.50	0.20	1.50	0.20	1.40
23-Sep-04	0.20	1.50	0.20	1.60	0.20	1.60	0.10	1.40	0.10	1.50
27-Sep-04	0.30	1.60	0.20	1.50	0.20	1.50	0.20	1.40	0.10	1.30
30-Sep-04	0.20	1.50	0.20	1.30	0.20	1.30	0.10	1.50	0.00	1.40
4-Oct-04	0.20	1.20	0.20	1.10	0.00	1.20	0.00	1.20	0.00	1.20
7-Oct-04	0.30	1.30	0.20	1.10	0.00	1.10	0.10	1.20	0.00	1.20
11-Oct-04	0.30	1.20	0.20	1.10	0.10	1.10	0.10	1.10	0.20	1.00
14-Oct-04	0.30	1.10	0.20	1.00	0.10	1.10	0.10	1.10	0.30	1.00
18-Oct-04	0.30	1.10	0.10	1.20	0.10	1.10	0.20	1.00	0.30	1.10
21-Oct-04	0.30	1.20	0.10	1.00	0.20	1.00	0.20	1.10	0.20	1.00
25-Oct-04	0.20	1.20	0.10	1.10	0.20	1.10	0.20	1.10	0.10	1.00
28-Oct-04	0.20	1.20	0.10	1.30	0.30	1.30	0.20	1.30	0.20	1.20
1-Nov-04	0.10	1.50	0.10	1.40	0.00	1.50	0.00	1.60	0.00	1.50
5-Nov-04	0.30	1.60	0.00	1.40	0.00	1.50	0.10	1.50	0.00	1.40
Mean	0.14	1.25	0.09	1.23	0.08	1.25	0.08	1.25	0.07	1.23
SD	0.13	0.20	0.09	0.18	0.10	0.21	0.08	0.23	0.10	0.18

Table B.3 The influent and effluent DO concentrations of Run III.

D/M/Y	R31		R32		R33		R34		R35	
	Influent (mg/L)	Effluent (mg/L)	Influent (mg/L)	Effluent (mg/L)	Influent (mg/L)	Effluent (mg/L)	Influent (mg/L)	Effluent (mg/L)	Influent (mg/L)	Effluent (mg/L)
14-Feb-05	0.10	2.20	0.10	2.40	0.10	2.30	0.00	2.20	0.10	1.70
17-Feb-05	0.10	2.10	0.00	2.40	0.00	2.20	0.00	1.70	0.00	1.70
21-Feb-05	0.20	1.80	0.20	1.80	0.20	2.00	0.20	1.70	0.10	1.90
24-Feb-05	0.00	2.00	0.10	1.80	0.10	1.90	0.00	1.80	0.10	2.10
28-Feb-05	0.00	1.90	0.00	1.90	0.00	1.80	0.00	1.90	0.00	1.80
3-Mar-05	0.20	2.20	0.20	2.00	0.20	2.10	0.30	1.80	0.00	2.10
7-Mar-05	0.20	1.80	0.30	2.00	0.30	2.20	0.20	1.70	0.00	1.90
10-Mar-05	0.10	1.70	0.20	1.60	0.00	1.90	0.00	2.20	0.00	2.30
14-Mar-05	0.00	1.70	0.00	1.70	0.00	1.70	0.00	1.70	0.10	1.90
17-Mar-05	0.00	2.20	0.00	1.80	0.00	1.80	0.00	1.70	0.10	1.80
21-Mar-05	0.00	1.80	0.00	1.70	0.20	1.90	0.00	2.10	0.10	1.80
24-Mar-05	0.30	1.90	0.20	1.80	0.10	1.80	0.20	1.70	0.20	1.70
28-Mar-05	0.20	1.70	0.10	1.60	0.20	1.80	0.10	1.70	0.20	1.70
31-Mar-05	0.20	1.60	0.20	1.50	0.20	1.50	0.20	1.80	0.20	1.80
4-Apr-05	0.30	1.80	0.30	1.70	0.20	1.70	0.20	1.80	0.20	2.10
7-Apr-05	0.10	1.70	0.20	1.70	0.20	1.80	0.10	1.60	0.10	1.80
11-Apr-05	0.20	1.90	0.20	1.80	0.20	1.60	0.10	1.80	0.20	1.80
14-Apr-05	0.30	2.10	0.20	2.20	0.10	2.20	0.10	2.10	0.30	1.80
18-Apr-05	0.20	1.80	0.30	2.10	0.30	2.00	0.20	2.00	0.30	1.90
21-Apr-05	0.30	1.60	0.30	1.80	0.20	2.20	0.20	2.10	0.20	2.00
25-Apr-05	0.20	1.40	0.20	1.40	0.20	1.90	0.20	2.10	0.10	2.10
28-Apr-05	0.20	1.70	0.10	1.50	0.30	1.80	0.20	1.80	0.20	2.10
2-May-05	0.10	1.80	0.10	1.90	0.00	2.10	0.00	1.60	0.00	1.70
6-May-05	0.30	1.70	0.20	1.50	0.00	1.80	0.10	1.50	0.00	1.60
Mean	0.16	1.84	0.15	1.82	0.14	1.92	0.11	1.84	0.12	1.88
SD	0.11	0.21	0.10	0.26	0.11	0.21	0.10	0.20	0.10	0.18

Table B.4 The influent and effluent pH of Run I.

D/M/Y	R11		R12		R13		R14		R15	
	Influent	**Effluent**	**Influent**	**Effluent**	**Influent**	**Effluent**	**Influent**	**Effluent**	**Influent**	**Effluent**
9-Feb-04	4.84	6.13	5.07	6.15	4.76	5.94	4.94	6.14	4.51	5.86
12-Feb-04	4.80	5.94	4.86	5.76	4.62	6.02	5.12	5.94	4.86	6.14
16-Feb-04	4.23	6.13	4.68	5.38	4.58	5.59	4.71	5.85	5.15	5.94
19-Feb-04	4.36	5.16	4.20	5.48	4.77	5.72	4.22	5.67	4.71	5.85
23-Feb-04	4.82	5.50	4.51	5.86	4.94	6.03	4.46	6.08	4.22	5.67
26-Feb-04	4.89	5.74	4.94	6.14	4.80	6.50	5.01	6.21	4.36	6.03
1-Mar-04	4.76	5.94	5.15	5.94	4.71	5.77	4.75	5.79	4.56	6.21
4-Mar-04	4.62	6.02	4.71	5.85	4.22	5.39	4.61	5.62	4.71	5.77
8-Mar-04	4.58	5.59	4.22	5.67	4.70	6.10	4.36	5.46	4.22	5.39
11-Mar-04	4.77	5.72	4.46	6.03	5.15	5.78	4.69	5.58	4.70	6.10
15-Mar-04	4.94	6.03	5.01	6.21	4.71	5.85	5.21	6.10	4.18	5.78
18-Mar-04	4.80	6.50	4.75	5.79	4.22	5.67	5.01	5.78	4.41	5.85
22-Mar-04	4.71	5.77	4.64	5.62	4.46	6.03	4.77	5.68	4.63	5.67
25-Mar-04	4.22	5.39	4.36	5.46	5.01	6.21	4.64	5.80	5.17	6.03
29-Mar-04	4.70	6.10	4.89	5.62	4.75	5.79	4.63	6.02	4.75	5.79
1-Apr-04	5.01	5.78	4.72	5.51	4.64	5.62	4.89	6.27	4.61	5.62
5-Apr-04	4.75	6.08	4.79	5.94	4.36	5.46	4.72	5.78	4.36	5.46
8-Apr-04	4.64	5.80	4.96	6.12	4.89	5.62	4.79	5.56	4.69	5.58
12-Apr-04	4.63	6.02	5.24	5.71	4.84	5.51	4.80	6.30	5.21	6.10
15-Apr-04	4.89	6.21	4.81	5.22	4.80	6.13	4.71	5.77	5.01	5.78
19-Apr-04	4.72	5.78	4.80	5.75	4.23	5.94	4.22	5.39	4.77	5.68
22-Apr-04	4.76	5.56	4.23	5.84	4.36	5.46	4.65	5.73	4.84	6.13
26-Apr-04	4.96	5.79	4.46	5.36	4.52	5.16	4.53	5.48	4.80	5.94
30-Apr-04	5.27	6.14	4.82	5.89	4.71	5.50	4.71	5.85	4.23	6.13
Mean	4.74	5.87	4.72	5.76	4.66	5.78	4.71	5.83	4.65	5.85
SD	0.23	0.30	0.29	0.27	0.25	0.31	0.25	0.26	0.30	0.23

Table B.5 The influent and effluent pH of Run II.

D/M/Y	R21		R22		R23		R24		R25	
	Influent	**Effluent**	**Influent**	**Effluent**	**Influent**	**Effluent**	**Influent**	**Effluent**	**Influent**	**Effluent**
16-Aug-04	4.92	6.69	4.79	6.99	5.07	6.88	4.92	7.18	4.85	7.10
19-Aug-04	4.62	6.61	4.55	6.50	4.53	6.60	4.66	7.09	5.20	6.54
23-Aug-04	5.32	6.86	5.16	6.66	5.03	6.63	4.79	6.56	5.42	6.59
26-Aug-04	5.35	6.73	5.28	6.57	5.51	6.55	5.60	6.64	5.07	6.40
30-Aug-04	5.45	6.63	4.86	6.95	5.24	6.49	5.05	6.56	5.33	6.47
2-Sep-04	4.72	6.58	4.85	6.47	4.94	6.48	5.20	6.99	4.59	6.46
6-Sep-04	4.50	6.60	4.50	6.64	4.31	6.57	4.68	6.48	4.96	6.57
9-Sep-04	4.86	6.69	4.87	6.59	4.68	6.56	4.65	6.58	5.14	6.36
13-Sep-04	5.22	6.60	5.24	6.72	5.28	6.69	4.04	6.67	4.82	6.46
16-Sep-04	4.66	6.42	4.80	6.60	4.54	6.63	4.81	6.91	5.54	6.82
20-Sep-04	4.73	6.49	4.66	6.65	4.45	6.58	5.64	6.61	5.15	6.53
23-Sep-04	5.18	6.61	5.15	6.75	5.27	6.66	4.74	6.75	4.62	6.70
27-Sep-04	4.81	6.65	4.59	6.77	4.81	6.70	4.49	6.89	4.74	6.83
30-Sep-04	4.32	6.66	4.56	6.91	4.67	6.84	4.57	6.91	4.72	6.77
4-Oct-04	5.06	7.13	5.05	7.34	5.02	7.33	5.63	7.71	5.06	7.23
7-Oct-04	4.66	7.28	5.21	7.42	5.12	7.48	5.28	6.87	4.65	6.82
11-Oct-04	5.25	6.97	5.08	7.07	4.77	7.13	5.04	6.71	4.41	7.39
14-Oct-04	5.35	6.99	5.41	7.28	4.98	7.31	4.76	6.81	4.67	7.41
18-Oct-04	4.94	6.83	5.13	6.93	5.26	7.13	5.03	7.22	5.16	6.98
21-Oct-04	4.90	6.91	5.33	6.67	5.19	7.04	5.14	7.24	5.35	7.01
25-Oct-04	4.62	7.39	4.56	7.37	5.25	7.41	5.15	7.20	4.68	6.87
28-Oct-04	5.29	6.76	5.72	6.86	4.80	7.04	4.28	6.71	4.73	6.37
1-Nov-04	4.22	7.44	4.58	7.42	4.60	7.70	4.56	7.27	4.35	6.40
5-Nov-04	4.62	7.44	4.54	7.63	5.11	7.84	5.24	7.90	5.50	7.36
Mean	4.90	6.83	4.94	6.91	4.93	6.93	4.92	6.94	4.95	6.77
SD	0.35	0.30	0.34	0.34	0.31	0.41	0.41	0.36	0.34	0.34

Table B.6 The influent and effluent pH of Run III.

D/M/Y	R31		R32		R33		R34		R35	
	Influent	**Effluent**	**Influent**	**Effluent**	**Influent**	**Effluent**	**Influent**	**Effluent**	**Influent**	**Effluent**
14-Feb-05	4.62	7.80	4.49	7.90	5.20	7.75	5.17	7.58	4.83	7.57
17-Feb-05	5.22	7.76	4.51	7.86	4.82	7.72	5.21	7.63	4.42	7.66
21-Feb-05	4.86	7.02	4.47	7.15	4.62	7.84	4.88	6.98	4.94	7.08
24-Feb-05	4.80	7.24	4.96	6.99	5.17	7.45	5.16	7.10	5.37	7.28
28-Feb-05	4.64	7.18	4.82	7.13	5.23	7.42	5.18	7.43	4.54	7.36
3-Mar-05	4.86	7.10	4.89	7.57	4.96	7.33	4.54	7.35	4.58	7.56
7-Mar-05	4.71	7.34	4.93	7.37	4.74	7.57	4.61	7.58	5.20	7.51
10-Mar-05	4.86	7.66	4.87	7.59	4.68	7.41	4.65	7.81	5.14	7.64
14-Mar-05	5.22	7.06	5.24	6.72	5.28	7.06	5.04	7.35	4.82	7.46
17-Mar-05	4.66	7.42	4.80	6.40	4.54	7.36	4.81	6.91	5.54	7.82
21-Mar-05	4.73	7.49	4.66	6.65	4.45	7.65	5.64	7.61	5.15	7.53
24-Mar-05	5.18	7.61	5.15	7.25	5.27	7.96	4.74	7.98	4.62	7.70
28-Mar-05	4.81	7.65	4.59	6.77	4.81	7.70	4.49	7.59	4.74	8.25
31-Mar-05	4.32	7.66	4.56	6.91	4.67	7.94	4.57	7.91	4.72	7.77
4-Apr-05	4.56	7.13	5.05	7.34	5.02	7.33	4.36	7.53	5.06	7.23
7-Apr-05	4.66	7.28	5.21	7.42	5.12	7.48	4.82	7.87	4.65	7.82
11-Apr-05	5.25	6.97	5.08	7.07	4.77	7.13	5.04	7.67	4.41	7.39
14-Apr-05	5.35	6.99	5.41	7.28	4.98	7.31	4.76	7.81	4.67	7.41
18-Apr-05	4.50	7.18	4.80	7.33	5.28	7.64	4.25	7.35	4.75	7.67
21-Apr-05	4.66	7.39	4.61	7.24	4.95	7.62	4.80	7.88	4.79	7.50
25-Apr-05	4.57	7.28	5.23	7.30	4.56	7.25	4.53	7.63	4.82	7.64
28-Apr-05	4.80	7.43	5.04	7.70	4.36	7.73	4.50	7.94	4.95	7.44
2-May-05	4.37	7.39	4.47	7.35	4.68	7.85	5.17	7.84	5.26	7.51
6-May-05	4.85	7.53	4.94	7.32	5.21	7.50	5.18	7.47	5.06	7.59
Mean	4.79	7.36	4.87	7.23	4.89	7.54	4.84	7.58	4.88	7.56
SD	0.28	0.25	0.28	0.37	0.29	0.25	0.34	0.29	0.30	0.23

Table B.7 The influent and effluent temperature of Run I.

D/M/Y	R11		R12		R13		R14		R15	
	Influent	**Effluent**	**Influent**	**Effluent**	**Influent**	**Effluent**	**Influent**	**Effluent**	**Influent**	**Effluent**
9-Feb-04	21.50	19.70	19.70	20.20	19.70	20.50	21.50	20.90	20.20	20.80
12-Feb-04	21.30	20.40	21.90	21.50	21.50	20.70	21.90	22.10	21.00	20.80
16-Feb-04	21.20	20.40	21.30	20.40	21.50	21.20	21.20	21.40	20.90	21.20
19-Feb-04	21.90	21.00	21.80	21.30	22.00	21.70	21.90	21.00	22.20	21.70
23-Feb-04	27.80	27.70	27.90	27.70	27.40	27.70	27.80	27.70	28.30	27.70
26-Feb-04	28.70	27.60	28.50	27.60	28.50	28.90	28.70	28.60	27.80	28.90
1-Mar-04	28.30	28.10	28.10	27.90	28.30	28.10	28.30	28.50	27.90	28.30
4-Mar-04	27.60	27.80	27.90	27.80	27.60	27.20	28.40	28.50	28.80	28.00
8-Mar-04	27.80	27.00	28.90	28.60	28.10	27.60	27.80	28.10	28.30	28.10
11-Mar-04	27.70	27.60	29.30	28.20	27.70	27.60	29.10	29.50	28.10	28.80
15-Mar-04	28.30	28.00	28.20	28.40	27.80	27.80	28.40	29.00	28.00	27.80
18-Mar-04	28.60	27.90	28.60	27.70	28.60	28.50	28.40	28.10	27.30	28.50
22-Mar-04	29.30	29.20	29.10	29.20	29.30	29.00	28.00	29.70	27.90	27.70
25-Mar-04	28.70	27.60	28.40	28.00	28.70	28.50	28.10	27.60	28.40	28.00
29-Mar-04	29.10	28.80	29.00	28.80	29.50	29.30	28.50	28.00	29.00	28.80
1-Apr-04	29.60	28.70	29.50	29.40	29.60	29.80	28.80	28.40	28.60	28.40
5-Apr-04	27.70	27.10	27.80	27.50	27.70	27.10	27.70	27.10	27.80	27.50
8-Apr-04	28.80	27.80	28.90	27.80	29.20	27.80	28.80	27.80	28.90	27.80
12-Apr-04	29.80	29.60	30.00	29.60	29.80	28.60	29.80	28.60	30.00	29.60
15-Apr-04	28.80	28.30	29.20	29.30	28.80	28.30	28.80	28.30	29.70	29.30
19-Apr-04	30.00	28.80	30.40	28.50	29.60	28.60	30.00	28.00	30.40	28.80
22-Apr-04	30.50	28.80	30.20	28.70	30.30	28.90	30.50	28.40	30.80	28.80
26-Apr-04	31.70	31.20	31.50	31.50	31.80	31.50	31.70	31.30	31.90	31.20
30-Apr-04	31.80	31.50	31.70	31.30	32.00	31.40	31.80	31.30	32.00	31.50
Mean	27.77	27.11	27.83	27.37	27.71	27.35	27.75	27.41	27.68	27.42
SD	3.09	3.27	3.23	3.16	3.23	3.09	3.00	2.95	3.28	3.04

Table B.8 The influent and effluent temperature of Run II.

D/M/Y	**R21**		**R22**		**R23**		**R24**		**R25**	
	Influent	**Effluent**	**Influent**	**Effluent**	**Influent**	**Effluent**	**Influent**	**Effluent**	**Influent**	**Effluent**
16-Aug-04	27.80	27.00	28.90	28.60	28.10	27.60	27.80	28.10	28.30	28.10
19-Aug-04	27.70	27.60	29.30	28.20	27.70	27.60	29.10	29.50	28.10	28.80
23-Aug-04	28.30	28.00	28.20	28.40	27.80	27.80	28.40	29.00	28.00	27.80
26-Aug-04	28.60	27.90	28.60	27.70	28.60	28.50	28.40	28.10	27.30	28.50
30-Aug-04	27.20	26.90	26.90	26.90	26.10	27.00	27.20	26.80	27.10	26.90
2-Sep-04	27.10	26.80	27.00	26.90	26.60	26.40	26.30	25.50	25.80	25.30
6-Sep-04	25.90	25.10	25.40	24.90	25.10	25.10	25.30	24.90	25.50	25.60
9-Sep-04	24.80	24.50	24.40	24.40	24.40	24.40	24.30	24.30	24.60	24.60
13-Sep-04	24.60	24.70	24.40	24.40	24.70	24.70	24.80	25.10	25.20	25.50
16-Sep-04	25.80	25.50	25.20	25.30	25.40	25.30	25.40	25.30	25.50	25.40
20-Sep-04	25.90	24.70	25.40	24.60	25.10	24.60	24.40	24.50	25.30	24.80
23-Sep-04	26.40	25.90	26.60	25.80	26.30	25.30	25.00	24.40	26.20	25.00
27-Sep-04	28.30	26.80	28.20	26.90	27.90	26.90	26.30	25.80	26.90	25.80
30-Sep-04	25.30	24.30	24.90	23.60	23.70	23.90	24.20	24.00	24.20	24.00
4-Oct-04	26.50	26.20	25.90	25.50	26.40	26.00	25.30	26.00	25.60	24.80
7-Oct-04	26.30	25.90	25.70	26.10	25.90	25.70	25.50	26.00	25.90	25.80
11-Oct-04	30.00	28.60	29.60	28.90	28.50	28.20	28.90	28.90	28.60	27.80
14-Oct-04	26.60	26.50	26.40	26.10	25.90	26.00	25.90	26.30	26.00	25.90
18-Oct-04	26.50	26.40	26.30	26.10	26.30	25.90	26.00	26.10	25.80	25.70
21-Oct-04	26.90	26.50	26.60	26.20	26.30	26.10	25.90	26.20	25.90	25.90
25-Oct-04	27.60	27.40	26.90	26.70	26.80	26.60	26.40	26.70	27.10	26.90
28-Oct-04	26.70	26.30	26.10	25.70	26.10	25.50	25.70	25.30	25.30	25.20
1-Nov-04	25.50	25.20	25.20	25.60	25.30	25.30	25.50	25.70	25.80	25.90
5-Nov-04	27.70	27.30	26.80	26.40	26.70	26.40	25.70	26.20	26.00	25.90
Mean	26.83	26.33	26.62	26.25	26.32	26.12	26.15	26.20	26.25	26.08
SD	1.28	1.18	1.51	1.41	1.30	1.23	1.43	1.53	1.17	1.29

Table B.9 The influent and effluent temperature of Run III.

D/M/Y	R31		R32		R33		R34		R35	
	Influent	**Effluent**	**Influent**	**Effluent**	**Influent**	**Effluent**	**Influent**	**Effluent**	**Influent**	**Effluent**
14-Feb-05	28.70	27.60	27.70	27.30	27.70	27.20	28.30	28.00	28.20	28.70
17-Feb-05	28.30	28.10	27.90	27.60	28.00	27.90	28.10	28.00	27.60	27.80
21-Feb-05	29.80	28.60	29.50	29.20	29.20	29.20	29.90	29.70	30.20	29.90
24-Feb-05	27.80	27.00	27.20	27.10	28.20	27.30	28.60	28.10	29.50	29.20
28-Feb-05	28.30	28.00	27.90	28.30	28.40	27.80	28.20	28.30	28.00	27.90
3-Mar-05	29.30	29.60	29.80	29.20	29.80	29.40	30.30	29.90	30.80	30.50
7-Mar-05	23.80	23.70	23.70	23.80	24.00	24.20	24.50	24.40	25.00	25.20
10-Mar-05	25.80	24.50	24.40	24.40	24.40	24.40	24.30	24.30	24.60	24.60
14-Mar-05	24.90	24.10	24.80	23.80	25.10	25.20	25.10	24.80	25.90	25.10
17-Mar-05	25.30	24.70	25.50	24.70	26.40	25.90	25.50	24.30	26.10	25.60
21-Mar-05	24.80	24.50	24.40	23.80	24.40	24.40	24.30	24.30	24.60	24.60
24-Mar-05	28.90	27.90	28.80	28.20	29.10	28.20	29.10	28.80	28.90	28.90
28-Mar-05	31.30	29.60	31.50	29.70	31.40	29.90	31.50	30.40	31.10	30.60
31-Mar-05	30.40	29.00	30.10	29.00	30.10	28.70	30.00	28.30	29.50	28.70
4-Apr-05	32.20	30.10	31.60	29.60	32.20	29.80	32.00	30.30	32.00	30.30
7-Apr-05	29.50	28.30	30.00	28.80	30.60	27.30	31.20	28.10	30.80	29.00
11-Apr-05	30.30	29.30	29.70	29.80	29.70	29.20	29.90	28.90	29.40	28.60
14-Apr-05	30.00	28.50	29.90	29.50	29.70	29.10	29.10	28.60	29.20	29.50
18-Apr-05	26.50	25.40	26.30	25.10	26.10	24.90	26.00	25.10	24.80	24.70
21-Apr-05	27.90	26.30	27.20	26.20	27.30	26.70	26.90	25.70	27.00	26.10
25-Apr-05	25.70	24.80	25.90	24.70	26.00	24.50	26.40	25.00	26.10	24.90
28-Apr-05	25.40	25.10	25.10	24.90	25.60	25.50	25.70	25.30	25.30	25.20
2-May-05	26.50	25.20	26.20	25.60	26.30	25.50	26.50	25.70	25.80	25.90
6-May-05	28.90	27.30	29.20	27.90	28.60	27.40	29.20	28.20	29.00	27.90
Mean	27.93	26.97	27.68	27.01	27.85	27.07	27.94	27.19	27.89	27.48
SD	2.28	2.02	2.34	2.17	2.30	1.90	2.37	2.12	2.31	2.12

Table B.10 The influent and effluent S-COD concentrations of Run I.

D/M/Y	R11			R12			R13			R14			R15		
	Influent (mg/L)	**Effluent (mg/L)**	**R.E. %**	**Influent (mg/L)**	**Effluent (mg/L)**	**R.E. %**	**Influent (mg/L)**	**Effluent (mg/L)**	**R.E. %**	**Influent (mg/L)**	**Effluent (mg/L)**	**R.E. %**	**Influent (mg/L)**	**Effluent (mg/L)**	**R.E. %**
9-Feb-04	763	213	72.08	725	127	82.48	725	225	68.97	763	300	60.68	813	230	71.71
12-Feb-04	658	146	77.81	658	155	76.44	642	232	63.86	658	310	52.89	658	217	67.02
16-Feb-04	664	182	72.59	709	109	84.63	664	173	73.95	709	291	58.96	664	217	67.32
19-Feb-04	646	143	77.86	673	109	83.80	646	168	73.99	682	218	68.04	709	186	73.77
23-Feb-04	743	189	74.56	709	169	76.16	677	146	78.43	677	258	61.89	649	170	73.81
26-Feb-04	694	138	80.12	688	106	84.59	706	106	84.99	659	212	67.83	659	253	61.61
1-Mar-04	709	109	84.63	682	182	73.31	682	164	75.95	727	145	80.06	727	167	77.03
4-Mar-04	686	171	75.07	754	234	68.97	686	246	64.14	714	137	80.81	714	173	75.77
8-Mar-04	767	183	76.14	719	186	74.13	767	136	82.27	782	174	77.75	719	165	77.05
11-Mar-04	677	134	80.21	646	141	78.17	646	169	73.84	711	168	76.37	711	196	72.43
15-Mar-04	700	141	79.86	721	268	62.83	721	175	75.73	737	234	68.25	700	206	70.57
18-Mar-04	731	145	80.16	698	168	75.93	698	126	81.95	731	249	65.94	731	223	69.49
22-Mar-04	654	175	73.24	654	195	70.18	630	254	59.68	711	210	70.46	654	186	71.56
25-Mar-04	614	138	77.52	614	174	71.66	697	171	75.47	660	175	73.48	614	171	72.15
29-Mar-04	683	206	69.84	637	154	75.82	683	103	84.92	771	137	82.23	720	243	66.25
1-Apr-04	637	158	75.20	637	203	68.13	600	179	70.17	679	158	76.73	637	158	75.20
5-Apr-04	670	157	76.57	703	165	76.53	670	178	73.43	746	114	84.72	697	211	69.73
8-Apr-04	689	136	80.26	747	244	67.34	689	239	65.31	658	111	83.13	747	186	75.10
12-Apr-04	717	196	72.66	696	153	78.02	717	254	64.57	733	109	85.13	717	173	75.87
15-Apr-04	741	188	74.63	741	186	74.90	779	241	69.06	718	210	70.75	741	167	77.46
19-Apr-04	650	145	77.69	717	167	76.71	717	185	74.20	650	233	64.15	733	180	75.44
22-Apr-04	650	138	78.77	667	168	74.81	667	167	74.96	724	183	74.72	724	183	74.72
26-Apr-04	684	167	75.58	732	126	82.79	732	179	75.55	658	163	75.23	658	232	64.74
30-Apr-04	651	186	71.43	663	174	73.76	663	159	76.02	651	173	73.43	663	251	62.14
Mean	687	162	76.43	691	169	75.51	688	182	73.49	705	195	72.37	698	198	71.69
SD	41	27	3.52	38	41	5.64	42	45	6.70	40	59	8.64	44	29	4.68

Table B.11 The influent and effluent S-COD concentrations of Run II.

D/M/Y	**R21**			**R22**			**R23**			**R24**			**R25**		
	Influent (mg/L)	**Effluent (mg/L)**	**R.E. %**	**Influent (mg/L)**	**Effluent (mg/L)**	**R.E. %**	**Influent (mg/L)**	**Effluent (mg/L)**	**R.E. %**	**Influent (mg/L)**	**Effluent (mg/L)**	**R.E. %**	**Influent (mg/L)**	**Effluent (mg/L)**	**R.E. %**
16-Aug-04	738	78	89.43	719	62	91.38	801	95	88.14	868	97	88.82	781	114	85.40
19-Aug-04	649	121	81.36	652	64	90.18	698	105	84.96	806	108	86.60	746	135	81.90
23-Aug-04	727	55	92.43	754	75	90.05	721	95	86.82	836	102	87.80	851	106	87.54
26-Aug-04	682	147	78.45	676	71	89.50	664	105	84.19	694	97	86.02	653	135	79.33
30-Aug-04	629	119	81.08	629	79	87.44	567	95	83.25	723	106	85.34	741	106	85.70
2-Sep-04	682	88	87.10	600	73	87.83	653	95	85.45	706	95	86.54	741	135	81.78
6-Sep-04	702	106	84.90	635	71	88.82	653	102	84.38	706	97	86.26	776	135	82.60
9-Sep-04	600	103	82.83	651	104	84.02	668	71	89.37	720	102	85.83	754	120	84.08
13-Sep-04	617	69	88.82	651	86	86.79	668	79	88.17	720	105	85.42	754	135	82.10
16-Sep-04	600	103	82.83	634	111	82.49	651	71	89.09	686	95	86.15	754	120	84.08
20-Sep-04	600	86	85.67	617	69	88.82	668	51	92.37	703	92	86.91	737	114	84.53
23-Sep-04	638	109	82.92	617	51	91.73	668	51	92.37	703	92	86.91	754	114	84.88
27-Sep-04	682	69	89.88	600	51	91.50	668	47	92.96	720	104	85.56	771	106	86.25
30-Sep-04	748	51	93.18	600	37	93.83	634	47	92.59	651	95	85.41	771	106	86.25
4-Oct-04	703	69	90.18	634	51	91.96	651	47	92.78	687	97	85.88	771	106	86.25
7-Oct-04	741	34	95.41	617	34	94.49	651	51	92.17	686	97	85.86	771	91	88.20
11-Oct-04	600	51	91.50	651	69	89.40	686	44	93.59	703	105	85.06	754	91	87.93
14-Oct-04	600	34	94.33	651	34	94.78	686	51	92.57	720	92	87.22	771	91	88.20
18-Oct-04	617	51	91.73	634	34	94.64	686	44	93.59	720	97	86.53	771	87	88.72
21-Oct-04	600	51	91.50	651	34	94.78	686	51	92.57	720	85	88.19	771	87	88.72
25-Oct-04	683	51	92.53	634	47	92.59	686	51	92.57	737	79	89.28	771	91	88.20
28-Oct-04	617	51	91.73	651	34	94.78	703	44	93.74	737	79	89.28	788	91	88.45
1-Nov-04	600	51	91.50	651	34	94.78	669	51	92.38	720	79	89.03	754	87	88.46
5-Nov-04	600	51	91.50	651	34	94.78	685	51	92.55	720	75	89.58	771	87	88.72
Mean	652	75	88.51	644	59	90.89	674	66	90.14	725	95	86.94	762	108	85.83
SD	53	31	4.77	35	23	3.53	40	23	3.52	48	9	1.43	32	18	2.72

Table B.12 The influent and effluent S-COD concentrations of Run III.

D/M/Y	R31			R32			R33			R34			R35		
	Influent (mg/L)	**Effluent (mg/L)**	**R.E. %**	**Influent (mg/L)**	**Effluent (mg/L)**	**R.E. %**	**Influent (mg/L)**	**Effluent (mg/L)**	**R.E. %**	**Influent (mg/L)**	**Effluent (mg/L)**	**R.E. %**	**Influent (mg/L)**	**Effluent (mg/L)**	**R.E. %**
14-Feb-05	735	115	84.36	606	102	83.17	649	105	83.83	606	124	79.55	620	115	81.45
17-Feb-05	697	141	79.78	617	102	83.47	644	120	81.38	617	115	81.36	625	115	81.59
21-Feb-05	617	102	83.47	644	95	85.25	617	105	82.98	617	102	83.47	625	120	80.80
24-Feb-05	617	102	83.47	617	95	84.61	651	102	84.34	720	102	85.83	720	115	84.03
28-Feb-05	667	83	87.56	617	115	81.36	617	105	82.97	667	138	79.30	700	120	82.86
3-Mar-05	720	83	88.47	720	115	84.03	668	115	82.78	668	147	77.99	720	135	81.25
7-Mar-05	651	115	82.33	600	83	86.17	600	102	83.00	600	147	75.50	630	138	78.10
10-Mar-05	600	115	80.83	651	102	84.33	668	120	82.04	720	138	80.83	720	138	80.83
14-Mar-05	617	83	86.55	651	83	87.25	668	135	79.79	720	102	85.83	668	138	79.34
17-Mar-05	686	75	89.07	634	102	83.91	651	102	84.33	686	138	79.88	651	102	84.33
21-Mar-05	671	75	88.82	741	115	84.48	741	102	86.23	671	138	79.43	741	147	80.16
24-Mar-05	812	102	87.44	847	115	86.42	847	120	85.83	812	138	83.00	812	154	81.03
28-Mar-05	720	141	80.42	720	102	85.83	668	102	84.73	668	120	82.04	720	138	80.83
31-Mar-05	671	115	82.86	600	120	80.00	600	115	80.83	600	115	80.83	671	115	82.86
4-Apr-05	617	135	78.12	667	120	82.01	667	102	84.71	700	120	82.86	667	138	79.31
7-Apr-05	606	120	80.20	620	102	83.55	606	135	77.72	649	120	81.51	620	135	78.23
11-Apr-05	833	141	83.07	933	120	87.14	800	144	82.00	933	138	85.21	900	135	85.00
14-Apr-05	800	141	82.35	933	115	87.67	933	105	88.75	933	135	85.53	933	135	85.53
18-Apr-05	847	154	81.82	847	102	87.96	812	105	87.07	812	135	83.37	812	135	83.37
21-Apr-05	847	154	81.82	847	120	85.83	847	102	87.96	847	120	85.83	847	120	85.83
25-Apr-05	847	141	83.35	847	115	86.42	847	105	87.60	812	120	85.22	812	115	85.84
28-Apr-05	800	115	85.63	800	92	88.50	933	102	89.07	933	120	87.14	900	135	85.00
2-May-05	700	115	83.57	667	95	85.76	700	102	85.43	700	120	82.86	667	120	82.01
6-May-05	671	102	84.79	671	95	85.84	671	105	84.35	671	115	82.85	671	102	84.80
Mean	710	115	83.78	712	105	85.25	713	111	84.47	723	125	82.68	727	128	82.47
SD	85	24	3.02	109	12	2.13	105	12	2.83	106	14	2.90	97	14	2.40

Table B.13 The influent and effluent TSS concentrations of Run I.

D/M/Y	R11			R12			R13			R14			R15		
	Influent (mg/L)	Effluent (mg/L)	R.E. %	Influent (mg/L)	Effluent (mg/L)	R.E. %	Influent (mg/L)	Effluent (mg/L)	R.E. %	Influent (mg/L)	Effluent (mg/L)	R.E. %	Influent (mg/L)	Effluent (mg/L)	R.E. %
9-Feb-04	84	8	90.48	90	22	75.56	100	22	78.00	136	26	80.88	98	26	73.47
12-Feb-04	112	12	89.29	102	14	86.27	94	14	85.11	94	16	82.98	92	20	78.26
16-Feb-04	108	14	87.04	92	14	84.78	110	22	80.00	98	10	89.80	102	16	84.31
19-Feb-04	116	14	87.93	92	16	82.61	106	16	84.91	76	16	78.95	114	20	82.46
23-Feb-04	104	6	94.23	92	12	86.96	104	14	86.54	94	34	63.83	112	14	87.50
26-Feb-04	132	11	91.67	124	28	77.42	138	12	91.30	108	10	90.74	120	18	85.00
1-Mar-04	110	6	94.55	80	12	85.00	92	14	84.78	90	12	86.67	98	28	71.43
4-Mar-04	130	20	84.62	90	34	62.22	114	40	64.91	86	32	62.79	112	26	76.79
8-Mar-04	96	4	95.83	98	18	81.63	116	30	74.14	96	16	83.33	106	14	86.79
11-Mar-04	108	16	85.19	118	12	89.83	120	20	83.33	92	22	76.09	86	18	79.07
15-Mar-04	94	8	91.49	124	10	91.94	90	20	77.78	104	12	88.46	92	10	89.13
18-Mar-04	112	14	87.50	84	18	78.57	112	24	78.57	128	24	81.25	114	24	78.95
22-Mar-04	124	22	82.26	96	24	75.00	96	18	81.25	110	16	85.45	86	18	79.07
25-Mar-04	104	14	86.54	86	12	86.05	138	26	81.16	116	22	81.03	92	20	78.26
29-Mar-04	118	14	88.14	112	14	87.50	116	26	77.59	122	16	86.89	88	22	75.00
1-Apr-04	98	8	91.84	106	18	83.02	112	28	75.00	114	22	80.70	126	12	90.48
5-Apr-04	86	28	67.44	88	20	77.27	106	32	69.81	112	14	87.50	118	14	88.14
8-Apr-04	116	14	87.93	112	24	78.57	122	14	88.52	114	18	84.21	108	14	87.04
12-Apr-04	122	26	78.69	90	12	86.67	98	32	67.35	120	20	83.33	92	28	69.57
15-Apr-04	142	16	88.73	132	16	87.88	104	26	75.00	96	32	66.67	104	32	69.23
19-Apr-04	92	22	76.09	116	26	77.59	116	24	79.31	120	38	68.33	108	24	77.78
22-Apr-04	94	14	85.11	96	18	81.25	128	32	75.00	80	34	57.50	114	30	73.68
26-Apr-04	122	10	91.80	118	18	84.75	136	26	80.88	128	20	84.38	124	28	77.42
30-Apr-04	94	12	87.23	118	18	84.75	130	24	81.54	110	32	70.91	98	32	67.35
Mean	109	14	87.28	102	18	82.49	112	23	79.39	106	21	79.80	104	21	79.71
SD	15	6	6.27	15	6	6.28	14	7	6.39	16	8	9.32	12	7	6.76

Table B.14 The influent and effluent TSS concentrations of Run II.

D/M/Y	R21			R22			R23			R24			R25		
	Influent (mg/L)	**Effluent (mg/L)**	**R.E. %**	**Influent (mg/L)**	**Effluent (mg/L)**	**R.E. %**	**Influent (mg/L)**	**Effluent (mg/L)**	**R.E. %**	**Influent (mg/L)**	**Effluent (mg/L)**	**R.E. %**	**Influent (mg/L)**	**Effluent (mg/L)**	**R.E. %**
16-Aug-04	148	29	80.41	156	20	87.18	150	22	85.33	139	23	83.45	143	24	83.22
19-Aug-04	130	28	78.46	145	18	87.59	129	11	91.47	126	25	80.16	127	23	81.89
23-Aug-04	137	23	83.21	124	11	91.13	171	17	90.06	118	25	78.81	149	25	83.22
26-Aug-04	157	12	92.36	167	19	88.62	124	29	76.61	191	15	92.15	177	17	90.40
30-Aug-04	182	29	84.07	206	17	91.75	149	16	89.26	200	14	93.00	181	13	92.82
2-Sep-04	162	19	88.27	161	15	90.68	189	26	86.24	224	12	94.64	221	14	93.67
6-Sep-04	155	21	86.45	140	29	79.29	157	25	84.08	170	14	91.76	206	18	91.26
9-Sep-04	182	16	91.21	105	18	82.86	156	16	89.74	139	23	83.45	237	21	91.14
13-Sep-04	229	18	92.14	118	20	83.05	182	25	86.26	199	23	88.44	193	20	89.64
16-Sep-04	188	13	93.09	160	10	93.75	186	26	86.02	129	19	85.27	151	28	81.46
20-Sep-04	146	21	85.62	126	15	88.10	227	12	94.71	129	14	89.15	140	23	83.57
23-Sep-04	173	25	85.55	131	16	87.79	199	12	93.97	150	27	82.00	158	16	89.87
27-Sep-04	162	18	88.89	176	12	93.18	152	29	80.92	199	11	94.47	203	29	85.71
30-Sep-04	190	41	78.42	202	27	86.63	195	28	85.64	168	12	92.86	146	19	86.99
4-Oct-04	221	17	92.31	159	12	92.45	243	13	94.65	207	17	91.79	133	29	78.20
7-Oct-04	157	20	87.26	155	18	88.39	174	28	83.91	127	16	87.40	115	10	91.30
11-Oct-04	140	22	84.29	188	12	93.62	151	21	86.09	150	24	84.00	123	13	89.43
14-Oct-04	153	10	93.46	186	20	89.25	136	13	90.44	158	23	85.44	130	15	88.46
18-Oct-04	149	22	85.23	166	22	86.75	199	15	92.46	182	24	86.81	161	29	81.99
21-Oct-04	142	11	92.25	175	13	92.57	124	20	83.87	155	15	90.32	128	26	79.69
25-Oct-04	137	16	88.32	180	18	90.00	112	24	78.57	130	25	80.77	144	23	84.03
28-Oct-04	124	25	79.84	153	25	83.66	123	23	81.30	128	13	89.84	130	20	84.62
1-Nov-04	126	12	90.48	171	18	89.47	113	26	76.99	129	14	89.15	157	27	82.80
5-Nov-04	139	17	87.77	166	26	84.34	138	24	82.61	154	16	89.61	182	15	91.76
Mean	160	20	87.33	159	18	88.71	162	21	87.08	158	19	88.32	160	21	87.04
SD	28	7	4.69	26	5	3.79	35	6	5.28	31	5	4.66	33	6	4.53

Table B.15 The influent and effluent TSS concentrations of Run III.

D/M/Y	R31			R32			R33			R34			R35		
	Influent (mg/L)	Effluent (mg/L)	R.E. %	Influent (mg/L)	Effluent (mg/L)	R.E. %	Influent (mg/L)	Effluent (mg/L)	R.E. %	Influent (mg/L)	Effluent (mg/L)	R.E. %	Influent (mg/L)	Effluent (mg/L)	R.E. %
14-Feb-05	107	13	87.85	124	14	88.71	111	6	94.59	128	24	81.25	114	17	85.09
17-Feb-05	122	10	91.80	129	21	83.72	97	10	89.69	122	27	77.87	120	12	90.00
21-Feb-05	124	13	89.52	165	14	91.52	161	14	91.30	177	13	92.66	137	8	94.16
24-Feb-05	104	17	83.65	136	16	88.24	152	24	84.21	142	35	75.35	132	10	92.42
28-Feb-05	146	33	77.40	140	18	87.14	170	30	82.35	169	33	80.47	135	16	88.15
3-Mar-05	126	21	83.33	145	11	92.41	140	16	88.57	179	25	86.03	146	11	92.47
7-Mar-05	128	10	92.19	157	23	85.35	159	18	88.68	183	15	91.80	127	10	92.13
10-Mar-05	172	37	78.49	197	22	88.83	164	33	79.88	194	22	88.66	172	24	86.05
14-Mar-05	166	26	84.34	237	52	78.06	184	29	84.24	235	57	75.74	166	18	89.16
17-Mar-05	197	32	83.76	201	58	71.14	193	31	83.94	215	52	75.81	197	28	85.79
21-Mar-05	226	44	80.53	179	34	81.01	175	42	76.29	179	48	73.11	179	16	91.06
24-Mar-05	185	31	83.24	185	16	91.35	219	27	87.90	226	52	76.99	140	19	86.43
28-Mar-05	155	24	84.52	216	32	85.19	209	31	85.13	205	32	84.39	140	25	82.14
31-Mar-05	171	19	88.89	182	51	71.98	189	39	79.31	168	41	75.52	164	32	80.49
4-Apr-05	211	46	78.20	126	4	96.83	158	0	100.00	134	10	92.54	146	23	84.25
7-Apr-05	188	25	86.70	145	0	100.00	108	0	100.00	132	0	100.00	182	37	79.67
11-Apr-05	175	18	89.71	151	6	96.03	148	6	96.27	135	23	82.90	153	10	93.77
14-Apr-05	185	21	88.92	176	20	88.60	160	32	79.94	169	21	87.54	163	13	92.31
18-Apr-05	164	13	92.07	150	4	97.66	204	5	97.79	159	2	99.05	183	16	91.23
21-Apr-05	180	12	93.61	150	7	95.65	200	9	95.75	182	21	88.46	175	10	94.27
25-Apr-05	206	35	83.25	237	41	82.91	176	25	85.80	173	37	78.90	163	26	84.05
28-Apr-05	185	25	86.49	198	25	87.37	207	35	83.09	224	51	77.18	192	45	76.50
2-May-05	223	33	85.20	153	13	91.50	159	11	93.38	153	10	93.46	153	0	100.00
6-May-05	203	17	91.63	142	0	100.00	180	3	98.61	172	14	91.86	147	0	100.00
Mean	169	24	85.84	167	21	87.55	168	20	88.25	173	28	84.01	155	18	88.59
SD	36	10	4.69	33	16	7.76	32	13	7.10	32	16	8.01	23	11	5.99

Table B.16 The influent and effluent S^{2-} concentrations of Run I.

D/M/Y	R11			R12			R13			R14			R15		
	Influent (mg/L)	**Effluent (mg/L)**	**R.E. %**	**Influent (mg/L)**	**Effluent (mg/L)**	**R.E. %**	**Influent (mg/L)**	**Effluent (mg/L)**	**R.E. %**	**Influent (mg/L)**	**Effluent (mg/L)**	**R.E. %**	**Influent (mg/L)**	**Effluent (mg/L)**	**R.E. %**
9-Feb-04	3.2	0.0	100.00	5.0	0.2	96.00	4.6	0.5	89.13	5.0	0.7	86.00	3.4	0.0	100.00
12-Feb-04	4.4	0.4	90.91	5.4	1.2	77.78	5.8	1.2	79.31	4.8	0.5	89.58	4.6	0.6	86.96
16-Feb-04	3.0	0.0	100.00	4.0	0.4	90.00	4.8	0.9	81.25	3.6	0.2	94.44	3.2	0.0	100.00
19-Feb-04	5.0	0.4	92.00	4.6	0.4	91.30	3.4	0.6	82.35	4.2	0.8	80.95	3.8	0.8	78.95
23-Feb-04	5.6	2.4	57.14	6.0	1.2	80.00	3.6	0.8	77.78	5.1	1.0	80.39	2.2	0.4	81.82
26-Feb-04	5.5	1.6	70.91	4.8	1.3	72.92	2.6	0.5	80.77	6.4	1.4	78.13	2.0	0.0	100.00
1-Mar-04	4.0	1.3	67.50	5.7	0.9	84.21	3.8	0.8	78.95	4.7	0.8	82.98	2.3	0.0	100.00
4-Mar-04	4.8	0.7	85.42	5.6	0.4	92.86	5.8	0.3	94.83	4.1	0.8	80.49	3.1	0.2	93.55
8-Mar-04	4.9	0.4	91.84	5.2	0.2	96.15	4.4	0.2	95.45	3.7	1.0	72.97	2.8	0.8	71.43
11-Mar-04	4.1	0.6	85.37	4.7	0.5	89.36	3.3	0.3	90.91	2.5	0.4	84.00	2.4	0.6	75.00
15-Mar-04	4.4	0.5	88.64	3.0	0.3	90.00	3.7	0.4	89.19	4.1	0.4	90.24	4.5	1.3	71.11
18-Mar-04	3.6	0.6	83.33	4.1	0.4	90.24	4.1	0.6	85.37	3.6	0.6	83.33	4.2	0.7	83.33
22-Mar-04	3.2	0.4	87.50	3.8	0.2	94.74	3.7	0.6	83.78	4.2	0.8	80.95	3.4	0.7	79.41
25-Mar-04	2.8	1.0	64.29	2.1	0.4	80.95	2.5	1.1	56.00	4.5	1.0	77.78	4.1	0.8	80.49
29-Mar-04	3.2	0.1	96.88	3.1	0.3	90.32	2.4	0.1	95.83	3.1	0.1	96.77	5.5	1.2	78.18
1-Apr-04	2.6	0.6	76.92	2.7	0.9	66.67	3.3	0.7	78.79	4.2	1.2	71.43	4.6	0.6	86.96
5-Apr-04	3.6	0.5	86.11	4.9	0.6	87.76	3.2	0.5	84.38	2.2	0.6	72.73	3.9	0.9	76.92
8-Apr-04	4.6	0.5	89.13	2.5	0.5	80.00	3.2	0.4	87.50	2.5	0.4	84.00	3.5	0.5	85.71
12-Apr-04	3.2	0.6	81.25	2.8	0.3	89.29	4.4	0.3	93.18	3.6	0.2	94.44	4.4	0.6	86.36
15-Apr-04	4.4	0.4	90.91	3.3	0.2	93.94	5.3	0.2	96.23	2.6	0.3	88.46	4.8	0.3	93.75
19-Apr-04	2.8	0.3	89.29	2.6	0.2	92.31	4.4	0.2	95.45	4.4	0.9	79.55	6.5	0.5	92.31
22-Apr-04	2.2	0.1	95.45	2.7	0.7	74.07	3.2	0.1	96.88	3.1	0.2	93.55	5.5	0.1	98.18
26-Apr-04	2.3	0.2	91.30	4.2	0.6	85.71	2.8	0.3	89.29	2.0	0.1	95.00	4.0	0.3	92.50
30-Apr-04	4.1	0.5	87.80	3.5	0.4	88.57	3.2	0.4	87.50	2.3	0.2	91.30	3.4	0.6	82.35
Mean	3.8	0.6	84.59	4.0	0.5	86.81	3.8	0.5	86.89	3.8	0.6	83.87	3.8	0.5	86.43
SD	1.0	0.5	10.95	1.2	0.3	7.82	1.0	0.3	9.02	1.1	0.4	7.46	1.1	0.4	9.30

Table B.17 The influent and effluent S^{2-} concentrations of Run II.

D/M/Y	R21			R22			R23			R24			R25		
	Influent (mg/L)	**Effluent (mg/L)**	**R.E. %**	**Influent (mg/L)**	**Effluent (mg/L)**	**R.E. %**	**Influent (mg/L)**	**Effluent (mg/L)**	**R.E. %**	**Influent (mg/L)**	**Effluent (mg/L)**	**R.E. %**	**Influent (mg/L)**	**Effluent (mg/L)**	**R.E. %**
16-Aug-04	5.0	0.7	86.00	5.6	0.2	96.43	5.2	0.1	98.08	4.5	0.2	95.56	4.6	0.2	95.65
19-Aug-04	2.7	0.3	88.89	4.8	0.3	93.75	3.2	0.4	87.50	3.7	0.6	83.78	3.9	0.4	89.74
23-Aug-04	3.4	1.1	67.65	3.5	0.3	91.43	4.5	0.2	95.56	4.1	1.1	73.17	3.1	0.1	96.77
26-Aug-04	4.0	0.3	92.50	4.2	0.2	95.24	3.8	0.1	97.37	3.0	0.6	80.00	4.3	0.6	86.05
30-Aug-04	3.8	0.3	92.11	4.9	0.1	97.96	3.5	0.1	97.14	4.6	0.5	89.13	3.4	0.2	94.12
2-Sep-04	2.4	0.3	87.50	3.6	0.4	88.89	3.5	0.2	94.29	3.9	0.3	92.31	4.6	0.1	97.83
6-Sep-04	4.0	0.6	85.00	5.1	0.7	86.27	4.7	0.4	91.49	5.4	1.0	81.48	5.0	0.2	96.00
9-Sep-04	3.3	0.2	93.94	4.0	0.6	85.00	3.2	0.2	93.75	4.2	0.4	90.48	3.5	0.2	94.29
13-Sep-04	3.4	0.3	91.18	3.8	0.4	89.47	3.5	0.1	97.14	3.5	0.6	82.86	5.7	1.0	82.46
16-Sep-04	4.4	0.4	90.91	2.5	0.7	72.00	5.1	0.6	88.24	4.8	0.4	91.67	4.6	0.3	93.48
20-Sep-04	6.2	0.5	91.94	3.3	0.2	93.94	3.4	0.1	97.06	4.7	0.4	91.49	3.7	0.6	83.78
23-Sep-04	4.9	0.3	93.88	5.3	0.1	98.11	2.3	0.2	91.30	5.2	0.4	92.31	4.9	0.4	91.84
27-Sep-04	4.4	0.4	90.91	5.0	0.3	94.00	3.1	0.2	93.55	3.2	0.3	90.63	5.5	0.3	94.55
30-Sep-04	5.6	0.1	98.21	3.9	0.2	94.87	3.9	0.1	97.44	4.3	0.1	97.67	4.2	0.1	97.62
4-Oct-04	3.8	0.5	86.84	4.3	0.4	90.70	5.1	0.5	90.20	5.6	0.2	96.43	4.0	0.3	92.50
7-Oct-04	4.6	0.3	93.48	3.4	0.2	94.12	4.1	0.2	95.12	4.2	0.3	92.86	5.8	0.1	98.28
11-Oct-04	3.8	0.2	94.74	3.8	0.3	92.11	3.4	0.2	94.12	3.9	0.4	89.74	3.5	0.2	94.29
14-Oct-04	4.0	0.4	90.00	4.6	0.7	84.78	4.7	0.5	89.36	2.7	0.4	85.19	3.2	0.3	90.63
18-Oct-04	2.8	0.3	89.29	4.1	0.2	95.12	3.6	0.3	91.67	3.8	0.4	89.47	2.5	0.2	92.00
21-Oct-04	3.1	0.7	77.42	5.2	0.6	88.46	4.4	0.5	88.64	2.9	0.4	86.21	2.8	0.3	89.29
25-Oct-04	3.8	0.3	92.11	3.7	0.4	89.19	3.7	0.5	86.49	2.4	0.3	87.50	3.1	0.2	93.55
28-Oct-04	4.1	0.7	82.93	2.6	0.9	65.38	2.9	0.4	86.21	3.1	0.5	83.87	4.1	0.3	92.68
1-Nov-04	2.9	0.6	79.31	4.1	0.7	82.93	3.3	0.6	81.82	2.6	0.5	80.77	2.8	0.4	85.71
5-Nov-04	3.0	0.4	86.67	2.1	0.6	71.43	2.7	0.5	81.48	2.8	0.6	78.57	2.7	0.3	88.89
Mean	3.9	0.4	89.08	4.1	0.4	90.04	3.8	0.3	92.07	3.9	0.5	88.29	4.0	0.3	92.36
SD	0.9	0.2	6.56	0.9	0.2	8.54	0.8	0.2	4.87	0.9	0.2	6.13	1.0	0.2	4.38

Table B.18 The influent and effluent S^{2-} concentrations of Run III.

D/M/Y	R31			R32			R33			R34			R35		
	Influent (mg/L)	**Effluent (mg/L)**	**R.E. %**	**Influent (mg/L)**	**Effluent (mg/L)**	**R.E. %**	**Influent (mg/L)**	**Effluent (mg/L)**	**R.E. %**	**Influent (mg/L)**	**Effluent (mg/L)**	**R.E. %**	**Influent (mg/L)**	**Effluent (mg/L)**	**R.E. %**
14-Feb-05	2.3	0.3	86.96	4.6	0.6	86.96	5.2	0.5	90.38	4.1	0.4	90.24	2.9	0.2	93.10
17-Feb-05	2.5	0.5	80.00	4.2	0.6	85.71	4.0	0.9	77.50	3.7	0.5	86.49	2.9	0.3	89.66
21-Feb-05	5.5	0.2	96.36	5.1	0.1	98.04	6.8	0.3	95.59	2.2	0.1	95.45	4.9	0.1	97.96
24-Feb-05	5.8	0.1	98.28	7.2	0.2	97.22	5.2	0.1	98.08	4.0	0.1	97.50	5.4	0.1	98.15
28-Feb-05	5.3	0.4	92.45	3.5	0.3	91.43	6.1	0.2	96.72	2.9	0.1	96.55	3.4	0.1	97.06
3-Mar-05	6.2	0.2	96.77	3.1	0.7	77.42	5.6	0.6	89.29	3.9	0.2	94.87	4.8	0.1	97.92
7-Mar-05	4.1	0.4	90.24	4.1	0.3	92.68	3.9	0.1	97.44	6.5	1.4	78.46	5.7	0.3	94.74
10-Mar-05	5.5	0.6	89.09	6.3	1.0	84.13	4.8	1.1	77.08	5.4	0.8	85.19	4.2	0.6	85.71
14-Mar-05	4.8	0.0	100.00	4.6	0.6	86.96	2.6	0.3	88.46	3.2	0.0	100.00	4.8	0.2	95.83
17-Mar-05	6.2	1.0	83.87	3.8	0.0	100.00	2.8	0.4	85.71	2.6	0.3	88.46	2.8	0.1	96.43
21-Mar-05	4.2	0.2	95.24	4.6	0.0	100.00	3.6	0.0	100.00	3.8	0.0	100.00	2.4	0.0	100.00
24-Mar-05	3.4	0.0	100.00	4.6	0.0	100.00	4.2	0.0	100.00	5.1	0.0	100.00	3.7	0.0	100.00
28-Mar-05	4.2	0.0	100.00	5.0	0.0	100.00	6.6	0.0	100.00	4.8	0.4	91.67	6.2	1.4	77.42
31-Mar-05	3.0	0.0	100.00	2.8	0.0	100.00	4.2	0.0	100.00	4.2	0.2	95.24	6.0	0.0	100.00
4-Apr-05	2.6	0.0	100.00	1.8	0.0	100.00	4.8	0.2	95.83	6.2	1.2	80.65	4.8	0.0	100.00
7-Apr-05	2.4	0.0	100.00	2.4	0.0	100.00	5.6	0.7	87.50	7.2	0.5	93.06	2.6	0.0	100.00
11-Apr-05	3.6	0.0	100.00	4.2	0.0	100.00	4.0	0.3	92.50	5.0	0.8	84.00	4.6	0.0	100.00
14-Apr-05	5.2	1.2	76.92	5.3	0.8	84.91	2.6	0.1	96.15	4.2	0.4	90.48	4.0	0.2	95.00
18-Apr-05	4.0	0.2	95.00	3.8	0.0	100.00	2.8	0.0	100.00	4.0	0.0	100.00	2.8	0.0	100.00
21-Apr-05	3.8	0.0	100.00	3.0	0.0	100.00	4.2	0.0	100.00	5.4	0.0	100.00	3.6	0.0	100.00
25-Apr-05	2.2	0.0	100.00	3.2	0.0	100.00	3.8	0.0	100.00	2.8	0.0	100.00	2.4	0.0	100.00
28-Apr-05	3.0	0.2	93.33	3.8	0.2	94.74	2.6	0.0	100.00	2.4	0.0	100.00	2.0	0.0	100.00
2-May-05	4.6	0.0	100.00	2.8	0.0	100.00	2.2	0.0	100.00	3.0	0.0	100.00	4.4	0.0	100.00
6-May-05	4.6	0.0	100.00	3.8	0.4	89.47	2.6	0.0	100.00	3.4	0.4	88.24	3.8	0.0	100.00
Mean	4.1	0.2	94.44	4.1	0.2	94.06	4.2	0.2	94.25	4.2	0.3	92.20	4.0	0.2	96.11
SD	1.3	0.3	6.91	1.2	0.3	6.93	1.3	0.3	7.03	1.3	0.4	6.74	1.2	0.3	5.51

Table B.19 The influent and effluent HCO_3^- concentrations of Run I.

D/M/Y	R11		R12		R13		R14		R15	
	Influent (mg/L)	**Effluent (mg/L)**	**Influent (mg/L)**	**Effluent (mg/L)**	**Influent (mg/L)**	**Effluent (mg/L)**	**Influent (mg/L)**	**Effluent (mg/L)**	**Influent (mg/L)**	**Effluent (mg/L)**
9-Feb-04	34	117	39	91	32	89	32	93	34	105
12-Feb-04	41	93	34	81	43	73	48	64	40	120
16-Feb-04	36	108	43	102	37	100	35	87	52	105
19-Feb-04	32	96	50	109	46	121	38	98	42	108
23-Feb-04	47	133	44	135	65	117	34	152	58	120
26-Feb-04	56	167	37	162	44	155	33	114	34	143
1-Mar-04	39	151	51	148	57	139	65	126	68	123
4-Mar-04	41	156	47	144	42	152	36	121	32	146
8-Mar-04	52	104	68	140	39	147	43	113	48	145
11-Mar-04	38	128	43	147	33	143	55	154	37	119
15-Mar-04	46	114	65	152	52	125	43	168	51	150
18-Mar-04	78	141	54	139	40	137	74	154	63	127
22-Mar-04	65	138	38	143	47	129	78	132	41	138
25-Mar-04	36	123	45	146	37	147	54	145	59	152
29-Mar-04	77	192	41	201	63	198	39	121	32	184
1-Apr-04	37	156	37	168	55	184	41	114	47	138
5-Apr-04	52	201	64	155	41	177	59	131	65	159
8-Apr-04	42	211	43	205	71	193	63	105	46	138
12-Apr-04	50	209	70	195	62	180	48	117	42	118
15-Apr-04	62	182	89	187	78	176	61	114	57	105
19-Apr-04	55	215	82	211	51	192	47	111	38	119
22-Apr-04	45	160	35	163	47	162	64	106	57	125
26-Apr-04	69	187	51	173	35	201	49	127	67	112
30-Apr-04	47	139	39	163	40	161	62	118	39	125
Mean	49	151	50	153	48	150	50	120	48	130
SD	13	38	15	34	12	35	13	24	12	20

Table B.20 The influent and effluent HCO_3^- concentrations of Run II.

D/M/Y	R21		R22		R23		R24		R25	
	Influent (mg/L)	Effluent (mg/L)	Influent (mg/L)	Effluent (mg/L)	Influent (mg/L)	Effluent (mg/L)	Influent (mg/L)	Effluent (mg/L)	Influent (mg/L)	Effluent (mg/L)
16-Aug-04	59	163	104	189	62	196	116	197	83	187
19-Aug-04	74	145	53	158	52	161	80	187	58	167
23-Aug-04	56	158	59	143	52	191	50	154	68	175
26-Aug-04	92	133	86	174	36	184	78	172	49	168
30-Aug-04	112	151	89	217	80	191	38	173	52	171
2-Sep-04	41	147	44	181	62	185	42	184	47	179
6-Sep-04	36	153	38	185	52	192	50	148	52	152
9-Sep-04	101	146	48	161	72	180	68	152	65	145
13-Sep-04	68	156	45	172	38	204	52	169	45	157
16-Sep-04	49	152	36	174	84	202	62	156	65	149
20-Sep-04	53	152	84	179	100	188	54	157	50	149
23-Sep-04	74	165	104	200	72	195	40	171	76	155
27-Sep-04	37	158	78	187	91	191	44	159	86	175
30-Sep-04	59	193	65	219	108	212	74	195	67	169
4-Oct-04	79	211	47	219	88	216	98	231	50	214
7-Oct-04	61	224	75	229	50	219	52	235	88	216
11-Oct-04	95	192	74	195	42	201	94	196	104	211
14-Oct-04	103	193	98	199	70	203	112	191	94	209
18-Oct-04	52	189	98	191	106	196	86	199	88	194
21-Oct-04	49	184	50	183	98	192	46	199	47	195
25-Oct-04	56	220	38	216	74	217	70	224	70	212
28-Oct-04	59	187	62	191	38	196	52	186	59	189
1-Nov-04	74	197	44	195	38	217	102	193	71	190
5-Nov-04	52	189	48	194	54	203	78	213	87	192
Mean	66	173	65	190	67	197	68	185	68	180
SD	21	26	23	21	23	13	24	25	17	23

Table B.21 The influent and effluent HCO_3^- concentrations of Run III.

D/M/Y	R31		R32		R33		R34		R35	
	Influent (mg/L)	Effluent (mg/L)	Influent (mg/L)	Effluent (mg/L)	Influent (mg/L)	Effluent (mg/L)	Influent (mg/L)	Effluent (mg/L)	Influent (mg/L)	Effluent (mg/L)
14-Feb-05	107	211	95	217	101	227	131	213	132	203
17-Feb-05	112	215	93	213	83	206	124	211	129	213
21-Feb-05	108	255	104	242	147	246	92	234	94	256
24-Feb-05	93	265	93	241	85	263	44	244	49	237
28-Feb-05	89	248	69	242	93	257	76	247	84	241
3-Mar-05	103	285	75	281	125	274	98	261	73	262
7-Mar-05	86	294	143	290	107	286	128	232	118	274
10-Mar-05	106	316	157	340	145	316	102	272	122	283
14-Mar-05	85	264	114	302	113	277	92	316	108	316
17-Mar-05	103	287	112	259	85	246	124	269	119	340
21-Mar-05	112	278	134	276	108	254	104	304	144	298
24-Mar-05	92	306	104	318	74	296	122	368	126	322
28-Mar-05	112	287	120	366	64	342	146	340	139	356
31-Mar-05	96	292	74	300	81	318	125	360	118	358
4-Apr-05	81	286	50	324	112	346	108	328	64	342
7-Apr-05	88	266	66	270	94	290	96	304	62	298
11-Apr-05	108	258	108	284	154	286	42	284	96	262
14-Apr-05	98	192	98	180	106	188	98	202	72	200
18-Apr-05	80	208	106	180	40	198	68	188	40	200
21-Apr-05	82	178	96	166	74	180	96	192	58	142
25-Apr-05	72	184	62	158	52	156	42	160	83	162
28-Apr-05	84	163	42	152	77	150	72	146	64	152
2-May-05	96	142	50	146	66	146	98	130	53	122
6-May-05	64	165	62	152	82	150	63	146	74	152
Mean	94	244	93	246	95	246	95	248	93	250
SD	13	51	30	66	29	62	29	69	32	72

APPENDIX C

EXPERIMENTAL DATA OF FATE OF CADMIUM IN FWS CONSTRUCTED WETLANDS

Table C.1 The influent and effluent cadmium concentrations in wastewater of Run I.

D/M/Y	R11			R12			R13			R14			R15		
	Influent (mg/L)	**Effluent (mg/L)**	**R.E. %**	**Influent (mg/L)**	**Effluent (mg/L)**	**R.E. %**	**Influent (mg/L)**	**Effluent (mg/L)**	**R.E. %**	**Influent (mg/L)**	**Effluent (mg/L)**	**R.E. %**	**Influent (mg/L)**	**Effluent (mg/L)**	**R.E. %**
9-Feb-04	0.133	0.125	6.02	5.300	1.102	79.21	10.300	2.214	78.50	24.650	5.565	77.42	50.200	13.216	73.67
12-Feb-04	0.162	0.149	8.02	6.000	1.125	81.25	9.400	2.105	77.61	25.350	5.485	78.36	52.000	14.280	72.54
16-Feb-04	0.143	0.133	6.99	5.100	1.196	76.55	10.050	2.016	79.94	25.710	5.207	79.75	53.440	15.220	71.52
19-Feb-04	0.267	0.252	5.62	4.820	1.099	77.21	9.650	2.113	78.10	24.390	5.517	77.38	53.460	14.690	72.52
23-Feb-04	0.114	0.101	11.40	5.130	1.012	80.27	9.440	2.227	76.41	24.220	4.859	79.94	47.300	15.190	67.89
26-Feb-04	0.138	0.126	8.70	4.740	1.180	75.11	10.070	2.074	79.40	25.680	5.190	79.79	50.930	14.360	71.80
1-Mar-04	0.125	0.125	0.00	5.000	0.729	85.43	10.620	1.911	82.01	26.140	5.050	80.68	51.000	13.160	74.20
4-Mar-04	0.245	0.243	0.82	4.800	0.811	83.10	10.580	2.156	79.62	25.570	4.920	80.76	47.000	12.423	73.57
8-Mar-04	0.315	0.301	4.44	5.200	0.962	81.50	9.710	1.843	81.02	24.220	5.360	77.87	48.000	11.550	75.94
11-Mar-04	0.194	0.191	1.55	5.110	0.885	82.68	9.630	1.686	82.49	24.010	5.750	76.05	49.000	12.733	74.01
15-Mar-04	0.231	0.226	2.16	4.690	0.744	84.14	9.750	1.734	82.22	24.440	4.944	79.77	47.670	11.950	74.93
18-Mar-04	0.377	0.358	5.04	4.850	0.991	79.58	10.220	1.738	82.99	25.820	4.660	81.95	52.310	11.720	77.60
22-Mar-04	0.171	0.169	1.17	5.040	0.868	82.78	10.400	2.019	80.59	25.110	5.100	79.69	50.890	12.590	75.26
25-Mar-04	0.423	0.395	6.62	4.900	0.684	86.04	9.850	1.556	84.20	24.550	4.958	79.80	51.540	13.051	74.68
29-Mar-04	0.419	0.417	0.48	4.530	0.792	82.51	9.680	1.653	82.92	24.960	4.796	80.79	53.160	12.937	75.66
1-Apr-04	0.203	0.199	1.97	5.010	1.017	79.71	9.990	1.856	81.42	24.500	5.502	77.54	51.380	12.480	75.71
5-Apr-04	0.129	0.125	3.10	5.280	0.853	83.84	10.090	1.812	82.04	24.960	5.766	76.90	51.070	12.380	75.76
8-Apr-04	0.149	0.139	6.71	5.420	0.929	82.86	10.250	2.058	79.92	25.450	5.293	79.20	52.760	11.541	78.13
12-Apr-04	0.246	0.213	13.41	5.740	0.710	87.63	10.140	2.167	78.63	25.010	4.650	81.41	49.340	12.237	75.20
15-Apr-04	0.212	0.205	3.30	4.820	0.836	82.66	10.200	1.852	81.84	24.860	5.432	78.15	51.710	11.852	77.08
19-Apr-04	0.446	0.451	0.00	4.640	0.722	84.44	9.860	1.552	84.26	26.140	5.207	80.08	53.040	12.193	77.01
22-Apr-04	0.130	0.139	0.00	5.280	0.863	83.66	9.910	1.785	81.99	25.120	5.350	78.70	51.680	12.441	75.93
26-Apr-04	0.340	0.318	6.47	4.283	0.643	84.99	9.545	1.968	79.39	24.210	5.151	78.72	46.380	12.752	72.51
30-Apr-04	0.107	0.115	0.00	4.340	0.890	79.49	9.235	1.742	81.14	26.670	4.909	81.59	48.050	11.802	75.44
Mean	0.226	0.217	3.76	5.001	0.902	81.97	9.940	1.910	80.79	25.073	5.193	79.29	50.555	12.865	74.55
SD	0.107	0.104	3.76	0.399	0.161	3.08	0.367	0.205	2.06	0.713	0.319	1.57	2.192	1.109	2.28

Table C.2 The influent and effluent cadmium concentrations in wastewater of Run II.

D/M/Y	R21			R22			R23			R24			R25		
	Influent (mg/L)	**Effluent (mg/L)**	**R.E. %**	**Influent (mg/L)**	**Effluent (mg/L)**	**R.E. %**	**Influent (mg/L)**	**Effluent (mg/L)**	**R.E. %**	**Influent (mg/L)**	**Effluent (mg/L)**	**R.E. %**	**Influent (mg/L)**	**Effluent (mg/L)**	**R.E. %**
16-Aug-04	0.018	0.003	0.00	5.127	0.670	86.93	10.413	1.248	88.01	26.112	4.039	84.53	49.626	7.046	85.80
19-Aug-04	0.002	0.007	0.00	4.855	0.803	83.46	9.805	1.175	88.02	25.742	3.947	84.67	51.660	6.958	86.53
23-Aug-04	0.331	0.004	0.00	5.042	0.542	89.25	10.110	1.045	89.66	24.530	4.012	83.64	48.210	6.933	85.62
26-Aug-04	0.952	0.003	0.00	5.386	0.456	91.53	10.061	1.168	88.39	25.160	3.980	84.18	48.910	6.578	86.55
30-Aug-04	0.216	0.218	0.00	5.200	0.510	90.19	10.269	0.901	91.23	26.210	3.180	87.87	47.170	7.260	84.61
2-Sep-04	0.190	0.191	0.00	5.067	0.375	92.60	10.287	0.775	92.47	24.520	3.411	86.09	47.710	6.906	85.53
6-Sep-04	0.438	0.436	0.46	4.830	0.476	90.14	10.270	0.880	91.43	24.220	2.870	88.15	47.250	6.809	85.59
9-Sep-04	0.326	0.303	7.06	4.962	0.361	92.72	9.762	1.017	89.58	26.010	3.272	87.42	48.000	6.107	87.28
13-Sep-04	0.288	0.267	7.29	4.689	0.421	91.02	10.484	0.977	90.68	26.260	2.927	88.85	52.230	6.260	88.01
16-Sep-04	0.635	0.594	6.41	4.733	0.392	91.72	9.792	1.147	88.29	23.710	2.433	89.74	51.560	5.865	88.62
20-Sep-04	0.596	0.512	14.06	4.649	0.424	90.88	9.773	0.946	90.32	24.804	3.318	86.62	50.590	6.068	88.01
23-Sep-04	0.576	0.723	0.00	4.747	0.367	92.27	10.308	1.387	86.54	23.820	2.958	87.58	52.412	6.347	87.89
27-Sep-04	0.624	0.581	6.83	4.943	0.348	92.96	10.333	1.173	88.65	25.290	2.621	89.64	53.220	6.449	87.88
30-Sep-04	0.510	0.490	3.90	4.539	0.481	89.40	9.792	1.248	87.25	25.310	3.118	87.68	49.140	6.102	87.58
4-Oct-04	0.171	0.147	13.81	4.666	0.381	91.83	10.120	1.130	88.83	26.740	2.804	89.51	51.603	6.052	88.27
7-Oct-04	0.475	0.500	0.00	5.065	0.404	92.02	9.882	1.479	85.03	26.050	3.251	87.52	47.750	6.289	86.83
11-Oct-04	0.423	0.390	7.71	4.796	0.392	91.83	9.340	1.263	86.48	26.860	2.924	89.11	48.200	5.558	88.47
14-Oct-04	0.419	0.319	23.78	4.991	0.414	91.71	9.866	1.166	88.18	26.280	2.535	90.35	47.720	5.397	88.69
18-Oct-04	0.416	0.276	33.64	4.626	0.435	90.60	10.100	1.007	90.03	26.430	3.440	86.98	49.200	6.470	86.85
21-Oct-04	0.221	0.155	29.90	5.109	0.426	91.66	9.188	1.090	88.14	26.520	2.446	90.78	49.736	6.110	87.72
25-Oct-04	0.269	0.256	4.95	4.577	0.402	91.22	9.776	1.303	86.67	25.800	3.290	87.25	48.521	5.676	88.30
28-Oct-04	0.031	0.038	0.00	4.862	0.382	92.14	9.849	0.942	90.44	26.490	2.501	90.56	47.450	6.492	86.32
1-Nov-04	0.043	0.029	32.55	5.283	0.410	92.24	9.545	0.668	93.01	26.210	3.151	87.98	46.380	5.959	87.15
5-Nov-04	0.007	0.005	30.56	5.340	0.397	92.57	10.235	1.047	89.77	26.670	2.909	89.09	48.050	5.802	87.93
Mean	0.341	0.269	21.14	4.920	0.445	90.96	9.973	1.091	89.06	25.656	3.139	87.77	49.262	6.312	87.19
SD	0.241	0.220	11.78	0.245	0.103	2.10	0.333	0.189	1.97	0.946	0.492	2.02	1.935	0.495	1.14

Table C.3 The influent and effluent cadmium concentrations in wastewater of Run III.

D/M/Y	R31			R32			R33			R34			R35		
	Influent (mg/L)	Effluent (mg/L)	R.E. %	Influent (mg/L)	Effluent (mg/L)	R.E. %	Influent (mg/L)	Effluent (mg/L)	R.E. %	Influent (mg/L)	Effluent (mg/L)	R.E. %	Influent (mg/L)	Effluent (mg/L)	R.E. %
14-Feb-05	0.018	0.003	86.03	5.127	0.265	94.83	10.413	0.475	95.44	26.112	1.139	95.64	49.626	2.646	94.67
17-Feb-05	0.302	0.268	11.45	4.585	0.269	94.13	10.805	0.447	95.86	25.742	1.247	95.16	51.660	2.658	94.85
21-Feb-05	0.000	0.000	0.00	5.042	0.240	95.24	10.110	0.545	94.61	24.530	1.012	95.87	48.210	2.733	94.33
24-Feb-05	0.000	0.000	0.00	5.086	0.245	95.18	11.061	0.480	95.66	25.160	1.298	94.84	48.910	2.578	94.73
28-Feb-05	0.008	0.005	36.84	4.428	0.222	95.00	13.496	0.529	96.08	26.054	1.022	96.08	48.040	2.098	95.63
3-Mar-05	0.006	0.004	36.21	4.930	0.155	96.86	10.870	0.421	96.12	24.883	1.285	94.83	49.630	2.543	94.88
7-Mar-05	0.002	0.000	91.30	5.001	0.118	97.63	10.820	0.377	96.51	26.907	1.357	94.96	49.058	2.431	95.04
10-Mar-05	0.000	0.000	0.00	5.249	0.136	97.41	10.610	0.563	94.69	25.474	1.206	95.27	49.395	2.696	94.54
14-Mar-05	0.000	0.000	0.00	4.716	0.106	97.75	10.180	0.449	95.59	24.468	1.299	94.69	50.977	2.895	94.32
17-Mar-05	0.000	0.000	0.00	5.071	0.127	97.49	10.142	0.346	96.59	25.038	1.254	94.99	52.925	2.182	95.88
21-Mar-05	0.228	0.194	15.04	4.951	0.153	96.90	11.056	0.542	95.10	25.330	1.148	95.47	50.226	2.027	95.96
24-Mar-05	0.000	0.000	0.00	4.602	0.157	96.59	10.521	0.481	95.43	25.611	0.974	96.20	51.901	2.020	96.11
28-Mar-05	0.078	0.000	100.00	6.141	0.142	97.69	11.318	0.401	96.45	24.151	1.116	95.38	50.421	2.679	94.69
31-Mar-05	0.000	0.000	0.00	5.849	0.163	97.22	12.637	0.536	95.76	26.666	1.389	94.79	48.186	2.816	94.16
4-Apr-05	0.000	0.000	0.00	5.891	0.142	97.60	11.566	0.487	95.79	24.386	1.299	94.67	51.846	2.592	95.00
7-Apr-05	0.000	0.000	0.00	4.810	0.218	95.46	11.749	0.460	96.09	25.678	1.239	95.17	51.718	2.786	94.61
11-Apr-05	0.000	0.000	0.00	4.769	0.164	96.56	9.437	0.487	94.84	25.223	1.180	95.32	50.623	2.430	95.20
14-Apr-05	0.000	0.000	0.00	4.654	0.230	95.07	10.929	0.430	96.07	26.400	0.927	96.49	49.270	2.330	95.27
18-Apr-05	0.243	0.000	100.00	4.940	0.181	96.34	12.329	0.514	95.83	27.291	1.164	95.73	49.581	2.276	95.41
21-Apr-05	0.431	0.000	100.00	5.136	0.131	97.45	12.678	0.535	95.78	24.965	1.045	95.81	48.589	2.004	95.88
25-Apr-05	0.000	0.000	0.00	5.442	0.215	96.05	9.839	0.356	96.38	24.269	1.153	95.25	52.394	2.149	95.90
28-Apr-05	0.000	0.000	0.00	5.105	0.158	96.90	9.360	0.482	94.85	24.561	0.947	96.14	50.471	2.049	95.94
2-May-05	0.000	0.000	0.00	5.308	0.213	95.99	9.336	0.447	95.21	24.607	1.135	95.39	50.337	2.317	95.40
6-May-05	0.000	0.018	0.00	5.672	0.172	96.97	10.210	0.415	95.94	25.384	1.096	95.68	51.254	2.129	95.85
Mean	0.055	0.020	62.76	5.104	0.180	96.47	10.895	0.467	95.71	25.370	1.164	95.41	50.219	2.419	95.18
SD	0.118	0.066	38.95	0.436	0.048	1.08	1.086	0.061	0.58	0.863	0.129	0.51	1.400	0.289	0.61

Table C.4 The cadmium accumulation in top soil along the reactor lengths of Run I.

R11	Cadmium accumulation along the lengths (mg/g)				
D/M/Y	**0.05 m**	**0.625 m**	**1.25 m**	**1.875 m**	**2.45 m**
19-Feb-04	0.0002	0.0003	0.0001	0.0002	0.0001
4-Mar-04	0.0001	0.0002	0.0003	0.0002	0.0001
18-Mar-04	0.0002	0.0004	0.0004	0.0005	0.0003
1-Apr-04	0.0002	0.0003	0.0001	0.0002	0.0001
15-Apr-04	0.0002	0.0003	0.0002	0.0001	0.0003
30-Apr-04	0.0004	0.0003	0.0006	0.0003	0.0005

R12	Cadmium accumulation along the lengths (mg/g)				
D/M/Y	**0.05 m**	**0.625 m**	**1.25 m**	**1.875 m**	**2.45 m**
19-Feb-04	0.0187	0.0222	0.0220	0.0207	0.0274
4-Mar-04	0.0674	0.0404	0.0441	0.0443	0.0447
18-Mar-04	0.0761	0.0653	0.0615	0.0615	0.0721
1-Apr-04	0.1247	0.0817	0.0882	0.0887	0.0929
15-Apr-04	0.1342	0.1259	0.1020	0.1109	0.1287
30-Apr-04	0.1680	0.1240	0.1242	0.1272	0.1390

R13	Cadmium accumulation along the lengths (mg/g)				
D/M/Y	**0.05 m**	**0.625 m**	**1.25 m**	**1.875 m**	**2.45 m**
19-Feb-04	0.0577	0.0405	0.0437	0.0308	0.0350
4-Mar-04	0.1054	0.0939	0.0903	0.0853	0.1000
18-Mar-04	0.1843	0.1585	0.1324	0.1223	0.1249
1-Apr-04	0.2091	0.1951	0.1755	0.1823	0.1992
15-Apr-04	0.2386	0.2037	0.2168	0.2054	0.2049
30-Apr-04	0.3208	0.2457	0.2423	0.2523	0.2635

R14	Cadmium accumulation along the lengths (mg/g)				
D/M/Y	**0.05 m**	**0.625 m**	**1.25 m**	**1.875 m**	**2.45 m**
19-Feb-04	0.1780	0.1174	0.1220	0.1061	0.1451
4-Mar-04	0.3559	0.2048	0.2208	0.2321	0.2249
18-Mar-04	0.4885	0.3123	0.3124	0.3182	0.3902
1-Apr-04	0.6118	0.4497	0.4649	0.4942	0.4585
15-Apr-04	0.8898	0.5271	0.5206	0.5503	0.6573
30-Apr-04	0.9828	0.6292	0.6467	0.6798	0.7293

R15	Cadmium accumulation along the lengths (mg/g)				
D/M/Y	**0.05 m**	**0.625 m**	**1.25 m**	**1.875 m**	**2.45 m**
19-Feb-04	0.3878	0.2780	0.2778	0.2761	0.2884
4-Mar-04	0.6278	0.4556	0.4556	0.4522	0.4877
18-Mar-04	1.0183	0.8946	0.7643	0.7837	0.7339
1-Apr-04	1.3132	0.9911	0.9112	0.9449	1.0538
15-Apr-04	1.7694	1.2039	1.2890	1.2806	1.2422
30-Apr-04	1.9843	1.4220	1.4337	1.4503	1.5161

Table C.5 The cadmium accumulation in top soil along the reactor lengths of Run II.

R21	**Cadmium accumulation along the lengths (mg/g)**				
D/M/Y	**0.05 m**	**0.625 m**	**1.25 m**	**1.875 m**	**2.45 m**
26-Aug-04	0.0002	0.0003	0.0001	0.0002	0.0001
9-Sep-04	0.0001	0.0002	0.0003	0.0002	0.0001
23-Sep-04	0.0002	0.0004	0.0004	0.0005	0.0003
7-Oct-04	0.0002	0.0003	0.0001	0.0002	0.0001
21-Oct-04	0.0002	0.0003	0.0002	0.0001	0.0003
5-Nov-04	0.0006	0.0005	0.0004	0.0004	0.0003

R22	**Cadmium accumulation along the lengths (mg/g)**				
D/M/Y	**0.05 m**	**0.625 m**	**1.25 m**	**1.875 m**	**2.45 m**
26-Aug-04	0.0187	0.0222	0.0220	0.0207	0.0274
9-Sep-04	0.0674	0.0404	0.0441	0.0443	0.0447
23-Sep-04	0.0761	0.0653	0.0615	0.0615	0.0721
7-Oct-04	0.1247	0.0817	0.0882	0.0887	0.0929
21-Oct-04	0.1342	0.1259	0.1020	0.0854	0.0868
5-Nov-04	0.1577	0.1478	0.1222	0.0701	0.0584

R23	**Cadmium accumulation along the lengths (mg/g)**				
D/M/Y	**0.05 m**	**0.625 m**	**1.25 m**	**1.875 m**	**2.45 m**
26-Aug-04	0.0577	0.0405	0.0437	0.0308	0.0350
9-Sep-04	0.1054	0.0939	0.0903	0.0853	0.1000
23-Sep-04	0.1843	0.1585	0.1324	0.1223	0.1249
7-Oct-04	0.2091	0.1951	0.1755	0.1823	0.1992
21-Oct-04	0.2386	0.2037	0.2168	0.2054	0.2049
5-Nov-04	0.2934	0.2679	0.2479	0.1859	0.1644

R24	**Cadmium accumulation along the lengths (mg/g)**				
D/M/Y	**0.05 m**	**0.625 m**	**1.25 m**	**1.875 m**	**2.45 m**
26-Aug-04	0.1780	0.1174	0.1220	0.1061	0.1451
9-Sep-04	0.3559	0.2048	0.2208	0.2321	0.2249
23-Sep-04	0.4885	0.3123	0.3124	0.3182	0.3902
7-Oct-04	0.6118	0.4497	0.4649	0.4942	0.4585
21-Oct-04	0.8898	0.5271	0.5206	0.5503	0.6573
5-Nov-04	0.8347	0.7767	0.7368	0.4936	0.4167

R25	**Cadmium accumulation along the lengths (mg/g)**				
D/M/Y	**0.05 m**	**0.625 m**	**1.25 m**	**1.875 m**	**2.45 m**
26-Aug-04	0.3878	0.2780	0.2778	0.2761	0.2884
9-Sep-04	0.6278	0.4556	0.4556	0.4522	0.4877
23-Sep-04	1.0183	0.8946	0.7643	0.7837	0.7339
7-Oct-04	1.3132	0.9911	0.9112	0.9449	1.0538
21-Oct-04	1.3634	1.1239	1.0224	1.0076	1.0732
5-Nov-04	1.4589	1.3967	1.2835	0.9756	0.8280

Table C.6 The cadmium accumulation in top soil along the reactor lengths of Run III.

R31	**Cadmium accumulation along the lengths (mg/g)**				
D/M/Y	**0.05 m**	**0.625 m**	**1.25 m**	**1.875 m**	**2.45 m**
24-Feb-05	0.0004	0.0004	0.0003	0.0003	0.0002
10-Mar-05	0.0003	0.0003	0.0002	0.0001	0.0003
24-Mar-05	0.0002	0.0002	0.0004	0.0004	0.0004
7-Apr-05	0.0002	0.0006	0.0005	0.0003	0.0005
21-Apr-05	0.0006	0.0008	0.0008	0.0009	0.0010
6-May-05	0.0004	0.0004	0.0006	0.0005	0.0006

R32	**Cadmium accumulation along the lengths (mg/g)**				
D/M/Y	**0.05 m**	**0.625 m**	**1.25 m**	**1.875 m**	**2.45 m**
24-Feb-05	0.0209	0.0197	0.0133	0.0093	0.0062
10-Mar-05	0.0449	0.0305	0.0215	0.0187	0.0143
24-Mar-05	0.0587	0.0581	0.0398	0.0245	0.0252
7-Apr-05	0.0830	0.0659	0.0410	0.0306	0.0287
21-Apr-05	0.0912	0.0926	0.0664	0.0433	0.0336
6-May-05	0.1186	0.1038	0.0722	0.0484	0.0393

R33	**Cadmium accumulation along the lengths (mg/g)**				
D/M/Y	**0.05 m**	**0.625 m**	**1.25 m**	**1.875 m**	**2.45 m**
24-Feb-05	0.0440	0.0428	0.0295	0.0144	0.0150
10-Mar-05	0.0980	0.0957	0.0658	0.0428	0.0450
24-Mar-05	0.1292	0.1166	0.0737	0.0698	0.0550
7-Apr-05	0.2206	0.2114	0.1216	0.0970	0.0750
21-Apr-05	0.2328	0.2276	0.1495	0.1096	0.0775
6-May-05	0.2790	0.2667	0.1634	0.1167	0.1025

R34	**Cadmium accumulation along the lengths (mg/g)**				
D/M/Y	**0.05 m**	**0.625 m**	**1.25 m**	**1.875 m**	**2.45 m**
24-Feb-05	0.1273	0.1351	0.0762	0.0510	0.0476
10-Mar-05	0.1945	0.1870	0.1623	0.1572	0.1517
24-Mar-05	0.3820	0.3431	0.2846	0.1579	0.1228
7-Apr-05	0.4029	0.3574	0.3461	0.2805	0.2303
21-Apr-05	0.5637	0.5718	0.4008	0.3130	0.2927
6-May-05	0.6283	0.5941	0.4460	0.3432	0.2973

R35	**Cadmium accumulation along the lengths (mg/g)**				
D/M/Y	**0.05 m**	**0.625 m**	**1.25 m**	**1.875 m**	**2.45 m**
24-Feb-05	0.1748	0.2281	0.1383	0.1283	0.1069
10-Mar-05	0.4495	0.3556	0.2877	0.2666	0.2539
24-Mar-05	0.5243	0.5284	0.4150	0.3698	0.3208
7-Apr-05	0.8199	0.7123	0.6534	0.5131	0.4774
21-Apr-05	0.9384	0.9804	0.7172	0.6829	0.5947
6-May-05	1.1567	1.1293	0.9019	0.7780	0.6849

Table C.7 The profiles of cadmium accumulation with reactor lengths at different depths during Run I.

R11	Cadmium accumulation along the depths (mg/g)			
Distances (m)	**0 cm.**	**15 cm.**	**30 cm**	**45 cm.**
0.050	0.0004	0.0002	0.0002	0.0001
0.625	0.0003	0.0004	0.0003	0.0002
1.250	0.0006	0.0004	0.0001	0.0003
1.875	0.0003	0.0005	0.0002	0.0002
2.450	0.0005	0.0003	0.0001	0.0001

R12	Cadmium accumulation along the depths (mg/g)			
Distances (m)	**0 cm.**	**15 cm.**	**30 cm**	**45 cm.**
0.050	0.1680	0.0556	0.0058	0.0005
0.625	0.1240	0.0576	0.0038	0.0006
1.250	0.1242	0.0311	0.0033	0.0004
1.875	0.1272	0.0238	0.0026	0.0006
2.450	0.1390	0.0266	0.0016	0.0004

R13	Cadmium accumulation along the depths (mg/g)			
Distances (m)	**0 cm.**	**15 cm.**	**30 cm**	**45 cm.**
0.050	0.3208	0.1127	0.0136	0.0003
0.625	0.2457	0.1071	0.0106	0.0004
1.250	0.2423	0.0620	0.0112	0.0003
1.875	0.2523	0.0437	0.0099	0.0002
2.450	0.2635	0.0166	0.0087	0.0001

R14	Cadmium accumulation along the depths (mg/g)			
Distances (m)	**0 cm.**	**15 cm.**	**30 cm**	**45 cm.**
0.050	0.9828	0.3562	0.0065	0.0002
0.625	0.6292	0.2524	0.0076	0.0004
1.250	0.6467	0.1741	0.0084	0.0002
1.875	0.6798	0.0660	0.0055	0.0003
2.450	0.7293	0.0871	0.0074	0.0001

R15	Cadmium accumulation along the depths (mg/g)			
Distances (m)	**0 cm.**	**15 cm.**	**30 cm**	**45 cm.**
0.050	1.9843	0.5615	0.0115	0.0003
0.625	1.4220	0.4722	0.0114	0.0002
1.250	1.4337	0.3135	0.0115	0.0003
1.875	1.4503	0.1533	0.0113	0.0001
2.450	1.5161	0.1110	0.0114	0.0002

Table C.8 The profiles of cadmium accumulation with reactor lengths at different depths during Run II.

R21	**Cadmium accumulation along the depths (mg/g)**			
Distances (m)	**0 cm.**	**15 cm.**	**30 cm**	**45 cm.**
0.050	0.0006	0.0005	0.0005	0.0003
0.625	0.0005	0.0005	0.0005	0.0003
1.250	0.0004	0.0003	0.0004	0.0002
1.875	0.0004	0.0005	0.0003	0.0002
2.450	0.0003	0.0006	0.0002	0.0003

R22	**Cadmium accumulation along the depths (mg/g)**			
Distances (m)	**0 cm.**	**15 cm.**	**30 cm**	**45 cm.**
0.050	0.1577	0.0853	0.0005	0.0002
0.625	0.1478	0.0617	0.0004	0.0003
1.250	0.1222	0.0319	0.0004	0.0002
1.875	0.0701	0.0254	0.0003	0.0003
2.450	0.0584	0.0104	0.0003	0.0003

R23	**Cadmium accumulation along the depths (mg/g)**			
Distances (m)	**0 cm.**	**15 cm.**	**30 cm**	**45 cm.**
0.050	0.2934	0.1180	0.0005	0.0003
0.625	0.2679	0.0878	0.0005	0.0002
1.250	0.2479	0.0719	0.0006	0.0002
1.875	0.1859	0.0423	0.0005	0.0001
2.450	0.1644	0.0421	0.0004	0.0001

R24	**Cadmium accumulation along the depths (mg/g)**			
Distances (m)	**0 cm.**	**15 cm.**	**30 cm**	**45 cm.**
0.050	0.8347	0.2328	0.0005	0.0002
0.625	0.7767	0.1801	0.0003	0.0001
1.250	0.7368	0.1232	0.0005	0.0003
1.875	0.4936	0.1027	0.0003	0.0003
2.450	0.4167	0.0925	0.0004	0.0002

R25	**Cadmium accumulation along the depths (mg/g)**			
Distances (m)	**0 cm.**	**15 cm.**	**30 cm**	**45 cm.**
0.050	1.4589	0.4641	0.0006	0.0002
0.625	1.3967	0.3782	0.0005	0.0003
1.250	1.2835	0.1461	0.0005	0.0003
1.875	0.9756	0.1404	0.0004	0.0002
2.450	0.8280	0.1283	0.0005	0.0004

Table C.9 The profiles of cadmium accumulation with reactor lengths at different depths during Run III.

R31	Cadmium accumulation along the depths (mg/g)			
Distances (m)	**0 cm.**	**15 cm.**	**30 cm**	**45 cm.**
0.050	0.0004	0.0006	0.0004	0.0002
0.625	0.0004	0.0005	0.0004	0.0001
1.250	0.0006	0.0003	0.0003	0.0002
1.875	0.0005	0.0002	0.0002	0.0002
2.450	0.0006	0.0003	0.0002	0.0002

R32	Cadmium accumulation along the depths (mg/g)			
Distances (m)	**0 cm.**	**15 cm.**	**30 cm**	**45 cm.**
0.050	0.1186	0.0673	0.0004	0.0002
0.625	0.1038	0.0477	0.0003	0.0001
1.250	0.0722	0.0337	0.0004	0.0001
1.875	0.0484	0.0139	0.0005	0.0002
2.450	0.0393	0.0110	0.0003	0.0002

R33	Cadmium accumulation along the lengths (mg/g)			
Distances (m)	**0 cm.**	**15 cm.**	**30 cm**	**45 cm.**
0.050	0.2790	0.0971	0.0084	0.0001
0.625	0.2667	0.0703	0.0105	0.0002
1.250	0.1634	0.0424	0.0063	0.0002
1.875	0.1167	0.0249	0.0105	0.0001
2.450	0.1025	0.0190	0.0073	0.0001

R34	Cadmium accumulation along the depths (mg/g)			
Distances (m)	**0 cm.**	**15 cm.**	**30 cm**	**45 cm.**
0.050	0.6283	0.1674	0.0105	0.0003
0.625	0.5941	0.1192	0.0084	0.0002
1.250	0.4460	0.0832	0.0106	0.0003
1.875	0.3432	0.0707	0.0096	0.0003
2.450	0.2973	0.0437	0.0085	0.0002

R35	Cadmium accumulation along the depths (mg/g)			
Distances (m)	**0 cm.**	**15 cm.**	**30 cm**	**45 cm.**
0.050	1.1567	0.3755	0.0105	0.0001
0.625	1.1293	0.2112	0.0093	0.0002
1.250	0.9022	0.1807	0.0107	0.0003
1.875	0.7780	0.1084	0.0086	0.0003
2.450	0.6849	0.0730	0.0054	0.0002

Table C.10 The total cadmium accumulation in soil along the lengths during the experimental run.

Reactor units	Cadmium accumulation in soil along the lengths (g)				Total accumulation (g)
	0.3125 m	0.9375 m	1.5625 m	2.1875 m	
R12	3.827	3.132	2.659	2.676	12.294
R13	7.487	6.177	5.312	4.779	23.755
R14	20.267	15.329	13.013	12.350	60.958
R15	39.140	31.719	27.395	25.106	123.359
R22	4.271	3.261	2.193	1.435	11.159
R23	6.918	5.943	4.714	3.695	21.271
R24	17.294	15.047	11.945	9.238	53.525
R25	32.212	26.460	20.100	16.620	95.391
R32	3.221	2.415	1.547	0.991	8.173
R33	6.515	4.891	3.182	2.431	17.018
R34	13.005	10.520	8.072	6.427	38.024
R35	24.811	20.250	16.292	13.149	74.503

Table C.11 The cadmium uptake in bulrush' stems during Run I.

R11	**Cadmium accumulation (mg/g)**			
D/M/Y	**Zone 1**	**Zone 2**	**Zone 3**	**Zone 4**
19-Feb-04	0.014	0.012	0.011	0.008
4-Mar-04	0.018	0.017	0.009	0.011
18-Mar-04	0.013	0.016	0.010	0.012
1-Apr-04	0.015	0.020	0.014	0.011
15-Apr-04	0.015	0.019	0.016	0.013
30-Apr-04	0.016	0.021	0.017	0.014

R12	**Cadmium accumulation (mg/g)**			
D/M/Y	**Zone 1**	**Zone 2**	**Zone 3**	**Zone 4**
19-Feb-04	0.159	0.172	0.150	0.142
4-Mar-04	0.280	0.312	0.419	0.303
18-Mar-04	0.669	0.580	0.511	0.474
1-Apr-04	1.076	0.952	0.836	0.608
15-Apr-04	1.218	1.238	1.035	0.648
30-Apr-04	1.371	1.344	1.152	0.781

R13	**Cadmium accumulation (mg/g)**			
D/M/Y	**Zone 1**	**Zone 2**	**Zone 3**	**Zone 4**
19-Feb-04	0.326	0.257	0.247	0.174
4-Mar-04	0.683	0.683	0.689	0.659
18-Mar-04	1.233	1.259	0.789	0.808
1-Apr-04	1.791	1.473	1.013	1.186
15-Apr-04	2.434	1.807	1.395	1.194
30-Apr-04	2.719	2.319	1.805	1.542

R14	**Cadmium accumulation (mg/g)**			
D/M/Y	**Zone 1**	**Zone 2**	**Zone 3**	**Zone 4**
19-Feb-04	0.690	0.530	0.342	0.483
4-Mar-04	2.155	1.390	1.336	0.775
18-Mar-04	2.353	2.684	2.037	1.258
1-Apr-04	3.900	2.339	2.644	2.291
15-Apr-04	5.495	3.492	2.798	2.382
30-Apr-04	5.997	4.516	3.479	2.939

R15	**Cadmium accumulation (mg/g)**			
D/M/Y	**Zone 1**	**Zone 2**	**Zone 3**	**Zone 4**
19-Feb-04	0.952	0.843	0.791	0.349
4-Mar-04	2.376	1.623	1.360	0.836
18-Mar-04	4.407	2.094	2.636	1.895
1-Apr-04	5.238	3.724	2.971	2.516
15-Apr-04	7.862	4.409	4.580	2.673
30-Apr-04	8.660	5.655	4.884	3.178

Notes: Zone 1 = 0.05-0.625 m, Zone 2 = 0.625-1.25 m, Zone 3 = 1.25-1.875 m, and Zone 4 = 1.875-2.45 m.

Table C.12 The cadmium uptake in bulrush’ stems during Run II.

R21	Cadmium accumulation (mg/g)			
D/M/Y	Zone 1	Zone 2	Zone 3	Zone 4
26-Aug-04	0.014	0.013	0.012	0.012
9-Sep-04	0.012	0.015	0.010	0.009
23-Sep-04	0.014	0.011	0.013	0.014
7-Oct-04	0.012	0.009	0.015	0.010
21-Oct-04	0.016	0.012	0.013	0.009
5-Nov-04	0.016	0.021	0.017	0.014

R22	Cadmium accumulation (mg/g)			
D/M/Y	Zone 1	Zone 2	Zone 3	Zone 4
26-Aug-04	0.087	0.095	0.089	0.045
9-Sep-04	0.158	0.296	0.136	0.085
23-Sep-04	0.229	0.320	0.216	0.112
7-Oct-04	0.487	0.400	0.264	0.183
21-Oct-04	0.609	0.618	0.423	0.195
5-Nov-04	0.793	0.835	0.527	0.291

R23	Cadmium accumulation (mg/g)			
D/M/Y	Zone 1	Zone 2	Zone 3	Zone 4
26-Aug-04	0.160	0.214	0.151	0.111
9-Sep-04	0.418	0.348	0.334	0.378
23-Sep-04	0.710	0.528	0.446	0.406
7-Oct-04	0.897	0.964	0.558	0.434
21-Oct-04	1.360	1.159	0.963	0.801
5-Nov-04	1.549	1.286	0.992	0.806

R24	Cadmium accumulation (mg/g)			
D/M/Y	Zone 1	Zone 2	Zone 3	Zone 4
26-Aug-04	0.541	0.654	0.606	0.320
9-Sep-04	1.110	1.704	1.438	0.445
23-Sep-04	1.804	3.203	1.819	0.857
7-Oct-04	2.386	2.846	2.563	1.082
21-Oct-04	3.145	3.372	3.144	1.519
5-Nov-04	3.185	4.172	3.344	1.561

R25	Cadmium accumulation (mg/g)			
D/M/Y	Zone 1	Zone 2	Zone 3	Zone 4
26-Aug-04	0.943	0.840	0.625	0.351
9-Sep-04	2.385	2.490	1.492	0.979
23-Sep-04	3.754	3.502	2.197	1.475
7-Oct-04	5.634	4.662	3.373	2.384
21-Oct-04	7.689	5.879	4.059	2.796
5-Nov-04	7.735	6.598	4.362	2.839

Notes: Zone 1 = 0.05-0.625 m, Zone 2 = 0.625-1.25 m, Zone 3 = 1.25-1.875 m, and Zone 4 = 1.875-2.45 m.

Table C.13 The cadmium uptake in bulrush’ stems during Run III.

R31	Cadmium accumulation (mg/g)			
D/M/Y	Zone 1	Zone 2	Zone 3	Zone 4
24-Feb-05	0.014	0.013	0.017	0.016
10-Mar-05	0.016	0.016	0.015	0.018
24-Mar-05	0.013	0.017	0.013	0.020
7-Apr-05	0.011	0.015	0.012	0.018
21-Apr-05	0.017	0.013	0.016	0.020
6-May-05	0.013	0.017	0.014	0.020

R32	Cadmium accumulation (mg/g)			
D/M/Y	Zone 1	Zone 2	Zone 3	Zone 4
24-Feb-05	0.086	0.099	0.091	0.050
10-Mar-05	0.301	0.310	0.221	0.136
24-Mar-05	0.569	0.443	0.257	0.161
7-Apr-05	0.733	0.575	0.426	0.290
21-Apr-05	0.925	0.674	0.526	0.342
6-May-05	0.972	0.732	0.548	0.357

R33	Cadmium accumulation (mg/g)			
D/M/Y	Zone 1	Zone 2	Zone 3	Zone 4
24-Feb-05	0.281	0.257	0.118	0.108
10-Mar-05	0.546	0.563	0.309	0.339
24-Mar-05	0.832	0.866	0.488	0.311
7-Apr-05	1.076	1.253	0.667	0.465
21-Apr-05	1.324	1.528	0.834	0.561
6-May-05	1.489	1.612	0.893	0.625

R34	Cadmium accumulation (mg/g)			
D/M/Y	Zone 1	Zone 2	Zone 3	Zone 4
24-Feb-05	0.223	0.365	0.261	0.294
10-Mar-05	0.790	1.002	0.702	0.670
24-Mar-05	1.357	1.319	1.185	0.977
7-Apr-05	1.371	1.817	1.515	1.233
21-Apr-05	1.823	2.794	1.886	1.707
6-May-05	2.168	2.949	2.277	1.930

R35	Cadmium accumulation (mg/g)			
D/M/Y	Zone 1	Zone 2	Zone 3	Zone 4
24-Feb-05	0.747	0.793	0.668	0.246
10-Mar-05	1.341	1.564	1.591	0.456
24-Mar-05	2.489	2.406	2.458	0.727
7-Apr-05	3.311	3.796	3.061	0.752
21-Apr-05	3.810	4.877	3.439	1.084
6-May-05	4.164	5.218	4.014	1.112

Notes: Zone 1 = 0.05-0.625 m, Zone 2 = 0.625-1.25 m, Zone 3 = 1.25-1.875 m, and Zone 4 = 1.875-2.45 m.

Table C.14 Cadmium accumulations in roots and stems of the bulrush plants until the end of Run I.

Reactors	**Parts**	**Zone (mg/g)**			
		1	**2**	**3**	**4**
R11	Roots	0.032	0.021	0.017	0.014
	Stems	0.016	0.021	0.017	0.014
R12	Roots	2.287	2.127	1.692	1.075
	Stems	1.371	1.344	1.152	0.781
R13	Roots	5.009	4.759	3.707	3.356
	Stems	2.719	2.319	1.805	1.542
R14	Roots	9.356	9.075	7.925	5.118
	Stems	5.997	4.516	3.479	2.939
R15	Roots	13.351	12.016	9.880	6.275
	Stems	8.660	5.655	4.884	3.178

Notes: Zone 1 = 0.05-0.625 m, Zone 2 = 0.625-1.25 m, Zone 3 = 1.25-1.875 m, and Zone 4 = 1.875-2.45 m.

Table C.15 Cadmium accumulations in roots and stems of the bulrush plants until the end of Run II.

Reactors	**Parts**	**Zone (mg/g)**			
		1	**2**	**3**	**4**
R21	Roots	0.040	0.033	0.038	0.035
	Stems	0.016	0.021	0.017	0.014
R22	Roots	1.667	1.746	1.067	0.617
	Stems	0.793	0.835	0.527	0.291
R23	Roots	1.838	1.994	1.176	0.680
	Stems	1.549	1.286	0.992	0.806
R24	Roots	5.702	6.540	5.970	2.680
	Stems	3.185	4.172	3.344	1.561
R25	Roots	9.140	10.876	8.591	4.296
	Stems	7.735	6.598	4.362	2.839

Notes: Zone 1 = 0.05-0.625 m, Zone 2 = 0.625-1.25 m, Zone 3 = 1.25-1.875 m, and Zone 4 = 1.875-2.45 m.

Table C.16 Cadmium accumulations in roots and stems of the bulrush plants until the end of Run III.

Reactors	Parts	Zone (mg/g)			
		1	2	3	4
R31	Roots	0.034	0.037	0.032	0.030
	Stems	0.013	0.017	0.014	0.020
R32	Roots	1.278	1.083	0.690	0.473
	Stems	0.972	0.732	0.548	0.357
R33	Roots	1.610	1.746	1.713	0.918
	Stems	1.489	1.612	0.893	0.625
R34	Roots	3.448	4.990	4.645	3.327
	Stems	2.168	2.949	2.277	1.930
R35	Roots	6.158	7.943	6.770	2.278
	Stems	4.164	5.218	4.014	1.112

Notes: Zone 1 = 0.05-0.625 m, Zone 2 = 0.625-1.25 m, Zone 3 = 1.25-1.875 m, and Zone 4 = 1.875-2.45 m.

Table C.17 Cadmium mass balance in the three experimental runs.

Reactors	Cadmium (mg/L)	Q (L/d)	Influent (g)	Mass Fraction (g)				Percent Fraction (%)			
				Effluent	Plants	Soil	Other	Effluent	Plants	Soil	Other
R12	5.001	51.75	21.22	3.83	4.77	12.29	0.33	18.03	22.50	57.93	1.54
R13	9.940	51.75	42.18	8.10	9.66	23.75	0.66	19.21	22.91	56.31	1.56
R14	25.073	51.75	106.40	22.03	21.71	60.96	1.69	20.71	20.40	57.29	1.59
R15	50.555	51.75	214.53	54.59	33.12	123.36	3.46	25.45	15.44	57.50	1.61
R22	4.920	36.96	14.91	1.35	2.15	11.16	0.25	9.04	14.43	74.84	1.69
R23	9.973	36.96	30.23	3.31	5.11	21.27	0.54	10.94	16.90	70.37	1.79
R24	25.656	36.96	77.76	9.51	13.33	53.52	1.39	12.23	17.14	68.84	1.79
R25	49.262	36.96	149.30	19.13	31.98	95.39	2.80	12.81	21.42	63.89	1.88
R32	5.104	25.88	10.83	0.38	2.05	8.17	0.23	3.53	18.90	75.45	2.12
R33	10.895	25.88	23.12	0.99	4.60	17.02	0.51	4.29	19.91	73.61	2.19
R34	25.370	25.88	53.84	2.47	12.15	38.02	1.19	4.59	22.57	70.62	2.22
R35	50.219	25.88	106.57	5.13	24.45	74.50	2.48	4.82	22.94	69.91	2.33

APPENDIX D

THE CHARACTERISTICS OF THE MEDIA BED

Table D.1 Characteristics of sand.

Properties	**Sand 1**	**Sand 2**	**Sand 3**	**Avg.**
Bulk volume (mL)	600.00	600.00	600.00	600.00
Mass (g)	703.76	695.12	717.88	705.59
Pore volume (mL)	300.00	285.00	299.00	294.67
Specific volume (mL) = (Bulk volume - Pore volume)	300.00	315.00	301.00	305.33
Bulk density (g/mL) = (Mass / Bulk volume)	1.17	1.16	1.20	1.18
Specific density (g/mL) = (Mass / Specific volume)	2.35	2.21	2.38	2.31
Solid fraction = (Specific volume / Bulk volume)	0.50	0.53	0.50	0.51
Porosity = (Pore volume / Bulk volume or 1-Solid fraction)	0.50	0.48	0.50	0.49
Effective pore volume (mL)	184.00	180.00	186.00	183.33
Effective porosity = (Effective pore volume / Bulk volume)	0.31	0.30	0.31	0.31

Table D.2 Characteristics of mixture of clay loam soil and sand.

Properties	**Mixture 1**	**Mixture 2**	**Mixture 3**	**Avg.**
Bulk volume (mL)	600.00	600.00	600.00	600.00
Mass (g)	754.11	726.27	736.51	738.96
Pore volume (mL)	246.00	257.00	240.00	247.67
Specific volume (mL) = (Bulk volume - Pore volume)	354.00	343.00	360.00	352.33
Bulk density (g/mL) = (Mass / Bulk volume)	1.26	1.21	1.23	1.23
Specific density (g/mL) = (Mass / Specific volume)	2.13	2.12	2.05	2.10
Solid fraction = (Specific volume / Bulk volume)	0.59	0.57	0.60	0.59
Porosity = (Pore volume / Bulk volume or 1-Solid fraction)	0.41	0.43	0.40	0.41
Effective pore volume (mL)	89.00	95.00	92.00	92.00
Effective porosity = (Effective pore volume / Bulk volume)	0.15	0.16	0.15	0.15

APPENDIX E

DETAILS OF THE HARVESTED BULRUSH PLANTS

Table E.1 The details of the harvested bulrush plants at the end of Run I.

Reactors	Zone	Diameter (cm)	Height (cm)	No. Plants	Roots		Stems		Total	
					Wet wt. (g)	**Dry wt. (g)**	**Wet wt. (g)**	**Dry wt. (g)**	**Wet wt. (g)**	**Dry wt. (g)**
R11	1	1.10	1.6-1.8	129	502.19	68.46	1,983.75	229.38	2,485.94	297.84
	2	1.00	1.5-1.8	247	986.06	145.73	3,610.22	469.68	4,596.28	615.40
	3	1.40	1.7-2.2	250	994.73	153.31	3,938.57	501.92	4,933.30	655.23
	4	1.50	1.5-2.3	191	772.22	120.10	3,343.55	398.43	4,115.77	518.52
R12	1	1.00	1.4-1.8	113	640.11	98.00	3,931.58	489.71	4,571.69	587.71
	2	1.30	1.6-2.0	230	1,332.95	219.06	7,811.96	895.55	9,144.91	1,114.60
	3	1.20	1.8-2.2	244	1,386.26	247.30	8,259.05	953.01	9,645.31	1,200.30
	4	1.50	1.8-2.3	180	1,025.06	172.47	5,185.68	650.59	6,210.75	823.06
R13	1	1.10	1.6-2.3	101	576.44	81.61	3,607.02	504.90	4,183.46	586.51
	2	1.40	1.3-2.1	173	985.43	143.66	6,192.02	879.44	7,177.45	1,023.11
	3	1.40	1.6-2.2	249	1,412.75	194.45	9,662.38	1,330.46	11,075.12	1,524.91
	4	1.50	2.0-2.4	206	1,180.60	165.77	7,274.14	959.29	8,454.74	1,125.06
R14	1	1.20	1.7-2.1	80	586.88	89.03	3,965.11	648.93	4,551.99	737.97
	2	1.30	1.5-2.0	159	1,133.85	165.72	7,636.59	1,214.04	8,770.45	1,379.76
	3	1.40	1.7-2.2	195	1,425.01	219.06	9,828.04	1,383.09	11,253.05	1,602.14
	4	1.40	1.5-1.9	124	1,008.34	176.54	6,856.79	866.70	7,865.13	1,043.25
R15	1	1.00	1.6-2.2	163	958.46	127.76	4,999.23	724.29	5,957.69	852.05
	2	1.20	1.8-2.0	288	1,609.22	201.99	7,429.88	1,082.93	9,039.10	1,284.91
	3	1.20	1.9-2.2	336	1,714.06	210.66	10,341.63	1,414.61	12,055.69	1,625.27
	4	1.30	1.8-2.4	439	2,344.80	342.25	12,036.99	1,714.34	14,381.78	2,056.59

Table E.2 The details of the harvested bulrush plants at the end of Run II.

Reactors	Zone	Diameter (cm)	Height (cm)	No. Plants	Roots		Stems		Total	
					Wet wt. (g)	Dry wt. (g)	Wet wt. (g)	Dry wt. (g)	Wet wt. (g)	Dry wt. (g)
R21	1	1.20	1.3-1.8	50	261.53	21.99	1,544.27	183.59	1,805.80	205.58
	2	1.10	1.4-1.9	160	871.55	85.28	4,600.13	533.69	5,471.68	618.97
	3	1.30	1.6-2.0	170	872.38	72.19	4,680.72	566.07	5,553.10	638.26
	4	1.40	1.5-2.2	113	578.61	50.15	3,203.86	393.71	3,782.47	443.86
R22	1	1.20	1.4-1.8	67	438.09	46.32	2,282.07	219.45	2,720.16	265.77
	2	1.40	1.5-2.3	190	1,197.95	139.33	7,570.77	881.55	8,768.71	1,020.88
	3	1.30	1.7-2.2	189	1,202.04	145.18	7,303.81	896.49	8,505.85	1,041.67
	4	1.50	1.9-2.4	128	886.44	103.12	3,780.78	392.95	4,667.23	496.07
R23	1	1.10	1.6-2.2	91	491.93	363.38	3,550.76	455.86	4,042.69	819.24
	2	1.20	1.9-2.1	182	1,221.76	122.71	7,224.42	940.58	8,446.18	1,063.30
	3	1.40	1.8-2.3	254	1,654.95	209.23	9,447.33	1,089.62	11,102.28	1,298.85
	4	1.50	1.5-2.4	196	889.04	143.60	8,216.42	1,063.74	9,105.46	1,207.34
R24	1	1.50	1.9-2.3	127	770.75	76.26	5,133.08	574.63	5,903.83	650.89
	2	1.70	1.5-2.2	209	1,164.29	171.97	6,616.33	901.30	7,780.63	1,073.27
	3	1.40	1.8-2.1	233	1,201.97	158.13	7,205.10	989.98	8,407.07	1,148.11
	4	1.50	1.8-2.2	176	883.90	125.03	7,257.50	1,018.29	8,141.41	1,143.32
R25	1	1.30	1.6-2.2	167	994.10	188.42	5,016.57	756.39	6,010.67	944.81
	2	1.50	1.5-2.2	292	1,373.53	253.39	9,914.81	1,255.68	11,288.34	1,509.07
	3	1.20	2.1-2.3	335	1,575.90	292.00	10,712.00	1,345.89	12,287.90	1,637.89
	4	1.60	1.8-2.4	340	1,885.97	221.93	10,622.99	1,420.51	12,508.96	1,642.44

Table E.3 The details of the harvested bulrush plants at the end of Run III.

Reactors	Zone	Diameter (cm)	Height (cm)	No. Plants	Roots		Stems		Total	
					Wet wt. (g)	Dry wt. (g)	Wet wt. (g)	Dry wt. (g)	Wet wt. (g)	Dry wt. (g)
R31	1	1.00	1.5-1.7	32	252.33	40.25	782.11	76.06	1,034.45	116.31
	2	1.20	1.4-1.8	113	777.52	120.11	3,886.73	463.87	4,664.25	583.98
	3	1.50	1.8-2.3	128	819.24	122.47	4,811.42	539.54	5,630.66	662.01
	4	1.50	1.7-2.1	64	384.05	72.92	2,316.90	248.34	2,700.95	321.26
R32	1	1.20	1.1-1.8	50	336.49	55.61	1,596.45	183.78	1,932.94	239.39
	2	1.50	1.9-2.2	171	1,265.82	194.48	7,255.60	804.71	8,521.42	999.19
	3	1.40	1.8-2.1	183	1,405.35	186.19	8,162.07	1,008.75	9,567.42	1,194.95
	4	1.50	2.0-2.3	130	1,015.02	168.04	5,761.20	663.74	6,776.22	831.78
R33	1	1.20	2.0-2.2	88	589.44	97.77	2,828.12	368.11	3,417.56	465.89
	2	1.50	1.0-2.3	169	1,064.30	179.93	6,927.86	784.78	7,992.16	964.71
	3	1.60	1.8-2.1	236	1,440.81	239.98	9,615.85	1,146.27	11,056.66	1,386.24
	4	1.50	2.0-2.4	187	1,082.59	172.82	9,547.47	1,159.95	10,630.06	1,332.77
R34	1	1.80	1.9-2.2	118	648.84	101.70	4,625.55	632.89	5,274.39	734.59
	2	1.50	1.8-2.1	193	875.10	164.61	7,587.15	1,122.06	8,462.24	1,286.67
	3	1.50	1.7-2.0	231	1,346.87	208.98	8,897.86	1,258.85	10,244.73	1,467.83
	4	1.40	1.8-2.2	166	1,145.40	228.17	6,613.82	882.35	7,759.22	1,110.52
R35	1	1.30	1.8-2.3	154	946.65	155.90	5,281.72	718.99	6,228.37	874.89
	2	1.50	1.8-2.0	268	1,614.42	274.70	9,716.32	1,373.08	11,330.74	1,647.78
	3	1.50	2.0-2.2	312	1,948.39	279.30	13,991.97	1,783.30	15,940.35	2,062.60
	4	1.50	2.0-2.3	277	1,817.13	259.27	11,393.33	1,359.49	13,210.45	1,618.76

APPENDIX F

REGRESSION ANALYSIS

Table F.1 Relationship between Cds and Cdww in FWS constructed wetland during three experimental runs.

Correlations

		Cdww (mg/L)	Cds (mg/kg)
Cdww (mg/L)	Pearson Correlation	1.000	0.730**
	Sig. (2-tailed)	0.000	0.000
	N	288	288
Cds (mg/kg)	Pearson Correlation	0.730**	1.000
	Sig. (2-tailed)	0.000	0.000
	N	288	288

** Correlation is significant at the 0.01 level (2-tailed).

Variables Entered/Removed[b]

Model	Variables Entered	Variables Removed	Method
1	Cdww (mg/L)[a]	0.000	Enter

a All requested variables entered.
b Dependent Variable: Cds (mg/kg)

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	0.730[a]	0.5324	0.531	43.24822

a Predictors: (Constant), Cdww (mg/L)

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	609174.02	1	609174.020	325.690	0.000[a]
	Residual	534936.92	286	1870.409		
	Total	1144110.94	287			

a Predictors: (Constant), Cdww (mg/L)
b Dependent Variable: Cds (mg/kg)

Table F.1 Relationship between Cds and Cdww in FWS constructed wetland during three experimental runs (Continued).

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients		
		B	**Std. Error**	**Beta**	**t**	**Sig.**
1	(Constant)	17.621	3.510		5.020	0.000
	Cdww (mg/L)	3.678	0.204	0.730	18.047	0.000

a Dependent Variable: Cds (mg/kg)

Table F.2 Relationship between Cdp and Cdww × mp in FWS constructed wetland during three experimental runs.

Correlations

		Cdww x mp (mg kgdw/L)	Cdp (mg/kg)
Cdww x mp (mg kgdw/L)	Pearson Correlation	1.000	0.789**
	Sig. (2-tailed)	0.000	0.000
	N	288	288
Cdp (mg/kg)	Pearson Correlation	0.789**	1.000
	Sig. (2-tailed)	0.000	0.000
	N	288	288

** Correlation is significant at the 0.01 level (2-tailed).

Variables Entered/Removed[b]

Model	Variables Entered	Variables Removed	Method
1	Cdww x mp (mg kgdw/L)[a]	0.000	Enter

a All requested variables entered.
b Dependent Variable: Cdp (mg/kg)

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	0.789[a]	0.622	0.620	1047.49336

a Predictors: (Constant), Cdww x mp (mg kgdw/L)

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	5.16E+08	1	515937433.2	470.213	0.000[a]
	Residual	3.14E+08	286	1097242.336		
	Total	8.30E+08	287			

a Predictors: (Constant), Cdww x mp (mg kgdw/L)
b Dependent Variable: Cdp (mg/kg)

Table F.2 Relationship between Cdp and Cdww × mp in FWS constructed wetland during three experimental runs (Continued).

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	346.813	87.798		3.950	0.000
	Cdww x mp (mg kgdw/L)	140.801	6.493	0.789	21.684	0.000

a Dependent Variable: : Cdp (mg/kg)

APPENDIX G

MODEL EQUATIONS USED IN STELLA PROGRAM

Table G.1 The details of model equation used in STELLA.

CdP1(t) = CdP1(t - dt) + (Uptake1)*dt

INIT CdP1 = 16.988*mp1

INFLOWS:

Uptake1 = ((f1*mp1*CdWW1)+Intercept1-CdP1)*0.09

CdP2(t) = CdP2(t - dt) + (Uptake2)*dt

INIT CdP2 = 16.988*mp2

INFLOWS:

Uptake2 = ((f2*mp2*CdWW2)+Intercept2-CdP2)*0.09

CdP3(t) = CdP3(t - dt) + (Uptake3)*dt

INIT CdP3 = 16.988*mp3

INFLOWS:

Uptake3 = ((f3*mp3*CdWW3)+Intercept3-CdP3)*0.09

CdP4(t) = CdP4(t - dt) + (Uptake4)*dt

INIT CdP4 = 16.988*mp4

INFLOWS:

Uptake4 = ((f4*mp4*CdWW4)+Intercept4-CdP4)*0.09

CdS1(t) = CdS1(t - dt) + (Adsorption1 - Desorption1)*dt

INIT CdS1 = 0.32*dryweight_of_soil

Table G.1 The details of model equation used in STELLA (Continued).

INFLOWS:

Adsorption1 = IF(CdS1<(Slope*CdWW1)+Intercept)THEN(((Slope*CdWW1)+Intercept-CdS1)*0.05)ELSE(0)

OUTFLOWS:

Desorption1 = IF(CdS1>(Slope*CdWW1)+Intercept)THEN((CdS1-Intercept)/Slope-CdWW1)ELSE(0)

CdS2(t) = CdS2(t - dt) + (Adsorption2 - Desorption2)*dt

INIT CdS2 = 0.32*dryweight_of_soil

INFLOWS:

Adsorption2 = IF(CdS2<(Slope*CdWW2)+Intercept)THEN(((Slope*CdWW2)+Intercept-CdS2)*0.05)ELSE(0)

OUTFLOWS:

Desorption2 = IF(CdS2>(Slope*CdWW2)+Intercept)THEN((CdS2-Intercept)/Slope-CdWW2)ELSE(0)

CdS3(t) = CdS3(t - dt) + (Adsorption3 - Desorption3)*dt

INIT CdS3 = 0.32*dryweight_of_soil

INFLOWS:

Adsorption3 = IF(CdS3<(Slope*CdWW3)+Intercept)THEN(((Slope*CdWW3)+Intercept-CdS3)*0.05)ELSE(0)

OUTFLOWS:

Desorption3 = IF(CdS3>(Slope*CdWW3)+Intercept)THEN((CdS3-Intercept)/Slope-CdWW3)ELSE(0)

CdS4(t) = CdS4(t - dt) + (Adsorption4 - Desorption4)*dt

INIT CdS4 = 0.32*dryweight_of_soil

Table G.1 The details of model equation used in STELLA (Continued).

INFLOWS:

Adsorption4 = IF(CdS4<(Slope*CdWW4)+Intercept)THEN(((Slope*CdWW4)+Intercept-CdS4)*0.05)ELSE(0)

OUTFLOWS:

Desorption4 = IF(CdS4>(Slope*CdWW4)+Intercept)THEN((CdS4-Intercept)/Slope-CdWW4)ELSE(0)

CdWW1(t) = CdWW1(t - dt) + (Inflow_mg_per_day + Desorption1 - Flow1 - Uptake1 - Adsorption1)*dt

INIT CdWW1 = 0.2*V_water

INFLOWS:

Inflow_mg_per_day = Inflow_L_per_day*Input_Cd_mg_per_L

Desorption1 = IF(CdS1>(Slope*CdWW1)+Intercept)THEN((CdS1-Intercept)/Slope-CdWW1)ELSE(0)

OUTFLOWS:

Flow1 = CdWW1

Uptake1 = ((f1*mp1*CdWW1)+Intercept1-CdP1)*0.09

Adsorption1 = IF(CdS1<(Slope*CdWW1)+Intercept)THEN(((Slope*CdWW1)+Intercept-CdS1)*0.05)ELSE(0)

CdWW2(t) = CdWW2(t - dt) + (Flow1 + Desorption2 - Flow2 - Uptake2 - Adsorption2)*dt

INIT CdWW2 = 0.2*V_water

INFLOWS:

Flow1 = CdWW1

Desorption2 = IF(CdS2>(Slope*CdWW2)+Intercept)THEN((CdS2-Intercept)/Slope-CdWW2)ELSE(0)

Table G.1 The details of model equation used in STELLA (Continued).

OUTFLOWS:

Flow2 = CdWW2

Uptake2 = ((f2*mp2*CdWW2)+Intercept2-CdP2)*0.09

Adsorption2 = IF(CdS2<(Slope*CdWW2)+Intercept)THEN(((Slope*CdWW2)+Intercept-CdS2)*0.05)ELSE(0)

CdWW3(t) = CdWW3(t - dt) + (Flow2 + Desorption3 - Flow3 - Uptake3 - Adsorption3)*dt

INIT CdWW3 = 0.2*V_water

INFLOWS:

Flow2 = CdWW2

Desorption3 = IF(CdS3>(Slope*CdWW3)+Intercept)THEN((CdS3-Intercept)/Slope-CdWW3)ELSE(0)

OUTFLOWS:

Flow3 = CdWW3

Uptake3 = ((f3*mp3*CdWW3)+Intercept3-CdP3)*0.09

Adsorption3 = IF(CdS3<(Slope*CdWW3)+Intercept)THEN(((Slope*CdWW3)+Intercept-CdS3)*0.05)ELSE(0)

CdWW4(t) = CdWW4(t - dt) + (Flow3 + Desorption4 - Uptake4 - Adsorption4 - Outflow_mg_per_day)*dt

INIT CdWW4 = 0.2*V_water

INFLOWS:

Flow3 = CdWW3

Desorption4 = IF(CdS4>(Slope*CdWW4)+Intercept)THEN((CdS4-Intercept)/Slope-CdWW4)ELSE(0)

Table G.1 The details of model equation used in STELLA (Continued).

OUTFLOWS:

Uptake4 = ((f4*mp4*CdWW4)+Intercept4-CdP4)*0.09

Adsorption4 = IF(CdS4<(Slope*CdWW4)+Intercept)THEN(((Slope*CdWW4)+Intercept-CdS4)*0.05)ELSE(0)

Outflow_mg_per_day = CdWW4

○ bulk_density_of_soil = 1210

○ dryweight_of_soil = bulk_density_of_soil*soil_volume/4

○ Efficiency% = (Inflow_mg_per_day-Outflow_mg_per_day)*100/Inflow_mg_per_day

○ Intercept = 17.621*dryweight_of_soil

○ Intercept1 = 346.813*mp1

○ Intercept2 = 346.813*mp2

○ Intercept3 = 346.813*mp3

○ Intercept4 = 346.813*mp4

○ f1 = 140.801*mp1/64.6875

○ f2 = 140.801*mp2/64.6875

○ f3 = 140.801*mp3/64.6875

○ f4 = 140.801*mp4/64.6875

Table G.1 The details of model equation used in STELLA (Continued).

○ Slope = 3.678*dryweight_of_soil/V_water

○ soil_volume = 0.375

○ V_water = 258.75/4

⊘ Inflow_L_per_day = GRAPH(time)
(0.00, 51.8), (3.57, 51.8), (7.13, 51.8), (10.7, 51.8), (14.3, 51.8), (17.8, 51.8), (21.4, 51.8), (25.0, 51.8), (28.5, 51.8), (32.1, 51.8), (35.7, 51.8), (39.2, 51.8), (42.8, 51.8), (46.3, 51.8), (49.9, 51.8), (53.5, 51.8), (57.0, 51.8), (60.6, 51.8), (64.2, 51.8), (67.7, 51.8), (71.3, 51.8), (74.9, 51.8), (78.4, 51.8), (82.0, 51.8)

⊘ Input_Cd_mg_per_L = GRAPH(time)
(0.00, 5.30), (3.57, 6.00), (7.13, 5.10), (10.7, 4.82), (14.3, 5.13), (17.8, 4.74), (21.4, 5.00), (25.0, 4.80), (28.5, 5.20), (32.1, 5.11), (35.7, 4.69), (39.2, 4.85), (42.8, 5.04), (46.3, 4.90), (49.9, 4.53), (53.5, 5.01), (57.0, 5.28), (60.6, 5.42), (64.2, 5.74), (67.7, 4.82), (71.3, 4.64), (74.9, 5.28), (78.4, 4.28), (82.0, 4.34)

⊘ mp1 = GRAPH(time)
(0.00, 0.63), (13.7, 0.7), (27.3, 0.78), (41.0, 0.85), (54.7, 0.94), (68.3, 1.02), (82.0, 1.11)

⊘ mp2 = GRAPH(time)
(0.00, 0.85), (13.7, 0.95), (27.3, 1.05), (41.0, 1.16), (54.7, 1.28), (68.3, 1.39), (82.0, 1.50)

⊘ mp3 = GRAPH(time)
(0.00, 1.05), (13.7, 1.17), (27.3, 1.31), (41.0, 1.46), (54.7, 1.59), (68.3, 1.73), (82.0, 1.86)

Table G.1 The details of model equation used in STELLA (Continued).

mp4 = GRAPH(time)
(0.00, 0.84), (13.7, 0.94), (27.3, 1.05), (41.0, 1.17), (54.7, 1.28), (68.3, 1.38), (82.0, 1.49)

MeasCdP1 = GRAPH(time)
(0.00, 10.7), (13.7, 72.2), (27.3, 142), (41.0, 374), (54.7, 659), (68.3, 811), (82.0, 985)

MeasCdP2 = GRAPH(time)
(0.00, 14.4), (13.7, 145), (27.3, 294), (41.0, 603), (54.7, 1083), (68.3, 1530), (82.0, 1793)

MeasCdP3 = GRAPH(time)
(0.00, 17.8), (13.7, 149), (27.3, 464), (41.0, 626), (54.7, 1120), (68.3, 1507), (82.0, 1809)

MeasCdP4 = GRAPH(time)
(0.00, 14.3), (13.7, 117), (27.3, 277), (41.0, 479), (54.7, 672), (68.3, 779), (82.0, 1014)

MeasCdWW1 = GRAPH(time)
(0.00, 12.9), (13.7, 292), (27.3, 300), (41.0, 287), (54.7, 300), (68.3, 294), (82.0, 279)

MeasCdWW2 = GRAPH(time)
(0.00, 12.9), (13.7, 235), (27.3, 240), (41.0, 223), (54.7, 236), (68.3, 241), (82.0, 235)

MeasCdWW3 = GRAPH(time)
(0.00, 12.9), (13.7, 148), (27.3, 149), (41.0, 146), (54.7, 149), (68.3, 153), (82.0, 143)

Table G.1 The details of model equation used in STELLA (Continued).

MeasCdWW4 = GRAPH(time)

(0.00, 12.9), (13.7, 84.8), (27.3, 80.3), (41.0, 85.8), (54.7, 83.9), (68.3, 77.6), (82.0, 75.3)

MeasOutflow = GRAPH(time)

(0.00, 71.3), (3.57, 72.8), (7.13, 77.4), (10.7, 71.1), (14.3, 65.5), (17.8, 76.3), (21.4, 47.1), (25.0, 52.5), (28.5, 62.2), (32.1, 57.3), (35.7, 48.1), (39.2, 64.1), (42.8, 56.1), (46.3, 44.3), (49.9, 51.2), (53.5, 65.8), (57.0, 55.2), (60.6, 60.1), (64.2, 45.9), (67.7, 54.1), (71.3, 46.7), (74.9, 55.8), (78.4, 41.6), (82.0, 57.6)

Meas_CdS1 = GRAPH(time)

(0.00, 36.3), (13.7, 535), (27.3, 1412), (41.0, 1852), (54.7, 2705), (68.3, 3409), (82.0, 3827)

Meas_CdS2 = GRAPH(time)

(0.00, 36.3), (13.7, 558), (27.3, 1066), (41.0, 1599), (54.7, 2144), (68.3, 2876), (82.0, 3132)

Meas_CdS3 = GRAPH(time)

(0.00, 36.3), (13.7, 452), (27.3, 935), (41.0, 1301), (54.7, 1871), (68.3, 2251), (82.0, 2659)

Meas_CdS4 = GRAPH(time)

(0.00, 36.3), (13.7, 483), (27.3, 895), (41.0, 1343), (54.7, 1826), (68.3, 2408), (82.0, 2676)

Table G.2 Explanation to names used in one sub-model of the cadmium removal model.

STATE VARIABLES IN SUB-MODEL (STOCKS)

Name in (sub) model	Unit	Explanation
CdWW1*	mg	Amount of cadmium in wastewater in compartment 1
CdP1*	mg	Amount of cadmium in plants in compartment 1
CdS1*	mg	Amount of cadmium in soil in compartment 1

FLOW ARROWS IN SUB-MODEL (PROCESS EQUATIONS)

Name in (sub) model	Unit	Explanation
Inflow mg per day	mg/day	Amount of cadmium in inflow
Uptake1*	mg	Amount of cadmium plants uptake in compartment 1
Adsorption1*	mg	Amount of cadmium adsorption in compartment 1
Desorption1*	mg	Amount of cadmium desorption in compartment 1
Flow1*	mg	Amount of cadmium in outflow from compartment 1
Outflow mg per day	mg/day	Amount of cadmium in outflow from compartment 4

*Names from each sub-model (compartment) are explained as the rest of model names are similar, but with different compartment numbers.

Table G.2 Explanation to names used in one sub-model of the cadmium removal model (Continued).

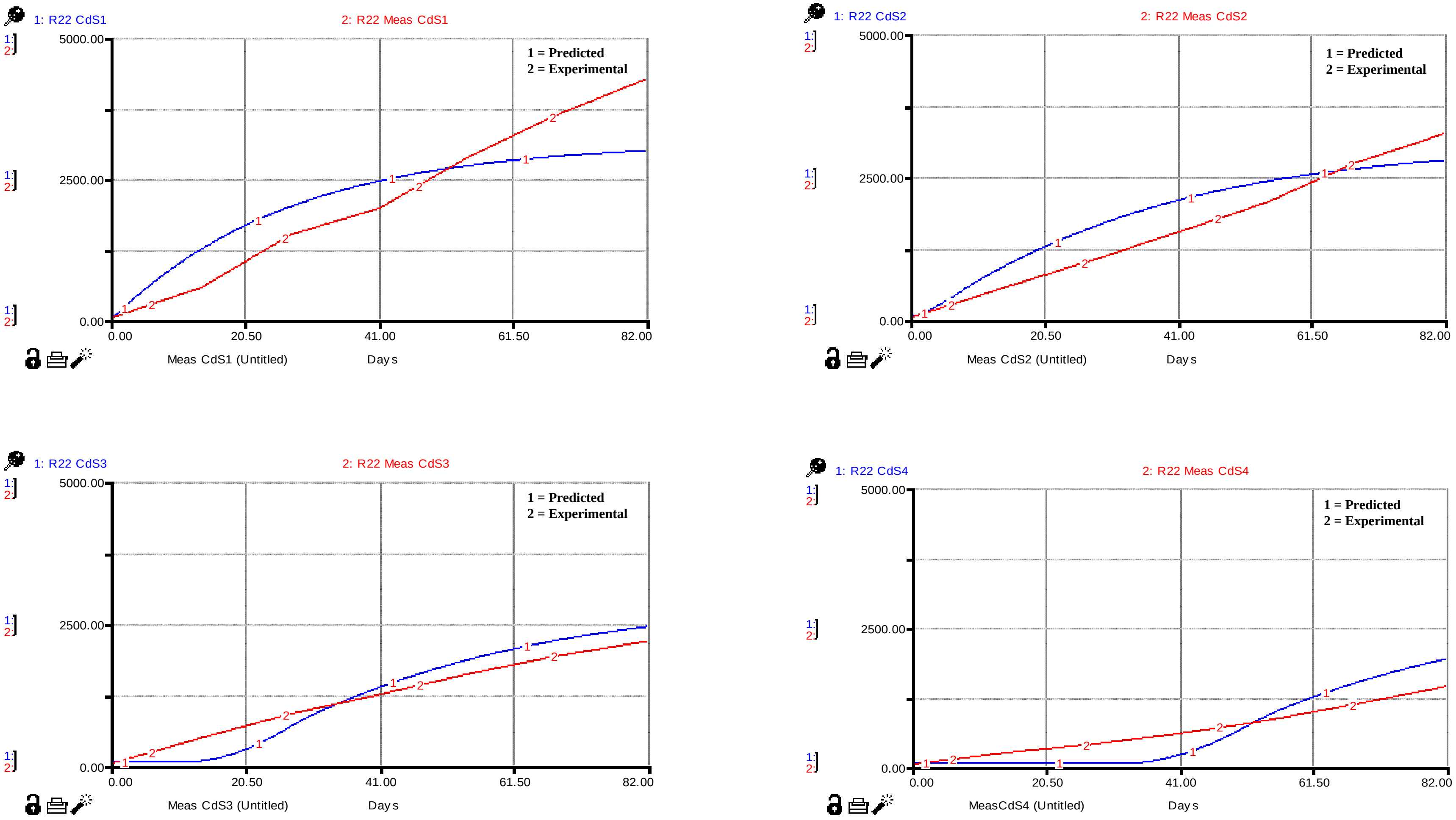
FORCING FUNCTIONS (INFLOWS, CONSTANTS, CONCENTRATIONS)

Name in (sub) model	**Unit**	**Explanation**
Inflow L per day	L/day	Inflow rate
Input Cd mg per L	mg/L	Cadmium concentration in inlet
f1*	1/kgdw	Slope from regression analysis (Eq. 5.10) in compartment 1
mp1*	kgdw	Dry weight of plants in compartment 1
Intercept1*	mg	Intercept from regression analysis (Eq. 5.11) in compartment 1
bulk density of soil	kgdw/m^3	Bulk density of soil in wetland unit
soil volume	m^3	Soil volume of constructed wetland
dry weight of soil	kgdw	Dry weight of soil in the compartment
V water	L	Volume of wastewater in the compartment
Slope	-	Slope from regression analysis (Eq. 5.5) in wetland unit
Intercept	mg	Intercept from regression analysis (Eq. 5.6) in wetland unit
Efficiency %	%	Percent removal efficiency

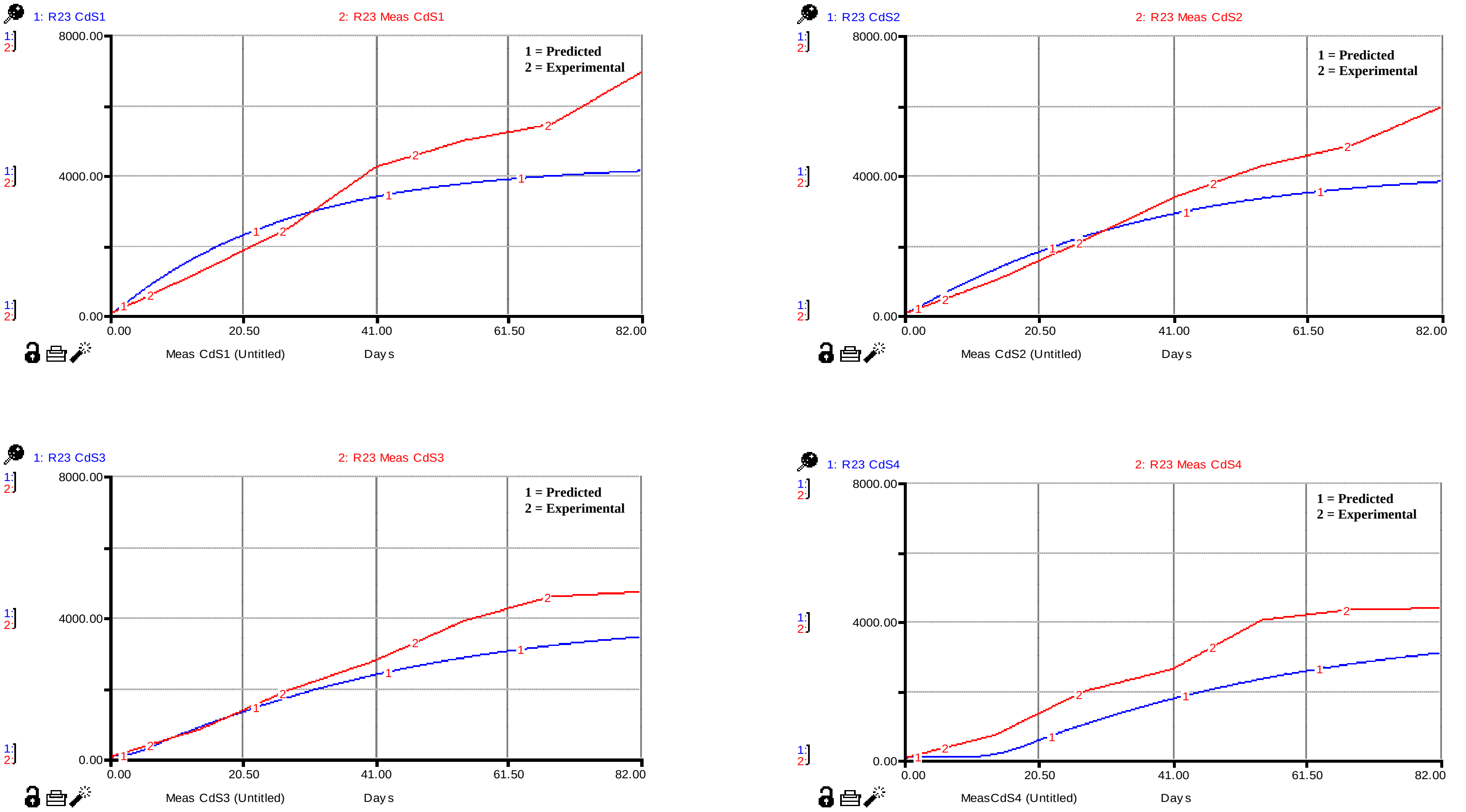
*Names from each sub-model (compartment) are explained as the rest of model names are similar, but with different compartment numbers.

APPENDIX H

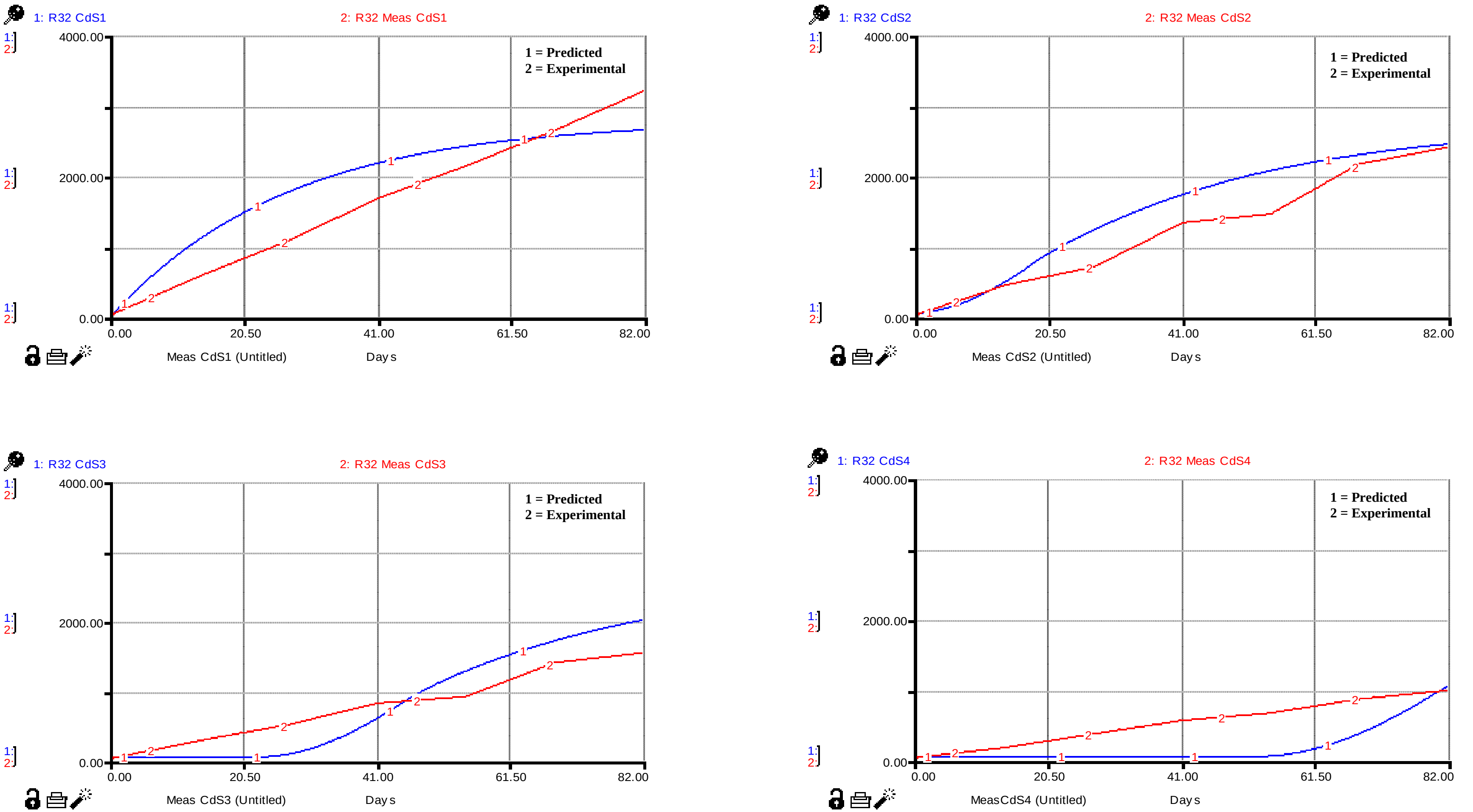
MODEL CALIBRATION AND VALIDATION



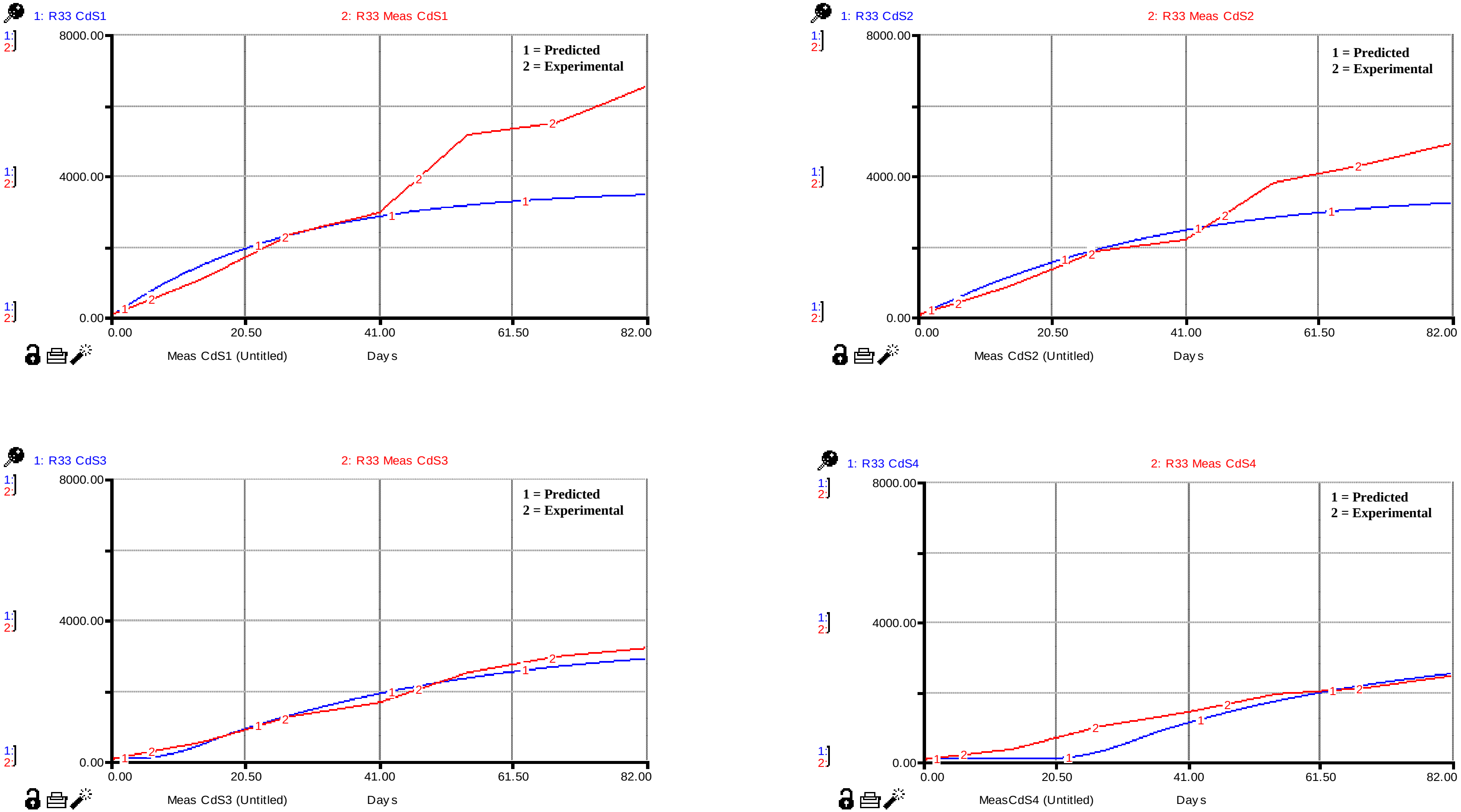
Figures H.1 Model calibration for adsorption of Cd in the soil in four compartments of reactor R22 (mg/d).



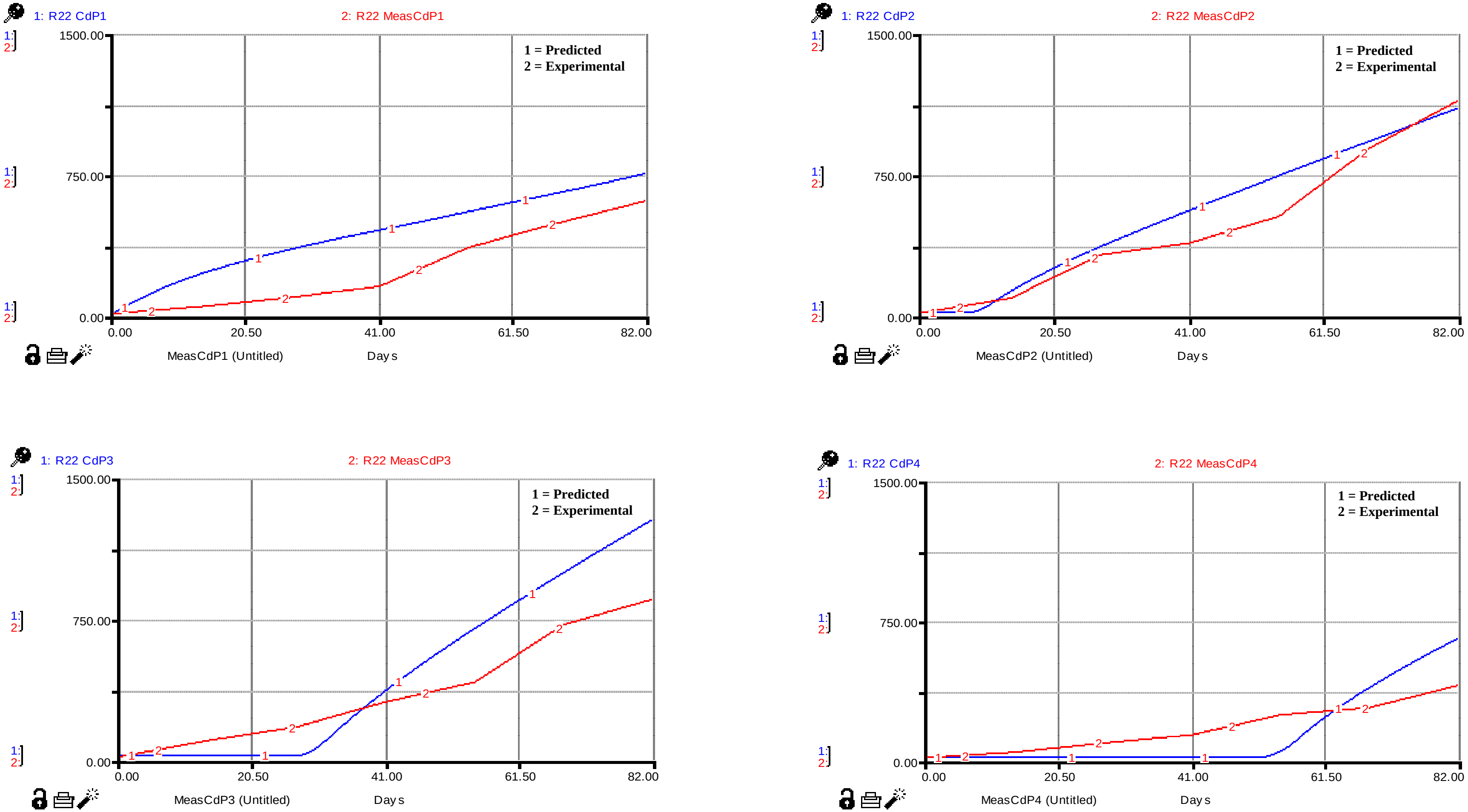
Figures H.2 Model calibration for adsorption of Cd in the soil in four compartments of reactor R23 (mg/d).



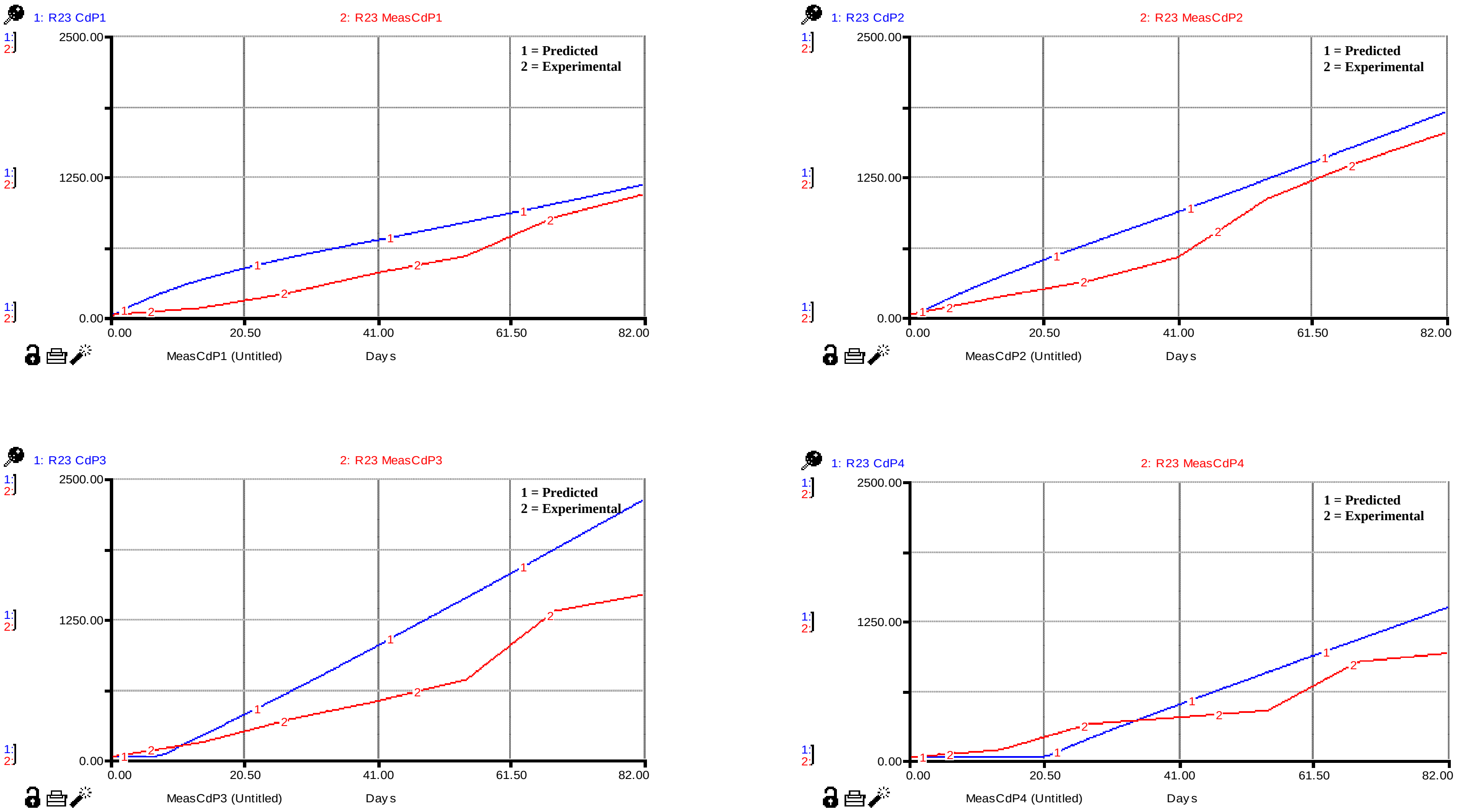
Figures H.3 Model calibration for adsorption of Cd in the soil in four compartments of reactor R32 (mg/d).



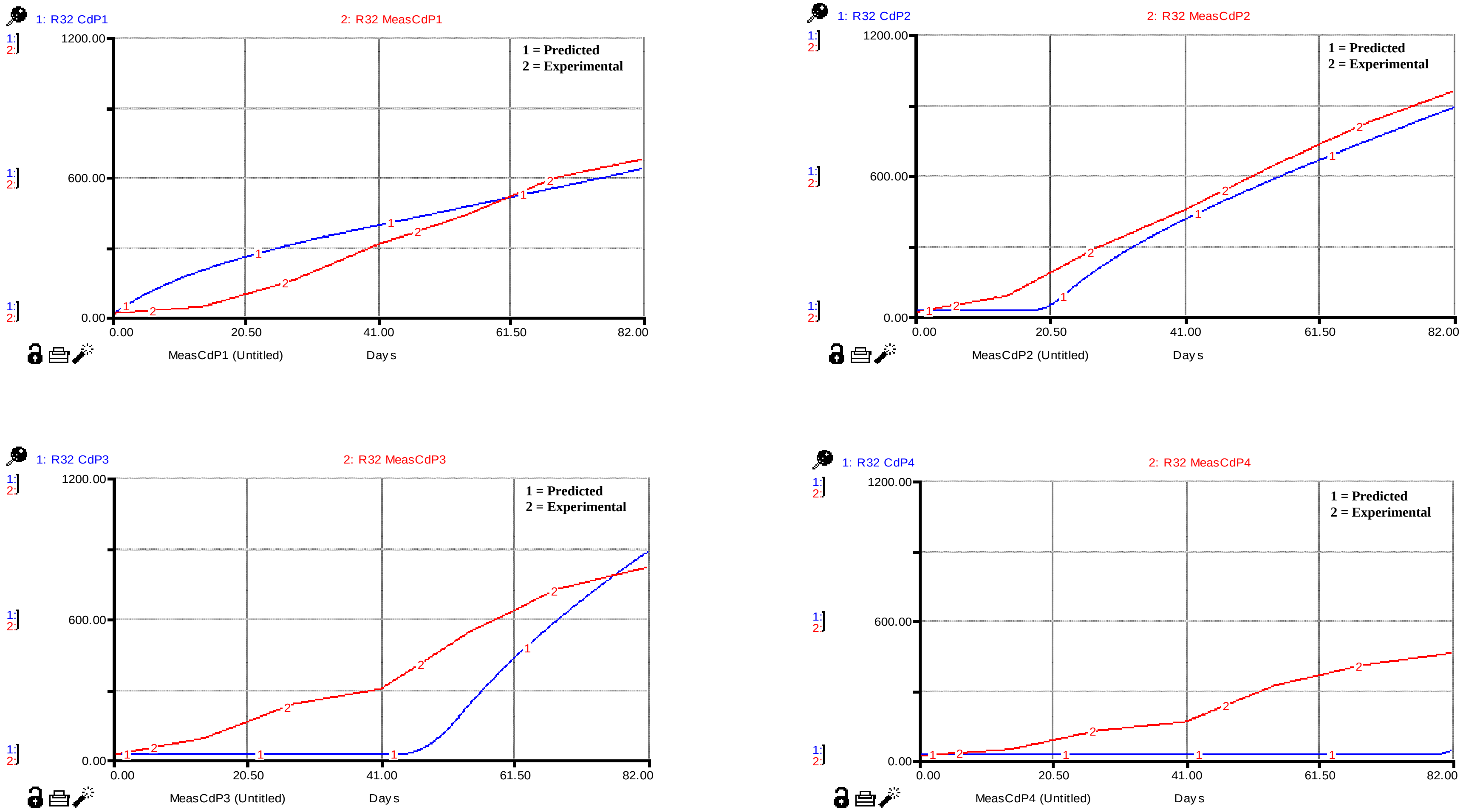
Figures H.4 Model calibration for adsorption of Cd in the soil in four compartments of reactor R33 (mg/d).



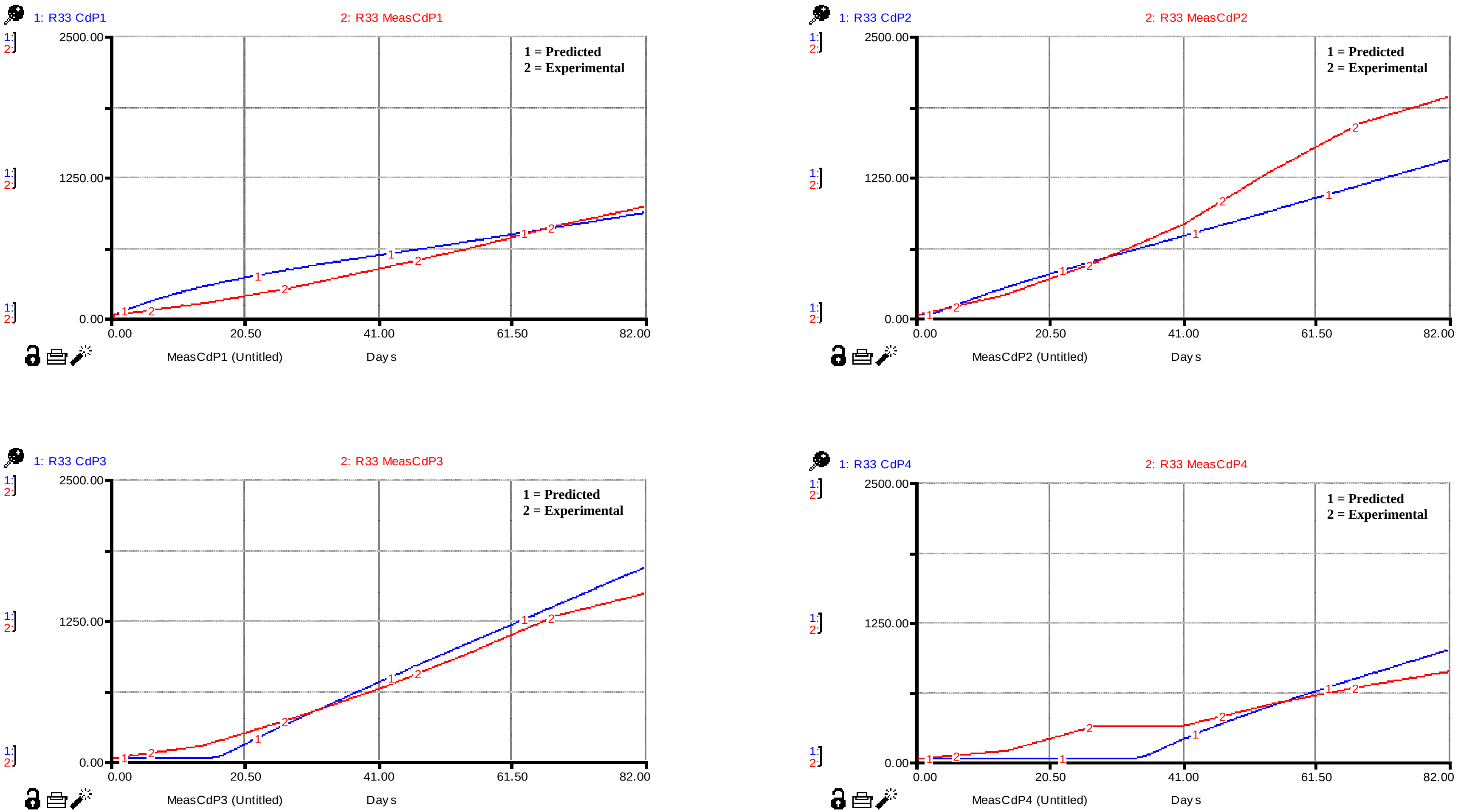
Figures H.5 Model calibration for plants uptake of Cd in four compartments of reactor R22 (mg/d).



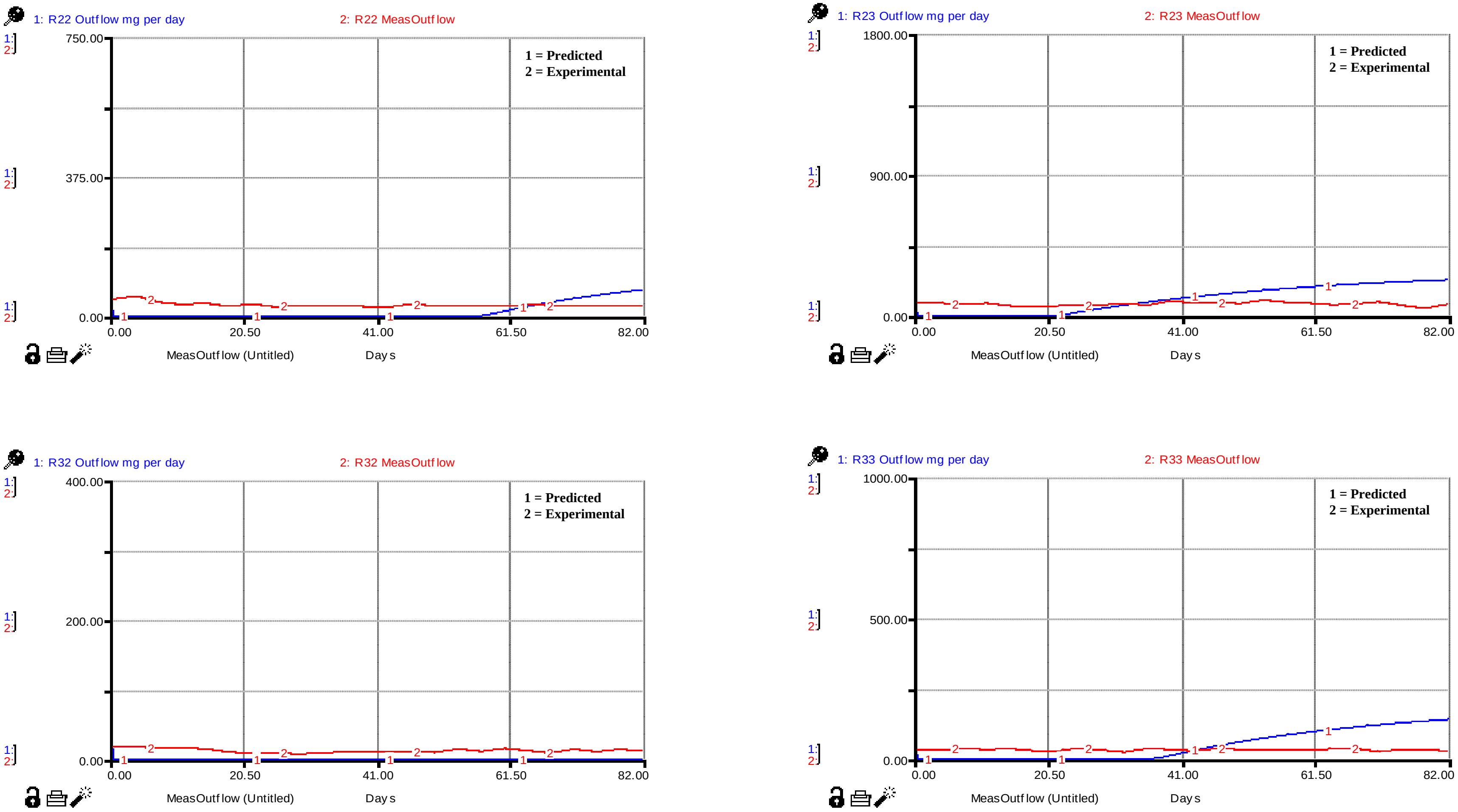
Figures H.6 Model calibration for plants uptake of Cd in four compartments of reactor R23 (mg/d).



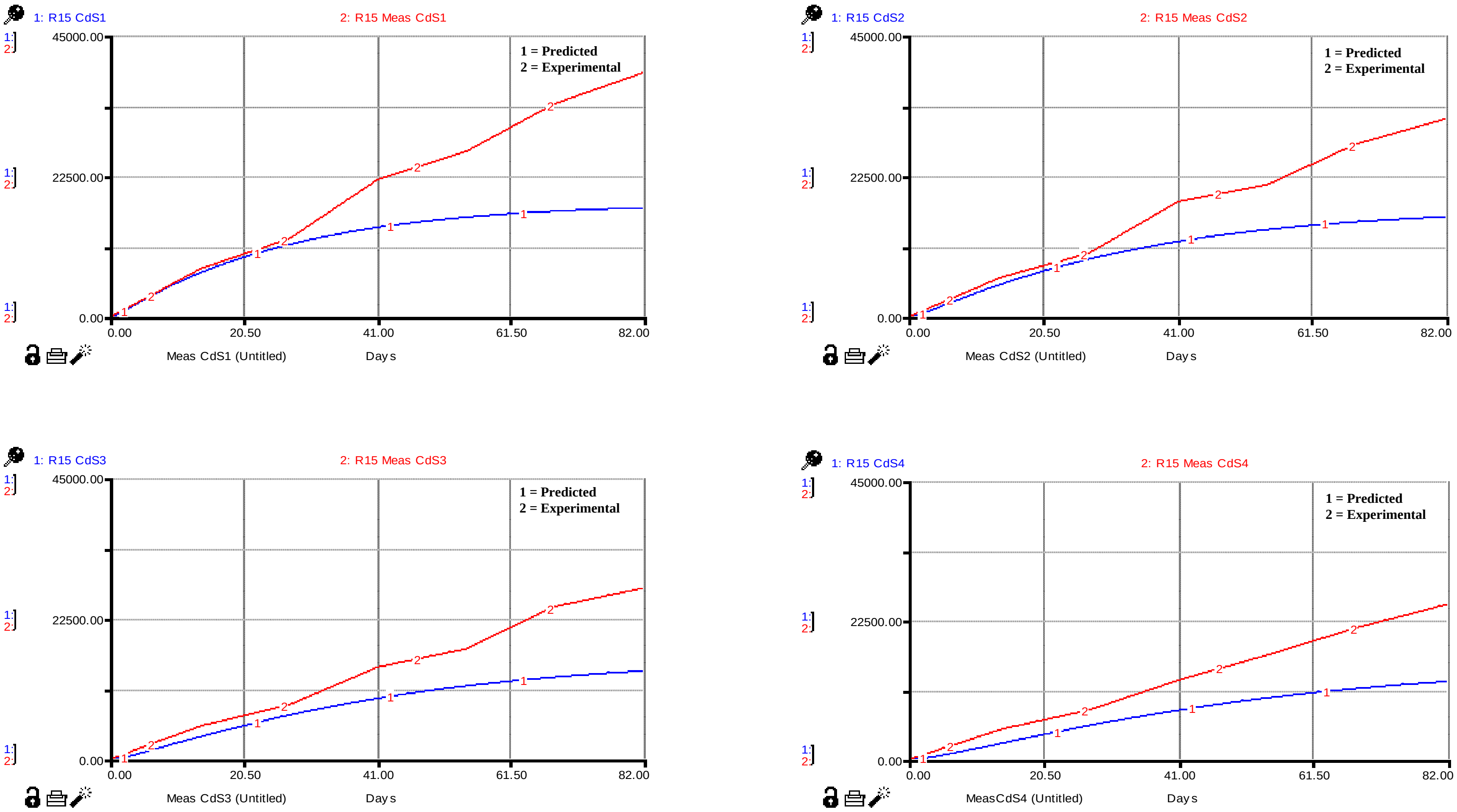
Figures H.7 Model calibration for plants uptake of Cd in four compartments of reactor R32 (mg/d).



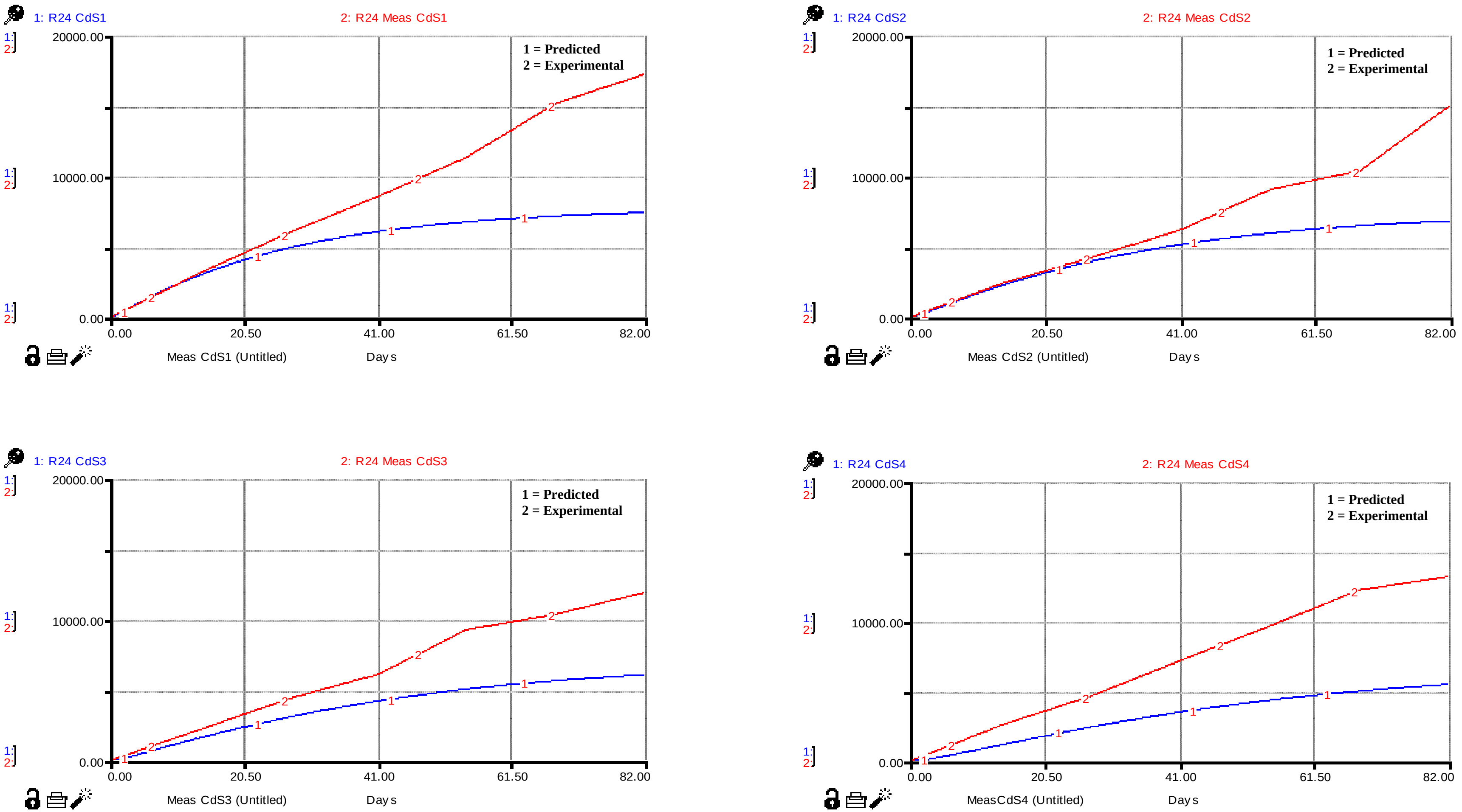
Figures H.8 Model calibration for plants uptake of Cd in four compartments of reactor R33 (mg/d).



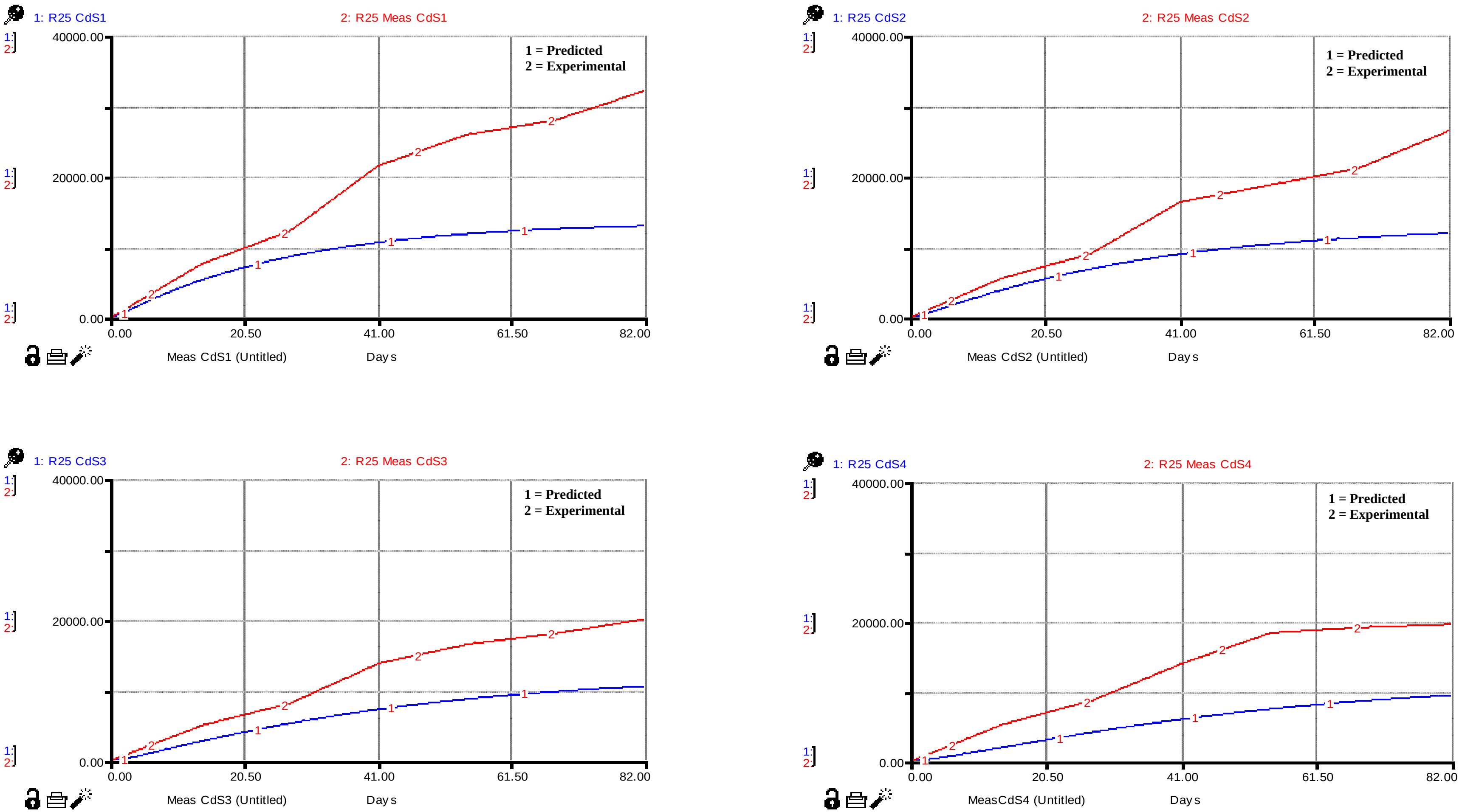
Figures H.9-H.12 Comparison of predicted and experimental values of outflow in model calibration for R22, R23, R32 and R33 (mg/d).



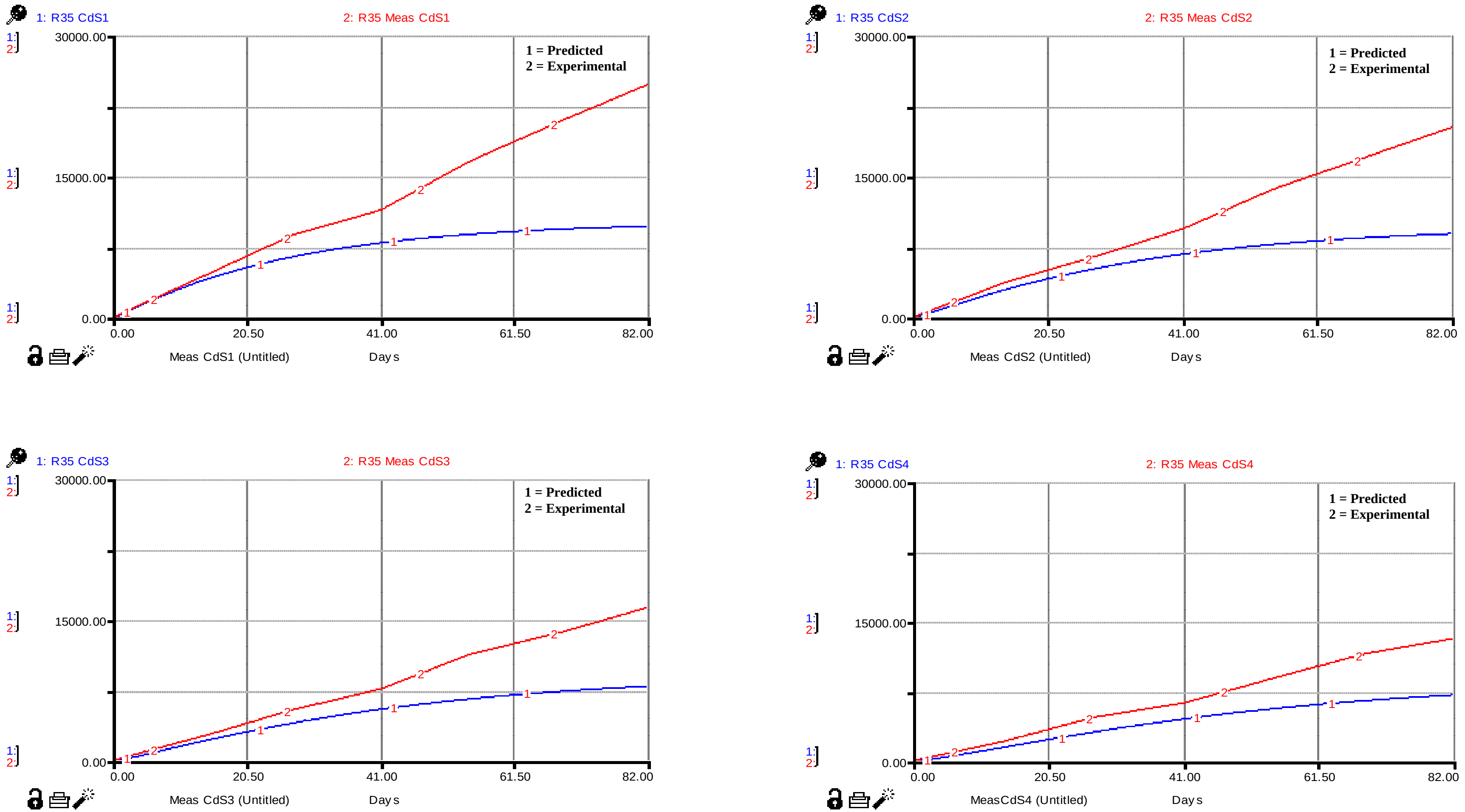
Figures H.13 Model validation for adsorption of Cd in the soil in four compartments of reactor R15 (mg/d).



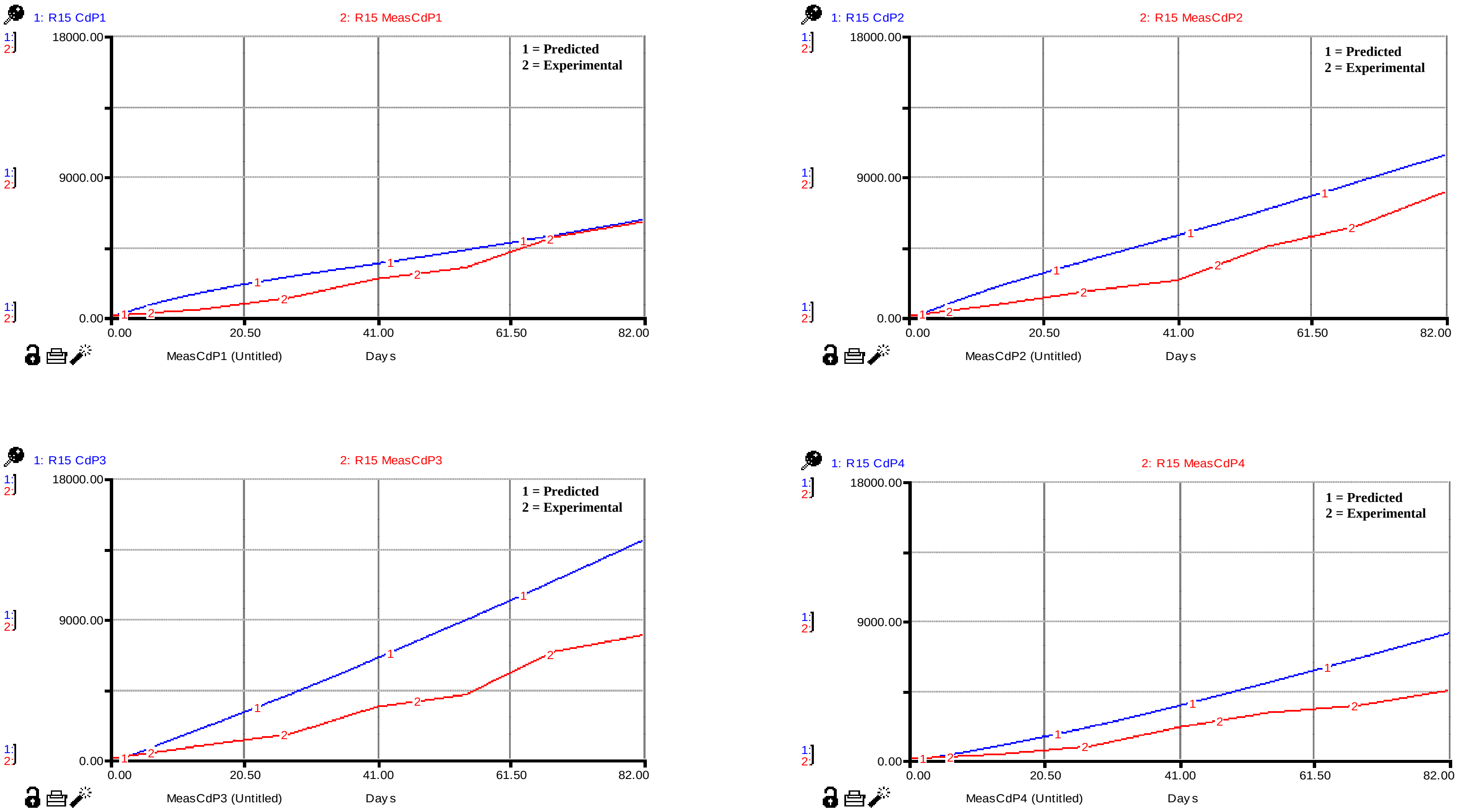
Figures H.14 Model validation for adsorption of Cd in the soil in four compartments of reactor R24 (mg/d).



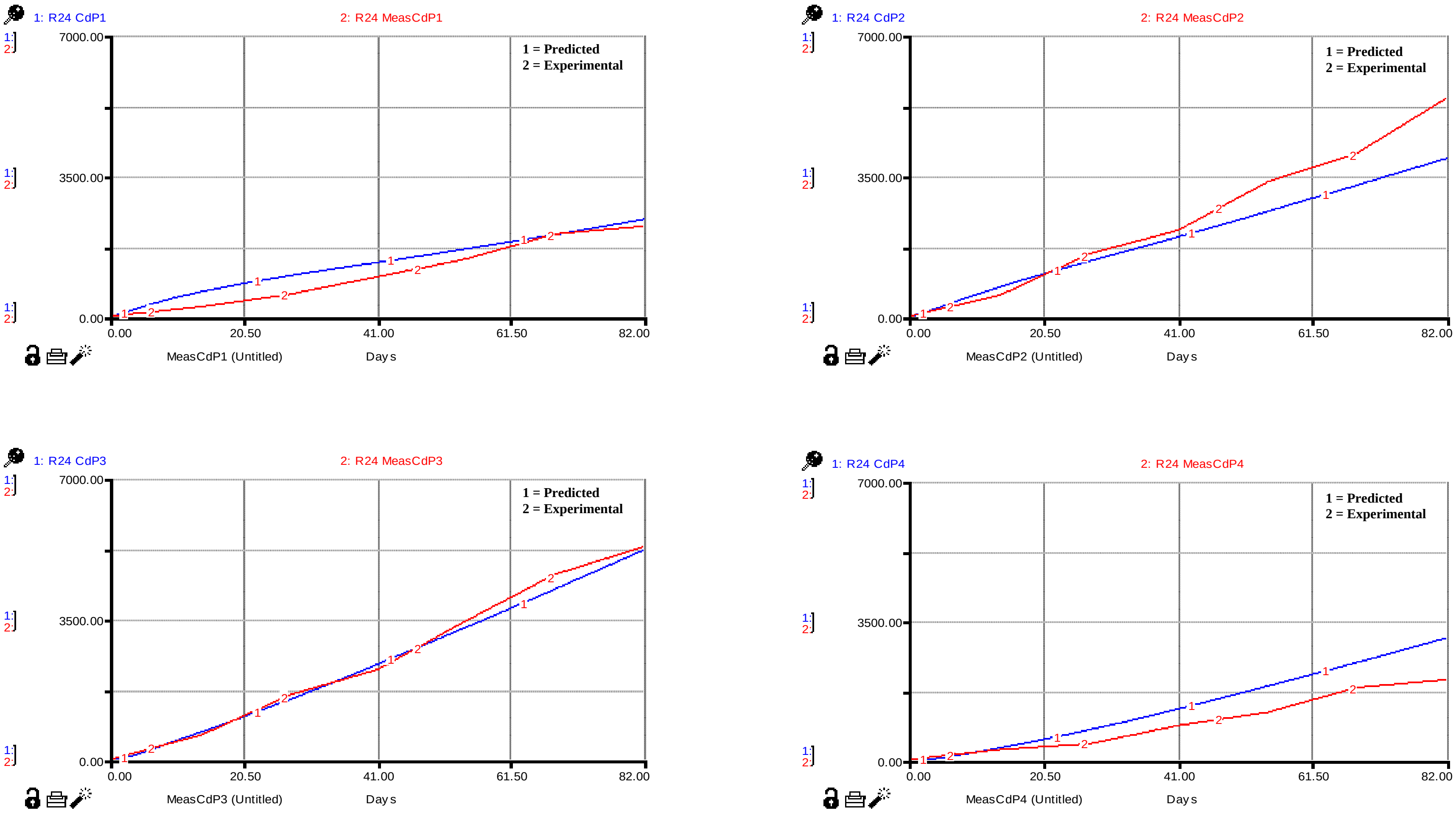
Figures H.15 Model validation for adsorption of Cd in the soil in four compartments of reactor R25 (mg/d).



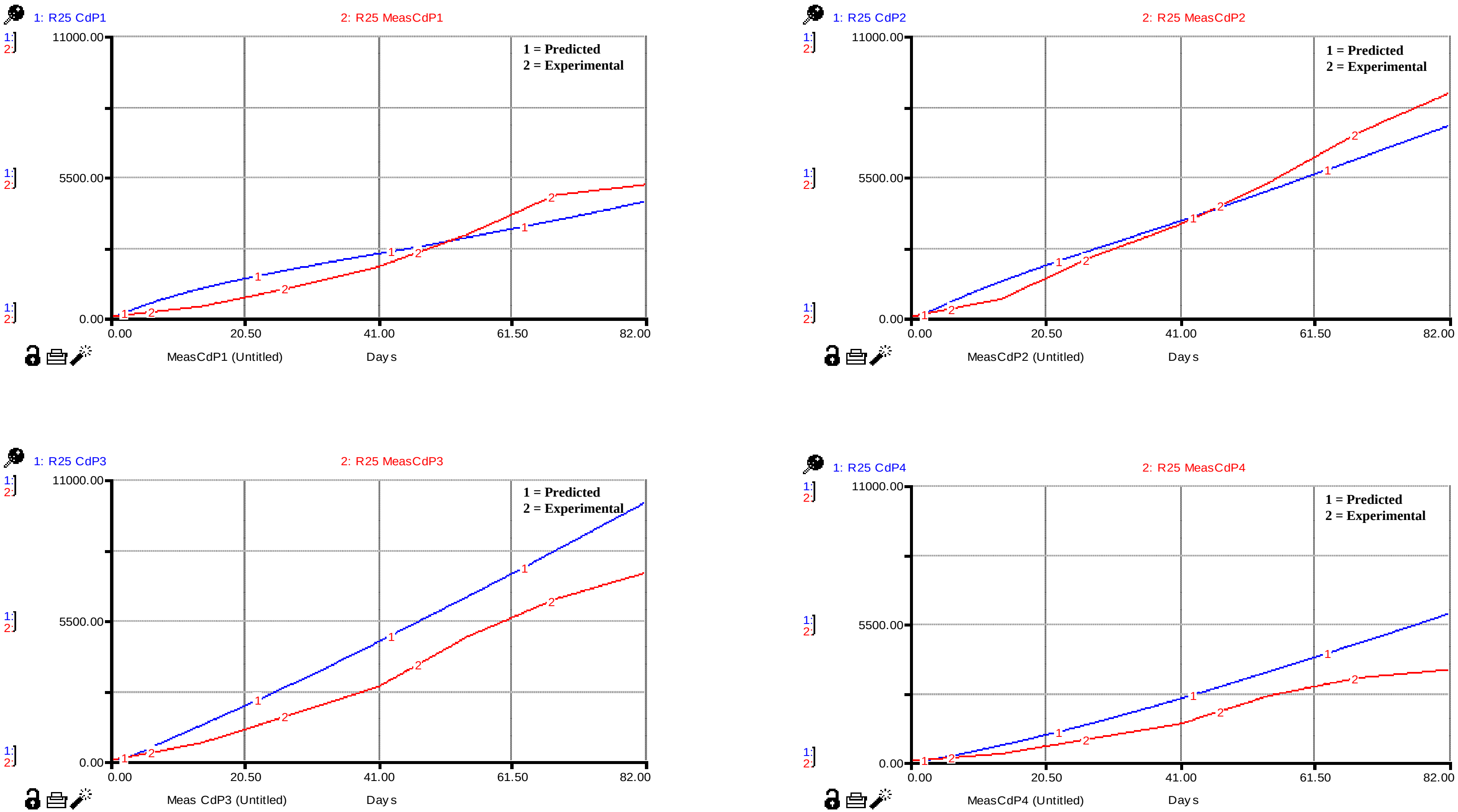
Figures H.16 Model validation for adsorption of Cd in the soil in four compartments of reactor R35 (mg/d).



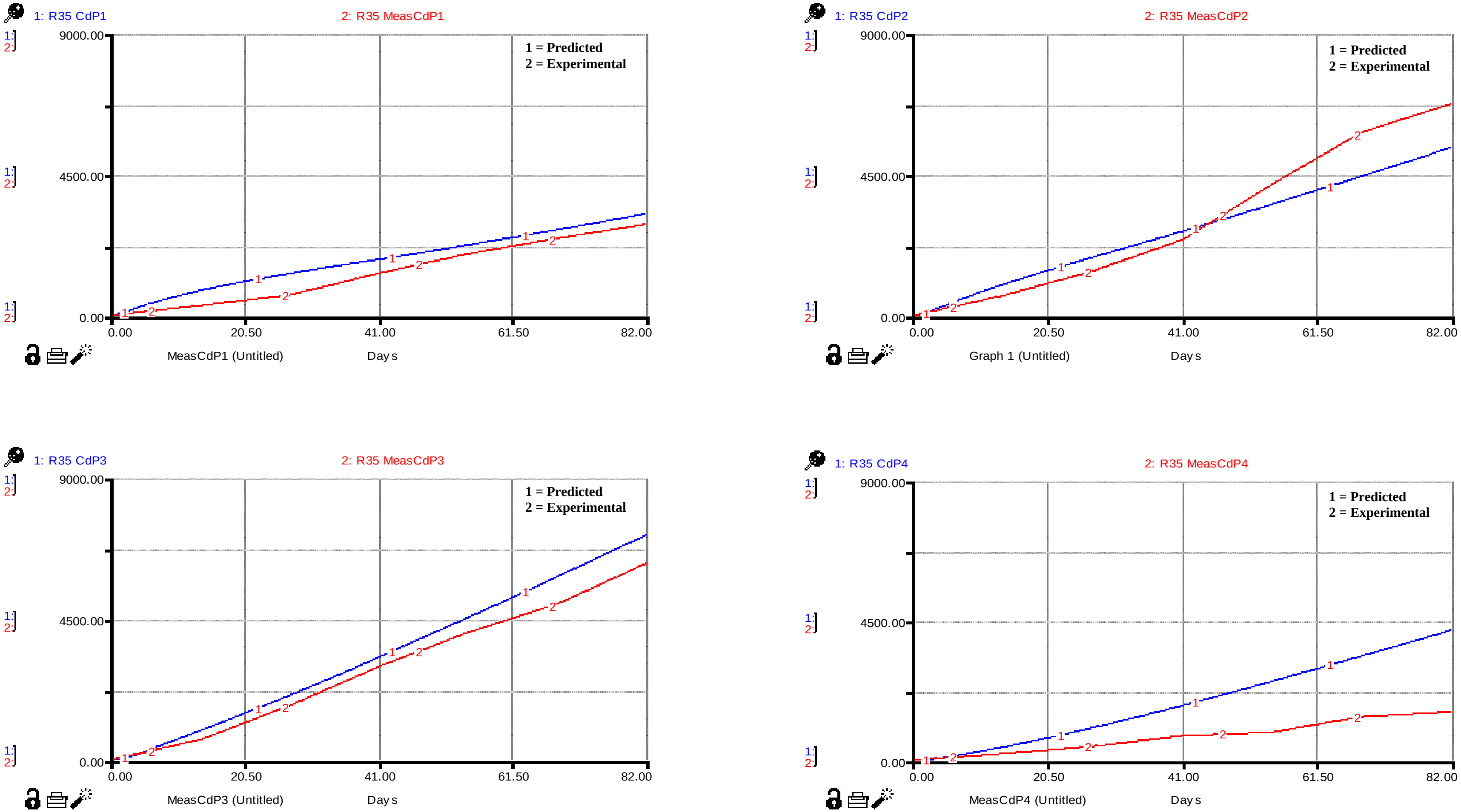
Figures H.17 Model validation for plants uptake of Cd in four compartments of reactor R15 (mg/d).



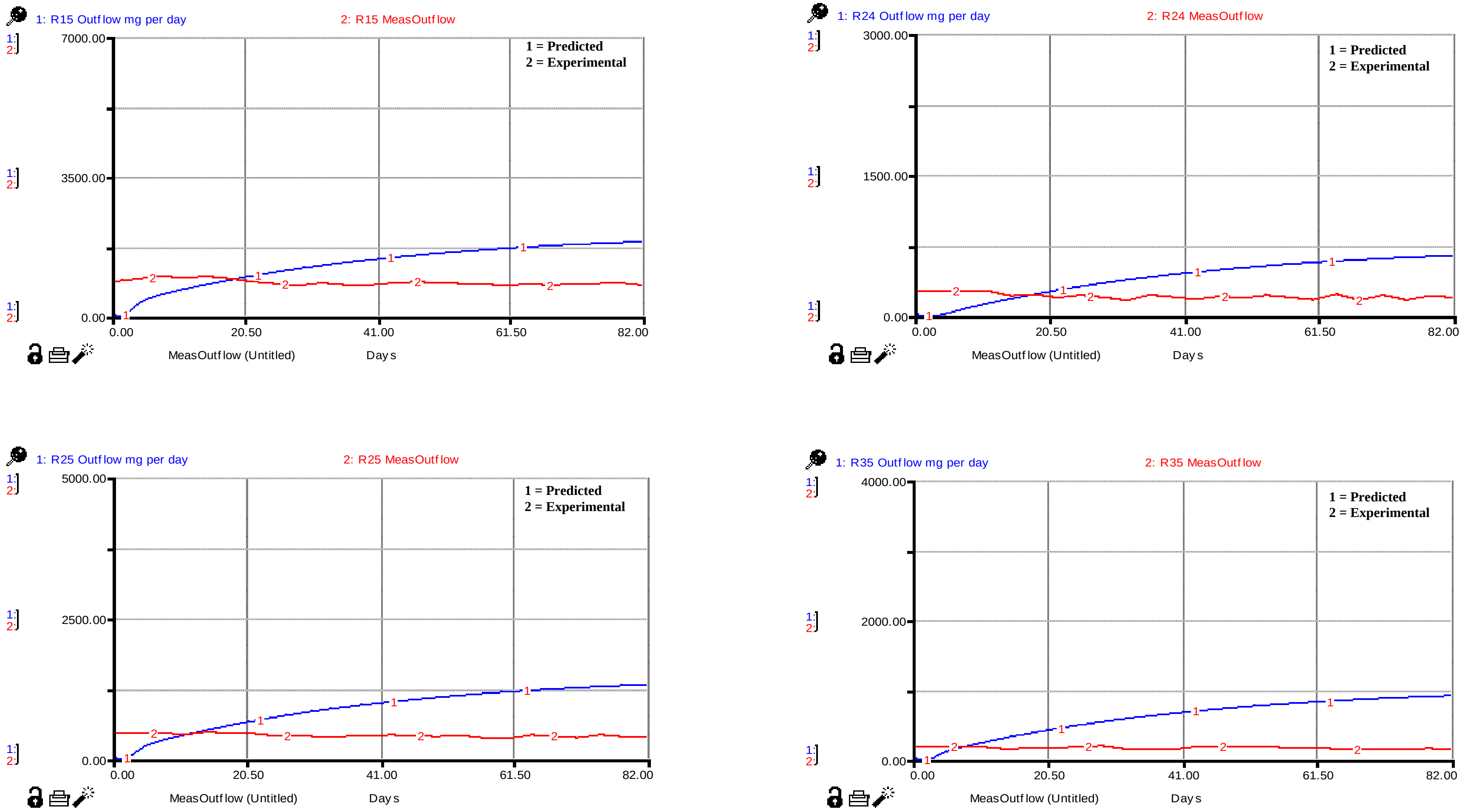
Figures H.18 Model validation for plants uptake of Cd in four compartments of reactor R24 (mg/d).



Figures H.19 Model validation for plants uptake of Cd in four compartments of reactor R25 (mg/d).



Figures H.20 Model validation for plants uptake of Cd in four compartments of reactor R35 (mg/d).



Figures H.21-H.24 Comparison of predicted and experimental values of outflow in model validation for R15, R24, R25 and R35 (mg/d).

APPENDIX I

THE CORRELATIONS BETWEEN MEASURED AND SIMULATED VALUES

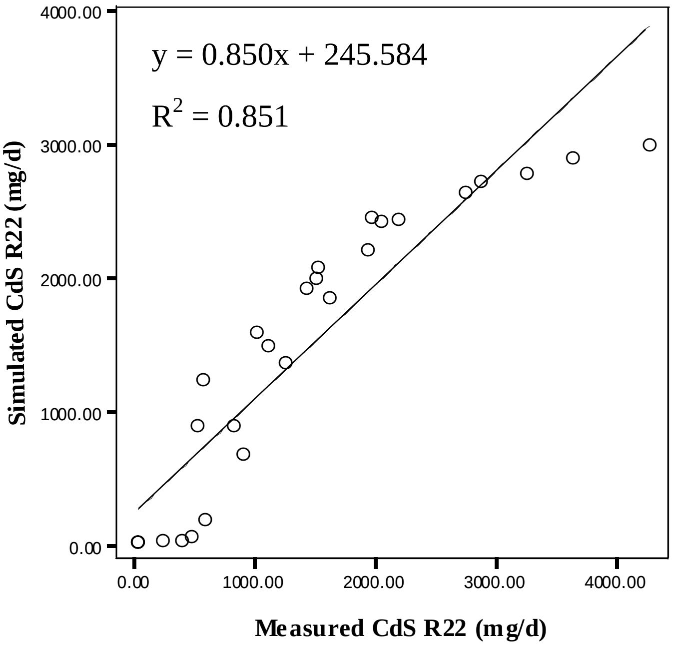


Figure I.1 Correlation between simulated and measured cadmium accumulation in soil for R22.

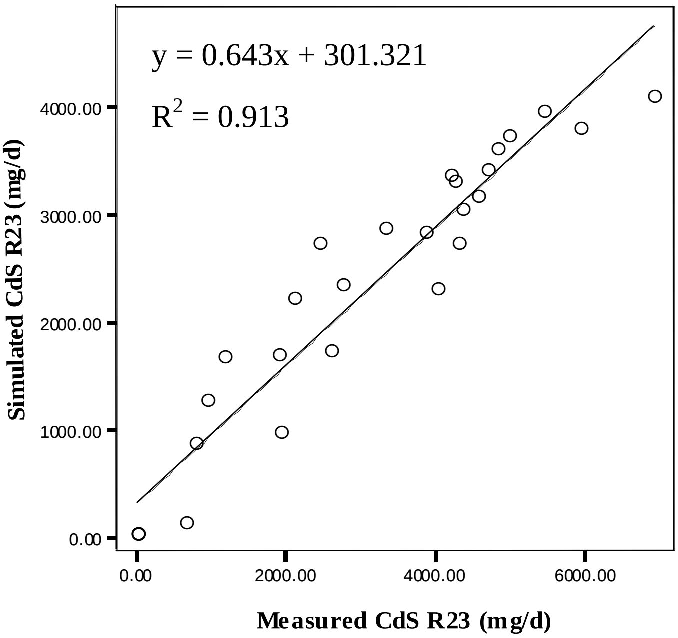


Figure I.2 Correlation between simulated and measured cadmium accumulation in soil for R23.

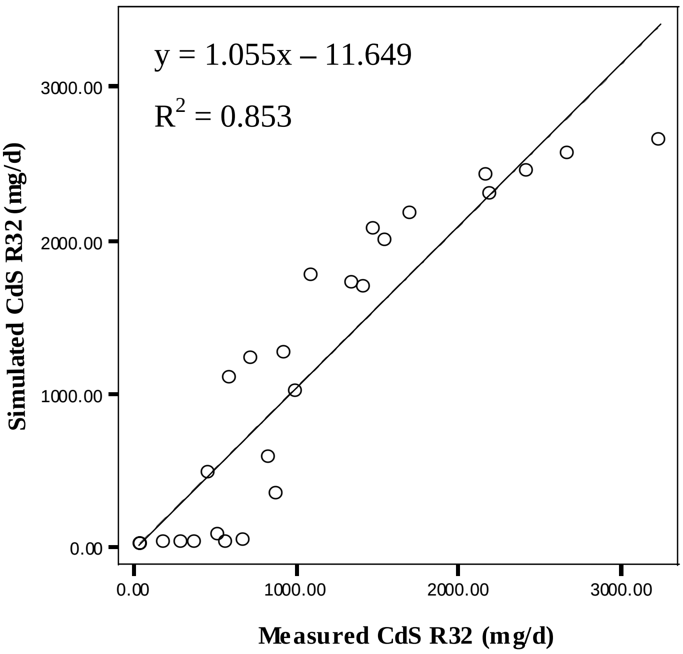


Figure I.3 Correlation between simulated and measured cadmium accumulation in soil for R32.

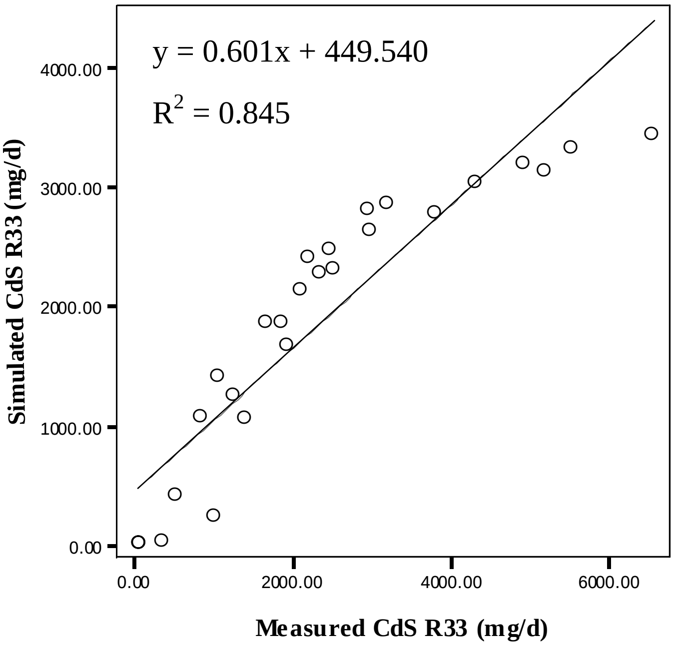


Figure I.4 Correlation between simulated and measured cadmium accumulation in soil for R33.

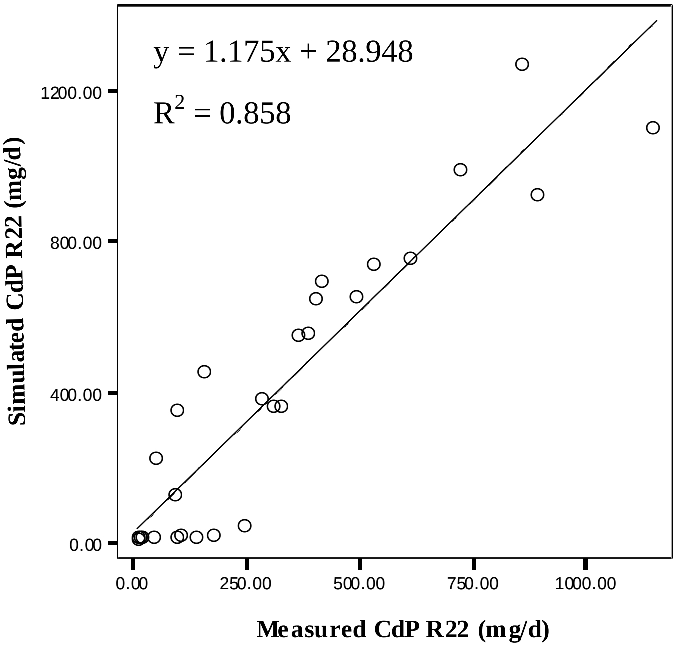


Figure I.5 Correlation between simulated and measured cadmium removal by plants uptake for R22.

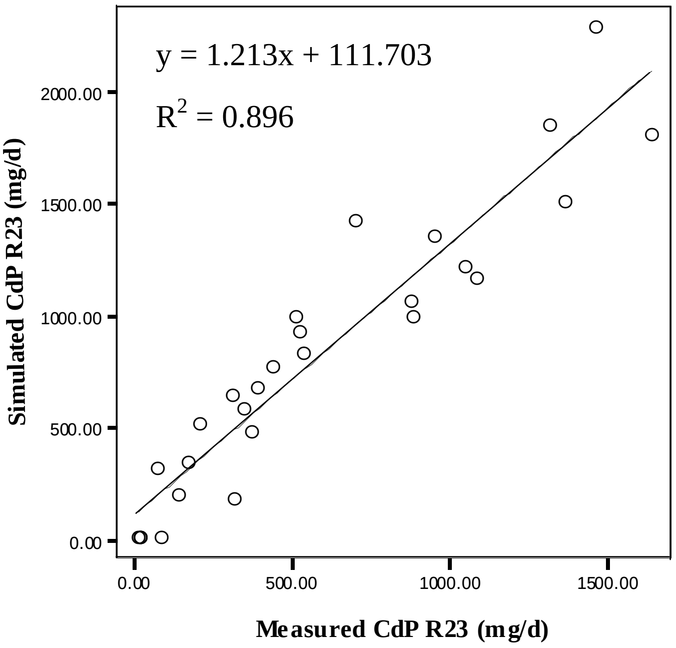


Figure I.6 Correlation between simulated and measured cadmium removal by plants uptake for R23.

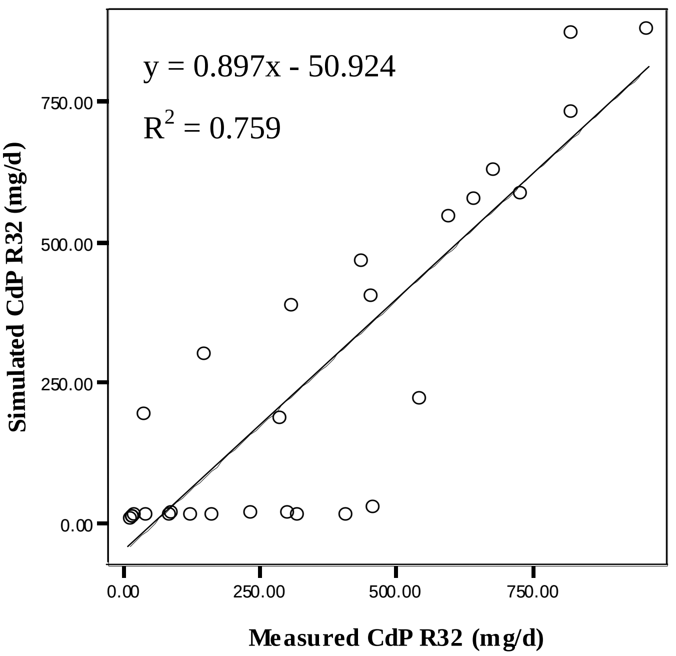


Figure I.7 Correlation between simulated and measured cadmium removal by plants uptake for R32.

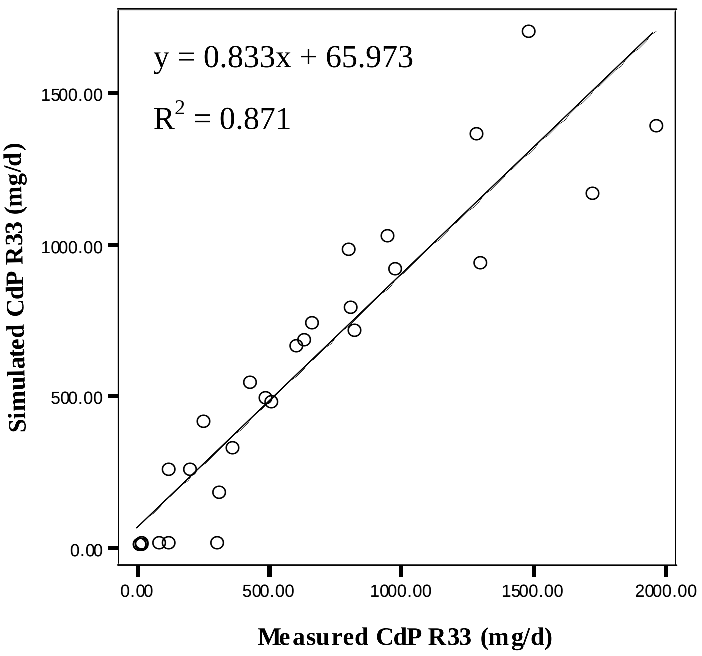


Figure I.8 Correlation between simulated and measured cadmium removal by plants uptake for R33.

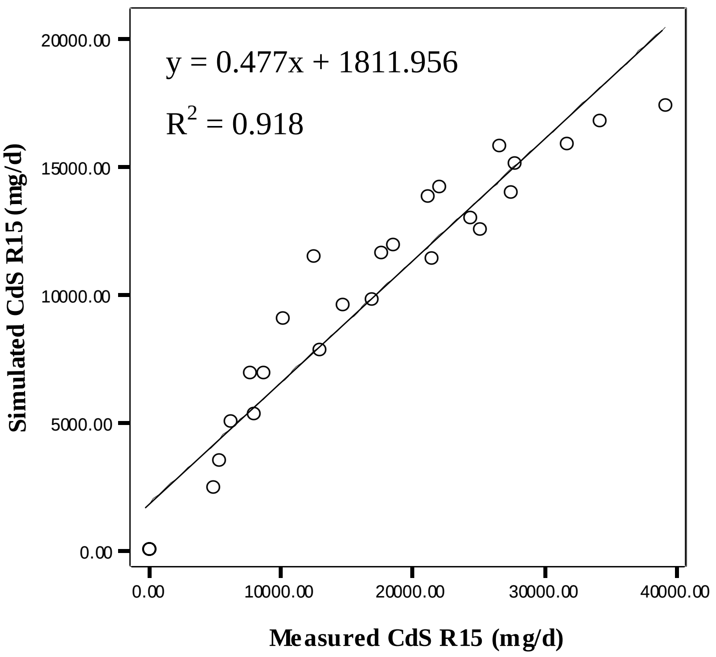


Figure I.9 Correlation between simulated and measured cadmium accumulation in soil for R15.

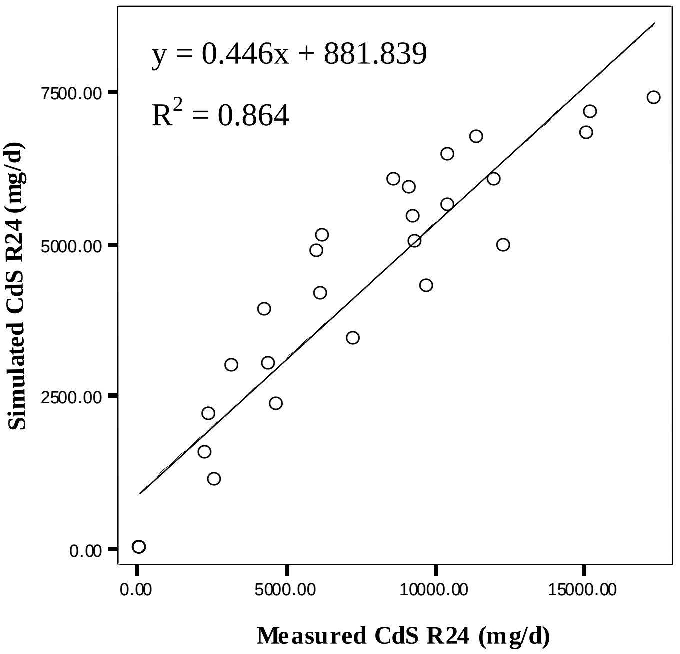


Figure I.10 Correlation between simulated and measured cadmium accumulation in soil for R24.

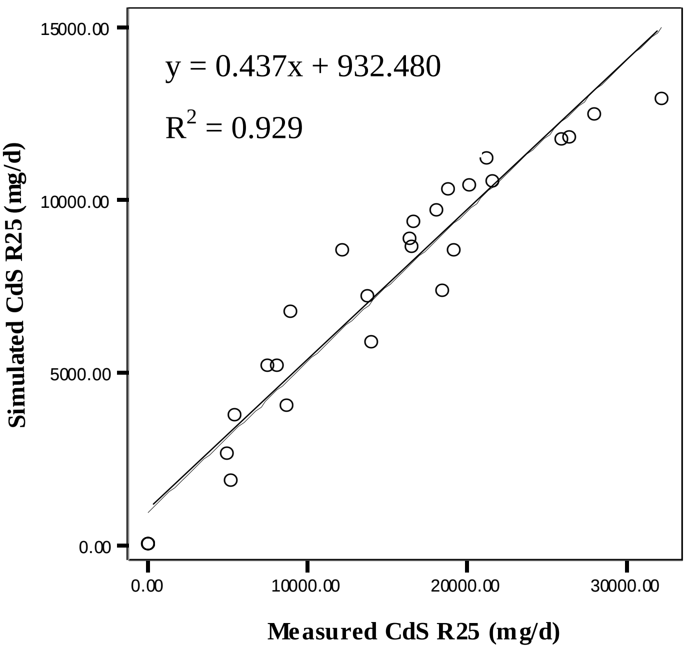


Figure I.11 Correlation between simulated and measured cadmium accumulation in soil for R25.

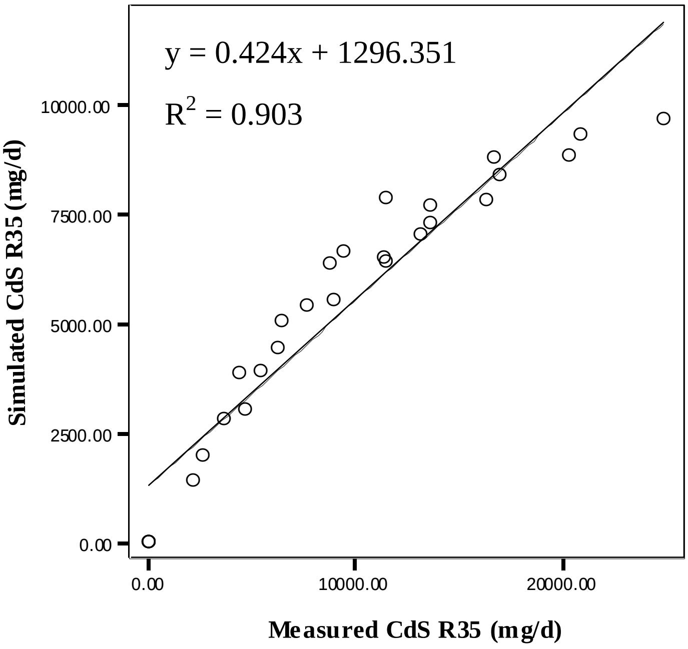


Figure I.12 Correlation between simulated and measured cadmium accumulation in soil for R35.

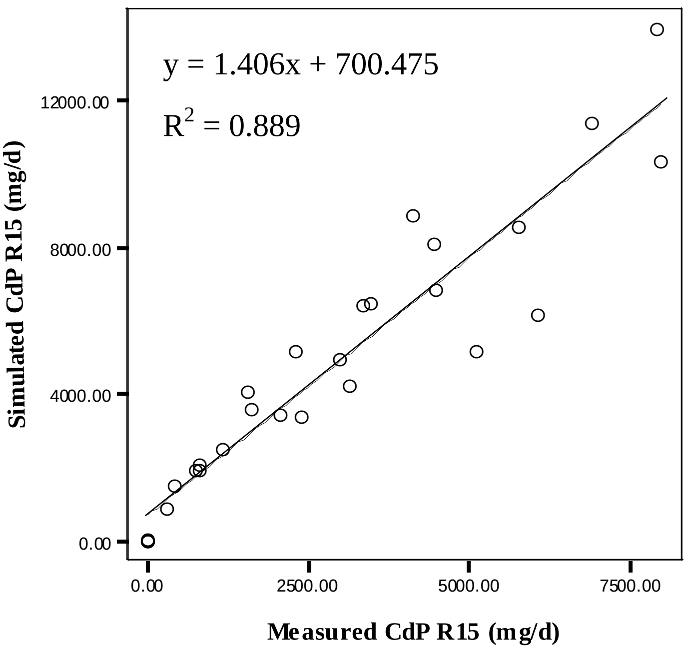


Figure I.13 Correlation between simulated and measured cadmium removal by plants uptake for R15.

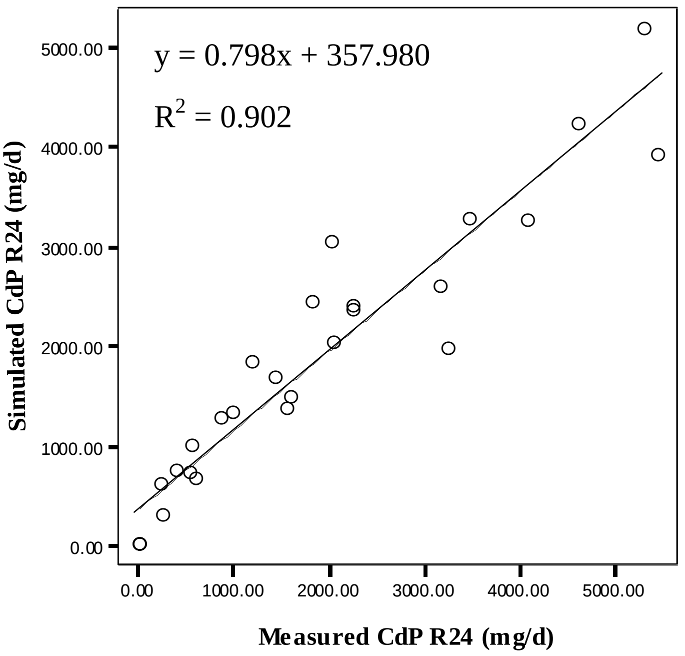


Figure I.14 Correlation between simulated and measured cadmium removal by plants uptake for R24.

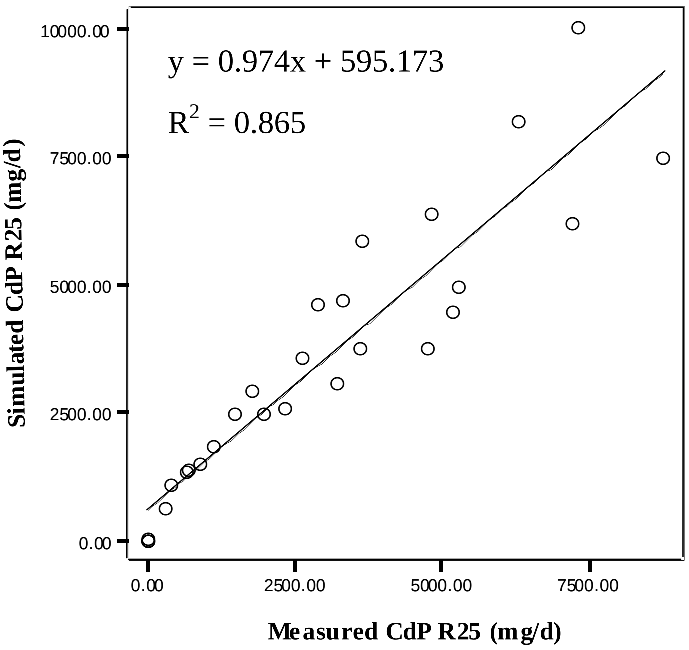


Figure I.15 Correlation between simulated and measured cadmium removal by plants uptake for R25.

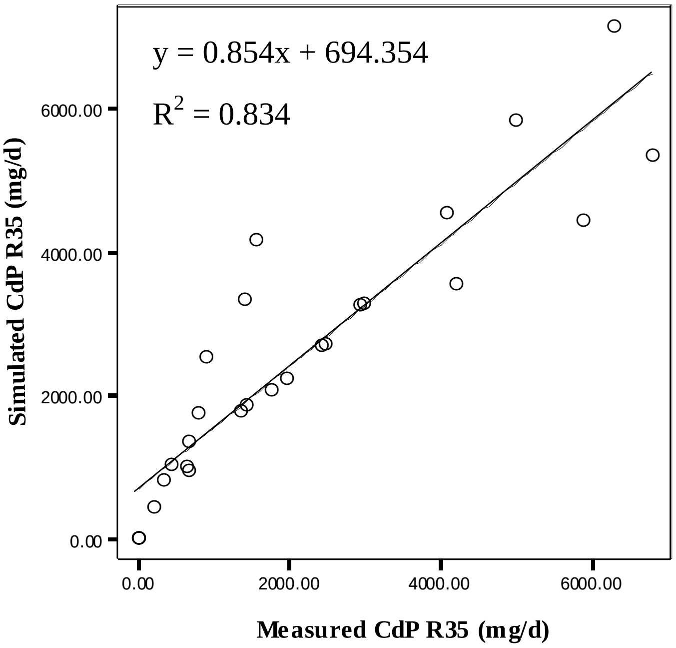


Figure I.16 Correlation between simulated and measured cadmium removal by plants uptake for R35.

APPENDIX J

LIST OF PUBLICATIONS

LIST OF PUBLICATIONS

Pimpan, P., and Jindal, R. (2007). Effect of high cadmium loading on performance of free water surface constructed wetlands. **ASCE Practice Periodical of Hazardous, Toxic and Radioactive Waste Management**. 11 (3).

Pimpan, P., and Jindal, R. (2005). Performance evaluation of free water surface constructed wetlands at high cadmium loading. **Proc. of the Third International Symposium on Southeast Asian Water Environment**. Asian Institute of Technology, Bangkok, Thailand, 6-8 December, pp. 147-154.

Pimpan, P., and Jindal, R. (2005). Investigation of cadmium removal in laboratory-scale constructed wetlands. **Proc. of the Eighth International In Situ and On-Site Bioremediation Symposium**. Baltimore, Maryland, USA, 6-9 June.

Pimpan, P., and Jindal, R. (2004). Investigation of cadmium removal from industrial wastewater in constructed wetlands. **Proc. of RGJ-Ph.D. Congress V**. Pattaya, Chonburi, Thailand, 23-25 April.

Samorkhom, N., Jindal, R., and Pimpan, P. (2002). Investigation of heavy metals removal from wastewater in constructed wetlands. **Proc. of the International Conference on Water and Wastewater: Perspectives of Developing Countries**. New Delhi, India, 11-13 December.

Samorkhom, N., Jindal, R., and Pimpan, P. (2002). A study of the fate of cadmium in wastewater effluents in constructed wetlands. **Proc. of the Third National Symposium on Graduate Research**. Suranaree University of Technology, Nakhon Ratchasima, Thailand, 18-19 July, pp. 321-322.

BIOGRAPHY

Miss Parita Pimpan was born on April 22, 1975, in Nakhon Sawan, a northern province of Thailand. She studied at the La Salle Chotiravi Nakhon Sawan School, Nakhon Sawan for her secondary school education. She received her bachelor degree in Transportation Engineering and masters degree in Environmental Engineering from Suranaree University of Technology (SUT). Following her masters degree graduation, she worked as environmental engineer for one year at Ninety-nine Reverse Osmosis, Ltd., Nakhorn Ratchasima. Subsequently, she started her doctoral study program (in Environmental Engineering at SUT, in 2001) supported by the funding from the Royal Golden Jubilee Ph.D. Scholarship Grant (RGJ-Ph.D.) of Thailand Research Fund (TRF).