Design of stormwater ponds towards the reduction of metal toxins in surface waters that are utilised for South African primary food production

by

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Declaration

By submitting this dissertation electronically, I declare that the entirety of the work contained therein is my own, original work, that I am the sole author thereof (save to the extent explicitly otherwise stated), that reproduction and publication thereof by Stellenbosch University will not infringe any third party rights and that I have not previously in its entirety or in part submitted it for obtaining any qualification.

This dissertation includes 5 unpublished publications. The development and writing of the papers (published and unpublished) were the principal responsibility of myself and, for each of the cases where this is not the case, a declaration is included in the dissertation indicating the nature and extent of the contributions of co-authors.

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Abstract

This research originated from a need for civil engineering practice to address metal pollution in stormwater runoff. Specific emphasis was placed on metals that could affect the quality of crops, livestock and fish in South Africa.

Detention and retention ponds are commonly used for surface water quality control, and these types of structures were therefore investigated. No prominent pond design methods were found, however, that directly incorporate consideration of metal pollution in the context of food security. In addition, there was a lack of information on how methods could be adapted to address metal pollution specifically. It was argued that focussing on relationships between pond efficiency and design could generate information towards augmenting design philosophies and methodologies. This became the project thesis.

The methodology used for the investigation into relationships between pond efficiency and design was constrained by the available data. Statistics and probability theory were the main tools used. Data was obtained from an international database and therefore little was known about possible sources of error. Although a large variety of data on a number of metal toxins and solids was found, individual data sets were often small. These factors meant that data trends (rather than specifics) between ponds were used as the basis for conclusions. Modelling was employed to theoretically test the validity of trends indicated by statistical analysis. These included identification of pond efficiency predictors with logistic regression, curve fitting of a time polynomial to outflow mass data to indicate the class of particulate settling, and hypothetical sedimentation modelling with MIKE 11 software.

Results indicated certain pond parameters that were influential in removal processes, but many of these were not explicitly included in prominent design methods. These methods were therefore found to be inadequate for efficient pond design. Data trends indicated a number of processes of importance in metals removals. This information was used to create conceptual models of pond functioning, which were used to augment established engineering theory for application in pond metals removal. The project thesis was therefore accepted.

A design philosophy of high levels of control on pond hydraulics and metal loads was recommended. Detention and retention pond functioning for metals removal was illustrated to be highly complex, making detailed modelling enterprises difficult, time consuming and costly. Control over hydraulics and in/out boundaries can simplify pond design.

Opsomming

Hierdie navorsing spruit uit ‘n behoefte vir die siviele inginieurswese praktyk om metaalbesoedeling in stormwater aan te spreek. Spesifieke klem was gelê op metale wat die voedingskwaliteit van landbou, veeteel- en visteelprodukte kan bëinvloed.

Detensie en retensie damme word algemeen gebruik vir vars water kwaliteitskontrole en hierdie tipe strukture was dus ondersoek. Geen prominente dam ontwerpsmetodes was gevind, wat direk oorweging van metaalbesoedeling in die konteks van voedsel sekuriteit geinkorporeer het, nie. Daar was ook ‘n tekort aan inligting oor hoe metodes aangepas kan word om spesifiek op metaalbesoedeling te fokus. Die argument het ontstaan dat ‘n fokus op verhoudings tussen damdoeltreffendheid en ontwerp inligting kan genereer wat gebruik kan word om waarde toe te voeg aan ontwerpsmetodes en filosofieë. Hierdie het die projek tesis geword.

Die metodologie wat gebruik was, was beperk deur die beskikbare data. Statistiek en waarskynlikheidsteorie was meestal gebruik. Data was van ‘n internasionale databasis verkry en dus was daar min inligting oor moontlike bronne van waarnemingsfoute. ‘n Wye verskeidenheid data was beskikbaar, maar die individuele datastelle was meestal klein. Hierdie faktore het daartoe gelei dat data tendense (eerder as spesifieke hoedanighede) gebruik was vir gevolgtrekkinge. Modellering was gebruik om die geldigheid van data neigings te toets en te staaf (of teen te staan). Dit het statistiese, wiskundige en rekenaar modellering met MIKE 11 sagteware ingesluit.

Resultate het sekere dam parameters aangedui as invloedryk in verwyderings prosesse, maar baie daarvan was nie eksplisiet ingesluit in prominente ontwerps metodes nie. Hierdie metodes was dus bevind om onbevoeg te wees vir doeltreffende dam ontwerp. Data neigings het ‘n aantal prosess aangedui wat belangrik was in metaal verwydering. Hierdie inligting is gebruik om konseptuele modelle vir dam funktionering te skep wat verder gebruik is om waarde toe te voeg aan bestaande ingenieursteorie vir gebruik in metaal verwydering in damme. Die projek tesis was dus aanvaar.

n Ontwerpsfilosofie van hoë vlakke van kontrole oor dam hidroulika en metaalladings was aanbeveel. Detensie en retensie dam funkstionering was gewys om hoogs kompleks te wees, wat gedetaileerde modelering moeilik, tydrowend en duur kan maak. Kontrole oor dam hidroulika en in/uit grense kan dam ontwerp vereenvoudig.

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DHI for use of the software program Mike 11, a subsection of Mike Zero (Release 2012, Copyright 1995-2012)

Contents

ADDENDA

List of figures

List of tables

List of Abbreviations

APWA	-	American Public Works Association
ASCE	-	American Society of Civil Engineers
BMP	-	Best Management Practice
CFP	-	Cumulative Frequency Plot
Conc.	-	Concentration
CSTR	-	Continuously Stirred Tank Reactor
Diss.	-	Dissolved
DP	-	Detention Pond
EMC	-	Event Mean Concentration
EPM	-	Effluent Probability Method
EURV	-	Excess Urban Runoff Volume
EWRI	-	Environmental and Water Resources Institute
FAO	-	Food and Agricultural Organisation (of the United Nations)
FHWA	-	Federal Highway Administration
Max.	-	Maximum
Min.	-	Minimum
MDL	-	Method Detection Limit
ND	-	Non Detect
NPP	-	Normal Probability Plot
Part.	-	Particulate
ROS	-	Regression on Order Statistics
RP	-	Retention Pond
SA	-	South Africa
Tot.	-	Total
TSS	-	Total Suspended Solids
TVS	-	Total Volatile Solids
UK	-	United Kingdom

USA - United States of America

USEPA - United States Environmental Protection Agency

UNEP - United Nations Environment Programme

WERF - Water Environment Research Foundation

WFD - Water Framework Directive

WQCV - Water Quality Capture Volume

IQR - Interquartile Range

Glossary

Best Management Practice	-	“A device, practice, or method for removing, reducing, retarding, or preventing targeted stormwater runoff constituents, pollutants, and contaminants from reaching receiving waters” (URS Greiner Woodward Clyde, Urban Drainage and Flood Control District, Urban Water Resources Research Council (UWRRC) of ASCE, 1999). “An action taken to achieve, or aid in the achievement of a best management measure for a specific situation” (United States Environment Protection Agency, 2005).
Case study	-	A specific pond structure, usually identified by the name for the structure provided in the source material such as the International Stormwater BMP Database.
Detention basin/pond	-	“A surface storage basin or facility that provides flow control through attenuation of stormwater runoff. In certain cases it may facilitate some settling of particulate pollutants. Basins are normally dry and may serve as recreational facilities” (Woods-Ballard et al., 2007).
Effectiveness	-	“A measure of how well a treatment system meets its goals in relation to all stormwater flows” (URS Greiner Woodward Clyde, Urban Drainage and Flood Control District, Urban Water Resources Research Council (UWRRC) of ASCE, 1999).
Efficiency	-	“A measure of how well a structure or system removes pollutants” (URS Greiner Woodward Clyde, Urban Drainage and Flood Control District, Urban Water Resources Research Council (UWRRC) of ASCE, 1999).
Event Mean Concentration (EMC)	-	“A statistical parameter used to represent the flow proportional average concentration of a particular parameter during a storm event. It is defined as the total constituent mass divided by the total runoff

		volume" (GeoSyntec Consultants , Wright Water Engineers, Inc., 2009)
Excess Urban Runoff Volume	-	"The difference between urban and pre-development runoff volumes" (Urban Drainage and Flood Control District, 2010).
Food security	-	Food security has been defined at the World Food Summit in 1996 as " when all people, at all times, have physical and economic access to sufficient, safe and nutritious food to meet their dietary needs and food preferences for an active and healthy life" (Ericksen, 2008).
Metal	-	A shiny solid element at room temperature (with the exception of mercury), which is malleable and ductile, and which conducts heat and electricity well (Silberberg, 2003:G-11). Metalloids are included in the term "metal" in this project.
Method Detection Limit (MDL)	-	"The minimum concentration of an analyte that can be identified, measured, and reported with 99% confidence that the analyte concentration is greater than zero" (Creed et al., 1994).
Non-detect	-	"Low-level concentrations of organic or inorganic chemicals with values known only to be somewhere between zero and the laboratory's detection/reporting limits .Measurements are considered too imprecise to report as a single number, so the value is commonly reported as being less than an analytical threshold" (Helsel, 2006).
Non-point Source Pollution	-	"Pollution that enters a water body from diffuse origins on the watershed and is not transported via discernible, confined or discrete conveyances" (United States Environmental Protection Agency, 2004a)
Performance	-	"A measure of how well a structure meets its goals for stormwater that it is designed to treat" (URS Greiner Woodward Clyde, Urban Drainage and Flood Control

		District, Urban Water Resources Research Council (UWRRC) of ASCE, 1999).
Primary food production	-	Primary food production refers to agricultural, livestock and aquaculture food production. Primary food sources refer to human food obtained from agriculture, livestock rearing or aquaculture.
Pollutant	-	“A substance that directly or indirecty damages humans or the environment” (United Nations Environmental Protection Agency, 2006).
Retention pond	-	“A surface basin with a permanent pool that can be designed to provide both stormwater attenuation and treatment as well as support aquatic vegetation along its shoreline” (Woods-Ballard et al., 2007).
Sub-set	-	A set of a specific metal, metalloid or solid data relating to a specific case study.
Stormwater runoff	-	“Surface water runoff (from storms) that flows into receiving waterbodies or into storm sewers” (Chen & Liew, 2003).
Toxin	-	“A natural or synthetic chemical substance that may cause adverse effects on living organisms, even when present at low concentrations” (Department of Water Affairs and Forestry, 1996c).

1. Introduction

1.1 Background

1.1.1 Introduction

South African food security depends on the availability of clean surface water, which is commonly used for the irrigation of crops, livestock watering and aquaculture. In South Africa, irrigated agriculture uses approximately 62% of fresh water, with rivers and dams as the largest suppliers (Strydom et al., 2010). Livestock watering is mostly reliant on ground water, but surface water abstraction is also used in many cases. Aquaculture is reliant on a number of water sources including springs, dams, irrigation canals and rivers (Department of Water Affairs and Forestry, 1996b,c).

Pollution can reduce the quality of surface water. The United Nations has stated that clean water and healthy freshwater ecosystems provide the basic goods upon which many livelihoods depend, including irrigation water, fertile floodplains for agriculture and grazing, and habitats for fish and shrimp that may be eaten or sold. The need for good quality water has had less emphasis in the past than the need for adequate quantities of water. However, both are necessary, and polluted water can reduce or eliminate the viability of many livelihoods (United Nations Environment Programme, 2010).

The most common contaminants reported in surface and shallow ground waters are metals (Plauborg et al., 2010). The USA nationwide urban runoff programme found as early as 1983 that heavy metals (including copper, zinc and lead) were the most prevalent priority pollutants in urban runoff within the country; with some metals present often enough, and in signficant concentrations, to potentially threaten beneficial uses (United States Environment Protection Agency, 1983). Metal toxins are typically found to be at trace concentrations and may not be seen as an acute threat to the human species. Such notions, however, overlook insidious metals behaviour in the environment e.g. (1) metals such as arsenic, cadmium, copper, lead and zinc are strongly sorbed to soil clay particles and can be expected to be retained in soil surface layers over long periods of time, with accumulation to phytotoxic levels before equilibrium between sorption and desorption is reached, and (2) certain metal toxins such as arsenic, cadmium and lead are known to bioaccumulate in crops and animals (Department of Water Affairs and Forestry, 1996a).

In many parts of the world, point sources of pollution are now well controlled and pollution of aquatic systems is thought to be mostly due to non-point source distribution of contaminants across the landscape and from the atmosphere (United Nations Environmental Protection Agency, 2006). Stormwater detention and retention ponds have internationally been used to intercept stormwater runoff pollution. However, prominent international design philosophies and methodologies from countries such as the USA, the UK and Australia do not directly address the removal of metal pollutants that may affect primary food production.

This project comprises a retrospective cross-case investigation performed on multiple international detention and retention pond case studies. The general objectives of the study were (1) to obtain insight into physical pond parameters that influence pond efficiencies in terms of the removal of metals known to have possible adverse effects on South African primary food sources, and (2) the use of the knowledge obtained in 1. to augment current international design philosophies and methodologies towards the improvement of pond metals removal efficiencies. A limited number of metals and metalloids were chosen for inclusion. These were:

1. Arsenic
2. Cadmium
3. Copper
4. Lead
5. Zinc

The choices were motivated by:

1. Known toxicity to crops, livestock, fish or humans (through bio-accumulation) as indicated in the South African Water Quality Guidelines, Vols. 4,5,6 (Department of Water Affairs, 1996 a, b, c).
2. Known common pollutants in stormwater runoff. The prevalence of substances in studied literature was used as a guide for this determination.
3. Prevalence in data. A preliminary analysis of data contained in the International Stormwater BMP Database (from where the project data was obtained), v.07.07.11, (available at www.bmpdatabase.org) was used in this determination.

Total and volatile suspended solids were also included for comparison.

1.1.2 Stormwater pollution

Stormwater pollution is widespread, diffuse in nature and of contemporary concern to sustainable human food production. Common diffuse runoff pollution sources include:

- Contaminated road run-off
- Drainage from urban areas
- Accidental chemical and oil spills

- Surplus nutrients, pesticides and eroded soils from farmlands

(Adapted from Environment Agency, 2007)

The international requirement for irrigation in primary food production is expected to increase due to an expected doubling of the world population (which currently stands at approximately 6.5 billion) in the next 58 years. In 2012 more than 99% of the world's food came from the terrestrial environment (the rest came from the oceans) (Food and Agricultural Organisation, 2012). Predictions by the United Nations of global population increase to the year 2025 require an increase in food production of approximately 40-45% (Food and Agricultural Organisation, 2012). In 2008, irrigated agriculture produced 36% of the world's food with approximately 70% of fresh water worldwide (Pimental & Pimental, 2008) (Food and Agricultural Organisation, 2012). In 2003, rain fed agriculture was already practiced to a maximum extent in most areas of the world, and therefore irrigated agriculture is expected to increase (Kirby et al., 2003). It is therefore imperative that future fresh water supplies, including surface waters utilised for agriculture, livestock rearing, and aquaculture, be protected from toxic pollution all over the world, including South Africa.

Metal pollutants are of primary concern. It has been shown that unnaturally high amounts of metal toxins may be deposited on rural and urban surfaces and subsequently washed off into surface waters by stormwater runoff (Food and Agricultural Organisation, 2012). The USEPA has listed a number of metals that are of primary interest because they may pose a toxic hazard. Among those listed were arsenic, cadmium, copper, lead and zinc (United States Environment Protection Agency, 2007). Such metals can pollute surface waters and can bioaccumulate in certain animal species (United States Environment Protection Agency, 2005). In South Africa, for example, fish kills in the Roodeplaat dam in 2004 were attributed, in part, to high levels of zinc (Hohls & van Ginkel, 2004).

In conjunction with possible future increases in metal pollutant load to surface waters, it was believed by Turton (2008) that South Africa has allocated around 98% of the national water resource and therefore has no more future surplus supplies, which may serve to buffer increases in pollution. This view was shared by the FAO, as regards many countries around the world. They held that pollution can no longer be remedied by dilution and therefore fresh water will become the principal limitation for sustainable development (Food and Agricultural Organisation, 2012). Such a loss of dilution capacity in surface waters renders the advancement of knowledge of diffuse runoff pollution controls in South Africa of paramount and contemporary importance.

1.1.3 International stormwater quality management strategies

Prominent philosophies towards the management of stormwater runoff pollution are existent in the USA, UK and Australia. South Africa has also recently started to create its own philosophies. These are discussed below.

United States of America (USA)

The United States of America (USA) has been at the forefront of non-point source stormwater pollution mitigation technological development since water pollution concerns were raised in the 1970’s. Through the past decades, they have developed a host of policies, philosophies and technological guidelines towards the mitigation of stormwater pollution. They can arguably be seen as the current leaders in the field.

In the USA, stormwater quality is controlled through the concept of Best Management Practices (BMPs). Although a standard and comprehensive definition of the term as used in literature has been elusive, the term has been defined specifically as (1) a “device, practice, or method for removing, reducing, retarding, or preventing targeted stormwater runoff constituents, pollutants, and contaminants from reaching receiving waters” (URS Greiner Woodward Clyde, Urban Drainage and Flood Control District, Urban Water Resources Research Council (UWRRC) of ASCE, 1999), and generally as (2) an action taken to achieve or aid in the achievement of a best management measure for a specific situation (United States Environment Protection Agency, 2005). Stormwater detention and retention ponds fall within the concept of BMP structures designed to form part of BMP practices.

United Kingdom (UK)

In the UK, the management of stormwater pollution is dealt with under the Sustainable Drainage Systems (SUDS) approach, which has been based on sustainability philosophies. The SUDS concept is used to focus decisions regarding drainage design, construction and maintenance on the quality of the receiving environment and on people. This concept employs the use of passive treatment to stormwater as an end of pipe control before discharge to the environment as one of its main categories. Structural controls, such as ponds, are designed with the aim of providing a sink for contaminants before stormwater is discharged to the environment (Charlesworth et al., 2003).

Australia

Australia uses the phrase Water Sensitive Urban Design (WSUD) when dealing with stormwater pollution. They also employ Best Management Practice philosophies (Environment Australia, 2002).

South Africa

Recently the South African Water Research Commission (WRC) published a report entitled “Water Sensitive Urban Design (WSUD) for South Africa: Framework and Guidelines” (Armitage et al., 2014). This document was aimed at introducing the concept of WSUD to South African role players and to show how this concept could be applied in South Africa. This approach was based on the Australian WSUD concept and also on incorporated philosophies of Sustainable Urban Drainage (SUDS) as seen in international literature. Here, detention and retention ponds were also included as regional structural controls that should be designed to act as a sink for contaminants.

1.1.4 The use of detention and retention ponds for stormwater quality improvement

The effects of diffuse pollution can be long term. The US Environment Agency have therefore stated that it is more cost effective to prevent pollutants from reaching natural waterbodies, than to treat the water after it has been polluted (Environment Agency, 2007). Infrastructure may be used to intercept pollutants before reaching surface waters. Beck (2005) performed a study on the vulnerability of water in an intensively developing urban watershed. It was his opinion that it is only through the reliability of pollution control infrastructure that polluting activities in urban watersheds do not become pollution actualities in rivers in streams.

The design of structures to control diffuse runoff pollution has been developing since the 1970’s. Many different design guidelines exist for pond structures. The most pertinent and prevalent in literature are those encapsulated in the USEPA Best Management Practices (BMPs) and the United Kingdoms’ Sustainable Urban Drainage Systems (SUDS).

Scholes et al. (2008) however, found that the potential for specific types of BMPs to remove particular pollutants and their treatment efficiency was rarely, if ever, used as a discriminatory criterion for pond design. Instead, catchment specific factors such as soil type and space available, capacity to store a design storm event, operation and maintenance requirements and cost were the basis for recommendations of BMP choice. The designer, therefore, currently has to rely on an estimated probability of success when using design methods, since long-term performance success remains as yet unproven. It is the opinion of the Water Environment Research Federation (WERF) that general approaches may be valid in some cases, but do not build on the accumulated experience of environmental process and wastewater engineering, or the skills that have been provided in the profesional civil and environmental engineering fields (Lampe et al., 2005).

The relatively recent advent of diffuse runoff pollution control theory means that the design and implementation of pond structures are still in a developing form. There has been as yet no comprehensive study into the efficiencies of pond structures, in view specifically of metals reduction. Current simplistic bases for design are not validated, and scope for further research exists.

1.2 Motivation

It is evident from published literature that metals are dispersed by anthropogenic activities on land and that they can end up in surface waters via stormwater runoff, accumulate in crop soils, adversely affect the health of, and bioaccumulate in, crops, livestock and fish. However, there is a lack of published research into the extent of the problem. This is perhaps due to the nature of the metal pollutant, which is often found to be at concentrations below levels that would cause immediate alarm. This attribute of metal runoff pollution makes it insidious in nature. Low concentrations do not mean low accumulated amounts of pollutant over long time periods in natural systems. The very fact that metals can accumulate in soils and bioaccumulate in animals and plants to toxic levels means that any toxic metals in surface runoff waters can, over time, threaten the health of crops, livestock and fish as well as humans who consume contaminated foods.

The civil engineering profession is the custodian of knowledge pertaining to infrastructure design and implementation towards the improvement of our future. It is therefore an ethical responsibility to develop philosophies for infrastructure design towards the efficient reduction of metal toxins that reach surface waters and may ultimately affect primary food production.

1.3 Problem statement

Current international design methods used in the design of stormwater detention and retention ponds are inadequate for the safeguarding of future SA water supplies, because they do not directly incorporate elements of metal toxin removal that are relevant to primary food production water quality in South Africa.

1.4 Research objectives

The following research objectives apply:

1. Identify physical detention and retention pond parameters that have a notable influence on pond efficiency as pertains to metal removal.
2. Apply the knowledge gained from objective 1 to augment current international design methodology and philosophy towards efficient interception of South African stormwater metal toxins of concern.

1.5 Thesis statement

The problem statement stressed a general deficiency in current design methodology, viz. specific application to metals removals. To address this deficiency, a research focus point that could be used to generate knowledge towards augmentation of design methods became the subject of this project. The thesis statement thus reads:

"Current water quality oriented design methods used for stormwater pond structures can be augmented, towards satisfying SA water quality requirements for metal toxins as relates to primary food production, through investigation of the relationships between efficiency and design in existing international pond case studies".

The assertion that design methodology can be augmented is in itself not greatly argumentative, because it is logical and generally accepted that there is always room for addition of knowledge to any methodology. The argument, however, incorporated the condition that this addition of knowledge can be effected through specific focus on the relationships between pond efficiency and design.

1.6 Delineations and limitations

1.6.1 Delineations

1. "Current water quality oriented design methods" refer only to those design methods that are documented and published in prominent peer reviewed and accepted documentation. Chosen were the USEPA Stormwater Best Management Practice Guidelines Volumes 1, 3 (United States Environment Protection Agency, 2004a,b) and the SUDS Manual (Woods-Ballard et al., 2007). The term "methods" must be read to include design philosophy by extension.
2. "Stormwater pond structures" refers only to detention and retention ponds designed to perform water quality treatment of stormwater runoff.
3. "Can be augmented" means that value can be added to current design methods and philosophies towards the achievement of a certain goal (read 4 below).
4. "Towards satisfying SA water quality requirements for metal toxins" means that the ultimate future goal is the reduction of effluent metal pollutants, that are indicated in the SA Water Quality Guidelines - Volumes 4, 5 and 6 (1996) as being of toxic concern for primary food production (see 5. below), to such an extent that they pose no threat. Please note: The purpose of this project is the augmentation of design methods with the goal of reducing metal toxins that are carried to surface waters via stormwater runoff. The purpose of this project is not the development of design methods that will always achieve

effluent concentration standard requirements for stormwater runoff into surface waters. To the author’s knowledge, such requirements do not yet exist in South Africa.

5. “Primary food production” refers to agriculture, livestock rearing and aquaculture.
6. “Relationships between efficiency and design” refer to structural physical characteristics of specific pond structures that influence efficiency (See Section 1.6.7 below for a definition of efficiency) e.g. volume, depth, width.
7. The focus of this study was on pond functioning only. Peripheral research areas such as influent loads were investigated only to the extent to which they affect pond functioning.
8. Case studies that contained temporal data were limited. The study therefore only focussed on spatial cross-case comparisons.
9. The evaluations of pond efficiencies were limited to comparisons between concentrations and masses at defined and monitored inlet and outlet points. Influent and effluent substances from other points such as direct overland inflows, precipitation or seepage were therefore not included in the calculation of pond efficiencies. The definition of efficiency in this project has therefore been specifically limited to differences between monitored and defined inlet and outlet substances (See section 1.6.7 below).

1.6.2 Limitations

General limitations were listed below. Limitations that were directly related to methodology were further discussed where relevant.

1. Data sources were limited. Data was obtained from outside sources rather than by individual experimentation for the following reasons:
    a) The amount and variety of data required for this study made individual experimentation impossible in the amount of time and resources allocated.
    b) Data adequate for use in this project have already been published for a variety of case studies, rendering individual experimentation inessential.
2. Documented metals data was limited, i.e. metal and metalloid toxins that were documented in literature as being prevalent in stormwater runoff, and which were also prevalent in data. These were arsenic, cadmium, copper, lead and zinc.
3. Relevant case studies were limited, i.e. the number of case studies found to contain pertinent metal and metalloid toxin data.
4. Resources of time and funding were limited.

1.7 Dissertation overview

1.7.1 Chapter 2 – Literature review

Literature included in this review contained pertinent background information relating to (1) the motivation for the study, (2) support for data analysis techniques used, (3) comparative information regarding stormwater modelling state of the art, and (4) comparative information regarding pond efficiencies and stormwater pond design state of the art.

1.7.2 Chapter 3: Data preparation

This chapter includes the results of initital data preparation for further use and quality control considerations.

1.7.3 Chapter 4: Efficiency evaluations

This chapter contains an exploratory overview of pond behaviour. The results provided directly comparative information between case studies and context within which results from further investigations could be interpreted. Additionally, a novel classification system for pond efficiency based on the Effluent Probability Method was developed.

1.7.4 Chapter 5: Relationships between pond efficiencies and physical parameters

Relationships between pond efficiencies and physical parameters were investigated. Correlations were performed between (1) metals and solids substances in inflow streams, outflow streams and fraction removals and (2) fraction removals and physical pond parameters. Logistic regression was used in data sets of (1) general pond efficiencies and physical pond parameters and (2) negative average efficiencies and physical pond parameters. The results contained in this chapter served to identify pond parameters that influenced efficiency, as required in the project objectives (see section 1.3 above) and provided a framework within which hypothetical behavioural conceptual models could be created.

1.7.5 Chapter 6: Modelling

Illustrative conceptual models for process behaviour were developed within the framework of results from efficiency evaluations, correlational analyses and information from literature regarding pond processes. Further theoretical testing of indications relating to sedimentation of particulate material was done through polynomial curve fitting and computer modelling with the MIKE 11 software program. The final model forms provided insights into the behaviour of substances within the studied ponds, which was used to augment pond design guidelines and philosophy towards metals removals.

1.7.6 Chapter 7: Design recommendations

Design recommendations towards the reduction of metals in stormwater runoff were summarised. Current international design methodologies and shortcomings thereof in light of the project results were discussed. Recommendations were based on the findings from previous chapters 4, 5, and 6 and were made with the view of practical application in South Africa.

1.7.7 Chapter 8: Conclusions

Main findings were summarised. The thesis was discussed, and suggestions for future research were made.

1.8 Assumptions

The following major assumptions were made in this project. Other minor assumptions were stated in the text as they occurred.

1. Data reliability: The general reliability of data was assumed. Refer to Chp. 3, section 3.2.2.6 for further discussion.
2. Conclusions based on the use of international case study data are valid for the South African context: The focus of this project was metals pollution. Shaver et al. (2007) have listed soil erosion, vehicle fluids, vehicle wear, household chemicals, industrial processes, paints, preservatives and pesticides as common sources of metals pollution in runoff. All these processes are common in South Africa and therefore the assertion is made that metals pollution does occur here.
3. Terminology: It was generally assumed that terminology encountered in design guidelines had similar meanings to similar terminology encountered in the data.
4. Temperature: It was assumed that temperature did not have a significantly singular effect on pond functioning, i.e. the effects of pond physical parameters outweighed the effects of temperature on pond efficiencies. This assumption was supported by published literature, viz. (1) a study performed by Barrett (2008) where it was found that a pond that was situated in a different climate produced an effluent quality similar to other ponds. From this the authors inferred that the seasonal differences in temperature may have had only a mild effect on settling (Refer to Chp. 2, section 2.5.2). (2) A study performed by the Water Environment Research Federation (2005 b) where no consistent effect on TSS removal in retention ponds was observed for decreasing temperatures (Refer to Chp. 2, section 2.5.2).

1.9 Project significance

This project originated from a need to develop a basis from which information could be gathered to add knowledge to current design methodology. Previous outside studies, although scarce, have had similar general objectives as this study and were summarised in Chapter 2 – Literature Review. Such studies, however, differed from the research presented in this dissertation as follows:

1.9.1 Theoretical significance

1. Conceptual models of detention and retention pond functioning for metals removals were developed based on the results of statistical analysis of data and efficiency evaluations. These models differed from those proposed in literature (see Section 2.6) in that they were descriptively aimed at illustrative pond functions indicated by data trends for the studied ponds. Published models were usually complex simulation models based wholly or partly on laboratory experiments and were therefore highly theoretical with little indication of application in realistic scenarios. The theoretical significance of the models developed in this project is that they are solely based on results from established ponds and therefore illustrated realistic pond functioning in a logical, simple and easy to grasp manner.
2. Pond evaluations found in literature often focussed on metal concentration reduction only. Concentration is a compound variable, a result of mass and volume. Studies into concentration reduction therefore may not accurately represent the amounts of metals that are in the pond outflows. For example, a pond with stormwater influxes along its sides may show a reduced outflow metal concentration due to increases in volume, even though the metal masses may have remained unchanged from those in the pond influent. This pond may then be seen as functioning well, even though in reality, it does not reduce the amount of metal in its influent. The research presented here was therefore focussed on metal concentration as well as mass removal in ponds.
3. Current literature did not include a standard methodology or format for pond efficiency comparison or documentation. The objectives of this research required that ponds from different case studies be evaluated for efficiency and compared on a standard basis. A novel methodology and format for pond efficiency classification, based on the effluent probability method, for use in comparison and documentation, was therefore developed.

1.9.2 Practical significance

Pond case studies published in literature have often been categorically grouped together to enable performance comparisons between different structure types, such as ponds, swales, wetlands and permeable pavements. This was done to ascertain the type of structure most suited to the removal of a specific substance. The goal of such an approach was to augment prescriptive methods used in determining structure choice when designing for stormwater quality improvement.

This research, in contrast, was focussed on comparing the efficiency of metals removal only of different case studies of the same structure type, viz. detention or retention ponds. This was done to ascertain which case studies were efficient or inefficient in certain metal removals, and why. The goal of this approach was to generate knowledge of physical pond parameters, which are significant in pond metals removal efficiency, in order to augment practical design methodology and philosophy.

This research therefore has practically significant application, in South Africa as well as internationally, for the design of ponds that are specifically used to intercept metal polluted stormwater. In addition, design recommendations were written in a South African context, with general considerations towards practical installation included.

2. Literature review

2.1 Introduction

Literature reviewed included (1) background and motivation for the study, (2) support for data analysis techniques used and (3) the state of the art of stormwater pond modelling and design techniques for later comparison with research results.

2.2 Background and motivation

2.2.1 Metal toxins in surface waters

Metals are widely produced, released and dispersed by human activities. They have been widely used by humans and are prominent in industrial processes, pesticides, herbicides, fungicides, wood preservatives, electronics (Department of Water Affairs and Forestry, 1996a,b,c) mining (United Nations Environmental Protection Agency, 2006), coal combustion and smelting (Feng & Qiu, 2008). These activities can be the source of unnaturally high concentrations of metals in the environment (United Nations Environmental Protection Agency, 2006). Metals have been released to the local urban or agricultural environment through processes such as industrial spills, pesticide and herbicide applications, the weathering of materials (Department of Water Affairs and Forestry, 1996a,b,c) and atmospheric deposition (Woods-Ballard et al., 2007). Trace metals can also be transported far from their original sources. Such long range transport has resulted, for example, in concerns in areas as remote as the arctic where unnaturally high lead and cadmium concentrations have been found at several monitoring stations (United Nations Environmental Protection Agency, 2006).

Deposition, wash off and transport:

Metal pollutants can be deposited directly or atmospherically on urban and rural land surfaces. These pollutants can then be washed off by stormwater runoff and deposited in surface waters (Woods-Ballard et al., 2007). The United States Environmental Protection Agency (2004a) has stated that it is probable that any pollutant that is derived from a land-based activity will end up in stormwater runoff in some concentration.

There are numerous relatively recent international case studies that have documented the occurrence of metals wash off from urban and rural surfaces to surface waters. A selected number are briefly discussed below:

- The National Urban Runoff Program (NURP) in the USA has conducted studies on surface runoff quality and has found that heavy metals has been the most prevalent priority pollutant in urban runoff (Chen & Liew, 2003).
- Al Bakri et al. (2008) performed a study on the sources and management of stormwater pollution in two adjacent rural catchments in New South Wales, Australia. The two catchments that were studied (rural and urban) were found to receive moderate to serious heavy metal pollution during storm events during the study period. It was concluded that the urban areas contributed stormwater pollutants to the natural waterways, regardless of the influence of treated sewage effluents. A comparison between the catchments revealed that the catchment that contained less intensive industrial and commercial sources as well as point sources, had a better stormwater runoff quality. It was also found that, in general, the water quality of waterways of both catchments declined as they ran through the urban area.
- Kang et al. (2009) performed a study on the characteristics of wet and dry period heavy metal discharges in the Yeongsan river, which runs through Gwangju city. Arsenic, cadmium, copper, lead and zinc were among the metals measured. It was found that metal concentrations and loads in the river showed distinct seasonal and spatial variability with higher loads eminating from the city in wet months. Wet weather flow from the city accounted for 44% to 93% of the total annual dissolved metal loads. Occurence of metal species in runoff was as follows: Mn>Zn>Cu. It was also found that metal loads increased as rainfall depth or antecedent dry periods increased. Metal species were found to predominantly exist in a particulate phase.
- Kang et al. (2010) performed a study on the linking of land use type and stormwater quality in the Yeongsan river basin, Korea. Zinc and copper were included among the substances measured. It was found that heavy metal concentrations were usually greater in urbanised areas when compared with rural areas, and that seasonal variations among substances were greater than spatial variations. It was also found that, in general, substance concentrations were greater in wet weather than in dry weather. Industrial and mining sources were identified as a substantial source of many metals.
- Naito et al. (2010) performed a study into the exposure and risk assessment of zinc in Japanese surface waters. They examined how zinc concentrations changed due to certain inputs in the Sakai river located in Kanagawa and Tokyo. It was found that, during rains, the influence of road runoff on zinc concentrations was significant. Total zinc concentrations just after runoff in the Sakai river increased by approximately 10 times to that of the normal level. It was also found that the concentrations decreased as the runoff volumes increased due to dillution effects. It was concluded that emissions from diffuse sources such as atmospheric

corrosion and tire wear might contribute more than 70% of the total zinc emissions to surface water in Japan.

- Zgheib et al. (2012) performed a study into the occurrence of priority pollutants, incl. lead copper and zinc, in Paris, France. They found that contamination in the measured storm sewers was higher than in the sediments of the Seine river, and it was therefore concluded that further discharge of untreated stormwater can adversely impact on the quality of the river.

Metal pollutants can be transported via surface waters to primary food production areas. Zhao et al. (2012) performed a study on the human health risks from soil heavy metal concentrations under different land uses near Daboashan mine, China. Four watersheds surrounding the mine were mainly polluted by mine drainage. The rivers were the primary water supply for human settlements and agriculture within these watersheds. Several areas with metal pollution have been identified and crops growing within the watersheds were contaminated with heavy metals. Although the metal toxin source was a mine and not polluted runoff, distributions of metals in agricultural areas due to irrigation from a polluted river source were evident.

Metal sinks:

Arsenic, cadmium, copper, lead and zinc are strongly adsorbed by soil clay particles and can be expected to be retained in the soil surface layers (Department of Water Affairs and Forestry, 1996a). Heavy metal contamination in agricultural soils is a concern, because it may enter the human food chain in significant amounts if taken up by plants. For example, it has been estimated that about half of human intake of lead is through food, with half of that being from plants (Nasreddine & Parent-Massin (2002) cited in Intawongse & Dean (2006) p. 36).

Bio-accumulation of metals in many types of primary food sources can pose a health hazard to humans. Metals of concern include: (1) arsenic and cadmium, which have been shown to bioaccumulate in certain crops, (2) and lead, which has been shown to bioaccumulate to toxic levels in fish and cattle milk (Department of Water Affairs and Forestry, 1996a,b,c).

Table 2-1 Bio-accumulation of metal toxins and effect on humans, adapted from (Department of Water Affairs and Forestry, 1996a,b,c)

Metal	**Route**	**Effect on humans**
Arsenic	Bio-accumulation in certain crops	Consumption of enriched crops can be toxic
Cadmium	Bio-accumulation in crops	Regular consumption of enriched crops over decades can be detrimental to health
Copper	Not stated	Not stated
Lead	1. Dietary excesses in cattle can appear in milk. 2. Bio-accumulation in fish	1. Consumption of contaminated milk can be toxic 2. Toxic effects after consumption of fish is rare but can occur
Zinc	Not stated	Not stated

Case studies of human exposure to metals via bio-accumulation have typically been focussed on fish and crop consumption. A few are conferred:

- Intawongse & Dean (2006) performed a study on the uptake of heavy metals by food plants grown in contaminated soil and their bioavailability in the human gastrointestinal tract. It was found that manganese and zinc were easily mobilised from soil to plants and tended to accumulate in certain food plants in high concentrations. Lead showed a low uptake. A further assessment of metal bioavalability was performed and it was shown that bioavailability was independent of metal and plant type. It was also observed that most of the metals in the gastro intestinal section were in the insoluble residual phase, which is not available for absorption. Certain metals were, however, solubilised in the gastric (acidic) extraction phase indicating a potential of absorbtion, these included copper, cadmium and zinc.
- Wang et al. (2005) did a study on the health risks of heavy metals (Cu, Pb, Zn and Cd) to the population of Tiajin, China due to consumption of vegetables and fish. The city of Tiajin is industrial and sources of heavy metals to farmlands and fish ponds were attributed to atmospheric deposition, solid waste emmisions, sludge applications and wastewater irrigation. Although stormwater runoff has not been mentioned as a pollution source, it is certain that it can be included as a source in the pollution of fish ponds, since these are dependent on surface waters, which are fed by runoff. The authors of the study expressed a concern for potential health risks if both fish and vegetables were consumed.
- Zheng et al. (2007) performed a study on the population health risk due to the dietary intake of heavy metals in the industrial area of Huludao city, China. Food consumed by the population came from the farmlands close to the city. Sources of heavy metals such as lead, cadmium, zinc and copper were attributed to atmospheric deposition, wastewater irrigation, sludge land application and solid waste emmisions. They identified food as the major pathway of human heavy metal exposure and found in their study that, although the intake of one food type (e.g. vegetables) does not pose a health hazard, the intake of a variety of contaminated foods can pose a risk to population health.

2.2.2 The effects of metal pollution on primary food production

The effects of metal pollution on primary food production have been widespread. Metal pollutants can affect the health and growth of crops, livestock and fish. They can also adversely affect human health via the dietary exposure route.

2.2.2.1 Effects on crop, livestock and fish production

All material in this section has been sourced from guidelines provided by the Department of Water Affairs and Forestry, (1996a,b,c):

Arsenic:

Arsenic, although beneficial to crops at low concentrations, depresses plant yield at high concentrations, depending on the soil type. Arsenic pollution in irrigation water also affects crop quality, as determined by arsenic toxicity to humans. The main effect on plants seems to be destruction of chlorophyll in the foliage. Arsenic poisoning in animals is usually acute or sub-acute, with chronic effects not well documented. Acute symptoms of exposure occur suddenly and include haemorrhagic diarrhoea, abdominal pain, dehydration and increased mortality. Sensitivity to poisoning is determined by type of animal. Arsenic exposure of fish can result in the precipitation of arsenic on the body surface and gills, with the production of a mucous film and gill damage with death by suffocation as a result.

Cadmium:

Cadmium interferes with plant metabolism and is toxic to many plants. Cadmium pollution in irrigation water affects crop yield and quality, as determined by cadmium toxicity to humans. Concentrations as low as 0.1 mg/l in nutrient solutions can be toxic to certain plants, notably beans, beets and turnips. Cadmium poisoning in livestock is uncommon, even though it is highly toxic. This is due to low absorption. Acute symptoms of poisoning include anaemia, abortions, stillbirths, a decline in immune responses, reduced feed intake and milk production, and increased mortality. Cadmium is toxic to fish at high concentrations. Most chemical forms of cadmium are similarly toxic. Toxic effects include gill damage, damage to ion regulating mechanisms and damage to the nervous system.

Copper:

Copper is an essential plant nutrient, but toxicity can occur at high concentrations. Yield reduction and crop failure are the main effects of copper pollution. Copper is an essential livestock nutritional element, but toxic effects at high dosages can occur. The difference between the amounts required for it to be an essential element or toxic is marginal and depends on a number of interactions. Acute symptoms of poisoning include diarrhoea, liver damage, jaundice and increased mortality. Copper exposure of fish can result in chronic or acute toxic effects. Chronic effects include damage to the nervous and immune systems. Acute effects include mucous clogging of the gills and subsequent damage, hepatic and renal disorders.

Lead:

Lead pollution in irrigation water can result in reduced crop yield and crop failure. It can also adversely affect crop quality, as determined by lead toxicity to humans. Lead has a fairly low phytotoxicity and is rarely encountered in the soil solution because it is strongly sorbed by soil. Lead poisoning in livestock is usually acute. Symptoms of exposure involve the nervous system and include muscle tremors and blindness. Increased mortality can also occur. Lead exposure of fish can result in chronic or acute toxic effects. Chronic effects include damage to the immune system and spinal deformities. Acute effects include renal disorders and disruption of haemoglobin synthesis.

Zinc:

Zinc is an essential plant nutrient, but toxicity can occur at high concentrations by inducing iron deficiency. Zinc deficiencies can occur in alkaline or zinc poor soils. Zinc is an essential livestock nutritional element and animals have high tolerance to excess zinc intake. Chronic symptoms of poisoning include inappetence, diarrhoea, abortions and stillbirths. Zinc exposure to fish can result in the precipitation of zinc on the gills, with gill damage and death as a result. Other effects include impairment of feeding and growth.

2.2.2.2 Effects on humans

The major exposure routes of humans to many metals are through food (Castro-Gonzalez & Mendez-Armenta, 2008). Bio-accumulation and bio concentration of trace metals in the food chain can put humans at risk (United Nations Environmental Protection Agency, 2006). However, risk assessments of metal exposure to humans via food is difficult. Limited data and complicated human behaviours and responses make estimation of toxin risk challenging. Estimates of the health significance of exposure via the dietary route are therefore uncertain (United States Environment Protection Agency, 2007).

2.2.3 South African studies

South African case studies have been done wherein metal polluted surface runoff has been implicated in having a possible adverse effect on agricultural practices downstream. These are briefly discussed below:

- A study into Cadmium levels in the Umtata river between May 1999 and March 2000 found levels ranging between 0.01 – 1.0 mg/l. Runoff from agricultural lands where fertilisers have been applied were implicated as a source of cadmium. Livestock watering and fishing were identified to be among the water uses of the river (Fatoki et al., 2004). Although the focus of the study was on fitness of use for domestic purposes, it was noted that the recorded cadmium levels were above the South African Water minimum water quality targets of 0.01mg/l and 1.8 µg/l for livestock watering and fish, respectively.
- A case study at the Tyume river in South Africa found that metals such as cadmium, copper, lead and zinc in vegetables grown next to the river could probably be attributed to irrigation with water from the river. Although levels were within acceptable ranges, it was cautioned that continual consumption of vegetables containing cadmium and lead could lead to accumulation

with adverse health implications such as renal diseases and cancer. River water levels of cadmium were found to be higher than the target water quality ranges as prescribed by the South African Water Quality Guidelines for irrigation and livestock watering. Agricultural runoff contaminated with metals from fertilisers were implicated as a probable source of cadmium in the river (Awofolu et al., 2005).

- An investigation was performed into fish kills (tilapia) in the Roodeplaat Dam by Hohls & van Ginkel (2004). Although the Roodeplaat Dam is not a commercial aquacultural dam, this case study illustrates how freshwater fish can be affected by metal pollution. High concentrations of un-ionised ammonia (NH_3-N) and zinc (Zn) were measured in water samples. A zinc concentration of 0.222 mg/l, which was higher than the acute effect value concentration of 0.036 mg/l, was measured. Possible contaminant sources were identified as industrial activity, fertiliser and pesticides.

2.3 Detention and retention ponds – international use

Internationally, the use of ponds to reduce or intercept stormwater runoff pollution has often formed part of a greater system, wherein ponds, aside from serving as water quality control infrastructure, also serve to attenuate stormwater peak flows. The two most prominent approaches to stormwater management found in the literature were the United Kingdom's sustainable urban drainage systems (SUDS) and the United States of America's best management practices (BMPs). Both used treatment train strategies. The SUDS treatment train is oriented towards management and consists of:

1. Prevention – relating to site design and housekeeping measures.
2. Source control – control of runoff at source with infrastructure such as soakaways and pervious pavements.
3. Site control – management of water at a local site.
4. Regional control – management of runoff from one or several sites.

(Woods-Ballard et al., 2007)

Detention and retention ponds are included under items 3 or 4. The SUDS philosophy recommends that runoff be managed in small, incremental areas, rather than having a scheme where all runoff is conveyed to a large system at the bottom of a drainage area (so called end-of-pipe solutions) (Woods-Ballard et al., 2007).

The USEPA treatment train layout is oriented towards infrastructure elements and consists of two or more of the following items:

1. Infiltration practices
2. Vegetated open channel practices
3. Filtering practices
4. Detention ponds or vaults
5. Retention ponds
6. Wetlands
7. Other

(United States Environment Protection Agency, 2005)

Other than water quality and quantity improvements, ponds can have additional effects. A possible positive secondary consequence of stormwater ponds is the creation of water habitats. A study by Moore & Hunt (2011) indicated that (1) ponds may become naturally inhabited by plants and animals, although plants tend to be aggressive invasive species, (2) predatory insect families tend to be attracted more to ponds with emergent vegetation, which improves diversity and (3) the inclusion of a littoral shelf in the design may improve diversity.

Possible negative secondary consequences are (1) the creation of habitats for pests like mosquitos and (2) metals accumulation in stormwater ponds may become a source of metals bio-accumulation in the environment. A study performed by Camponelli et al. (2010) on a stormwater pond in Baltimore, USA, showed that copper and zinc runoff can potentially act as stressors to organisms that inhabit retention ponds and may bioaccumulate in such organisms and therefore become a source of metals to predators.

2.4 General data analysis techniques

The purpose of this section was to provide supportive information for the choice and structure of research methodology, as documented in Chapter 3.

2.4.1 Data sources

The thesis debate required a large amount of varied data on different pond case studies. This rendered self-generated data in a laboratory setup and data sourced from journal papers too limited in scope for use. Databases were therefore investigated. There are a number of databases available for access on the internet where water quality data is stored. Most databases, however, did not contain data specifically for stormwater ponds. Two databases that did contain such data were investigated.

A comprehensive source of water quality data for stormwater ponds is the International Stormwater BMP database, v.07.07.11, available at www.bmpdatabase.org. It has been developing for the past two decades as an account of work sponsored by the Water Environment Research Foundation (WERF), the American Society of Civil Engineers (ASCE), Environmental and Water Resources Institute (EWRI), the American Public Works Association (APWA), the Federal Highway Administration (FHWA), and U.S. Environmental Protection Agency (USEPA) (Wright Water Engineers, Inc.; GeoSyntec Consultants, Inc., 2010).

The International Stormwater BMP Database is intended to provide researchers with consistent and defensible data on Best Management Practice designs and performance. Its main purpose is as a data exchange tool, which permits characterisation of BMPs upon their measured performance by using consistent protocols for measurements and reporting information. The bases of the project are the BMP monitoring and reporting protocols as well as the BMP Database itself, which has been developed based on input and intensive review by many experts (Wright Water Engineers, Inc.; GeoSyntec Consultants, Inc., 2010).

From 2010, the BMP Database has logged more than 400 BMP studies. It has an extensive range of parameters such as test site characteristics, BMP layout characteristics, flow and water quality data. It is freely available on the project website, which also contains statistical analyses data. The project team additionally review data for consistency and accuracy prior to accepting studies for inclusion (Wright Water Engineers, Inc.; GeoSyntec Consultants, Inc., 2010).

Another available database is STORET, the United States of America Environmental Protection Agency (USEPA) repository for water quality, biological and physical data. Information in the International Stormwater BMP Database is based on the STORET nomenclature and input formats (Wright Water Engineers, Inc.; GeoSyntec Consultants, Inc., 2010).

The STORET database is fully web based (available at www.epa.gov/storet). The system required case by case searches via the internet and information on the structure and watershed such as the watershed zip code was required to enable a search. This database therefore required previous knowledge of specific case studies, rendering it difficult to use for research involving the identification of case studies without such previous knowledge, as was required for this project.

In conclusion, only two databases with applicable data were discovered during the course of this project. The International Stormwater BMP Database was found to be superior in ease of use, diversity and expanse of data. All data for the project was therefore obtained from it.

2.4.2 Data preparation

2.4.2.1 The USEPA final data and exploration technique

GeoSyntec Consultants et al. (2000) published a report on final data and exploration for the American Society of Civil Engineers (ASCE) and the United States Environment Protection Agency (USEPA). The scope of this report covered the analysis of data contained in the International Stormwater BMP database. It was therefore used as a basis for data analysis methodology in this project.

In the data preparation phase of the study, the water quality data was broken down into two different types, viz.:

1. Composite data such as manual or automatic compositing and flow weighted event mean concentrations (EMCs).
2. Discrete data such as grab samples and field measurements.

In certain cases composite and discreet data were combined, e.g. a numerical composite was calculated for a pond with both runoff and pumped inflow. In the cases where ponds had multiple inflows, a composite EMC was calculated with the following equation:

$$\text{Composite EMC} = \frac{\sum_{i=1}^{n} \mathbf{EMCi.Vi}}{\sum_{i=1}^{n} \mathbf{Vi}}$$

Where: i = inflow monitoring station

n = total number of inflows

EMC = Event Mean Concentration

V = Flow Volume

(GeoSyntec Consultants, Inc.; District, Urban Drainage and Flood Control; URS; Council, ASCE Urban Water Research, 2000)

After the initial compositing of data, it was tested for normal distribution. On the grounds of work done in other studies, it was assumed in this study that data was most likely to show log-normal distribution. Exploration of this distribution was done in the following ways:

1. A comparison was made between parametric and non-parametric analysis of variance (p values within 10%) in order to assess the differences found in using the different methods.
2. In cases where adequate data points where available, a Pearson-Chi test was used to see whether the normal distribution was a good estimate of central tendency and the distribution of event concentrations in logarithm space.
3. Graphical probability plots of influent and effluent data where examined.

(GeoSyntec Consultants, Inc.; District, Urban Drainage and Flood Control; URS; Council, ASCE Urban Water Research, 2000)

The approach followed by GeoSyntec Consultants et al. (2000) had two limitations. Firstly, the practice of combining composite and discrete data required that a significant assumption be made, viz. that the grab samples reflect the EMCs of the specific flows. Such an assumption seemingly has no supporting basis. Secondly, there was an assumption of normality in cases with few data points, which was unproven.

2.4.2.2 Non-detects (NDs) and the method detection limit (MDL)

Non-detects were reported in the data used in this project. These data types have been defined by Helsel (2006) as low-level concentrations of organic or inorganic chemicals with values known only to be somewhere between zero and the laboratory's detection/reporting limits. Measurements are believed to be too imprecise to report as a single number, so the measurement is usually reported less than some analytical threshold. Such values add complication to statistical calculations such as descriptive statistics, correlational analysis and regression calculations (Helsel, 2006).

Helsel (2006) also stated that it is not wise to remove non-detects from a data set. He reasoned that such an action can create an upward bias in measures of location such as means and medians, obscuring the information that could have been provided by the original data set.

There are a number or approaches that have historically been used to deal with NDs. These include simple substitution, maximum likelihood estimation, regression on order statistics and the Kaplan-Meier method (GeoSyntec Consultants , Wright Water Engineers, Inc., 2009).

The Regression on Order Statistics (ROS) method was recommended by the International Stormwater BMP database project team for use in statistical analysis of non-detects. The advantages of the ROS method include a capability to handle small data sets (fewer than 30 detected values); it is applicable to any dataset in which 0-80% of values are censored and is simple to apply (GeoSyntec Consultants , Wright Water Engineers, Inc., 2009).

The ROS method provides an estimated censored value based on assumptions of log-normal distribution. Although it can be argued that this assumption may not be valid in all cases, there is no known alternative method that is proven to yield results that are more reliable. Although the accurate values of non-detect samples will never be known, the ROS method provides a logical estimate of the true values (GeoSyntec Consultants , Wright Water Engineers, Inc., 2009).

Helsel (2005) recommends that the ROS method be used with uncensored observations to model the distribution of the sample population and must not be considered as values that would have existed in the absence of censoring, i.e. the modelled values cannot be interpreted to be the same as the values that would have been measured if the laboratory instrument possessed better resolution.

2.5 Pond efficiency evaluation

The purpose of this review was to provide both (1) support for the choice and structure of the research methodology and (2) comparative information from case studies.

2.5.1 The effluent probability method

The Effluent Probability Method, which provides a statistical view of influent and effluent quality, has been recommended by GeoSyntec Consultants , Wright Water Engineers, Inc. (2009) under support from *inter alia* the Water Environment Research Foundation (WERF), the United States Environmental Protection Agency (USEPA) and the American Society of Civil Engineers (ASCE). Data analysis was therefore partly based on this methodology.

This methodology broadly comprises of the following steps:

1. Determine whether the BMP is providing treatment by calculating statistical significance at 95% confidence level between influent and effluent values.
2. Examine a cumulative distribution function or standard parallel probability plot of influent and effluent quality.

(GeoSyntec Consultants , Wright Water Engineers, Inc., 2009)

The advantages of the Effluent Probability Method are that it is simple and gives an analytical basis for comparing the differences between influent and effluent water quality. The method does, however, have a number of shortcomings. These are discussed below.

2.5.1.1 Statistical Significance between inflow and outflow values

Statistical significance is a term used in the field of statistics to interpret the outcome of a hypothesis test. When a hypothesis is tested, and the null hypothesis is rejected, then the outcome is said to be statistically significant at a predefined level. This process only concludes that there is or is not a difference, it gives no indication of the magnitude of the difference (Creswell et al., 2011).

Dickson & Baird (2011:218) have raised the question of whether a small p-value indicates a causal relationship of some sort. This issue is debateable and they believe that it must be generally acknowledged that it is difficult, if not impossible, to identify specific causal relationships on the basis of statistical significance without an appeal to some theory, which is as yet non-existent. Although statistical significance testing has become the standard in many scientific explorations, the assumption that a significant difference is due to some causal relationship is an article of faith rather than a well-established principle. On the choice of the significance level, Dickson & Baird (2011:224) stated that the choice of significance level is in itself statistically insignificant. It is in fact arbitrary and not based on theory.

It may therefore be asked, why use statistical significance testing at all? It is the author's opinion that this approach is used so often simply because there is no other theory that can currently take its place in terms of the purposes it is used for. It is a flawed approach, but rather than using the flaws to eliminate it from use in practice, the knowledge of the flaws can be used to inform interpretations of results until viable alternative approaches are developed. Statistical significance testing for stormwater structures has the purpose of providing a quick indication of how efficiently a structure is performing. The flaws in the test means that it can never be used on its own and must be used as part of a larger group of efficiency evaluations only as indicators of pond efficiency. The statistical significance test is currently (since percentage removal has been proven to be unreliable) the only test that provides an explicit numeric that can be used for comparisons between different data sets.

The sign test can be used to test for statistically significant differences in pond inflow/outflow values. It does not take into account the size of the differences between paired values, making the Wilcoxon test preferable in cases where data is symmetric (Montgomery & Runger, 2003:581). However, symmetry was not found in the project data and therefore the Sign test was chosen.

The sign test is considered by (Dixon & Mood, 1946) to be most useful when:

1. There are pairs of observations of the two things being compared.
2. Each of the two observations of a given pair arose under similar conditions.
3. The different pairs were observed under different conditions. This condition generally makes the t-test invalid.

These conditions suited the use of the data of this project where (1) pond inflow and outflow data can be seen as pairs, (2) the inflow and outflow data arose under the same storm and runoff conditions, and (3) different storm inflow and outflow data pairs arose under different storms and different runoff conditions.

2.5.1.2 Cumulative Frequency Plots (CFPs)

In this project, establishment of pond efficiencies for comparative purposes did not require the establishment of theoretical distributions such as the cumulative distribution function. Therefore, sample approximating Cumulative Frequency Plots (CFPs), were deemed adequate for the graphical representation of data.

CFPs are useful in pond efficiency evaluations because they can indicate the relative inflow and outflow data ranges over which ponds perform poorly or well. However, they provide only a sense of pond performance that does not allow for direct comparison between ponds. Personal and subjective judgement must be used to conclude whether a pond performs well or poorly in relation to other ponds.

2.5.2 Case studies

This section provides examples of the use of pond efficiency evaluation methods in practice and recent study results that were of interest.

2.5.2.1 Barrett (2008)

Barrett (2008) did a comparison of BMP performance using the International BMP Database (data available in 2003). The goal of the study was to understand the causes of reported variations in data, which relate to facility design and watershed characteristics. The author felt that, in this way, the performance of facilities built to a “similar” design level in “similar” watersheds could be compared. The performance evaluation of the study was based on a comparison of the effluent quality obtained by structures as compared to influent concentrations. The main results where:

Retention ponds

1. Suspended solids were removed through sedimentation. Therefore the expected discharge concentration should have been a function of many variables, including the influent concentration, the size of the permanent pool (affecting residence time), pond geometry, temperature (affects viscosity), area of the pond and the degree of quiescent settling during and after a storm event. It was difficult to quantify much of this with the available data and variability in performance was therefore expected.
2. A comparison of influent and effluent TSS concentrations revealed a relatively strong relationship between the two ($p = 0.008$).
3. Design guidelines were aimed at producing plug-flow in ponds to clean ponds of the pollutants of previous storms. The results showed that the guidelines had not achieved the desired effect, otherwise effluent concentrations would be independent of influent concentrations for storms that produce less runoff than the permanent pool volume.
4. It was expected that cold weather influenced water viscosity and therefore settling processes. However, it was found that Heritage Pond, situated in Canada, produced an effluent quality similar to other ponds. Therefore the seasonal differences in temperature may have had only a mild effect on settling.

5. Mean TSS and metals discharge concentrations were not significantly correlated with permanent pool volume, even though this was a prominent design element. This was found to be the case when the volume equaled or exceeded the mean runoff from the mean storm of the area.
6. Conversely to 5. above, it was indicated that there was a minimum size above which pond performance tended to decline markedly.
7. The relationship between discharge TSS concentration and pool volume indicated that settling occurred rapidly, after which small suspended particles remained, which would not settle much more with increased time.
8. Larger permanent pool volumes resulted in less variability in discharge concentrations and performed better under individual events with larger runoff volumes. Pools 2 to 3 times the mean storm volume for the area appeared sufficient. Larger pools may have had no further effect on discharge quality.

<u>Extended Detention Basins</u>

1. Insufficient data made the establishment of a relationship between influent and effluent quality impossible.
2. Data indicated that an irreducible minimum TSS discharge concentration of around 30mg/l could be expected for basins treating influent up to 150 mg/l.
3. It was noted that detention times for small storm events were usually only a few hours. Therefore the first flush runoff, containing the most polluted water, received the least treatment.
4. No significant relationship between TSS removal and basin depth was observed with the available data.
5. Concentrations of total zinc and copper were significantly reduced between influent and effluent ($p = 0.008$ and 0.032 respectively). Dissolved concentrations showed no significant reduction.

This study provided insight into the use of simple linear regression to evaluation correlations between design elements and pond performance. The use of data from the International BMP Stormwater Database means that it was possible to compare certain results with results obtained in this dissertation, since some of the case studies used by Barrett (2008) have also been used in the dissertation data analysis (See Chapters 4 and 5).

The data analysis included only concentration data. Concentration is a compound parameter and is a combination of mass and volume. Variations in masses and volumes in pond influent and effluent flows are masked by the use of the concentration paramenter only. Further analysis of influent and effluent masses may have provided better insight into pond performance (see discussion in Chapter 4.1).

2.5.2.2 Dufresne et al. (2010)

A study performed by Dufresne et al. (2010) produced results that were pertinent to the modelling of stormwater ponds and was therefore reviewed and summarised below.

Dufresne et al. (2010) performed an experimental investigation into flow pattern, preferential regions of deposition and trap efficiency as a function of length in shallow rectangular reservoirs. They noted that the prediction of deposition as a function of the geometry of the reservoir, the hydraulic conditions and the sediment characteristics was still a great challenge. Existing models could not determine the spatial distribution of deposits for which knowledge of the flow pattern was a pre-requisite. They also questioned whether the imprecise results of existing models were due to the fact that they do not take flow pattern into consideration.

The experimental setup consisted of a rectangular tank with uniform inflow and outflow velocity. The flow suddenly expanded to the width of the tank at the inlet and suddenly contracted to the width of the outflow channel at the outflow. The characterstic sediment size and settling velocity of granular plastic was measured. A single inflow velocity was used for all tests. Both flow pattern and sediment deposition were studied (Dufresne et al., 2010).

A number of different flow patterns were highlighted with dye. Patterns were complex and variable. It was found that bed load was the predominant mode of sediment transport in the reservoir and that the spatial distributions of the deposits were a function of the flow pattern.

Trap efficiencies were found to be a function of length to width and, possibly, depth ratio. Variations in results were attributed to unsteadiness of flow, unsteadiness of sediment input and the nature of dominant bed-load sediment transport. It was noted that even under controlled experimental conditions, sediment discharge exhibited significant variations with time (Dufresne et al., 2010).

This case study highlights the effect that pond shape can have on sediment trap efficiencies, flow regimes within the pond and sediment deposition within the pond. It showed that even within a simple rectangular pond shape, flow regimes within the pond and resultant trap efficiencies can be highly variable.

2.5.2.3 Hossain et al. (2005)

A study performed by Hossain et al. (2005) contained results pertinent to the design of stormwater ponds in general. They performed a study on the efficiency and flow regime of a highway detention pond (Spokane pond in Washington, USA). Percentage concentration removal efficiencies were calculated for TSS and selected metals (cadmium, copper, lead and zinc) over a period of two years of continual monitoring.

It was noted that smaller metal removal efficiencies corresponded with smaller influent concentrations and that total removal efficiencies where rather variable. A correlation analysis between metal removal efficiencies and TSS removal efficiencies was performed. It was found that total metal removal efficiency of metals was 72.5% to 86.9% of TSS removal efficiencies, with correlation coefficients ranging from 0.58 to 0.87 respectively (Hossain et al., 2005).

The pond flow regime was evaluated with tracer tests. It was found that dead volume, i.e. the volume that does not mix with incoming flows and therefore reduces effective volume, was approximately 38% of total volume. As a result, the actual residence time of the pond was approximately 64% of the theoretical residence time (Hossain et al., 2005).

This study highlights the possible importance of sediment removal when designing for metal removal in ponds. It also indicates that the design residence time of a pond may greatly differ from the actual residence time due to flow regimes within the pond.

2.5.2.4 Water Environment Research Federation (2005)

In 2005 WERF published a report entitled “Performance and Whole Life Costs of Best Management Practices and Sustainable Urban Drainage Systems” (Lampe et al., 2005). The scope of work included a review of data included in the International BMP Database and a review of data from the Scottish Monitoring Programme. Structures that were evaluated included ponds and extended detention basins.

An objective of the WERF project was to establish a relationship between various design parameters such as pond depth, retention time and slope and the pollutant removal performance of the structure. Although this objective was similar to the objectives of this project, there were a number of significant differences in the methodology and focus of the work. These have been listed below:

1. The studies were lumped together in a categorical analysis and an attempt was made to obtain correlations across studies. For example, event mean concentrations for all studies in and out of the structure were compared simultaneously to look for correlations across the studies. The approach followed is different to the one that was followed in this dissertation, wherein performance was firstly evaluated on a case-by-case basis to ascertain statistical significance and degree of pollutant removal.
2. The focus of the WERF analysis was on copper and zinc concentrations only.

Pertinent results of the WERF analysis were:

<u>Retention Ponds:</u>

1. Mean TSS and metals discharge concentrations were independent of permanent pool volume when that volume equalled or exceeded runoff from the mean storm in the area.
2. Discharge concentrations were often a function of influent concentration but could not be accurately expressed as a percent reduction of the influent concentrations.
3. Larger permanent pools (4 – 6 times the mean storm runoff volume) resulted in less variability in effluent concentrations.
4. Ponds tended to have poorer performance in areas were rainfall occurred more often.
5. TSS removal was not correlated with pond surface area where the area was at least 0.3% of the tributary area.
6. Pond performance was adversely affected by frozen surfaces.
7. No consistent effect on TSS removal was observed for decreasing temperatures.

<u>Extended Detention Basins (EDBs):</u>

1. An irreducible minimum concentration of around 30 mg/l TSS could be expected for ponds treating inflows up to 150 mg/l.
2. No relationship between basin depth and TSS removal was observed.
3. Total copper and zinc concentrations were substantially reduced, but dissolved concentrations were less affected.
4. Percent reductions were highly dependent on influent concentrations.

(Lampe et al., 2005)

2.6 Modelling

Simulation modelling may be used as a tool for describing and understanding pond function. The state-of-the-art of simulation modelling was investigated by means of a summary of literature published on the subject in the past five years. Older literature was included if found to be highly relevant to metals removal in ponds.

2.6.1 Water quality models applicable to both detention and retention ponds

The use of computational fluid dynamics (CFD) for solute (dissolved substance) transport modelling was investigated by Stovin et al. (2008). The authors applied two modelling approaches to a storage tank. They claim that the results show that CFD can be used to optimise residence time distribution characteristics of urban drainage structures (design model) and to characterise the behaviour of such structures (simulation mode). It is diffucult too see, however, how this approach may be realistically validated and applied to detention or retention pond structures with varying irregular shapes and boundary conditions due to sedimentation, plant growth, etc.

2.6.2 Water quality models applicable to detention ponds

Akan (2010) presented a set of pollutant removal efficiency charts for use in the quick evaluation of existing detention basins as well as preliminary sizing of extended dry detention basins. The basis of the charts are the hydrological storage equation, viz. change in storage = volume in – volume out, for volume routing and a complete-mixing model for pollutant routing. The charts were specifically developed for orifice type outflow structures. A constant cross sectional area was assumed for simplification and the model was tested on data from a continuously stirred simple rectangular basin in a laboratory setup. The model requires knowledge of sediment settling velocities and calibration was used during the experiment to obtain a representative velocity for the material used. Metals were not specifically included in this model.

Espinosa-Villegas & Schnoor (2009) tested the results of a range of empirical equations for sediment trap efficiency in ponds with data from a reservoir in the USA. They found that the investigated models underestimated the true trap efficiencies of the reservoir. Metals were once again not specifically included.

2.6.3 Water quality models applicable to retention ponds

Adamsson et al. (2005) performed an investigation into the use of computational fluid dynamics (CFD) for simulation and design of ponds. A rectangular tank in a laboratory setting was used. This study highlighted a number of complexities in the use of such models and brings the application of such models to low monetary value detention ponds in question. Measured flow and tracer patterns were haphazard and highly complex compared to simulations, indicating that even highly controlled situations are difficult to model accurately. A number of practical design considerations were, however, seen. For example, a positioning of the inlet and outlet directly across each other created a jet of water that ran straight from the inflow to the outflow.

Weiss et al. (2006) developed a simple model specifically for application to design of ponds for metals removal. Pond functioning was assumed well-mixed at the outset of model development. The model represented a load contaminant flux via inflow and removal of contaminant via sediment, plant uptake and outflow fluxes. This model is simplistic and gives no consideration to differences in contaminant type, hydraulic variation with subsequent affects on settling or re-suspension within the ponds. In addition, it includes a singular plant uptake coefficient with no consideration of variation over time due to natural growth or change in seasons. An example was provided of how such uptakes could be determined in a laboratory setting, but this did not include any of the metals investigated in this dissertation.

Cheng (2008) presented a numerical finite element model to simulate hydraulic conditions and unsteady sediment discharge resulting from different pond inlet locations. The model includes consideration of sediment advection, diffusion and settling. It includes coefficients such as flow kinematic eddy viscosity, settling coefficients, settling velocities and diffusion coefficients. These coefficients require field data for calibration and the author has stated that the model had yet to be validated.

Youn & Pandit (2012) presented an annual wet pond efficiency simulation model named WEANES. The model is based on mass removal of substances, uses a specific USA method for creation of runoff hydrographs and local curve numbers and can only model prismatoid shapes with rectangular bottom areas. The model is very simple, with no consideration of removal processes within ponds, instead, output event mean concentrations must be specified by the modeller. This model is highly specific and not applicable to the variety of ponds found in reality. In addition to an outlay of the development of this model, the authors have indicated flaws in the USEPA SWMM model when used for water quality modelling. These include a lack of consideration of important factors such as pool volume and outlet structure design.

2.6.4 The Engelund-Hansen model for sedimentation

A sedimentation model set up with MIKE 11 software was used in this study as described in Chapter 6 of this dissertation. The Engelund & Hansen (1967) model describes total sediment load as both bed and suspended load. It incorporates consideration of bed slope, particle size and specific gravity, critical shear stress and flow regimes. This model was purposefully developed for sediment with sizes between 0.06 – 20mm. Engelund & Hansen (1967) stated, to this effect, that application of the sedimentation theory to the transport of very fine particles may under-predict discharge.

Metal-containing sediment in stormwater has been found to be mostly very fine with values as low as 8 microns. Brodie & Dunn (2009) tested for suspended solids size fractions in runoff from a galvanised iron roof, a concrete carpark and an asphalt roadway in a city in Australia. They found that fine particles (8 – 63 μm) made up the largest proportion of sediment in the runoff. Very fine particles (< 8 μm) constituted only 15 – 20% of sediment by mass. Lee, et al. (2010) tested suspended particle sizes in runoff from a parking lot, an urban motorway and a residential area in a city in China. They found that more than 90% of particles were larger than 6 μm. Zuo, et al. (2011) tested road runoff in a city in China. They found that just under 20% of particles were in the 0.45 – 10 μm size range.

The literature showed 80% plus of suspended solids were larger than the 6 – 10 μm range in the tested urban stormwater runoff from in two different countries in the world. A critical particle size of 8μm was thereby chosen for the MIKE 11 simulations. This size has the disadvantage that it falls outside the recommended size fractions of the Engelund & Hansen (1967) model. This was further discussed in Chapter 6.

2.7 Design

Design criteria for ponds have been developed in different countries and the most pertinent of these were outlined below. Technical summaries of the design techniques as well as description of terms are presented in Addendum A.

2.7.1 Water quality volume (WQV) approaches

Water quality volume approaches calculate a theoretical volume required for water treatment. The bases of the methodologies differ between countries. In the USA the WQV depends mainly on the percent imperviousness of the site. In the UK, the WQV depends on percent imperviousness, soil type and rainfall depth.

USA:

Many states in the USA require the calculation of a water quality volume as shown in Addendum A. These methodologies do not incorporate any consideration of influent pollutant load or even influent pollutant type. Drainage time, which is the time it takes for stormwater to drain out of ponds, was prescriptive and performance was assumed.

UK:

In the United Kingdom, two approaches have been followed in Scotland and England, viz. the variable rainfall depth method and the fixed rainfall depth method, respectively. These are discussed in the SUDS Manual (Woods-Ballard et al., 2007).

As for USA WQV approaches, these methods do not incorporate any consideration of influent pollutant load or even influent pollutant type. Performance was assumed.

2.7.2 Sediment routing

This methodology is contained in United States Environment Protection Agency (2004b). It incorporates mechanistic relationships between sediment removals in ponds and the factors which influence removal. Although it seems to present a realistic representation of sediment removal processes, it requires knowledge of parameters that may be difficult to obtain. These include knowledge of the type of sediment particles in the influent, flow regimes within the ponds which affect quiescent conditions and particle settling velocities.

This methodology provided a more powerful tool than water quality volume approaches to the designer for the prediction of pond performance when dealing with sediment removal. This, however, made it more complex and more cumbersome to use. It also required a large amount of data before it could be applied.

2.7.3 Chemical pollutant routing

A calculation methodology for chemical pollutant routing is presented in the Stormwater Best Management Practice Design Guidelines (United States Environment Protection Agency, 2004b) as a method to be used when sizing detention and retention ponds for the purpose of chemical pollutant reduction. The approach for pond volume determination was mechanistic. It considered contaminant loads to be adhered to clay particles, conservative if dissolved, or settleable. Pond efficiencies in terms of chemical pollutant removals were predicted with the aid of realistic parameters.

Although this methodology seems to present a realistical representation of chemical removal processes, it also requires additional knowledge of parameters, which may be difficult to obtain. These include knowledge of the size fraction of particles in the influent, flow regimes within the ponds which affect quiescent conditions, the fraction of the material bound to sediment particles, the fraction of the material in dissolved or particulate phase and particle settling velocities.

This methodology provides a more powerful tool than water quality volume approaches for the prediction of pond efficiency when dealing with chemical removal.

2.7.4 Prescriptive design guidelines

A number of prescriptive detention and retention pond design guidelines have been developed e.g. UDFCD (2010), USEPA (2004b) and CIRIA (2007). Such guidelines typically prescribe design criteria and parameters with little inclusion of modelling or design calculations. They are therefore very easy to apply, but cannot reliably predict the success of metals removals by structures. The main value of such guidelines is guidance towards application of practical considerations such as maintenance, access and public safety.

3. Data preparation and descriptive analysis

3.1 Introduction

Data preparation consisted of data categorisation, case study selection, substance selection, treatment of non-detects, investigations into data quality and testing for normality in data. Statistical analysis was used for initial data exploration, which included investigation into the number of data points analysed, data ranges and measures of central tendency and dispersion.

3.2 Methodology

3.2.1 Research instruments

The internet was the main research instrument. Water quality data for stormwater ponds was obtained from the International Stormwater BMP database, v.07.07.11, available on www.bmpdatabase.org (Water Environment Research Federation, Federal Highway Administration, American Public Works Association, Environmental and Water Resources Institute, 2011).

Additional information on the case studies was obtained in the form of reports via email correspondence with data entry providers or through searches of organisational websites.

3.2.2 General data preparation

3.2.2.1. Data categorisation

Data per case study was categorised as illustrated in Figure 3.1.

3.2.2.2 Case study selection

The (United States Environmental Protection Agency, 2004a) have stated that, in general, the variability in stormwater quality is so high that statistical evaluation is not worthwhile unless at least four storm events have been sampled. Possible detention and retention pond case studies were therefore only incorporated in the project if they conformed to the following selection criteria:

1. Flow data was required to have a minimum of five paired storm events and associated event mean concentration (EMC) data.
2. All case studies were required to have a minimum of three physical pond characteristics (volume, length, width, depth etc.). This was required for correlational analysis and logistic regression (Chapter 5) between pond physical characteristics and efficiency.

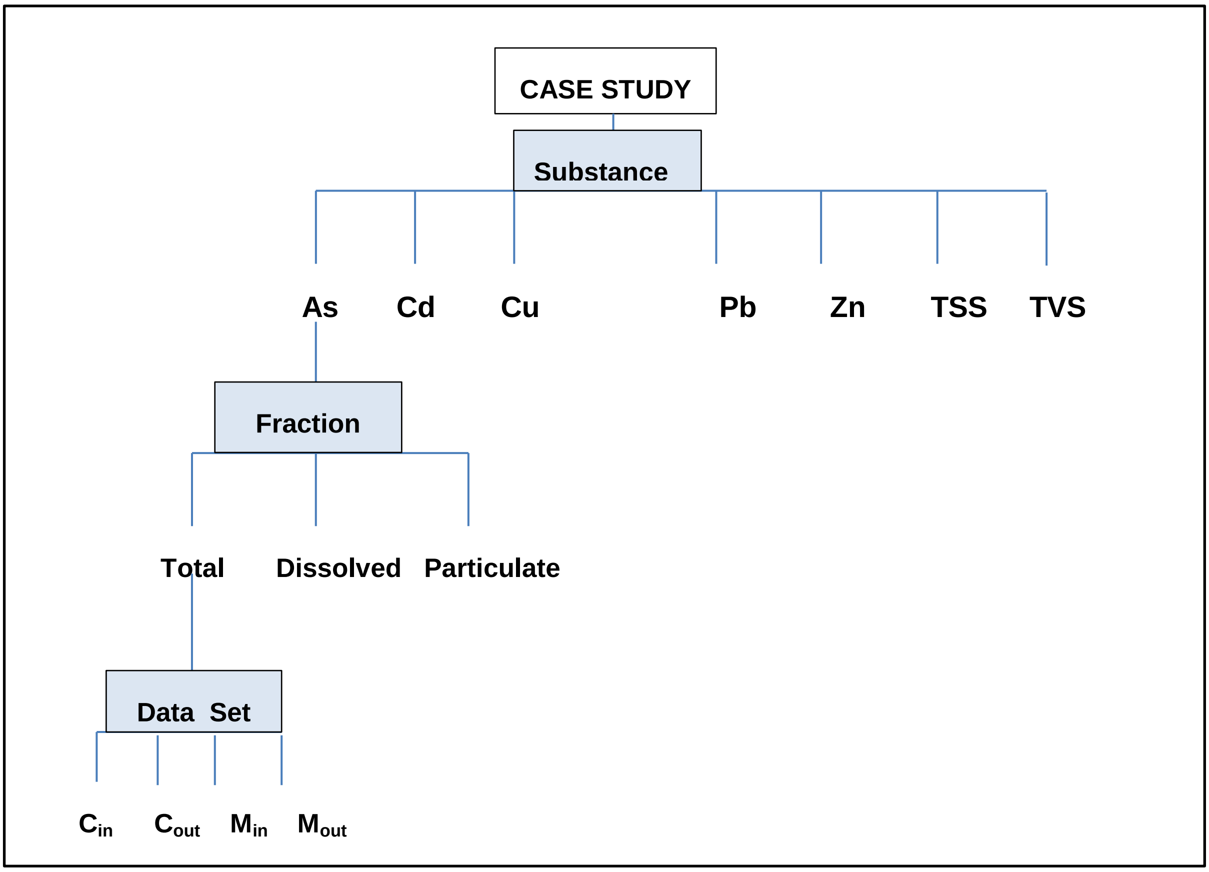
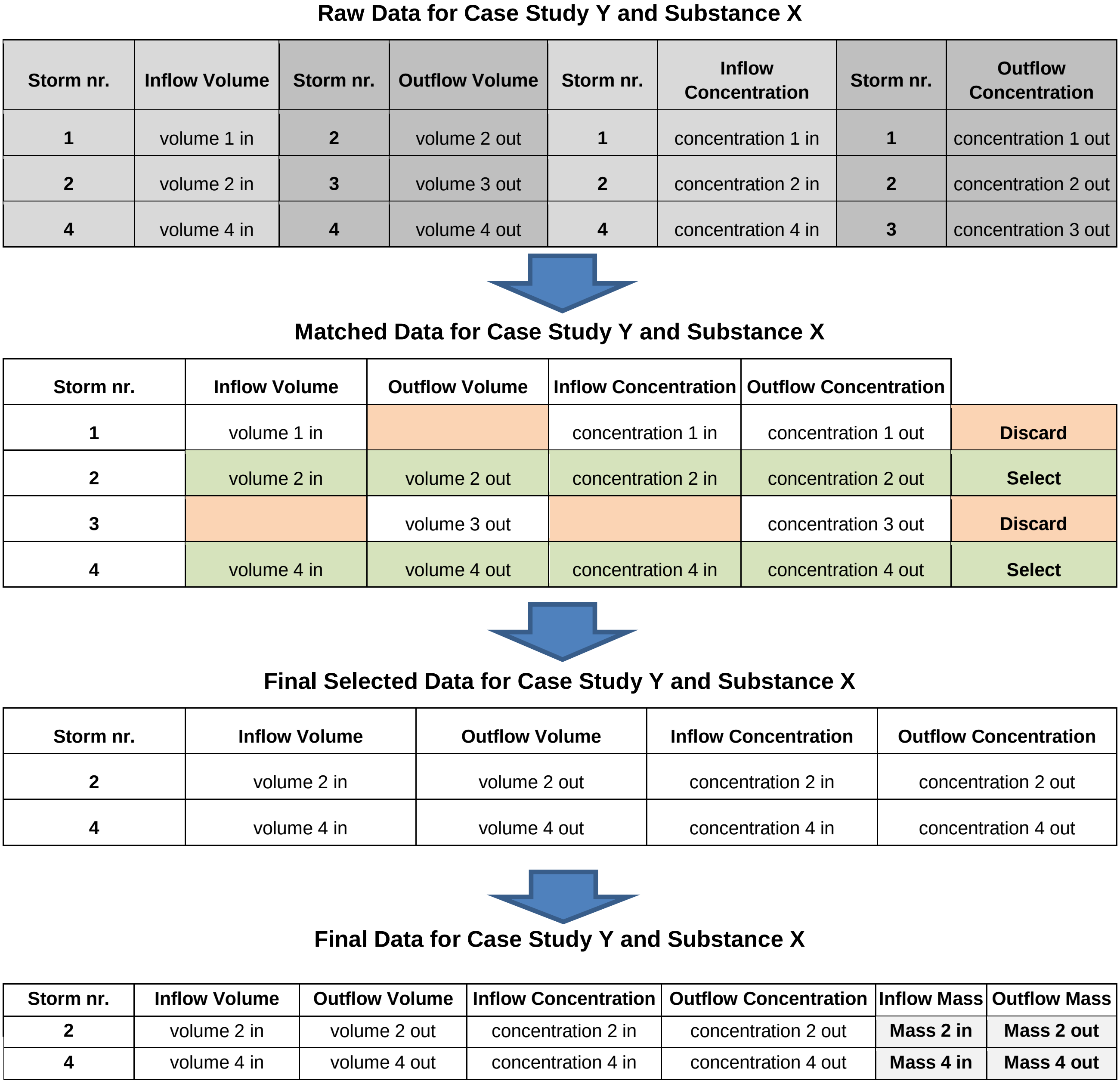


Figure 3-1 Data categorisation

3.2.2.3 Data selection and mass calculations

Raw data often included unmatched storm events, e.g. a storm for which pond influent data was captured had no corresponding effluent data. Therefore, total and dissolved data per case study for each substance was matched per storm event and unmatched data was discarded. Inflow and outflow masses were calculated for matched pairs. The steps that were followed are illustrated in Figure 3.2.

Inflow and outflow masses for each case study and metal were calculated with the formula M = EMC (V), where M= mass, EMC = the Event Mean Concentration obtained from the data and V = the event total influent or effluent volume obtained from the data.



Raw Data for Case Study Y and Substance X

Storm nr.	Inflow Volume	Storm nr.	Outflow Volume	Storm nr.	Inflow Concentration	Storm nr.	Outflow Concentration
1	volume 1 in	**2**	volume 2 out	**1**	concentration 1 in	**1**	concentration 1 out
2	volume 2 in	**3**	volume 3 out	**2**	concentration 2 in	**2**	concentration 2 out
4	volume 4 in	**4**	volume 4 out	**4**	concentration 4 in	**3**	concentration 3 out

Matched Data for Case Study Y and Substance X

Storm nr.	Inflow Volume	Outflow Volume	Inflow Concentration	Outflow Concentration	
1	volume 1 in		concentration 1 in	concentration 1 out	**Discard**
2	volume 2 in	volume 2 out	concentration 2 in	concentration 2 out	**Select**
3		volume 3 out		concentration 3 out	**Discard**
4	volume 4 in	volume 4 out	concentration 4 in	concentration 4 out	**Select**

Final Selected Data for Case Study Y and Substance X

Storm nr.	Inflow Volume	Outflow Volume	Inflow Concentration	Outflow Concentration
2	volume 2 in	volume 2 out	concentration 2 in	concentration 2 out
4	volume 4 in	volume 4 out	concentration 4 in	concentration 4 out

Final Data for Case Study Y and Substance X

Storm nr.	Inflow Volume	Outflow Volume	Inflow Concentration	Outflow Concentration	Inflow Mass	Outflow Mass
2	volume 2 in	volume 2 out	concentration 2 in	concentration 2 out	**Mass 2 in**	**Mass 2 out**
4	volume 4 in	volume 4 out	concentration 4 in	concentration 4 out	**Mass 4 in**	**Mass 4 out**

Figure 3-2 Data selection

3.2.2.4 Treatment of non-detects

The Regression on Order Statistics (ROS) method was used to estimate non-detect (censored) values for statistical calculations. The software application NADA for R version 2.15.0 (The R foundation for statistical computing, copyright 2012) was used for calculations. The procedure, as described in Helsel (2005) was as follows:

1. The data set containing the non-detect values for relevant case studies was saved in comma deliminated .csv files in the following table format:

observed	censored
value 1	TRUE/FALSE
value 2	TRUE/FALSE
etc.	TRUE/FALSE

where: a) the “observed” values are all the detected and non-detected values for the dataset.

b) the non-detect values were specified to be TRUE under the “censored” heading and the detected values were specified to be FALSE.

2. The NADA application was loaded into the R-software program.

3. The relevant .csv file was loaded into the R-software program with the following input:

read.csv(file=”*file name*.csv”,header=TRUE,sep=”,”)

4. The file name, for further use in the program, was specified with the following input:

file name<-read.csv(“*file name.*csv”)

5. The model for use in the NADA application was specified with the following input:

*file name*Model=ros(obs=*file name*$obs, censored=*file name*$censored)

6. The data frame containing the original sorted observations (obs), the associated indication of censoring (censored), the calculated plotting positions (pp), and the modelled data (modelled) values was retrieved with the following input:

as.data.frame(*file name*Model)

Due to uncertainty of the actual non-detect value, no particulates and generally few masses were calculated. Mass calculations utilised modelled concentration values only in cases where the position of the modelled value in relation to volume data was clear, i.e. where there was no doubt that the modelled value related to a specific storm event. An investigation was performed into the effect of using such values for mass results. The methodology was:

1. Substances where the position of the modelled value in relation to volume data was clear were identified.
2. Masses were calculated from (a) the reported concentration value (Mass (rc)) and (b) the ROS estimated value (Mass (ros)) and compared with Mass (rc) / Mass (ros).
3. Total masses were calculated and compared.
4. The median and interquartile ranges were calculated.

Data sets with > 80% non-detects could not be modelled and were left unchanged. A decision on the use of such data was specific to further analyses. Such cases were extremely rare.

3.2.2.5 Quality assurance: data reviews

Raw data obtained from the International Stormwater BMP Database was reviewed by the Project Team for consistency and accuracy prior to accepting the studies for inclusion in the Database (Wright Water Engineers, Inc.; GeoSyntec Consultants, Inc., 2010). Nonetheless, data was not always simply trusted on face value.

Checks were implemented to weed out data that were obviously erroneous. Data was deleted from the datasets in the following cases:

1. Paired datasets where the measured dissolved concentration was reported to be a value larger than the measured total concentration. It was not possible to ascertain where the error occurred, and therefore total and soluble data in such cases were wholly removed from the datasets.
2. Datasets where the non-detects where reported with a MDL which was higher than any of the measured data. This scenario does not allow for any insight into the placement of data on a ranking scale, it only shows that the non-detects are somewhere within the whole range of the measured data.
3. Data that had been identified in the database by the data providers as “not for further use in water quality or volumetric analyses”.
4. Data coded as grab samples by the data providers. Grab samples could not be assumed to represent event mean concentrations (EMCs).

Data preparation involved data categorisation and matching processes as well as mass calculations. The following checks were performed:

1. Spot comparisons between all categorised, matched and selected datasets and the original datasets obtained from the International Stormwater BMP database were performed. One spot check each for inflow and outflow volumetric and water quality dataset was performed per substance fraction and case study. This comparison was performed to reduce the possibility of input errors.
2. Spot checks of particulate concentration and mass calculations were performed for inflow and outflow data. This comparison was done to reduce the possibility of calculation errors.

3.2.3 Descriptive statistics

3.2.3.1 Normality of data distributions

Normality was tested as recommended by (GeoSyntec Consultants , Wright Water Engineers, Inc., 2009) for all log-transformed (natural logarithm) and untransformed data sets. The Shapiro-Wilk W test for normality was used. The software program STATISTICA v.10 (Copyright© StatSoft, Inc. 1984-2011) was used for all calculations.

Montgomery & Runger (2003:215) have stated that generally, if the sample size is small (< 30), much deviation from a straight line can occur and only severe departures should be interpreted to indicate nonnormality. Most data sets in this project contained < 30 points, however, the level at which a departure from a straight line can be classified as “severe” was undefined. This resulted in a rejection of normality on a subjective numerical basis, viz. when the test yielded $p < 0.05$.

3.2.3.2 Data description

Descriptive statistics were calculated with the software program STATISTICA v.10 (Copyright© StatSoft, Inc. 1984-2011). The results of normality testing indicated a lack of normality in a number of log-transformed as well as untransformed data sets (Refer to section 3.3.2.1). Non-parametric descriptive statistics were therefore employed. The following statistics were determined for the untransformed data sets:

1. Sample sizes. These were classified as small if they contained < 50 data points.
2. The data ranges.
3. Medians were investigated as measures of location. The median statistic was used because it is a non-parametric statistic for data description that is resistant to extremes in data which were encountered.
4. Quartile ranges were investigated as measures of data spread.

Box plots were additionally employed in the interpretation of the statistical results. The plots were created, with the software program STATISTICA v.10 (Copyright© StatSoft, Inc. 1984-2011).

3.2.4 Hypothesis testing

The results of the data set normality tests indicated that normality could not be assumed in many data sets; therefore non-parametric tests were used for statistical significance testing between inflow and outflow data. The software program STATISTICA v.10 (Copyright© StatSoft, Inc. 1984-2011) was used for all calculations. Statistical significance of differences between inflow and outflow data was accepted when the results of the test yielded $p < 0.05$.

The Wilcoxon test can be seen as a preferential nonparametric alternative to the t-test. The test assumes symmetry in the data set created by calculating the differences between the inflow and outflow concentration or mass values. GeoSyntec Consultants, Inc.& Wright Water Engineers, Inc. (2011) used log-transformation of the inflow and outflow data sets to improve symmetry in the difference data sets. (Kasuya, 2010) has shown that the Wilcoxon test may give an increased rate of Type 1 error in skewed data and the less powerful Sign test has been recommended as an alternative in such cases. Data symmetry was therefore evaluated. No reference to indications of the skewness level at which the Wilcoxon test should be rejected in favour of the Sign test has, however, been found in the literature.

Due to unsymmetrical data (see section 3.3.5.1) the Sign test was ultimately chosen for statistical significance hypothesis testing. Inferences about population behaviour from statistical significance hypothesis testing with the Sign test were investigated by means of power estimations for total fraction data sets. These data sets were used because they were the highest populated of all substance fractions and were therefore most suited to the provision of information on hypothesis testing inferences. Procedures from a paper by Dixon (1952) were used to estimate power ranges for all total case studies and substances. Effect size was additionally considered.

3.2.5 Limitations of the methodology

1. The use of a database for data sourcing resulted in a limited number of case studies, limited water quality parameter measurements per case study and country specific data, i.e. the majority of case studies were from the USA. This choice, however, was necessitated by the need for a large number of accessible case studies for data analysis.
2. Investigations into data quality were limited to the identification of obvious data inconsistencies. Due to the second hand nature of the data, identification of source errors such as incorrect instrument readings and data input was not possible.
3. Data for inlet and outlet points was limited, i.e. direct overland inflow, precipitation and seepage was generally not monitored.
4. Data sets were limited in the variety of temporal data that they included. Many data sets did not contain inflow and outflow volume start and end times.
5. Data sets were limited by the variety of general data that they included. For example, almost no data for detention pond forebays or micropools were found.
6. Limitations to methodology were imposed by small ($N < 50$) to very small ($N<10$) datasets and a lack of normal distributions in a large number of datasets. These factors limited analysis to the use of non-parametric methods and affected the inferences that could be gained from the results.

3.2.6 Experimental and data collection methods

Experimental methods used by the case study researchers were generally well documented in the International Stormwater BMP Database and case study reports (Report summaries can be found in Addendum B).

Data collection methods varied. The manual provided to data collectors by the International Stormwater BMP Database team (GeoSyntec Consultants , Wright Water Engineers, Inc., 2009) includes acceptable methods that were available to data collectors. Flow measurement devices listed in the manual needed to be capable of measuring a range of flows and included flumes, weirs, submerged orifices, acoustic meters, mechanical meters etc. (GeoSyntec Consultants , Wright Water Engineers, Inc., 2009).

Specific criteria were provided for metals measurement and reporting. Metals were measured by inductively-coupled plasma atomic emission spectrometry, inductively coupled plasma mass spectrometry or electrothermal atomic absorption spectrometry. The manual states that sampling locations must be chosen to ensure that samples are well mixed and representative. Event Mean Concentrations (EMCs) are stated to be calculated from flow weighted composite samples over the course of the storm.

Suspended solids measurement techniques included a sample preparation protocol and standard methodologies (GeoSyntec Consultants , Wright Water Engineers, Inc., 2009).

3.2.7 Error

Possible sources of error in the results are discussed in the relevant sections.

3.3 Results and discussion

3.3.1 General data preparation

3.3.1.1 Case study selection

The case study selection process yielded 10 detention pond and 20 retention pond case studies for inclusion in the project. Out of the possible 31 detention pond and 58 retention pond case studies in the International Stormwater BMP Database, 21 detention pond and 38 retention pond case studies were discarded on the bases of insufficient flow data, water quality data or pond physical characteristics data.

Approximately 51% of detention pond and 43% retention pond case studies were ineligible for inclusion due to insufficient flow data, making this the most common culprit for poor data sets. Insufficient water quality data accounted for approximately 16% of detention pond and 14% of retention pond case studies.

3.3.1.2 Substance selection

Summaries of relevant substance data for detention (DP) and retention (RP) ponds yielded by each case study are shown in Table 3.1 and Table 3.2. Fractionation of substances into total and dissolved fractions yielded 168 data sets, not including particulate data sets. Only 1 detention pond and 2 retention pond case studies contained manganese data. The retention pond data set had only 2 case studies that contained arsenic data. No detention or retention pond data sets contained mercury data. Four or less substances were not eligible for correlational analysis and no further analysis was therefore performed on the mercury, manganese and retention pond arsenic.

Table 3-1 Useable DP data yielded per case study

Study Name	**Arsenic**	**Cadmium**	**Copper**	**Lead**	**Manganese**	**Mercury**	**Zinc**	**TSS**	**TVS**	**Total number of metal data sets in each case study**
I5/SR56 EDB	YES	YES	YES	YES	NO	NO	YES	YES	NO	5
Grant Ranch, Orchard pond	NO	NO	NO	NO	YES	NO	YES	YES	NO	2
I15/SR78 EDB	YES	YES	YES	YES	NO	NO	YES	YES	NO	5
I605/SR91 EDB	NO	NO	YES	YES	NO	NO	YES	YES	NO	3
Greenville pond	NO	NO	YES	YES	NO	NO	YES	YES	NO	3
Mountain Park pond	NO	NO	NO	NO	NO	NO	YES	YES	NO	1
I5/Manchester East	YES	YES	YES	YES	NO	NO	YES	YES	NO	5
Lexington Hills pond	YES	YES	YES	YES	NO	NO	YES	YES	NO	5
I5/I605 EDB	YES	YES	YES	YES	NO	NO	YES	YES	NO	5
El Dorado detention pond	NO	NO	YES	NO	NO	NO	NO	YES	NO	1
Total number of comparable data sets between case studies	**5**	**5**	**8**	**7**	**1**	**0**	**9**	**10**	**0**	**35**

Table 3-2 Useable RP data yielded per case study

Study Name	**Arsenic**	**Cadmium**	**Copper**	**Lead**	**Manganese**	**Mercury**	**Zinc**	**TSS**	**TVS**	**Total number of metal data sets in each case study**
Greens Bayou surge basin	NO	NO	YES	YES	NO	NO	YES	YES	NO	3
UNH retention pond	NO	NO	NO	NO	NO	NO	YES	YES	NO	1
De Bary pond	NO	YES	YES	YES	NO	NO	YES	YES	NO	4
Tampa office pond 1	NO	NO	NO	NO	NO	NO	YES	YES	NO	1
Tampa office pond 2	NO	YES	YES	NO	NO	NO	YES	YES	NO	2
Tampa office pond 3	NO	YES	YES	YES	YES	NO	YES	YES	NO	4
Lake Ridge pond	NO	NO	NO	YES	NO	NO	NO	YES	YES	1
McKnight basin	NO	NO	NO	YES	NO	NO	NO	YES	YES	1
I5 La Costa East pond	YES	YES	YES	YES	NO	NO	YES	YES	NO	5
Silver Star road pond	NO	NO	NO	YES	NO	NO	YES	YES	YES	2
Pinellas park pond	NO	NO	YES	YES	NO	NO	YES	YES	YES	3
Pittsfield pond	NO	NO	NO	YES	NO	NO	NO	YES	NO	1
Lakeside (LS) pond	NO	NO	NO	NO	NO	NO	YES	YES	NO	1
Central park pond	NO	YES	YES	YES	NO	NO	YES	YES	YES	4
Cockroach bay pond	NO	NO	YES	YES	YES	NO	NO	YES	NO	3
Phantom lake pond A	YES	NO	YES	YES	NO	NO	YES	YES	NO	4
Heritage estates pond	NO	YES	YES	YES	NO	NO	YES	YES	NO	4
Madison, Monroe st. pond	NO	NO	NO	YES	NO	NO	NO	YES	YES	1
Runaway bay (RB) pond	NO	NO	NO	NO	NO	NO	YES	YES	NO	1
Lake Ellyn	NO	NO	YES	YES	NO	NO	YES	YES	NO	3
Total number of comparable data sets between case studies	**2**	**4**	**11**	**15**	**2**	**0**	**15**	**20**	**6**	**49**

3.3.1.3 Treatment of non-detects

A substantial number of non-detects were found in some data sets. The limited nature of data obtained for this project engendered the motivation to delete as little data as possible from any data set for any specific analysis. Non – detects were therefore carefully evaluated according to (1) the specific analysis that data was to be used for and (2) the possible effect that using such data may have on the interpretation of results.

A large number of substances had no non-detects (Refer to Table 3.3 below). Of the 336 total and dissolved, inflow and outflow data sets, 258 (approximately 77%) had no non-detects measured in the data. 9 Data sets (approximately 3%) were found to have non-detects greater than 80% of the total number of measurements and were ineligible for ROS calculations.

Table 3-3 Percentage non-detects per substance

Pond Name	Arsenic				Cadmium				Copper				Lead				Zinc				TSS		TVS	
	Tot.		Diss.		Tot.		Diss.		Tot.		Diss.		Tot.		Diss.		Tot.		Diss.		Tot.		Tot.	
	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out
Retention Ponds																								
Central Park					55	70	n/a	n/a	0	40	n/a	n/a	5	10	n/a	n/a	0	5	n/a	n/a	5	0	0	0
Cockroach Bay									0	0	n/a	n/a	69	50	n/a	n/a					0	2		
De Bary					58	**92**	67	**92**	0	0	0	0	27	36	46	55	0	0	0	0	0	0		
Greens Bayou									22	0	33	11	25	0	**86**	57	0	0	33	0	9	0		
Heritage Estates					0	0	0	0	0	0	n/a	n/a	0	0	n/a	n/a	0	0	n/a	n/a	0	0		
I5 La Costa East					0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
Lake Ellyn									0	0	0	0	0	0	0	0	0	0	0	0	0	0		
Lake Ridge													0	0	25	25					0	0	0	0
Lakeside (LS)																	0	43	n/a	n/a	0	43		
Madison, Monroe Street													62	52	76	**86**					0	0	0	0
McKnight Basin													0	0	0	0					0	0	0	0
Phantom Lake Pond A									0	8	n/a	n/a	0	8	n/a	n/a	0	0	n/a	n/a	0	0		
Pinellas									17	33	n/a	n/a	0	50	n/a	n/a	0	17	n/a	n/a	0	17	0	0
Pittsfield													14	14	n/a	n/a					0	14		
Runaway Bay																	0	0	n/a	n/a	0	0		
Silver Star Road													0	0	0	0	0	0	0	0	0	0	0	0
Tampa Office Pond 1																	0	0	n/a	n/a	0	0		
Tampa Office Pond 2					35	25	n/a	n/a	20	15	n/a	n/a					0	0	n/a	n/a	0	0		
Tampa Office Retention Pond 3					13	58	n/a	n/a	0	2	n/a	n/a	12	62	n/a	n/a	0	0	n/a	n/a	0	0		
UNH pond																	0	27	n/a	n/a	0	9		
Detention Ponds																								
El Dorado									0	17	8	25									0	6		
Grant Ranch																	24	43	29	33	0	0		
Greenville									0	0	0	0	0	0	n/a	n/a	0	0	n/a	n/a	0	0		
I5/I605 EDB	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
I5/SR56 EDB	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
I5 Manchester East	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
I15/SR78 EDB	0	0	11	0	0	10	**100**	**90**	0	0	0	0	0	0	53	63	0	0	0	0	0	0		
I605/SR91 EDB									0	0	0	0	0	0	0	0	0	0	0	0	0	0		
Lexington Hills	0	0	0	0	46	55	73	**91**	0	0	0	0	0	0	**100**	**92**	0	0	0	0	0	0		
Mountain Park																	0	10	n/a	n/a	10	0		

Table 3-4 Comparison between masses calculated with reported and ROS concentrations

Case Study	Substance	Storm event	Reported concentration (rc) value	ROS estimated concentration (ros) value	Mass(rc)[1] / Mass(ros)[2]	Total Mass(rc) / Total Mass(ros) [3]
Detention Ponds						
I15/SR78	Arsenic - Dissolved	15	0.25	0.34	0.74	0.98
	Cadmium - Total	17	0.10	0.19	1.90	1.01
El Dorado	Copper - Total	4	5.00	3.20	1.56	
		23	1.50	2.27	0.66	0.99
	TSS	2	2.5	2.61	0.96	1.00
Mountain Park	TSS	8	2.5	2.05	1.22	1.00
	Zinc - Total	2	12.5	7.04	1.78	1.00
Retention Ponds						
Phantom Lake Pond A	Copper - Total	6	0.125	1.60	0.08	0.99
	Lead - Total	6	0.125	0.68	0.18	0.99
Pinellas	Copper – Total In	4	0.25	1.92	0.13	0.98
	Copper – Total Out	4	0.281	0.81	0.35	
		5	0.219	0.81	0.27	0.97
	Lead - Total	4	0.225	2.21	0.10	
		5	0.219	2.21	0.10	
		6	0.250	2.21	0.11	0.76
	Zinc - Total	5	2.48	12.75	0.20	0.98
	TSS	146	0.247	2.28	0.11	0.99
	TVS	4	0.247	1.11	0.22	0.99
Pittsfield	Lead – Total In	6	1.00	9.39	9.39	1.27
	Lead – Total Out	6	1.00	3.76	3.76	1.09
Central Park	TSS	146	5.00	14.3	0.35	0.99
Cockroach Bay	TSS	2	13.50	8.58	1.57	1.00
Greens Bayou	TSS	8	2.50	55.8	0.04	1.00
UNH	TSS	9	5.00	3.16	1.58	1.00
Statistics						
Median					0.35	0.99
Interquartile Range					1.45	0.02

1 – Mass(rc) is the mass of a metal or solid calculated with the reported concentration value.
2 – Mass(ros) is the mass of a metal or solid calculated with the ROS calculated concentration value
3 - Total Mass is the sum of all masses for the case study, either calculated with the reported concentration (rc) value or the ROS calculated concentration (ros) value.

In order to ascertain the difference between using ROS values or reported values, a comparison was made between masses calculated from these two value types. The results were summarised in Table 3.4 below. The ratios of masses calculated from reported values to masses estimated with ROS values (Mass(rc) / Mass(ros)) showed much variability, with values ranging from 0.04 to 9.39. The median of the values was 0.35 and the interquartile range was 1.45. The ratios of total masses calculated from reported values to total masses calculated for ROS values (Mass(rc) / Mass(ros)) were not greatly variable and generally ranged from 0.97 to 1.09, with a median of 0.99 and an interquartile range of 0.02. Two exceptions were the Pinellas total lead and Pittsfield total lead (in) ratios with values of 0.76 and 1.27 respectively.

The high variability in the Mass(rc) / Mass(ros) values indicates that the difference in the use of substituted values and ROS estimated values can be substantial in individual cases of mass calculations. However, the low variability of Total Mass (rc) / Total Mass (ros) values and tendency of central location to a value close to 1 (0.99 in this case) indicates that the general mass change trend of ponds was not greatly affected over many storm events, probably due to relatively small numbers of non-detects in relation to the total number of measurements.

Helsel (2006) argued that the deletion of non-detect data from data sets can result in an upward bias in measures of location such as means and medians, obscuring the information that could have been provided by the original data. He has also stated that the ROS method for non - detect estimation was intended to be used together with the uncensored observations to model the distribution of the sample population and was not considered to be the values that would have existed in the absence of censoring (Refer to Chp.2, section 2.4.2.2).

The use of mass values that were calculated from non-detects, therefore could not be justified where information was directly achieved from specific data points such as the investigation into correlations between pond efficiencies for specific storm events. However, in cases where information is obtained from exploring general trends in data such as descriptive statistics and efficiency evaluations, it was felt that valuable information would be obtained by including mass values. This is because information obtained from comparison between trends in the concentration and mass data may be lost if the corresponding mass value of a non-detect data point is deleted. It is for this reason that mass values calculated from non-detect values were included in the descriptive statistics and efficiency evaluations sections of this project, but not in the correlational analysis and logistic regression sections.

3.3.1.4 Quality assurance: data reviews

A number of case studies were found to have obvious data discrepancies. Lists of case studies where discrepancies were found and such data was removed from the data sets are given in Table 3.5 and Table 3.6 below.

The International Stormwater BMP Database project team relies on standardised reporting protocols and data reviews to safeguard data quality. This approach is accepted to be highly effective in most cases; however it cannot identify all data discrepancies. Out of 168 metals and solids data sets investigated, 13 sets were found to have reported soluble concentrations higher than total concentrations for a specific measurement and 8 sets reported non-detects with a MDL higher than the data range.

Table 3-5 Paired data sets where soluble concentrations were larger than total

Case study name and substance	Storm event(s)
Detention Ponds	
I5/SR56 EDB – Arsenic	14
I5 Manchester East – Arsenic	8
I15/SR78 – Arsenic	12
Lexington Hills – Cadmium	1,3
Lexington Hills – Zinc	2
El Dorado – Copper	1,2,3,5,12
I5/I605 EDB – Zinc	2
Retention Ponds	
Greens Bayou – Copper	2,5,14
Greens Bayou – Zinc	2,4,5
Lake Ellyn – Copper	10,18
Lake Ellyn – Lead	18
I5/La Costa East – Zinc	14
Silver Star rd. – Zinc	12

Table 3-6 Data sets where non-detects had a MDL higher than data range

Case study name and substance	Storm event(s)
Detention Ponds	
El Dorado – Copper	4,10
Retention Ponds	
Tampa Office pond 2 – Cadmium	61,64,68,71,92,98,102,112,115
Tampa Office pond 2 – Copper	87,88,97,98,112
Tampa Office pond 3 – Cadmium	118,120,132,133,137,141,144,148,149,151,153,154,157,158,171,179,180,182,186,189,192,194,196
Tampa Office pond 3 – Copper	196
Tampa Office pond 3 – Lead	117,118,119,120,121,122,133,135,136,137,139,141,143,144,148,149,150,151,154,157,158,159,170,171,182,186,194
Greens Bayou – Copper	10,12,17
Madison, Monroe str. – Lead	1,2,3,5,6,9,10,15,16,19,21

3.3.2 Descriptive Statistics

The results and discussion of the descriptive statistics analysis of all data sets is presented below. Box plots were used to aid in the results interpretations.

3.3.2.1 Normality of data distributions

Normal probability plots (NPPs) and Shapiro Wilk W test results for untransformed and log-transformed data were calculated.. Table 3.7 contains a summary of the results. The following key applies:

░	Percentage of acceptance fell
▒	Percentage of acceptance rose

Table 3-7 Percentage of data sets where normality was accepted

Substance	**Total Fraction**				**Dissolved Fraction**				**Particulate Fraction**			
	Not transformed		Log transformed		Not transformed		Log transformed		Not transformed		Log transformed	
	C	M	C	M	C	M	C	M	C	M	C	M
Detention Ponds												
Arsenic	100	30	90	90	100	40	80	70	70	20	80	80
Cadmium	50	50	90	100	40	17	20	100	67	33	67	83
Copper	50	50	100	81	57	29	93	86	43	21	93	79
Lead	43	29	93	93	20	40	60	100	25	25	100	100
Zinc	44	50	79	86	57	36	93	86	50	43	86	93
TSS	40	10	90	90	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Retention Ponds												
Cadmium	17	30	25	100	0	100	0	100	50	50	-	-
Copper	45	32	73	100	75	38	100	100	38	25	63	88
Lead	27	37	67	96	25	20	25	100	20	0	80	100
Zinc	37	27	77	87	20	50	90	100	40	30	67	89
TSS	43	28	90	85	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
TVS	33	83	42	75	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a

Note: "C" = concentration, "M" = mass, "-" = insufficient data

On average, in detention pond data, a normal distribution for metal substances was accepted in 54% of total concentration, 57% of dissolved concentration, 50% of particulate concentration, 40% of total mass, 33% of dissolved mass and 29% of particulate mass data sets. Log transformation of the data sets increased the number of data sets where normality was accepted to 91% of total concentration, 77% of dissolved concentration, 87% of particulate concentration data sets, 90% of total mass, 87% of dissolved mass and 87% of particulate mass data sets. Similarly, an increase in the number of data sets where normality was accepted was seen in the solids substances, where normality for concentration data sets was increased from 40% to 90% in the transformed concentration data sets and 10% to 90% for the mass data sets.

On average, in retention pond data, a normal distribution for metal substances was accepted in 33% of total concentration, 33% of dissolved concentration, 47% of particulate concentration, 32% of total mass, 40% of dissolved mass and 24% of particulate mass data sets. Log transformation of the data sets increased the number of data sets where normality was accepted to 66% of total concentration, 61% of dissolved concentration, 70% of particulate concentration data sets, 94% of total mass, 100% of dissolved mass and 91% of particulate mass data sets. Similarly, an increase in the number of data sets where normality was accepted was seen in the solids substances, where normality was increased in the concentration data sets from 40% to 88% in the transformed concentration data sets. The number of solids normal mass data sets increased from 31% to 83% in the transformed data sets.

In conclusion, log transformation of data (natural logarithm) was seen to increase the acceptance of normality in all investigated substances. Such increases were often very high with the rate of acceptance of normality in log transformed data being higher than 80% of data sets in the majority of cases. However, acceptance of normality was rarely increased to 100% in transformed data sets and a general assumption of normality in either untransformed or log transformed data was therefore not merited in this project.

3.3.2.2 Data set sizes

All data sets contained less than 50 data points and were therefore classified as small. In this project, the effects of sample sizes generally related to statistical inference, viz. (1) the determination of confidence intervals of sample point estimators and (2) the determination of the statistical power of hypothesis tests. The effects of the small sample sizes on such determinations were further discussed in section 3.3.3 below.

The numbers of case studies that were available for comparison in the case of each substance directly affected the interpretation of correlational results. The effects of limited case studies for comparison were further discussed in Chapter 5.

3.3.2.3 Data ranges

Arsenic:

Detention ponds: All individual case studies displayed similar data ranges for the total, dissolved and particulate fractions. Total inflow and outflow concentrations ranged from 0.5 - 5.3µg/l and 0.4 - 3.4 µg/l respectively. Total inflow and outflow masses ranged from 0.1 - 2.5g and 0.02 – 2.5g respectively. Dissolved inflow and outflow concentrations ranged from 0.3 – 2.7µg/l and 0.5 – 2.7 µg/l respectively. Dissolved inflow and outflow masses ranged from 0.03 - 2.2g and 0.0 – 1.0g respectively. Particulate inflow and outflow concentrations ranged from 0.0 – 2.9µg/l and 0.0 – 2.8 µg/l respectively. Particulate inflow and outflow masses ranged from 0.0 – 1.3g and 0.0 – 1.7g respectively.

The I5/I605 EDB, I5/SR56 EDB and I5/Manchester East EDB displayed total and particulate maximum outflow mass data values that were greater than, or equal to, the maximum inflow mass data values. The I5/SR56 EDB also displayed a dissolved maximum outflow mass value that was greater than the maximum inflow mass value. See Table 3.8 below. This indicates the occurrence of particulate and dissolved arsenic wash out.

Table 3-8 DP arsenic maximum inflow and outflow mass values

Case Study	**Max. Total Mass (g)**		**Max. Particulate Mass (g)**		**Max. Dissolved Mass (g)**	
	Inflow	Outflow	Inflow	Outflow	Inflow	Outflow
I5/I605 EDB	2.5	2.5	1.0	1.7	n/a	n/a
I5/SR56 EDB	1.5	2.0	0.9	1.2	0.6	0.8
I5/Manchester East	1.1	1.2	0.6	1.0	n/a	n/a

Cadmium:

Detention ponds: All individual case studies displayed similar data ranges for the total, dissolved and particulate fractions. Total inflow and outflow concentrations ranged from 0.01 – 3.0µg/l and 0.01 – 1.6 µg/l respectively. Total inflow and outflow masses ranged from 0.01 – 1.4g and 0.005 – 0.5g respectively. Dissolved inflow and outflow concentrations ranged from 0.2 – 0.8µg/l and 0.2 – 1.0 µg/l respectively. Dissolved inflow and outflow masses ranged from 0.01 – 0.3g and 0.01 – 0.3g respectively. Particulate inflow and outflow concentrations ranged from 0.0 – 2.8µg/l and 0.0 – 1.1 µg/l respectively. Particulate inflow and outflow masses ranged from 0.0 – 1.2g and 0.0 – 0.3g respectively.

As was observed in the arsenic case study, the I5/I605 EDB displayed total and particulate maximum outflow mass data values that were greater than the maximum inflow mass data values. See Table 3.9 below. This again indicates the occurrence of particulate wash out.

Table 3-9 DP cadmium maximum inflow and outflow mass values

Case Study	Max. Total Mass (g)		Max. Particulate Mass (g)		Max. Dissolved Mass (g)	
	Inflow	Outflow	Inflow	Outflow	Inflow	Outflow
I5/I605 EDB	0.42	0.45	0.28	0.33	n/a	n/a

Retention ponds: All individual case studies displayed similar data ranges for the total fractions, with the exception of the Heritage Estates retention pond, which displayed maximum concentration and mass values 10 to 20 times greater than those observed for the other case studies. Total inflow and outflow concentrations ranged from 0.05 – 1.9µg/l and 0.05 – 0.9µg/l respectively. Total inflow and outflow masses ranged from 0.001 – 5.8g and 0.001 – 7.5g respectively.

All individual case studies displayed similar data ranges for the dissolved fractions. Total inflow and outflow concentrations ranged from 0.1 – 1.0µg/l and 0.1 – 0.9µg/l respectively. Total inflow and outflow masses ranged from 0.005 – 0.3g and 0.004 – 0.3g respectively.

The I5/La Costa East EDB was the only case study with particulate data. Total inflow and outflow concentrations ranged from 0.4 – 1.6µg/l and 0.0 – 0.1 µg/l respectively. Total inflow and outflow masses ranged from 0.01 – 0.3g and 0.0 – 0.05g respectively.

The Central Park and Heritage Estates case studies displayed total maximum outflow mass data values that were greater than the maximum inflow mass data values. See Table 3.10 below. This indicates the occurrence of wash out.

Table 3-10 RP cadmium maximum inflow and outflow mass values

Case Study	**Max. Total Mass (g)**		**Max. Particulate Mass (g)**		**Max. Dissolved Mass (g)**	
	Inflow	Outflow	Inflow	Outflow	Inflow	Outflow
Central Park	5.8	7.5	no data	no data	no data	no data
Heritage Estates	64.5	66.1	no data	no data	no data	no data

Copper:

Detention ponds: Individual case studies displayed more variable data ranges for the total, dissolved and particulate fractions than was observed for the arsenic and cadmium case studies. Total inflow and outflow concentrations ranged from 2.3 - 230µg/l and 1.9 – 82.0 µg/l respectively. Total inflow and outflow masses ranged from 0.01 – 387.3g and 0.04 – 209.4g respectively. Dissolved inflow and outflow concentrations ranged from 1.4 – 39µg/l and 1.3 – 44 µg/l respectively. Dissolved inflow and outflow masses ranged from 0.01 – 83.8g and 0.03 – 119.4g respectively. Particulate inflow and outflow concentrations ranged from 0.1 – 214.0µg/l and 0.4 – 73.6 µg/l respectively. Particulate inflow and outflow masses ranged from 0.003 – 41.8g and 0.01 – 27g respectively.

The data values ranged from relatively small to relatively large values when compared with the arsenic and cadmium case study values. Concentration values ranged from fractions to hundreds of micrograms per litre and mass values ranged from fractions to hundreds of grams.

The El Dorado detention pond displayed total, dissolved and particulate maximum outflow mass data values that were greater than the maximum inflow mass data values. As in the arsenic and cadmium case studies, the I5/SR56 EDB displayed a dissolved maximum outflow mass value that was greater than the maximum inflow mass value; as did the Lexington Hills detention pond. See Table 3.11 below. This indicates particulate and dissolved copper wash out.

Table 3-11 DP copper maximum inflow and outflow mass values

Case Study	**Max. Total Mass (g)**		**Max. Particulate Mass (g)**		**Max. Dissolved Mass (g)**	
	Inflow	Outflow	Inflow	Outflow	Inflow	Outflow
El Dorado	88.8	209.4	16.4	27.0	83.8	119.4
I5/SR56 EDB	n/a	n/a	n/a	n/a	4.8	7.2
Lexington Hills	n/a	n/a	n/a	n/a	1.7	1.8

Retention ponds: Individual case studies displayed more variable data ranges for the total, dissolved and particulate fractions than was observed for the cadmium case studies. Total inflow and outflow concentrations ranged from 1.0 – 9500µg/l and 0.8 – 130µg/l respectively. Total inflow and outflow masses ranged from 0.03 – 31200g and 0.01 – 930g respectively. Dissolved inflow and outflow concentrations ranged from 2.0 – 40µg/l and 2.2 – 27µg/l respectively. Dissolved inflow and outflow masses ranged from 0.2 – 109g and 0.1 – 174g respectively. Particulate inflow and outflow concentrations ranged from 0.0 – 9490µg/l and 0.0 – 25µg/l respectively. Particulate inflow and outflow masses ranged from 0.0 – 1550g and 0.0 – 122g respectively.

The data values ranged from relatively small to relatively large values when compared with the cadmium case study values. Concentration values ranged from fractions to thousands of micrograms per litre and mass values ranged from fractions to tens of thousands of grams.

The Tampa Office Pond 2 case study displayed a total maximum outflow mass data value that was greater than the maximum inflow mass data value. This indicates wash out. The De Bary retention pond and Lake Ellyn displayed dissolved maximum outflow mass values that were greater than the maximum inflow mass values. This indicates sources of dissolved copper other than from the measured inflows, or indicates speciation within the ponds. See Table 3.12 below.

Table 3-12 RP copper maximum inflow and outflow mass values

Case Study	**Max. Total Mass (g)**		**Max. Particulate Mass (g)**		**Max. Dissolved Mass (g)**	
	Inflow	Outflow	Inflow	Outflow	Inflow	Outflow
De Bary	n/a	n/a	n/a	n/a	15.5	16.9
Lake Ellyn	n/a	n/a	n/a	n/a	109.3	173.6
Tampa Office Pond 2	5.6	12.2	no data	no data	no data	no data

Lead:

<u>Detention ponds</u>: Individual case studies displayed more variable data ranges for the total, dissolved and particulate fractions than was observed for arsenic and cadmium. Total inflow and outflow concentrations ranged from 0.6 – 440.0µg/l and 0.4 – 131.0µg/l respectively. Total inflow and outflow masses ranged from 0.05 – 645.5g and 0.01 – 396.1g respectively. Dissolved inflow and outflow concentrations ranged from 0.1 – 32µg/l and 0.1 – 26.0µg/l respectively. Dissolved inflow and outflow masses ranged from 0.01 – 8.0g and 0.004 – 9.0g respectively. Particulate inflow and outflow concentrations ranged from 4.1 – 439.0µg/l and 3.7 – 70.6 µg/l respectively. Particulate inflow and outflow masses ranged from 0.4 – 85.2g and 0.04 – 64.4g respectively.

The data values ranged from relatively small to relatively large values when compared with arsenic and cadmium case study values. As was observed for copper, concentration values ranged from fractions to hundreds of micrograms per litre and mass values ranged from fractions to hundreds of grams.

In contrast to arsenic, copper and cadmium case studies, no indication of particulate matter wash out during storm events was observed. The I5/I506 EDB case study was the only pond that displayed a dissolved maximum outflow mass value that was greater than the maximum inflow mass value See Table 3.13 below. This indicates dissolved lead wash out.

Table 3-13 DP lead maximum inflow and outflow mass values

Case Study	Max. Total Mass (g)		Max. Particulate Mass (g)		Max. Dissolved Mass (g)	
	Inflow	Outflow	Inflow	Outflow	Inflow	Outflow
I5/I605 EDB	n/a	n/a	n/a	n/a	8.0	9.0

Retention ponds: As for the copper case study, individual case studies displayed more variable data ranges for the total, dissolved and particulate fractions than was observed for cadmium. Total inflow and outflow concentrations ranged from 0.001 – 2300µg/l and 0.2 – 133µg/l respectively. Total inflow and outflow masses ranged from 0.1 – 10 534g and 0.21 – 17 556g respectively. Dissolved inflow and outflow concentrations ranged from 0.3 – 240µg/l and 1.0 – 37µg/l respectively. Dissolved inflow and outflow masses ranged from 0.05 – 668g and 0.02 – 763g respectively. Particulate inflow and outflow concentrations ranged from 0.0 – 2283µg/l and 0.0 – 122µg/l respectively. Particulate inflow and outflow masses ranged from 0.0 – 7016g and 0.0 – 737g respectively.

As was observed in the copper data, the data values ranged from relatively small to relatively large values when compared with the cadmium case study values. Concentration values ranged from fractions to thousands of micrograms per litre and mass values ranged from fractions to tens of thousands of grams.

The Central Park, De Bary and Pittsfield retention pond case studies displayed total maximum outflow mass data values that were greater than the maximum inflow mass data values. The Silver Star rd. retention pond case study displayed a particulate maximum outflow mass data value that was greater than the maximum inflow mass data value. This indicates lead wash out. The De Bary, Greens Bayou, Madison Monroe str. retention ponds and Lake Ellyn displayed dissolved maximum outflow mass values that were greater than the maximum inflow mass values. This indicates sources of dissolved substance other than from the measured inflows, or indicates speciation within the ponds. See Table 3.14 below.

Table 3-14 RP lead maximum inflow and outflow mass values

Case Study	Max. Total Mass (g)		Max. Particulate Mass (g)		Max. Dissolved Mass (g)	
	Inflow	Outflow	Inflow	Outflow	Inflow	Outflow
Central Park	165.1	259.7	no data	no data	no data	no data
De Bary	6.6	12.2	n/a	n/a	0.6	0.7
Greens Bayou	n/a	n/a	n/a	n/a	14.0	23.7
Lake Ellyn	n/a	n/a	n/a	n/a	109.3	762.9
Madison, Monroe str.	n/a	n/a	n/a	n/a	12.4	14.5
Pittsfield	10 534.0	17 556.0	no data	no data	no data	no data
Silver Star rd.	n/a	n/a	0.0	382.2	n/a	n/a

Zinc:

<u>Detention ponds</u>: As was observed for the copper and lead case studies, individual case studies displayed more variable data ranges for the total, dissolved and particulate fractions than was observed for the arsenic and cadmium case studies. Total inflow and outflow concentrations ranged from 4.6 – 2100µg/l and 0.05 – 920.0 µg/l respectively. Total inflow and outflow masses ranged from 0.6 – 4131g and 0.03 – 1851g respectively. Dissolved inflow and outflow concentrations ranged from 1.3 – 319µg/l and 1.4 – 222µg/l respectively. Dissolved inflow and outflow masses ranged from 0.2 – 149g and 0.03 – 55g respectively. Particulate inflow and outflow concentrations ranged from 1.4 – 2071µg/l and 2.3 – 200µg/l respectively. Particulate inflow and outflow masses ranged from 0.2 – 1074g and 0.1 – 127g respectively.

As was observed for the copper and lead case studies, the data values ranged from relatively small to relatively large values when compared with the arsenic and cadmium case study values. Concentration values ranged from fractions to thousands of micrograms per litre and mass values ranged from fractions to thousands of grams.

No indication of particulate matter wash out during storm events was observed.

<u>Retention ponds</u>: As for the copper and lead case studies, individual case studies displayed more variable data ranges for the total, dissolved and particulate fractions than was observed for the cadmium case studies. Total inflow and outflow concentrations ranged from 2.0 – 2000µg/l and 1.0 – 883µg/l respectively. Total inflow and outflow masses ranged from 0.7 – 22 000g and 0.1 – 9007g respectively. Dissolved inflow and outflow concentrations ranged from 5.9 – 150µg/l and 1.0 – 346µg/l respectively. Dissolved inflow and outflow masses ranged from 1.0 – 571g and 0.04 – 314g respectively. Particulate inflow and outflow concentrations ranged from 0.0 – 1956µg/l and 0.0 – 489µg/l respectively. Particulate inflow and outflow masses ranged from 0.0 – 3816g and 0.0 – 955g respectively.

As was observed for copper and lead, the data values ranged from relatively small to relatively large values when compared with cadmium. Concentration values ranged from singles to thousands of micrograms per litre and mass values ranged from fractions to tens of thousands of grams.

The Central Park, Greens Bayou, Runaway Bay, Silver Star rd. and Tampa Office Pond 2 retention pond case studies displayed total maximum outflow mass data values that were greater than the maximum inflow mass data values. The Greens Bayou and Silver Star rd. retention pond case studies displayed particulate maximum outflow mass data values that were greater than the maximum inflow mass data values. This indicates wash out. The Greens Bayou and I5 La Costa East case studies displayed dissolved maximum outflow mass values that were greater than the maximum inflow mass values. This indicates sources of dissolved substance other than from the measured inflows, or indicates speciation within the ponds. See Table 3.15 below.

Table 3-15 RP zinc maximum inflow and outflow mass values

Case Study	**Max. Total Mass (g)**		**Max. Particulate Mass (g)**		**Max. Dissolved Mass (g)**	
	Inflow	Outflow	Inflow	Outflow	Inflow	Outflow
Central Park	891.2	2241.0	no data	no data	no data	no data
Greens Bayou	686.5	9007.1	448.3	708.5	238.2	313.5
I5 La Costa East	n/a	n/a	n/a	n/a	7.9	9.4
Runaway Bay	6436.2	8275.1	no data	no data	no data	no data
Silver Star rd.	408.7	536.5	99.4	297.8	n/a	n/a
Tampa Office Pond 2	23.4	58.7	no data	no data	no data	no data

TSS:

Detention ponds: Individual case studies displayed variable data ranges. Total inflow and outflow concentrations ranged from 2.1 – 500mg/l and 2.6 – 378mg/l respectively. Total inflow and outflow masses ranged from 0.02 – 7918kg and 0.02 – 2126kg respectively.

The data values ranged from relatively small to relatively large values. Concentration values ranged from singles to hundreds of milligrams per litre and mass values ranged from fractions to thousands of kilograms.

The El Dorado detention pond, Grant Ranch detention pond, I5/I605 EDB and I5/SR56 EDB displayed maximum outflow mass data values that were greater than the maximum inflow mass data values. See Table 3.16 below. This indicates wash out.

Table 3-16 DP TSS maximum inflow and outflow mass values

Case Study	**Max. Total Mass (kg)**	
	Inflow	Outflow
El Dorado	670	2126
Grant Ranch	169	363
I5/I605 EDB	137	247
I5/SR56 EDB	78	136

Retention ponds: Individual case studies displayed variable data ranges. Total inflow and outflow concentrations ranged from 1.0 – 1440mg/l and 0.1– 246mg/l respectively. Total inflow and outflow masses ranged from 0.1 – 40 782kg and 0.01 – 33 011kg respectively.

The data values ranged from relatively small to relatively large values. Concentration values ranged from fractions to thousands of milligrams per litre, and mass values ranged from fractions to tens of thousands of kilograms.

The Pinellas and Runaway Bay case studies displayed maximum outflow mass data values that were greater than the maximum inflow mass data values. See Table 3.17 below. This indicates solids wash out during storm events.

Table 3-17 RP TSS maximum inflow and outflow mass values

Case Study	**Max. Total Mass (kg)**	
	Inflow	Outflow
Pinellas	2240	3170
Runway Bay	6042	6568

TVS:

Retention ponds: Individual case studies displayed variable data ranges. Total inflow and outflow concentrations ranged from 1.3 – 376mg/l and 1.0– 217mg/l respectively. Total inflow and outflow masses ranged from 1.0 – 4758kg and 0.3 – 1674kg respectively.

The data values ranged from relatively small to relatively large values. Concentration values ranged from singles to hundreds of milligrams per litre and mass values ranged from fractions to thousands of kilograms.

The Central Park, Pinellas and Silver Star rd. case studies displayed maximum outflow mass data values that were greater than the maximum inflow mass data values. See Table 3.18 below. This indicates organic solids wash out during storm events.

Table 3-18 RP TVS maximum inflow and outflow mass values

Case Study	**Max. Total Mass (kg)**	
	Inflow	Outflow
Central Park	299	313
Pinellas	1180	1400
Silver Star rd.	119	495

3.3.2.4 Measures of central tendency and dispersion

Arsenic:

Detention ponds: Total inflow and outflow concentrations tended to locate around 1.2 to 3.0µg/l and 0.9 to 2.5µg/l respectively for all case studies. Dissolved inflow and outflow concentrations tended to locate around 0.5 to 1.3µg/l and 0.5 to 1.4µg/l respectively. Particulate inflow and outflow concentrations tended to locate around 0.5 to 1.8µg/l and 0.5 to 1.1µg/l respectively.

Total concentration quartile ranges had maximum inflow and outflow values of 1.9 and 1.3µg/l respectively. Dissolved concentration quartile ranges had maximum inflow and outflow values of 1.5 and 1.0µg/l respectively. Particulate concentration quartile ranges had maximum inflow and outflow values of 1.4 and 1.1µg/l respectively. These ranges were considered to be relatively narrow

Total inflow and outflow masses tended to locate around 0.3 to 0.6g and 0.1 to 0.3µg/l respectively for all case studies. Dissolved inflow and outflow masses tended to locate around 0.1 to 0.2g. Particulate inflow and outflow concentrations tended to locate around 0.1 to 0.3g and 0.04 to 0.1g respectively.

Total mass quartile ranges had maximum inflow and outflow values of 1.0 and 1.4g respectively. Dissolved mass quartile ranges had maximum inflow and outflow values of 0.4 and 0.6g respectively. Particulate mass quartile ranges had maximum inflow and outflow values of 0.6 and 0.5g respectively. These ranges were considered to be relatively narrow

The similar inflow and outflow medians and narrow quartile ranges for concentrations and masses could indicate poor pond efficiencies or that the minimum achievable pond effluent concentrations are similar to the inflow concentrations. The similar inflow medians and narrow quartile ranges indicate similarly loaded catchment areas and similar flow volumes without large shock load occurrences.

Cadmium:

<u>Detention ponds</u>: Total inflow and outflow concentrations tended to locate around 0.2 to 1.6µg/l and 0.03 to 0.4µg/l respectively for all case studies. Dissolved inflow and outflow concentrations tended to locate around 0.2 to 0.4µg/l. Particulate inflow and outflow concentrations tended to locate around 0.2 to 1.3µg/l and 0.0 to 0.3µg/l respectively.

Total concentration quartile ranges had maximum inflow and outflow values of 1.8 and 0.5µg/l respectively. Dissolved concentration quartile ranges had maximum inflow and outflow values of 0.3 and 0.3µg/l respectively. Particulate concentration quartile ranges had maximum inflow and outflow values of 0.7 and 0.5µg/l respectively. These ranges were considered to be relatively narrow

Total inflow and outflow masses tended to locate around 0.3 to 0.6g and 0.1 to 0.3µg/l respectively for all case studies. Dissolved inflow and outflow masses tended to locate around 0.1 to 0.2g. Particulate inflow and outflow concentrations tended to locate around 0.1 to 0.3g and 0.04 to 0.1g respectively.

Total mass quartile ranges had maximum inflow and outflow values of 0.5 and 0.3g respectively. Dissolved mass quartile ranges had maximum inflow and outflow values of 0.2 and 0.2g respectively. Particulate mass quartile ranges had maximum inflow and outflow values of 0.2 and 0.1g respectively. These ranges were considered to be relatively narrow

Seemingly greater dissimilarities were observed between the medians of the inflow and outflow total and particulate concentrations and masses than for the arsenic substances. This indicates better pond efficiencies for cadmium. As for the arsenic substance, the narrow inflow quartile ranges indicates that cadmium catchment loading was generally subject to unchanging continuous loading without large shock load occurrences.

<u>Retention ponds</u>: Total inflow and outflow concentrations tended to locate around 0.3 to 8.2µg/l and 0.1 to 6.0µg/l respectively for all case studies. Dissolved inflow and outflow concentrations tended to locate around 0.2 to 0.3µg/l. The I5/La Costa East pond was the only case study that contained particulate data with median inflow and outflow concentrations of 1.0 and 0.0µg/l respectively.

Besides the Heritage Estates retention pond, total concentration quartile ranges had maximum inflow and outflow values of 1.0 and 0.3µg/l respectively. Dissolved concentration quartile ranges had maximum inflow and outflow values of 0.5 and 0.0µg/l respectively. The I5/La Costa East pond was the only case study that contained particulate data with maximum inflow and outflow values of 1.1 and 0.02µg/l respectively. The Heritage Estates pond had relatively larger total quartile ranges with an inflow and outflow range of 9.3 and 9.0µg/l respectively.

Total inflow and outflow masses tended to locate around 0.1 to 15.2g and 0.04 to 13.7µg/l respectively for all case studies. Dissolved inflow and outflow masses tended to locate around 0.03 to 0.3g. The I5/La Costa East pond had median inflow and outflow masses of 0.1 and 0.01g respectively.

Besides the Heritage Estates retention pond, total mass quartile ranges had maximum inflow and outflow values of 1.6 and 2.7g respectively. Dissolved mass quartile ranges had maximum inflow and outflow values of 0.04 and 0.04g respectively. The I5/La Costa East pond had maximum inflow and outflow values of 0.2 and 0.0g respectively. These ranges were considered to be relatively narrow. The Heritage Estates pond had relatively larger total quartile ranges with an inflow and outflow range of 18.8 and 18.7g respectively.

The similar inflow and outflow medians for concentrations and masses indicate poor pond efficiencies or may simply indicate that the minimum achievable pond effluent concentrations were similar to the inflow concentrations.

Copper:

<u>Detention ponds</u>: Total inflow and outflow concentrations had medians varying from 3.4 to 82.0µg/l and 2.4 to 28.0µg/l respectively for all case studies. Dissolved inflow and outflow concentrations had medians varying from 2.0 to 14.3µg/l and 2.7 to 17.0µg/l respectively. Particulate inflow and outflow concentrations had medians varying from 0.7 to 62.0µg/l and 0.6 to 13.0µg/l respectively.

The El Dorado and Lexington Hills case study data had relatively narrow concentration quartile ranges. The Greenville case study inflow data set displayed the widest inflow and outflow quartile range for total concentrations, viz. 36.0 and 27.5 µg/l respectively. The I5/Manchester East EDB displayed the widest range for dissolved and particulate inflow and outflow concentrations.

Total inflow and outflow masses had medians varying from 2.4 to 144g and 0.6 to 58g respectively for all case studies. Dissolved inflow and outflow masses had medians varying from 0.5 to 11.8g and 0.4 to 7.4g respectively. Particulate inflow and outflow masses had medians varying from 1.3 to 10.5g and 0.2 to 1.6g respectively.

As in the concentration results, the Lexington Hills case study data had relatively narrow mass quartile range, but the El Dorado study had a much more dispersed mass range. The Greenville case study inflow data set displayed the widest inflow and outflow quartile ranges for total masses, viz. 176 and 87g respectively. The El Dorado study displayed the greatest dissolved mass inflow and outflow quartile ranges, viz. 46 and 24g respectively. The I15/SR78 study displayed the greatest particulate mass inflow quartile range, viz. 18g.

The medians of the copper concentrations and masses were seemingly more varied between case studies and showed seemingly greater dissimilarities between inflow and outflow total and particulate values, than was observed in the arsenic and cadmium substances. The dissimilar inflow medians between case studies indicate dissimilarly loaded catchment areas and/or dissimilar flow volumes.

Relatively large dissimilarities between inflow and outflow medians for the total as well as the particulate sub groups were observed for the Greenville, I5 Manchester East, I5/SR56 EDB and I605/SR91 EDB detention ponds. Differences between dissolved concentration and mass inflow and outflow values were less pronounced. This indicates efficient particulate, but inefficient dissolved copper removal in these case studies.

The inflow total, dissolved and particulate quartile ranges varied from narrow (around 1µg/l) to wide (36µg/l) for different case studies. This indicates that copper catchment loading was more variable than was observed for the arsenic and cadmium sub-groups. The narrow total concentration, but large total mass quartile ranges of the El Dorado case study indicates highly variable volume loadings.

<u>Retention ponds</u>: Total inflow and outflow concentrations had medians varying from 3.3 to 874µg/l and 1.9 to 17µg/l respectively for all case studies. Dissolved inflow and outflow concentrations had medians varying from 3.3 to 20µg/l and 4.3 to 9.1µg/l respectively. Particulate inflow and outflow concentrations had medians varying from 1.0 to 854µg/l and 0.6 to 12.7µg/l respectively.

The De Bary, Phantom Lake, Pinellas and Tampa Office Ponds case study data had relatively narrow concentration quartile ranges. The Cockroach Bay case study inflow data set displayed the widest inflow and outflow quartile range for total concentrations, viz. 139 and 15µg/l respectively. The I5/La Costa East displayed the widest range for dissolved and particulate inflow and outflow concentrations.

Total inflow and outflow masses had medians varying from 1.5 to 6100g and 1.0 to305g respectively for all case studies. Dissolved inflow and outflow masses had medians varying from 1.8 to 53g and 1.0 to 54g respectively. Particulate inflow and outflow masses had medians varying from 0.5 to 255g and 0.5 to 25g respectively.

As in the concentration results, the De Bary, Phantom Lake and Tampa Office Ponds case study data had relatively narrow mass quartile range, but the Pinellas study had a much more dispersed mass range. The Cockroach Bay study inflow data set displayed the widest inflow and outflow quartile ranges for total masses, viz. 2500 and 430g respectively. Lake Ellyn displayed the greatest dissolved and particulate mass inflow and outflow quartile ranges.

As for the detention ponds, the medians of the copper concentrations and masses were seemingly more varied between case studies and showed seemingly greater dissimilarities between inflow and outflow total and particulate values, than was observed in the cadmium substance. The dissimilar inflow medians between case studies indicate dissimilarly loaded catchment areas and/or dissimilar flow volumes.

Relatively large dissimilarities between inflow and outflow medians for the total as well as the particulate sub groups were observed for the Cockroach Bay, Heritage Estates, I5 La Costa East and Lake Ellyn retention ponds. As was observed in the detention pond case studies, differences between dissolved concentration and mass inflow and outflow values were less pronounced. This indicates efficient particulate, but inefficient dissolved copper removal in these case studies.

The inflow total, dissolved and particulate quartile ranges varied from narrow (around 1µg/l) to wide (139µg/l) for different case studies. This indicates that copper catchment loading was more variable than was observed for cadmium.

Lead:

<u>Detention ponds</u>: Total inflow and outflow concentrations had medians varying from 1.8 to 99µg/l and 1.3 to 36µg/l respectively for all case studies. Dissolved inflow and outflow concentrations had medians varying from 0.9 to 5.1µg/l and 0.6 to 4.5µg/l respectively. Particulate inflow and outflow concentrations had medians varying from 30 to 92µg/l and 6.7 to 32µg/l respectively.

As for copper, the Lexington Hills case study data had relatively narrow total concentration quartile ranges. The Greenville case study inflow data set displayed the widest inflow and outflow quartile range for total concentrations, viz. 98 and 43µg/l respectively. The I5/I605 EDB displayed the widest range for dissolved and particulate inflow and outflow concentrations.

Total inflow and outflow masses had medians varying from 0.6 to 251g and 0.1 to 82g respectively for all case studies. Dissolved inflow and outflow masses had medians varying from 0.2 to 1.4g and 0.2 to 0.6g respectively. Particulate inflow and outflow masses had medians varying from 5.3 to 15g and 0.7 to 4.6g respectively.

As for the concentration data, the Greenville case study inflow data set displayed the widest inflow and outflow quartile ranges for total masses, viz. 395 and 78g respectively. The dissolved quartile ranges were narrow for all case studies. The I605/SR91 EDB study displayed the greatest particulate mass inflow quartile range, viz. 19.9g.

The medians of the lead inflow concentrations and masses were seemingly more varied for the total and particulate sub groups than for the dissolved sub-groups. This indicates catchment sediment build up between rain events.

As was observed in the copper sub-groups, relatively large dissimilarities between inflow and outflow medians for the total as well as the particulate sub groups were observed for the Greenville, I5 Manchester East, I5/SR56 EDB and I605/SR91 EDB detention ponds. Differences between dissolved concentration and mass inflow and outflow values once again were less pronounced. As for copper, this indicates efficient particulate, but inefficient dissolved removal.

The inflow total, dissolved and particulate quartile ranges varied from narrow (around 1µg/l) to very wide (98µg/l) for different case studies. This indicates that, as for the copper data set, lead catchment loading was more variable than was observed for the arsenic and cadmium sub-groups.

<u>Retention ponds</u>: Total inflow and outflow concentrations had medians varying from 5.0 to 446µg/l and 1.3 to 50µg/l respectively for all case studies. Dissolved inflow and outflow concentrations had medians varying from 1.3 to 75µg/l and 1.7 to 25µg/l respectively. Particulate inflow and outflow concentrations had medians varying from 0.0 to 438µg/l and 3.1 to 41µg/l respectively.

The Cockroach Bay, De Bary, Greens Bayou, Phantom Lake, Pinellas and Tampa Office Pond 3 case study data had relatively narrow concentration quartile ranges. The Lake Ellyn case study inflow data set displayed the widest inflow and outflow quartile range for total concentrations, viz. 335 and 14µg/l respectively. The dissolved and particulate quartile ranges were varied across case studies.

Total inflow and outflow masses had medians varying from 2.1 to 4320g and 0.5 to 3610g respectively for all case studies. Dissolved inflow and outflow masses had medians varying from 0.6 to 160g and 0.6 to 282g respectively. Particulate inflow and outflow masses had medians varying from 0.0 to 2180g and 0.6 to 122g respectively.

As in the concentration results, the De Bary, Phantom Lake and Tampa Office Pond 3 case study data had relatively narrow mass quartile ranges, but the Cockroach Bay, Greens Bayou and Pinellas studies had more dispersed ranges. The Pittsfield study inflow data set displayed the widest inflow and outflow quartile ranges for total masses, viz. 7360 and 3130g respectively. The dissolved and particulate quartile ranges were varied across case studies.

As for the detention ponds and copper, the medians of the lead concentrations and masses were seemingly more varied between case studies and showed seemingly greater dissimilarities between inflow and outflow total and particulate values, than was observed in the cadmium substance. The dissimilar inflow medians between case studies indicate dissimilarly loaded catchment areas and/or dissimilar flow volumes.

Relatively large dissimilarities between inflow and outflow medians for the total as well as the particulate sub groups were observed for the Cockroach Bay, I5 La Costa East and Lake Ellyn, Lake Ridge, Madison Monroe str. and McKnight Basin retention ponds. As was observed in previous studies, differences between dissolved concentration and mass inflow and outflow values were less pronounced. This indicates efficient particulate, but inefficient dissolved substance removal in these case studies.

The Greens Bayou retention pond had median inflow concentrations and masses that were higher than the inflow values. Lake Ellyn had outflow dissolved concentration and mass values that were markedly higher than the inflow values. This indicates sources of particulate and dissolved lead to the ponds other than the inflow stream or speciation within the ponds.

The inflow total, dissolved and particulate quartile ranges varied from narrow (around 3µg/l) to wide (140µg/l) for different case studies. This indicates that, as for copper, lead catchment loading was more variable than was observed for cadmium.

Zinc:

<u>Detention ponds</u>: Total inflow and outflow concentrations had medians varying from 38 to 550µg/l and 20 to 160µg/l respectively for all case studies. Dissolved inflow and outflow concentrations had medians varying from 4.7 to 176µg/l and 4.5 to 87µg/l respectively. Particulate inflow and outflow concentrations had medians varying from 31 to 420µg/l and 14 to 77µg/l respectively.

All the case studies had relatively wide concentration quartile ranges. The I15/SR78 EDB case study inflow data set displayed the widest quartile range for total concentrations, viz. 450µg/l. The Greenville case study outflow data set displayed the widest quartile range for total concentrations, viz. 311µg/l. The I5/I605 EDB displayed the widest range for dissolved inflow and outflow concentrations, viz. 114 and 41µg/l respectively. The I15/SR78 case study particulate data set displayed the widest quartile range for total concentrations, viz. 470 and 53µg/l respectively.

Total inflow and outflow masses had medians varying from 3.3 to 1600g and 1.0 to 705g respectively for all case studies. Dissolved inflow and outflow masses had medians varying from 1.7 to 23g and 0.8 to 9.4g respectively. Particulate inflow and outflow masses had medians varying from 2.6 to 98g and 0.7 to 10.0g respectively.

The Greenville case study inflow data set displayed the widest inflow and outflow quartile ranges for total masses, viz. 1767 and 630g respectively. As in the concentration data, the I5/I605 EDB displayed the widest range for dissolved inflow and outflow concentrations, viz. 45 and 19µg/l respectively. As for lead, the I605/SR91 EDB study displayed the greatest particulate mass inflow quartile range, viz. 178g.

As was observed for copper and lead, relatively large dissimilarities between inflow and outflow medians for the total as well as the particulate sub groups were observed for the Greenville, I5 Manchester East, I5/SR56 EDB and I605/SR91 EDB as well as for the Grant Ranch, Lexington Hills and Mountain Park detention ponds. Besides the I605/SR91 EDB, differences between dissolved concentration and mass inflow and outflow values once again were less pronounced. As in the copper and lead sub-groups, this indicates efficient particulate, but inefficient dissolved substance removal in these case studies.

The inflow total, dissolved and particulate quartile ranges were very wide for all the case studies. This indicates that, as for copper and lead, zinc catchment loading was more variable than was observed for the arsenic and cadmium.

<u>Retention ponds:</u> Total inflow and outflow concentrations had medians varying from 21 to 508µg/l and 1.6 to 328µg/l respectively for all case studies. Dissolved inflow and outflow concentrations had medians varying from 10 to 60µg/l and 1.5 to 108µg/l respectively. Particulate inflow and outflow concentrations had medians varying from 7.7 to 453µg/l and 0.1 to 43µg/l respectively.

The Lakeside data had a relatively narrow concentration quartile range. Pinellas inflow data displayed the widest quartile range for total concentrations, viz. 155µg/l respectively. The dissolved and particulate quartile ranges were varied across case studies.

Total inflow and outflow masses had medians varying from 7.0 to 4320g and 1.2 to 2440g respectively for all case studies. Dissolved inflow and outflow masses had medians varying from 4.6 to 242g and 0.9 to 128g respectively. Particulate inflow and outflow masses had medians varying from 1.7 to 1170g and 0.2 to 279g respectively.

In contrast to the concentration data, the Lakeside case study had a much more dispersed mass range. The Pinellas study data set displayed the widest inflow and outflow quartile ranges for total masses, viz. 4010 and 2500g respectively. The dissolved and particulate quartile ranges were varied across case studies.

As for the detention ponds as well as copper and lead, the medians of the concentrations and masses were seemingly more varied between case studies and showed seemingly greater dissimilarities between inflow and outflow total and particulate values, than was observed for cadmium. The dissimilar inflow medians between case studies once again indicate dissimilarly loaded catchment areas and/or dissimilar flow volumes.

Relatively large dissimilarities between inflow and outflow medians for the total as well as the particulate sub groups were observed for the I5 La Costa East, Lake Ellyn, Lakeside, Pinellas, UNH and Tampa Office Pond 3 retention ponds. Besides Lake Ellyn, differences between dissolved concentration and mass inflow and outflow values were less pronounced. This indicates efficient particulate, but inefficient dissolved substance removal in these case studies.

As for lead, the Greens Bayou retention pond had median outflow concentrations and masses that were higher than the inflow values. This indicates sources of particulate and dissolved lead to the ponds other than the inflow stream or speciation within the ponds.

The inflow total, dissolved and particulate quartile ranges varied from narrow (around 2µg/l) to wide (215µg/l) for different case studies. This indicates that, as for copper and lead, zinc catchment loading was more variable than was observed for cadmium.

TSS:

Detention ponds: Total inflow and outflow concentrations had medians varying from 35 to 204mg/l and 20 to 74mg/l respectively for all case studies. Total inflow and outflow masses had medians varying from 7.3to 1500kg and 1.2 to 204kg respectively.

All the case studies had relatively wide concentration quartile ranges. The I5/Manchester East EDB case study inflow data displayed the widest quartile range, viz. 160mg/l. The Mountain Park case study outflow data displayed the widest quartile range, viz. 63mg/l. The Greenville case study inflow and outflow data sets displayed the widest quartile range for masses, viz. 463 and 139kg respectively.

Similarly to the observations for particulate copper, lead and zinc, relatively large dissimilarities between inflow and outflow medians were observed for the Grant Ranch, Greenville, I5 Manchester East, I5/SR56 EDB and I605/SR91 EDB and Lexington Hills detention ponds. This indicates that particulate matter was efficiently removed in these ponds. Interestingly, the Mountain Park outflow concentration median was higher than that of the inflow concentration. This indicates sources of TSS to the pond other than from the inflow.

The quartile ranges were wide for all the case studies. This indicates that, as for copper, lead and zinc, loading was more variable than was observed for arsenic and cadmium.

Retention ponds: Total inflow and outflow concentrations had medians varying from 13 to 444mg/l and 1.0 to 166mg/l respectively for all case studies. Total inflow and outflow masses had medians varying from 6.0 to 7600kg and 0.5 to 6400kg respectively for all case studies.

As in the detention pond data, all the case studies had relatively wide concentration quartile ranges. The Lake Ridge case study inflow data set displayed the widest quartile range for concentrations, viz. 625mg/l. The Silver Star rd. case study outflow data set displayed the widest quartile range, viz. 63mg/l. The Pittsfield case study inflow and outflow data sets displayed the widest quartile range for masses, viz. 9930 and 5680kg respectively.

Similarly to the observations for particulate copper, lead and zinc, relatively large dissimilarities between inflow and outflow medians were observed for the Cockroach Bay, I5 La Costa East and Lake Ellyn, Lake Ridge, Lakeside, Madison Monroe str., UNH, McKnight Basin and Tampa Office Pond 3 retention ponds. This indicates that particulate matter was efficiently removed in these ponds.

Interestingly, the Silver Star rd. outflow concentration and mass medians were higher than the inflow values. The Pinellas outflow mass median was higher than the inflow value. This indicates sources of TSS other than the inflow.

The quartile ranges were wide for all the case studies. This indicates that, as for copper, lead and zinc, TSS loading was more variable than was observed for the cadmium.

TVS:

Retention ponds: Total inflow and outflow concentrations had medians varying from 5.6 to 105mg/l and 5.2 to 43mg/l respectively for all case studies. Total inflow and outflow masses had medians varying from 28 to 498kg and 71 to 583kg respectively for all case studies.

The Lake Ridge inflow data displayed the widest quartile range for concentrations, viz. 82mg/l. The Madison Monroe str. outflow data displayed the widest quartile range, viz. 26mg/l. The Pinellas case study inflow and outflow data displayed the widest quartile ranges for masses, viz. 590 and 590kg respectively.

Similarly to the observations for particulate copper, lead and zinc, relatively large dissimilarities between inflow and outflow medians were observed for the Lake Ridge, Madison Monroe str. and McKnight Basin 3 retention ponds. This indicates that particulate matter was efficiently removed in these ponds.

As for TSS, the Silver Star rd. outflow concentration and mass medians were higher than the inflow values and the Pinellas outflow mass median was higher than the inflow value. This indicates sources of TVS to the pond other than from the inflow.

The inflow total, dissolved and particulate quartile ranges varied from narrow (around 6µg/l) to wide (82mg/l) for different case studies. This indicates that TVS loading was variable.

3.3.3 Hypothesis testing

3.3.3.1 Evaluation of data symmetry

It was found that data symmetry was poor in the majority of data sets. Log-transformation of the inflow and outflow concentration values improved symmetry in the majority of data sets. However, improvements were not good enough to render the data perfectly symmetrical in the majority of cases. The Sign test was therefore chosen for tests of statistical significance.

3.3.3.2 Power of the Sign test

The power of the sign test was estimated from Table 1 in Dixon (1952). The results were summarised in Table 3.20. The results were low ($0.2 < x \leq 0.4$) to very low ($x < 0.2$) in approximately 31% of data sets, medium ($0.4 < x \leq 0.6$) in approximately 2% of data sets, high ($0.6 < x \leq 0.8$) to very high ($0.8 < x \leq 1.0$) in approximately 54% of data sets.

A few detention pond case studies had consistent low to very low power across metals and solids sub-cases, viz.: the El Dorado detention pond and I5/I605 EDB. A few detention and retention pond case studies had consistently high to very high power across metals and solids sub-cases, viz.: Grant Ranch, Greenville, I5 La Costa East WB, Lake Ridge and Phantom Lake. Consistently very high to almost certain power results were found for the I15/SR78 EDB and Lake Ellyn. Therefore, due to effect size, case studies that may have shown statistically significant differences between inflow and outflow values if the sample sizes were larger may not have shown such differences in the recorded data.

The implication of this result is that efficiency evaluations were not solely based on the results of statistical significance testing, but were also based on evaluations of plots that showed the behaviour of pond inflow and outflow substance masses and concentrations comparatively (Cumulative Frequency Plots).

Table 3-19 Approximate power of the sign test for total concentrations and masses

Sub-cases	**Cadmium**		**Copper**		**Lead**		**Zinc**		**TSS**		**Arsenic**	
Case studies	Conc.	Mass	Conc.	Mass	Conc.	Mass	Conc.	Mass	Conc.	Mass	Conc.	Mass
Detention Ponds												
El Dorado			< 0.2	< 0.2					0.2 – 0.4	0.2 – 0.4		
Grant Ranch							> 0.8	0.6 – 0.8	0.6 – 0.8	> 0.8		
Greenville			0.6 – 0.8	0.6 – 0.8	0.6 – 0.8	0.6 – 0.8	0.6 – 0.8	0.6 – 0.8	0.6 – 0.8	0.6 – 0.8		
I5/I605 EDB	< 0.2	< 0.2	0.6 – 0.8	< 0.2	< 0.2	< 0.2	0.2 – 0.4	0.2 – 0.4	< 0.2	< 0.2	< 0.2	< 0.2
I5/SR56 EDB	< 0.2	< 0.2	< 0.8	0.6 – 0.8	> 0.8	0.6 – 0.8	> 0.8	0.6 – 0.8	> 0.8	0.2 – 0.4	0.2-0.4	< 0.2
I5 Manchester East EDB	> 0.8	> 0.8	> 0.8	> 0.8	> 0.8	> 0.8	> 0.8	> 0.8	> 0.8	> 0.8	0.2-0.4	0.6 – 0.8
I15/SR78 EDB	0.6 – 0.8	> 0.8	> 0.99	> 0.99	> 0.99	> 0.99	> 0.99	> 0.99	> 0.99	> 0.99	> 0.8	> 0.8
I605/SR91 EDB			0.2 – 0.4	0.6 – 0.8	0.6 – 0.8	0.6 – 0.8	0.6 – 0.8	0.6 – 0.8	0.6 – 0.8	> 0.8		
Lexington Hills	< 0.2	0.2 – 0.4	0.6 – 0.8	> 0.8	> 0.8	> 0.8	> 0.8	> 0.8	> 0.8	> 0.8	> 0.8	> 0.8
Mountain Park							0.6 – 0.8	0.6 – 0.8	< 0.2	< 0.2		
Retention Ponds											**TVS**	
Central Park	0.6 – 0.8	0.6 – 0.8	> .99	< 0.2	> 0.99	0.6 – 0.8	> 0.99	0.6 – 0.8	> 0.8	< 0.2	> 0.8	0.2 – 0.4
Cockroach Bay			0.2 – 0.4	0.6 – 0.8	0.4 – 0.6				0.2 – 0.4	0.4 – 0.6		
De Bary			0.6 – 0.8	< 0.2	0.2 – 0.4		> 0.8	> 0.8	> 0.8	> 0.8		
Greens Bayou			< 0.2	< 0.2	0.2 – 0.4	< 0.2	> 0.8	> 0.8	0.6 – 0.8	0.2 – 0.4		
Heritage Estates	0.2 – 0.4	0.2 – 0.4	0.6 – 0.8	0.6 – 0.8	< 0.2	0.2 – 0.4	> 0.8	> 0.8	0.2 – 0.4	0.2 – 0.4		
I5 La Costa East	0.6 – 0.8	0.6 – 0.8	> 0.8	> 0.8	> 0.8	> 0.8	> 0.8	> 0.8	> 0.8	> 0.8		
Lake Ellyn			> 0.99	> 0.99	> 0.99	> 0.99	> 0.99	> 0.99	> 0.99	> 0.99		
Lake Ridge					0.6 – 0.8	0.6 – 0.8			> 0.8	> 0.8	> 0.8	> 0.8
Madison, Monroe str.					0.2 – 0.4	< 0.2			> 0.99	> 0.99	> 0.8	> 0.8
McKnight Basin					> 0.99	> 0.99			> 0.99	> 0.8	> 0.8	> 0.8
Phantom Lake			0.6 – 0.8	0.6 – 0.8	> 0.8	> 0.8	> 0.8	> 0.8	> 0.8	> 0.8		
Silver Star rd.					< 0.2	< 0.2	< 0.2	< 0.2	> 0.8	> 0.8	< 0.2	< 0.2
Tampa Office Pond 1							> 0.8	> 0.99	0.6 – 0.8	0.2 – 0.4		
Tampa Office Pond 2	< 0.2	< 0.2	< 0.2	0.2 – 0.4			0.2 – 0.4	> 0.8	0.6 – 0.8	> 0.8		
Tampa Office Pond 3	> 0.8	0.4 – 0.6	> 0.8	0.4 – 0.6	> 0.99	> 0.8	> 0.99	> 0.99	> 0.99	> 0.99		
UNH							> 0.8	0.6 – 0.8	0.6 – 0.8	0.2 – 0.4		
Lakeside							0.6 – 0.8		0.6 – 0.8			
Pinellas			0.6 – 0.8	0.6 – 0.8	0.6 – 0.8	0.6 – 0.8	0.6 – 0.8	0.2 – 0.4	< 0.2	< 0.2	< 0.2	< 0.2
Pittsfield					0.2 – 0.4	0.2 – 0.4			0.6 – 0.8	0.6 – 0.8		
Runaway Bay							< 0.2	< 0.2	0.2 – 0.4	0.2 – 0.4		

3.3.4 Experimental methods

No information was found for 5 ponds. These were Central Park, Grant Ranch, Greenville, Heritage Estates and Lexington Hill. The reports for Lake Ellyn, Lake Ridge and McKnight Basin simply stated that “USEPA approved” methods were used. For the rest of the case studies, the following chemical analysis methods were used:

Table 3-20 Chemical analysis methods used in case studies

Substance	Case Study	Method
Cadmium	El Dorado, Phantom Lake Pond A, Greens Bayou	EPA 200.8
	Mountain Park	EPA 200.7
	Cockroach Bay, De Bary, Tampa 1, 2 and 3	Standard Methods for the Examination of Water and Wastewater
Copper	El Dorado, Phantom Lake Pond A, Greens Bayou, All Roads	EPA 200.8
	Mountain Park	EPA 200.7
	Cockroach Bay, De Bary, Tampa 1, 2 and 3	Standard Methods for the Examination of Water and Wastewater
	Pinellas	USGS Standard Procedures 1989
Lead	El Dorado, Phantom Lake Pond A, Greens Bayou, All Roads	EPA 200.8
	Mountain Park	EPA 200.7
	Cockroach Bay, De Bary, Tampa 1, 2 and 3	Standard Methods for the Examination of Water and Wastewater
	Lake Ridge	Flame atomic absorption spectrophotometric method (AA)
	Pinellas, Silver star rd.	USGS Standard Procedures 1989
Zinc	El Dorado, Phantom Lake Pond A, Greens Bayou, All Roads	EPA 200.8
	Mountain Park	EPA 200.7
	Cockroach Bay, De Bary, Tampa 1,2 and 3	Standard Methods for the Examination of Water and Wastewater
	University of New Hampshire	EPA 6010 b
	Lakeside, Runaway Bay	Flame atomic absorption spectrophotometric method (AA)
	Pinellas, Silver star rd.	USGS Standard Procedures 1989
TSS	El Dorado, Mountain Park, Madison Monroe str., Greens Bayou, UNH, All Roads	EPA 160.2
	Cockroach Bay, De Bary, Lakeside, Runaway Bay, Tampa 1, 2 and 3	Standard Methods for the Examination of Water and Wastewater
	Pinellas, Silver star rd.	USGS Standard Procedures 1989
TVS	Madison Monroe Str.	EPA 160.4

Most methods used were EPA approved, ranging from the determination of trace elements in water by inductively coupled plasma-mass spectrometry (EPA 200.8), inductively coupled plasma – atomic emission spectrometry (EPA 200.7, EPA 6010 b), electrothermal atomic absorption spectrometry (SM 3113 B) to the determination of TSS (EPA 160.2) and TVS (EPA 160.4) by gravimetric analysis. The USGS standard procedures of 1989 were published by the US Geological Survey. All methods used were therefore deemed to be of high quality and reliable by association with the organisations that endorsed them.

4. Efficiency evaluations

4.1 Introduction

Efficiency evaluations of case studies based on the effluent probability method (EPM) were performed. These evaluations were a starting point for to the development of an understanding of pond behaviour. Result informed the direction of subsequent research, provided information used in conceptual model development and informed design recommendations. In addition, the development of a novel efficiency classification system based on the EPM (Addendum C2) provided a theoretical contribution to stormwater quality engineering.

A preparatory investigation into whether there was substantive proof for the use of substance concentration as a proxy for mass in the Effluent Probability Method was performed. This was motivated by the favoured use of the concentration parameter in literature for pond water quality efficiency determinations. The results revealed that mass, and not concentration, should be used in such determinations.

Individual efficiency evaluations of the included case studies were performed next. Ponds were categorised in terms of metal and solids removal efficiencies. The main results were: (1) long rectangular pond shapes may worsen removal efficiencies, (2) detention and retention pond behaviour differed in terms of dissolved substance removal, (3) both pond types were generally least efficient with dissolved substance removals. Additionally, the importance of adequate sample size determinations for stormwater quality enterprises was emphasised.

4.2 The use of mass vs concentration parameters in the effluent probability method

In the past, the use of the concentration parameter has been favoured in general stormwater structure efficiency determinations (Greb & Bannerman (1997), Strecker et al. (2001), Hossain et al. (2005), Barrett (2008)) as well as specifically with use of the Effluent Probability Method (EPM) (Chen et al. (2009), GeoSyntec Consultants & Wright Water Engineers, Inc. (2011), Fassman, (2012))

The term “efficiency” has often been used in literature without explanation of its exact meaning. In this section, the following definition applies: “Efficiency is a measure of how well a structure or system removes a substance”. This definition was adapted from an original definition proposed by Strecker et al. (2001) which reads: “Efficiency is a measure of how well a BMP (read Best Management Practice) or BMP system removes pollutants”. The revised definition omitted references to the term “BMP” and replaced the original term “pollutants” with the term “substance”. This was done to generalise the definition since the term “BMP” is specific mainly to literature originating in the USA, and the meaning of the term “pollutant” is specific to its application.

Furthermore, the definition of efficiency is delineated here to refer only to differences between monitored pond point influents and effluents, i.e. the definition does not include substance sources such as direct overland flow or base flow, which cannot be easily monitored.

The definition of efficiency used in this research therefore refers to the removal (positive or negative) of a tangible element, i.e. a substance, by a stormwater structure. Therefore, there is a fundamental fallacy in the use of a concentration parameter when determining pond efficiencies; viz. concentration is not a tangible element. It is a mathematical construct comprised of physically measureable quantities: mass and volume. It is also an abstract concept: one cannot see or feel concentration. Terms such as “removal of concentration” are therefore ill advised. Concentration does not *exist* physically and cannot be *removed* physically. Concentration, however, can be *changed* through removal or addition of the physical elements found in its compound parameters, viz. mass and volume.

Nevertheless, the favoured use of the concentration parameter in literature necessitated further investigation into whether the concentration parameter may be used as a proxy parameter for mass, to ascertain the amount of substance removed by a structure. The aforementioned hypothesis is the subject of this section. This hypothesis has the theoretical weakness that concentration, although directly related to substance mass, is also influenced by volume, which is wholly unrelated to the amount of substance removed. The use of the term “efficiency”, as defined above, in conjunction with the concentration parameter (albeit theoretically established here as a fallacy), has been continued in this section.

4.2.1 Methods

4.2.1.1 The effluent probability method

The effluent probability method (EPM) was reviewed in section 2.5.1. In this section, the method was adapted as follows:

1. Statistical significance at 95% confidence level between influent and effluent values was calculated with the Sign test (see discussion in section 3.3.2.1).
2. The results of 1. were coupled with examinations of cumulative frequency plots (CFPs).

The software program STATISTICA v.10 (Copyright© StatSoft, Inc. 1984-2011) was used for all calculations. In CFPs the Lowess smoothing method was used in the generation of regression lines while graphical observations were limited to visual categorisation of graphical behaviour according to plot point and regression line proximity.

4.2.1.2 Classification of pond efficiencies

A comprehensive technical note on the classification system used is provided in Addendum C2. Relationships between input and output CFPs resulted in the classification of general pond efficiencies into 2 different observational types. Additional consideration of statistical significance results led to the establishment of 5 different behavioural types (BTs), which are further discussed below. The criteria for the selection of BTs are shown in Table 4.1.

Table 4-1 Pond efficiency behavioural types observed in data

Graphical Observation of input and output CFPs	**Indication**	**Statistically Significant Difference Between Influent/Effluent Data?**	**Pond Efficiency Behavioural Types (BTs)**
A **Influent/effluent CFPs generally coincidental, closely adjacent and intersecting**	Pond efficiencies are unresponsive and varied across the data range.	No	BT1 Pond efficiency behaviour is accepted to be generally unresponsive and varied across the data range.
		Yes	
B **Influent/Effluent CFPs generally non-coincidental and distant in many areas**	Possibly significant general efficiency.	Yes	BT2 Pond efficiency behaviour is generally positive and statistically significant.
			BT3 Pond efficiency behaviour is generally negative and statistically significant.
		No	BT4 Pond efficiency behaviour is generally positive but not statistically significant.
			BT5 Pond efficiency behaviour is generally negative but not statistically significant.

4.2.2 Results and discussion

4.2.2.1 Data set efficiency classifications

Pond efficiencies were classified separately for substance type (metals and solids) as well as fraction (total, dissolved or particulate). Tables 4.2 to 4.5 contain detention and retention ponds with similar and dissimilar concentration and mass efficiency classification results.

The power of the Sign test results was low for the majority of detention and retention pond total (concentration and mass) cases where statistical significance between influent and effluent values was not found. It is therefore possible that, due to effect size, these case studies may have produced significant results if larger sample sizes had been available. However, the subject of this investigation was to ascertain if concentration and mass data provide similar interpretations of efficiency with the EPM. Therefore, the focus was on the data at hand, and hypotheses regarding different outcomes with larger data samples were considered to be irrelevant.

Table 4-2 DPs with identical concentration and mass efficiency classification results

Case Study	Substance	Fraction	Classification
El Dorado	Cu	Tot., Diss., Part.	Generally Unresponsive
	TSS	Tot.	Generally Unresponsive
Grant Ranch	Zn	Tot., Part.	Significantly Positive
	Zn	Diss.	Generally Unresponsive
	TSS	Tot.	Significantly Positive
Greenville	Cu, Pb, Zn, TSS	Tot.	Significantly Positive
I5/I605 EDB	As, Cd, Cu, Pb, Zn	Tot., Diss., Part.	Generally Unresponsive
	TSS	Tot.	Not Significantly Positive
I5 Manchester East EDB	As	Part.	Significantly Positive
	Cd, Cu, Pb, Zn, TSS	Tot., Part.	Significantly Positive
	Pb	Diss.	Generally Unresponsive
I5 SR56 EDB	As	Tot., Diss.	Generally Unresponsive
	As	Part.	Not Significantly Positive
	Cd	Tot., Part.	Not Significantly Positive
	Cd	Diss.	Generally Unresponsive
	Cu, Pb, Zn	Tot., Part.	Significantly Positive
	Cu, Pb, Zn	Diss.	Generally Unresponsive
I15 SR78 EDB	As, Cu, Zn	Tot., Part.	Significantly Positive
	As, Zn	Diss.	Generally Unresponsive
	Cd, Pb, TSS	Tot.	Significantly Positive
I605 SR91 EDB	Cu	Part.	Significantly Positive
	Pb, Zn, TSS	Tot., Part.	Significantly Positive
Lexington Hills	As, Cu, Zn, TSS	Tot., Part.	Significantly Positive
	Cd	Tot.	Not Significantly Positive
	Pb	Tot.	Significantly Positive
	Zn	Diss.	Not Significantly Positive
Mountain Park	Zn	Tot.	Significantly Positive
	TSS	Tot.	Generally Unresponsive

Classifications where subjectivity may have resulted in arguable outcomes, viz. classifications labelled as “not significantly positive”, “not significantly negative” or “generally unresponsive” were found in a number of cases. Efficiency classifications of such cases may have been found to be identical rather than contradictory if (1) more data had been available to improve the power and change the outcome of the statistical significance results, or (2) a different (and subjective) decision regarding the graphical display of data had been made.

Therefore, it is possible that, under different circumstances, similar concentration and mass classifications may have been found for cases where the classifications were combinations of: (1) not significantly positive *and* significantly positive; (2) not significantly negative *and* significantly negative, and; (3) not significantly positive/negative *and* generally unresponsive. In this research, such cases include the following: I5 Manchester East EDB (dissolved cadmium), I5 SR56 EDB (TSS), I605 SR91 EDB (total copper, dissolved zinc), Lexington Hills pond (dissolved arsenic), Central Park pond (total copper, TSS, TVS), Cockroach Bay pond (total copper), Greens Bayou (total and particulate copper, total and dissolved zinc, TSS), I5 La Costa East EDB (dissolved cadmium), Lakeside pond (total zinc, TSS), Pinellas pond (total zinc), Tampa Office Pond 1 (TSS), Tampa Office Pond 2 (total copper), Tampa Office Pond 3 (total cadmium, total copper) and University of New Hampshire pond (TSS).

Table 4-3 RPs with identical concentration and mass efficiency classification results

Case Study	Substance	Fraction	Classification
Central Park	Pb, Zn	Tot.	Significantly Positive
Cockroach Bay	Pb	Tot.	Not Significantly Negative
	TSS	Tot.	Not Significantly Positive
De Bary	Cu	Part.	Generally Unresponsive
	Pb	Tot.	Not Significantly Positive
	Zn	Tot., Diss.	Significantly Positive
	Zn	Part.	Not Significantly Positive
	TSS	Tot.	Significantly Positive
Greens Bayou	Cu	Diss.	Not Significantly Negative
	Pb	Tot.	Not Significantly Negative
	Zn	Part.	Not Significantly Negative
Heritage Estates	Cd	Tot.	Generally Unresponsive
	Cu	Tot.	Significantly Positive
	Pb, Zn, TSS	Tot.	Not Significantly Positive
I5 La Costa East	Cd, Cu, Pb, Zn, TSS	Tot., Part.	Significantly Positive
	Cu, Zn	Diss.	Not Significantly Positive
	Pb	Diss.	Significantly Positive
Lake Ellyn	Cu, Pb, Zn, TSS	Tot., Part.	Significantly Positive
	Pb	Diss.	Significantly Negative
	Zn	Diss.	Significantly Positive
Lake Ridge	Pb, TSS, TVS	Tot.	Significantly Positive
Madison Monroe str.	Pb	Tot.	Not Significantly Positive
	TSS, TVS	Tot.	Significantly Positive
McKnight Basin	Pb, TSS, TVS	Tot.	Significantly Positive
Phantom Lake Pond A	Cu, Pb, Zn, TSS	Tot.	Significantly Positive
Pinellas	Cu	Tot.	Significantly Positive
	TSS, TVS	Tot.	Generally Unresponsive
Pittsfield	Pb	Tot.	Not Significantly Positive
	TSS	Tot.	Significantly Positive
Runaway Bay	Zn, TSS	Tot.	Not Significantly Positive
Silver Star rd.	Pb, Zn	Tot.	Generally Unresponsive
	Pb	Diss.	Significantly Positive
	Pb	Part.	Significantly Negative
	Zn	Diss., Part.	Generally Unresponsive
	TSS, TVS	Tot.	Significantly Negative
Tampa Office Pond 1	Zn	Tot.	Significantly Positive
Tampa Office Pond 2	Cd, Zn	Tot.	Not Significantly Positive
	TSS	Tot.	Significantly Positive
Tampa Office Pond 3	Pb, Zn, TSS	Tot.	Significantly Positive
University of New Hampshire	Zn	Tot.	Significantly Positive

Table 4-4 DPs with contradictory concentration/mass efficiency classification results

Case Study	Substance	Fraction	Classification - Concentration	Classification - Mass	Strength of result
I5 Manchester East EDB	As	Tot.	Generally Unresponsive	Significantly Positive	Informative
	As	Diss.	Not Significantly Negative	Not Significantly Positive	Informative
	Cd	Diss.	Not Significantly Positive	Generally Unresponsive	Arguable
	Cu	Diss.	Generally Unresponsive	Significantly Positive	Informative
	Zn	Diss.	Generally Unresponsive	Significantly Positive	Informative
I5 SR56 EDB	TSS	Tot.	Significantly Positive	Not Significantly Positive	Arguable
I15 SR78 EDB	Cu	Diss.	Generally Unresponsive	Significantly Positive	Informative
I605 SR91 EDB	Cu	Tot.	Not Significantly Positive	Significantly Positive	Arguable
	Cu	Diss.	Not Significantly Negative	Significantly Positive	Informative
	Pb	Diss.	Generally Unresponsive	Significantly Positive	Informative
	Zn	Diss.	Not Significantly Positive	Significantly Positive	Arguable
Lexington Hills	As	Diss.	Generally Unresponsive	Not Significantly Positive	Arguable
	Cu	Diss.	Not Significantly Negative	Not Significantly Positive	Informative

Table 4-5 RPs with contradictory concentration/mass efficiency classification results

Case Study	Substance	Fraction	Classification - Concentration	Classification - Mass	Strength of result
Central Park	Cd	Tot.	Significantly Positive	Significantly Negative	Informative
	Cu, TSS, TVS	Tot.	Significantly Positive	Not Significantly Positive	Arguable
Cockroach Bay	Cu	Tot.	Not Significantly Positive	Significantly Positive	Arguable
De Bary	Cu	Tot., Diss.	Significantly Positive	Generally Unresponsive	Informative
Greens Bayou	Cu	Tot., Part.	Not Significantly Negative	Generally Unresponsive	Arguable
	Zn	Tot., Diss.	Significantly Negative	Not Significantly Negative	Arguable
	TSS	Tot.	Significantly Positive	Not Significantly Positive	Arguable
I5 La Costa East	Cd	Diss.	Not Significantly Positive	Generally Unresponsive	Arguable
Lake Ellyn	Cu	Diss.	Significantly Positive	Generally Unresponsive	Informative
Lakeside	Zn, TSS	Tot.	Significantly Positive	Not Significantly Positive	Arguable
Pinellas	Pb	Tot.	Significantly Positive	Generally Unresponsive	Informative
	Zn	Tot.	Significantly Positive	Not Significantly Positive	Arguable
Tampa Office Pond 1	TSS	Tot.	Significantly Positive	Not Significantly Positive	Arguable
Tampa Office Pond 2	Cu	Tot.	Generally Unresponsive	Not Significantly Positive	Arguable
Tampa Office Pond 3	Cd, Cu	Tot.	Significantly Positive	Not Significantly Positive	Arguable
University of New Hampshire	TSS	Tot.	Significantly Positive	Not Significantly Positive	Arguable

Cases where the differences between influent and effluent values were statistically significant combined with CFPs that were obviously distant, classifications such as “significantly positive” or “significantly negative” are well founded and not considered to be arguable. Therefore, cases where the concentration and mass classifications were combinations of (1) positive *and* negative, or (2) generally unresponsive *and* significantly positive/negative had notable differences between concentration and mass efficiencies. Such cases included the following: I5 Manchester East EDB (total and dissolved arsenic, dissolved copper, dissolved zinc), I15 SR78 EDB (dissolved copper), I605 SR91 EDB (dissolved copper, dissolved lead), Lexington Hills (dissolved copper), Central Park pond (total cadmium), De Bary pond (total and dissolved copper), Lake Ellyn (dissolved copper) and the Pinellas pond (total lead).

No evidence was found to suggest that contradictory concentration/mass classifications may be linked to specific substances. Contradictory results for both detention and retention ponds encompassed all metals (arsenic, cadmium, copper, lead, zinc) and solids sub-cases (TSS, TVS).

4.2.2.2 Graphical data behaviour

Investigation of CFPs showed differences in concentration and mass data behaviour that were obscured by the simplistic singular efficiency classification results. Two informative cases were selected for illustrative purposes (see Figures 4.1 to 4.4 below).

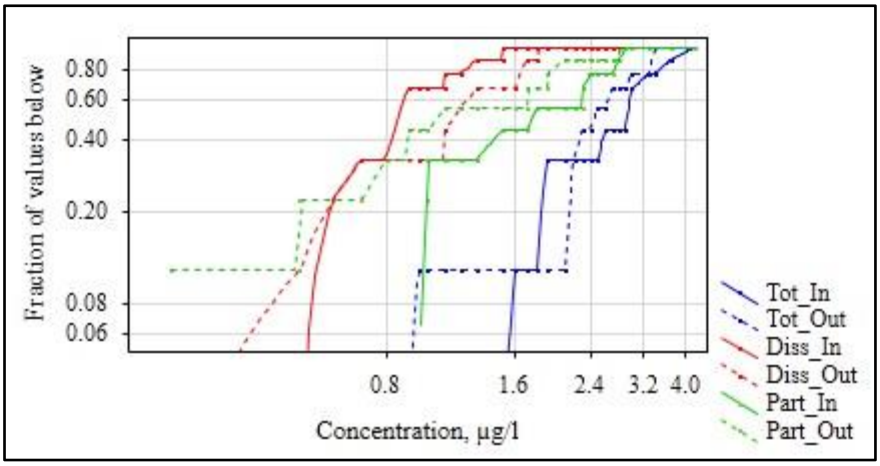


Figure 4-1 I5 Manchester East EDB CFP for arsenic concentration influent/effluent values

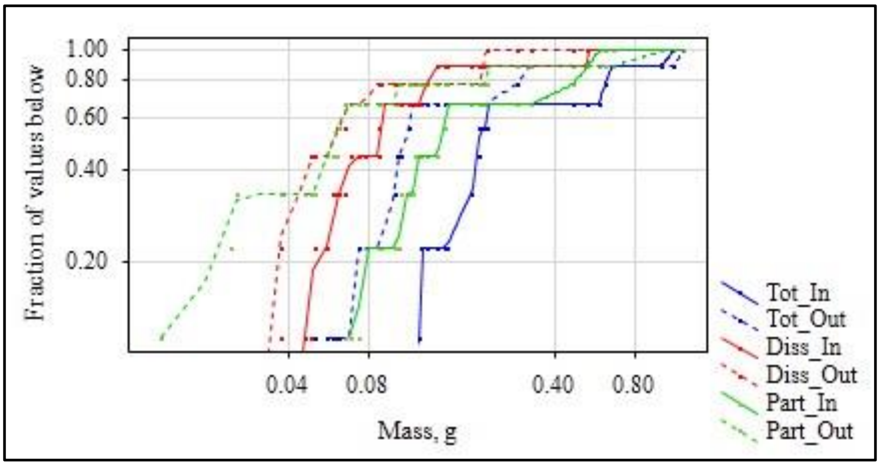


Figure 4-2 I5 Manchester East EDB CFP for arsenic mass influent/effluent values

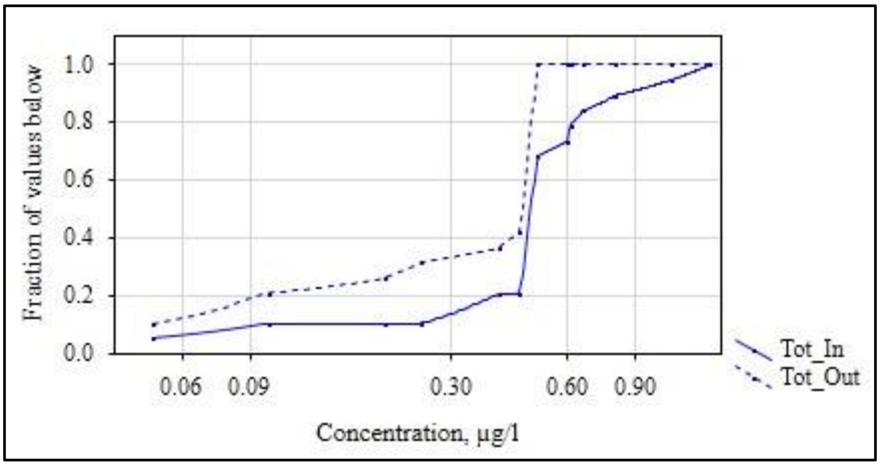


Figure 4-3 Central Park pond CFPs for total cadmium concentration influent/effluent values

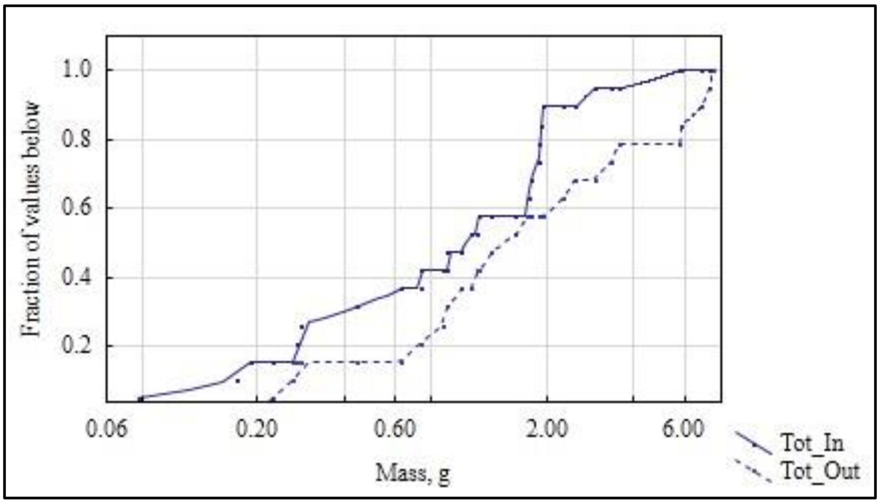


Figure 4-4 Central Park pond CFPs for total cadmium mass influent/effluent values

The I5 Manchester East EDB (arsenic) CFPs indicate markedly different total and dissolved arsenic concentration and mass efficiencies. Total concentration influent/effluent data behaviour is closely adjacent along the majority of the data range while, in contrast, total mass influent/effluent data is distant along the majority of the data range. Dissolved concentration influent/effluent CFPs indicate negative removals along the majority of the data range while, in contrast, the mass influent/effluent CFPs indicate positive removals along the majority of the data range. Interpretation of the concentration graphs therefore leads to an inference of poor total and negative dissolved pond efficiencies, while the interpretation of the mass data indicates considerably better and generally positive pond efficiencies.

The Central Park pond CFPs (total cadmium) indicates positive concentration efficiencies and negative mass efficiencies. Therefore, interpretation of the concentration graph leads to an inference of positive total pond efficiencies, while the interpretation of the mass data indicates much poorer negative efficiencies.

These graphs illustrate erroneous conclusions that can be made regarding pond efficiencies through the use of concentration as a parameter for the determination of the amount of substance removed, viz. (1) in the I5 Manchester East EDB it is possible that physical pond functioning influenced influent arsenic concentrations in such a way that substances were more concentrated when they reached the pond effluent stream. This does not mean that the pond did not remove substances as was evidenced by the mass data, only that the substances became more concentrated within the pond, (2) the Central Park pond sources of influent other than the influent stream, such as direct overland flow, direct rainfall or base flow, may have increased pond volumes and decreased influent cadmium concentrations, thereby reducing effluent concentrations. This does not mean that the pond removed cadmium, as was evidenced by the mass data, only that the substance became less concentrated within the pond.

4.2.3 Conclusion

The subject of this section is an investigation into the hypothesis that the concentration parameter may be used as a proxy parameter for mass in the Effluent Probability Method (EPM) to ascertain the amount of substance removed by a structure, i.e. its efficiency. The results of theoretical considerations as well as data analyses negate this hypothesis. Theoretically, the hypothesis has the weakness that concentration, although mathematically directly related to mass, is also influenced by volume, which is unrelated to mass. Concentration is calculated as mass divided by volume. It is never directly measured; rather the amount of particles or mass of particles within a sample is measured and divided by sample volume to provide sample concentration.

Data investigations showed that many of the resultant contradictory classifications for concentration and mass data may be arguable. Different graphical interpretations may have resulted in similar classifications for concentration and mass data in some cases. However, a noteworthy number of cases had contradictory concentration and mass classifications that were not deemed to be fundamentally arguable. Cases wherein (1) concentration and mass removals were opposite (i.e. positive and negative) or (2) where significant removals were found for concentration and generally unresponsive behaviour was seen for mass (and vice versa), were deemed to have unarguably contradictory concentration and mass data behaviours.

Therefore, the efficiency classification results indicate that different classifications were possible for evaluations of concentration and mass efficiencies. Such differences were due to different concentration and mass data behaviours as illustrated. Pond influent concentrations changed within ponds with subsequent increases or decreases in effluent concentration values without concurrent increases or decreases in mass values.

The results demonstrate erroneous conclusions that can be made through the use of the concentration parameter viz., (1) increases in effluent concentrations compared to influent concentrations does not necessarily mean that the pond did not remove substances, only that the substances become more concentrated within the pond, (2) decreases in effluent concentrations compared to influent concentrations does not necessarily mean that the pond removed substances, only that the substances become less concentrated within the pond.

Therefore, the results suggest that not only is the use of the concentration parameter as a proxy parameter for mass unfounded, but in addition, erroneous conclusions regarding pond efficiencies can be made if it is used within the EPM. It is therefore recommended that only the mass parameter be used for determination of pond efficiencies with the EPM.

4.3 Case study efficiency evaluations

This section presents stormwater metals removal efficiency determinations for 10 detention and 20 retention pond case studies. The aim of this stage in the research was the classification of pond efficiencies in order to identify ponds with good or poor efficiencies. This served as a guiding platform for further investigation into said relationships. Earlier research into pond efficiencies was deficient for this purpose because: (1) they contained only concentration data (e.g. Barrett (2008), Fassman (2012)), which was found to be a poor parameter for efficiency determinations, (2) were focussed on only one pond (e.g. Dufresne et al. (2010), Hossain et al. (2005)), (3) were focussed on categorical analysis e.g. comparison of different structures such as ponds, swales and wetlands (e.g. Fassman (2012), Lampe et al. (2005)), or (4) contained few metals variables (e.g. Lampe et al. (2005)).

4.3.1 Methods

Case study efficiencies were determined and classified as described in section 4.2.1 above. It was assumed that graphical trends of pond behaviour would not have been markedly different had larger sample sizes been available. Therefore in BT1 (generally unresponsive efficiency) classifications wherein graphical observations of pond behaviour were paramount to classification, numerical results of statistical significance testing and their associated power results were deemed irrelevant. Statistical significance was, however, deemed informative in all other behavioural type classifications. Where there was failure to reject the null hypothesis (no significant difference between pond inflow and outflow values) coupled with low power values (<0.8), BT2 or BT3 (significantly positive or negative efficiency) behaviour may have been erroneously classified as BT4 or BT5 (not significantly positive or negative efficiency) behaviour.

4.3.2 Results and discussion

Initial data analysis indicated concentration to be a poor parameter for pond efficiency determinations and therefore only mass data was investigated. Comparative literature on case study efficiencies was also included where possible. Such literature usually contained concentration and/or mass percentage removal results and was therefore not always directly comparable. Rather, they were included as indications of pond efficiencies found by other researchers to document support or contradiction to the results found in this project.

4.3.2.1 Statistical Significance

Tables 4.6 and 4.7 contain Sign test p – values for the detention and retention pond influent/effluent comparisons. Explicit values calculated for the power of the Sign test results were not included and values with low statistical power (< 0.8) were indicated in italics.

Table 4-6 Sign test p-values for detention pond inflow/outflow masses

Case Study	**Sub-Case**															
	Arsenic			**Cadmium**			**Copper**			**Lead**			**Zinc**			**TSS**
	Tot.	Diss.	Part.	Tot.	Diss.	Part.	Tot.	Diss.	Part.	Tot.	Diss.	Part.	Tot.	Diss.	Part.	
El Dorado	-	-	-	-	-	-	*0.8*	*0.8*	*0.8*	-	-	-	-	-	-	*0.3*
Grant Ranch	-	-	-	-	-	-	-	-	-	-	-	-	**0.02**	*0.06*	**0.05**	**0.01**
Greenville	-	-	-	-	-	-	**0.01**	-	-	**0.01**	-	-	**0.01**	-	-	**0.01**
I5/I605 EDB	*0.7*	*1.0*	*0.7*	*0.6*	*1.0*	*1.0*	*0.2*	*1.0*	*0.8*	*0.6*	*0.6*	*1.0*	*0.2*	**0.009**	*0.8*	*0.3*
I5 Manchester East EDB	**0.05**	*0.2*	**0.05**	**0.004**	*0.1*	**0.03**	**0.0009**	**0.03**	**0.0009**	**0.0005**	*0.06*	**0.0005**	**0.0009**	**0.009**	**0.0009**	**0.0005**
I5/SR56 EDB	*0.7*	*0.7*	*0.7*	*0.5*	*0.1*	*0.5*	**0.04**	*0.8*	**0.04**	**0.04**	*0.4*	**0.04**	**0.04**	*0.8*	**0.009**	*0.2*
I15/SR78 EDB	**0.008**	*0.5*	**0.008**	**0.004**	-	-	**0.00004**	**0.001**	**0.00004**	**0.00004**	-	-	**0.00004**	*1.00*	**0.00004**	**0.0002**
I605/SR91 EDB	-	-	-	-	-	-	**0.04**	**0.04**	**0.04**	**0.04**	**0.04**	**0.04**	**0.04**	**0.04**	**0.04**	**0.008**
Lexington Hills	**0.004**	*0.1*	**0.004**	*0.4*	-	-	**0.006**	*0.3*	**0.006**	**0.0009**	-	-	**0.009**	*0.8*	**0.009**	**0.006**
Mountain Park	-	-	-	-	-	-	-	-	-	-	-	-	**0.03**	-	-	*0.3*

Note: 1. Values in bold are statistically significant at $p \leq 0.05$. (2) Values in italics denote total fraction data sets with low statistical power. (3) "-" denotes "no data".

Statistically significant differences between inflow and outflow values generally occurred less often in the dissolved fraction than in the total and particulate fractions for both detention and retention ponds. The CFPs often indicated generally unresponsive pond behaviour in these cases, i.e. inflow/outflow regression lines were generally coincidental, closely adjacent and intersecting. In addition Type II error, which can be greatly dependent on sample size, was not accepted to be a likely reason for this result because the particulate fraction sample sizes were in all cases no larger than the dissolved sample sizes. Therefore, it was accepted that both detention and retention ponds were generally less efficient at dissolved fraction removal than at particulate fraction removal.

Table 4-7 Sign test p-values for retention pond inflow/outflow masses

Case Study	Sub-Case													
	Cadmium			**Copper**			**Lead**			**Zinc**			**TSS**	**TVS**
	Tot.	Diss.	Part.	Tot.	Diss.	Part.	Tot.	Diss.	Part.	Tot.	Diss.	Part.		
Central Park	**0.03**	-	-	*0.5*	-	-	**0.04**	-	-	**0.04**	-	-	*0.8*	*0.07*
Cockroach Bay	-	-	-	**0.04**	-	-	-	-	-	-	-	-	*0.06*	-
De Bary	-	-	-	*0.8*	*0.8*	*0.6*	0.6	-	-	**0.003**	**0.001**	*0.2*	**0.004**	-
Greens Bayou	-	-	-	*1.0*	*0.7*	*1.0*	*0.7*	*1.00*	-	0.2	*0.7*	*0.7*	*0.07*	-
Heritage Estates	*0.07*	-	-	**0.02**	-	-	*0.07*	-	-	**0.003**	-	-	*0.07*	-
I5 La Costa East	**0.01**	*0.7*	**0.01**	**0.0009**	*0.1*	**0.0009**	**0.0009**	**0.006**	**0.0009**	**0.001**	0.2	**0.001**	**0.0009**	-
Lake Ellyn	-	-	-	**0.0002**	*0.5*	**0.0002**	**0.0002**	**0.0007**	**0.0002**	**0.00006**	**0.002**	**0.0004**	**0.00006**	-
Lake Ridge	-	-	-	-	-	-	**0.03**	-	-	-	-	-	**0.0005**	**0.006**
Lakeside	-	-	-	-	-	-	-	-	-	*0.6*	-	-	*0.1*	-
Madison Monroe str.	-	-	-	-	-	-	*1.0*	-	-	-	-	-	**0.00005**	**0.0008**
McKnight Basin	-	-	-	-	-	-	**0.0007**	-	-	-	-	-	**0.004**	**0.004**
Phantom Lake Pond A	-	-	-	**0.02**	-	-	**0.009**	-	-	**0.003**	-	-	**0.009**	-
Pinellas	-	-	-	**0.04**	-	-	0.7	-	-	*0.2*	-	-	*0.7*	*0.7*
Pittsfield	-	-	-	-	-	-	*0.1*	-	-	-	-	-	**0.02**	-
Runaway Bay	-	-	-	-	-	-	-	-	-	*0.3*	-	-	*0.08*	-
Silver Star rd.	-	-	-	-	-	-	*0.4*	**0.001**	**0.001**	*0.8*	*0.6*	*0.6*	**0.009**	*1.00*
Tampa Office Pond 1	-	-	-	-	-	-	-	-	-	**0.0002**	-	-	*0.1*	-
Tampa Office Pond 2	*0.6*	-	-	*0.1*	-	-	-	-	-	**0.01**	-	-	**0.01**	-
Tampa Office Pond 3	*0.2*	-	-	*0.06*	-	-	**0.002**	-	-	**0.0000**	-	-	**0.0000**	-
UNH	-	-	-	-	-	-	-	-	-	**0.01**	-	-	*0.07*	-

Note: 1. Values in bold are statistically significant at $p \leq 0.05$. (2) Values in italics denote total fraction data sets with low statistical power. (3) "-" denotes "no data".

4.3.2.2 Cumulative Frequency Plots (CFPs)

Interpretations of pond efficiencies from CFPs were implicitly incorporated into the pond efficiency summaries below and attached in Addendum C1.

4.3.2.3 Pond Efficiencies

Detention ponds

El Dorado: The CFPs indicated generally unresponsive behaviour for all copper fractions (BT1). The power of the statistical significance results was low (< 0.8) for TSS, which was classified as not significantly positive (BT4). A statistically significant result may have been obtained with a larger sample size in this case, resulting in a change in classification from BT4 to BT2. Therefore the results indicate that pond behaviour was generally inefficient in terms of copper (all fractions) and TSS removals.

Grant Ranch: Total and particulate zinc as well as TSS removals were significantly positive (BT2). The dissolved zinc CFP indicated generally unresponsive behaviour (BT1). Therefore the results indicate that pond behaviour was generally (1) efficient in terms of total and particulate zinc as well as TSS and (2) inefficient in terms of dissolved zinc removals.

Table 4-8 Summary of DP efficiency classifications

Case Study	Fraction	Sub-Case					
		Arsenic	**Cadmium**	**Copper**	**Lead**	**Zinc**	**TSS**
El Dorado	Tot./Diss./Part.	-	-	BT1:Generally Unresponsive	-	-	BT4: Not Significantly Positive
Grant Ranch	Tot /Part.	-	-	-	-	BT2: Significantly Positive	BT2: Significantly Positive
	Diss.	-	-	-	-	BT1: Generally Unresponsive	n/a
Greenville	Tot.	-	-	BT2: Significantly Positive	BT2: Significantly Positive	BT2: Significantly Positive	BT2: Significantly Positive
I5 I605 EDB	Tot./Diss./Part.	BT1: Generally Unresponsive	BT1: Generally Unresponsive	BT1: Generally Unresponsive	BT1:Generally Unresponsive	BT1: Generally Unresponsive	BT4: Not significantly Positive
I5 Manchester East EDB	Tot./Part	BT2: Significantly Positive	BT2: Significantly Positive	BT2: Significantly Positive	BT2: Significantly Positive	BT2: Significantly Positive	BT2: Significantly Positive
	Diss.	BT1: Generally Unresponsive	BT1: Generally Unresponsive	BT2: Significantly Positive	BT1: Generally Unresponsive	BT2: Significantly Positive	n/a
I5 SR56 EDB	Tot.	BT1: Generally Unresponsive	BT1: Generally Unresponsive	BT2: Significantly Positive	BT2: Significantly Positive	BT2: Significantly Positive	BT4: Not Significantly Positive
	Diss.	BT1: Generally Unresponsive	BT1: Generally Unresponsive	BT1: Generally Unresponsive	BT1: Generally Unresponsive	BT1: Generally Unresponsive	n/a
	Part.	BT1:Generally Unresponsive	BT1: Generally Unresponsive	BT2: Significantly Positive	BT2: Significantly Positive	BT2: Significantly Positive	n/a
I15 SR78 EDB	Tot.	BT2: Significantly Positive	BT2: Significantly Positive	BT2: Significantly Positive	BT2: Significantly Positive	BT2: Significantly Positive	BT2: Significantly Positive
	Diss.	BT1:Generally Unresponsive	-	BT2: Significantly Positive	-	BT1:Generally Unresponsive	n/a
	Part.	BT2: Significantly Positive	-	BT2: Significantly Positive	-	BT2: Significantly Positive	n/a
I605 SR91 EDB	Tot./Diss./Part.	-	-	BT2: Significantly Positive	BT2: Significantly Positive	BT2: Significantly Positive	BT2: Significantly Positive
Lexington Hills	Tot.	BT2: Significantly Positive	BT4: Not Significantly Positive	BT2: Significantly Positive	BT2: Significantly Positive	BT2: Significantly Positive	BT2: Significantly Positive
	Diss.	BT4: Not Significantly Positive	-	BT4: Not Significantly Positive	-	BT4: Not Significantly Positive	n/a
	Part.	BT2: Significantly Positive	-	BT2: Significantly Positive	-	BT2: Significantly Positive	n/a
Mountain Park	Tot.	-	-	-	-	BT2: Significantly Positive	BT1: Generally Unresponsive

Note: "-" denotes "no data"

A study by Piza & Eisel (2009) indicated non-significant differences between inflow and outflow zinc values. This discrepancy in results may possibly be due to different sample sizes and data collecting periods for the two studies. The study included data from 29 storm events in 2009, while the results presented in this section were based on data from 50 storm events for 2009/10.

Greenville: Total copper, lead, zinc as well as TSS removals were significantly positive (BT2). The results therefore indicate that pond behaviour was generally efficient in terms of total copper, lead, and zinc as well as TSS removals. A study by Stanley (1994) found generally positive percentage mass removals for copper, lead, zinc and TSS. His findings do not contradict the above stated results.

I5/I605 EDB: CFPs indicated generally unresponsive behaviour (BT1) for all fractions of arsenic, cadmium, copper, lead and zinc. A statistically significant result for dissolved zinc was not taken to negate this. TSS removal behaviour was not significantly positive (BT4). The power for this result was < 0.8 and therefore a larger sample size may have resulted in a BT2 classification.

Pond efficiencies were monitored during a pilot study by the California Department of Transportation (2004). An ANOVA indicated that (1) none of the copper, lead, zinc (total, particulate and dissolved), and TSS concentration removals were statistically significant, and that (2) percentage removals for the concentrations and masses of sub-cases were positive. These efficiency indications do not contradict the above stated results.

I5 Manchester East EDB: Total and particulate arsenic, cadmium, copper, lead, zinc as well as TSS removals were. Dissolve significantly positive (BT2). Dissolved copper and zinc removals were also significantly positive (BT2). CFPs indicated generally unresponsive behaviour (BT1) for dissolved arsenic, cadmium and lead removals. Therefore the results indicate that pond behaviour was generally efficient in terms of all stated substance and fraction removals, excepting dissolved arsenic, cadmium and lead.

Pond efficiencies were monitored during a pilot study by the California Department of Transportation (2004). Percentage removals for the concentrations and masses of total copper and TSS were positive (>60%). These efficiency indications do not contradict the above stated results.

I5 SR56 EDB: CFPs indicated generally unresponsive behaviour (BT1) for arsenic and cadmium (all fractions) as well as dissolved fraction removals of copper, lead and zinc. Total and particulate copper, lead and zinc removals were significantly positive (BT2). TSS removals were not significantly positive (BT4), but a power result of <0.8 indicates that this classification may have been changed to BT2 had a larger sample size been available.

The results therefore indicate that (1) pond behaviour was generally efficient in terms of total and particulate copper, lead, zinc and possibly TSS removals, (2) generally inefficient in terms of all dissolved fraction removals and (3) generally inefficient in terms of all fractions of arsenic and cadmium removals.

Pond efficiencies were monitored during a pilot study by the California Department of Transportation (2004). Percentage removals for the concentrations and masses of total copper and TSS were positive (>50%). These efficiency indications do not contradict the above stated results.

I15 SR78 EDB: Total arsenic, cadmium, copper, lead, zinc and TSS removals were significantly positive (BT2). Particulate data was only available for arsenic, copper and zinc. Removals of these substances were also significantly positive (BT2). CFPs indicated generally unresponsive behaviour (BT1) for dissolved arsenic and zinc removals. Dissolved copper removal was significantly positive (BT2).

The results therefore indicate that (1) the pond efficiently removed particulate arsenic, copper and zinc and well as total arsenic, cadmium, copper, lead, zinc and TSS, (2) the pond efficiently removed dissolved copper and (3) the pond was inefficient at dissolved arsenic and zinc removals.

Pond efficiencies were monitored during a pilot study by the California Department of Transportation (2004). Percentage removals for the concentrations and masses of total copper and TSS were positive (>60%). These efficiency indications do not contradict the above stated results.

I605 SR91 EDB: All fractions of copper, lead and zinc as well as TSS removals were significantly positive (BT2). Pond efficiencies were monitored during a pilot study by the California Department of Transportation (2004). Percentage removals of total copper and TSS were positive (>70%). These efficiency indications do not contradict the above stated results.

Lexington Hills: Total and particulate arsenic, copper, zinc and TSS removals were significantly positive (BT2). Total lead removals were significantly positive (BT2). Total cadmium, dissolved arsenic, dissolved copper and dissolved zinc removals were not significantly positive (BT4), but power results of <0.8 for all these substances indicate that this behaviour may have classified as BT2 if a larger sample sizes had been available.

Mountain Park: Total zinc removals were significantly positive (BT2). TSS removals were generally unresponsive.

Retention ponds

Efficiency classifications for retention ponds are summarised in Table 4.9 and Table 4.10 below and are discussed.

Central Park: Total lead and zinc removals were significantly positive (BT2). Total copper, TSS and TVS removals were not significantly positive (BT4). Power values of <0.8 for these results indicate that, had larger sample sizes been available, removals may have been classified as statistically significant (BT2). Total cadmium removals were significantly negative.

The results therefore indicate (1) efficient removals of total lead and zinc, (2) possible efficient removals of total copper, TSS and TVS and (3) sources of cadmium to the pond other than the influent stream. Information on pond performances was provided by the City of Austin (1998). This technical note indicated positive (> 70%) pond concentration percentage removals for TSS, lead and zinc. These efficiency indications do not contradict the above stated results.

Table 4-9 Summary of RP efficiency classifications (1)

Case Study	Fraction	Substance					
		Cadmium	**Copper**	**Lead**	**Zinc**	**TSS**	**TVS**
Central Park	Tot.	BT3: *Significantly Negative*	BT4: Not Significantly Positive	BT2: Significantly Positive	BT2: Significantly Positive	BT4: Not Significantly Positive	BT4: Not Significantly Positive
Cockroach Bay	Tot.	-	BT2: Significantly Positive	-	-	BT4: Not Significantly Positive	-
De Bary	Tot.	-	BT1: Generally Unresponsive	BT1: Generally Unresponsive	BT2: Significantly Positive	BT2: Significantly Positive	-
	Diss.	-	BT1: Generally Unresponsive	-	BT2: Significantly Positive	n/a	n/a
	Part.	-	BT1: Generally Unresponsive	-	BT4: Not Significantly Positive	n/a	n/a
Greens Bayou	Tot.	-	BT1: Generally Unresponsive	BT1: Generally Unresponsive	BT5: *Not Significantly Negative*	BT4: Not Significantly Positive	-
	Diss.	-	BT1: Generally Unresponsive	-	BT5: *Not Significantly Negative*	n/a	n/a
	Part.	-	BT1: Generally Unresponsive	-	BT5: *Not Significantly Negative*	n/a	n/a
Heritage Estates	Tot.	BT4: Not Significantly Positive	BT2: Significantly Positive	BT4: Not Significantly Positive	BT2: Significantly Positive	BT4: Not Significantly Positive	-
I5 La Costa East WB	Tot./Part.	BT2: Significantly Positive	BT2: Significantly Positive	BT2: Significantly Positive	BT2: Significantly Positive	BT2: Significantly Positive	-
	Diss.	BT1: Generally Unresponsive	BT4: Not Significantly Positive	BT2: Significantly Positive	BT4: Not Significantly Positive	n/a	n/a
Lake Ellyn	Tot./Part.	-	BT2: Significantly Positive	BT2: Significantly Positive	BT2: Significantly Positive	BT2: Significantly Positive	-
	Diss.	-	BT1 :Generally Unresponsive	BT3: *Significantly Negative*	BT2: Significantly Positive	n/a	n/a
Lake Ridge	Tot.	-	-	BT2: Significantly Positive	-	BT2: Significantly Positive	BT2: Significantly Positive
Lakeside	Tot.	-	-	-	BT4: Not Significantly Positive	BT4: Not Significantly Positive	-
Madison Monroe str.	Tot.	-	-	BT4: Not Significantly Positive	-	BT2: Significantly Positive	BT2: Significantly Positive

Note: "-" denotes "no data"

Table 4-10 Summary of RP efficiency classifications (2)

Case Study	Fraction	Substance					
		Cadmium	**Copper**	**Lead**	**Zinc**	**TSS**	**TVS**
McKnight Basin	Tot.	-	-	BT2: Significantly Positive	-	BT2: Significantly Positive	BT2: Significantly Positive
Phantom Lake Pond A	Tot.	-	BT2: Significantly Positive	BT2: Significantly Positive	BT2: Significantly Positive	BT2: Significantly Positive	-
Pinellas	Tot.	-	BT2: Significantly Positive	BT1: Generally Unresponsive	BT4: Not Significantly Positive	BT1: Generally Unresponsive	BT1: Generally Unresponsive
Pittsfield	Tot.	-	-	BT4: Not Significantly Positive	-	BT2: Significantly Positive	-
Runaway Bay	Tot.	-	-	-	BT4: Not Significantly Positive	BT4: Not Significantly Positive	-
Silver Star rd.	Tot.	-	-	BT1: Generally Unresponsive	BT1: Generally Unresponsive	BT3: *Significantly Negative*	BT1: Generally Unresponsive
	Diss.	-	-	BT2: Significantly Positive	BT1: Generally Unresponsive	n/a	n/a
	Part.	-	-	BT3: *Significantly Negative*	BT1: Generally Unresponsive	n/a	n/a
Tampa Office Pond 1	Tot.	-	-	-	BT2: Significantly Positive	BT4: Not Significantly Positive	-
Tampa Office Pond 2	Tot.	BT1: Generally Unresponsive	BT4: Not Significantly Positive	-	BT2: Significantly Positive	BT2: Significantly Positive	-
Tampa Office Pond 3	Tot.	BT4: Not Significantly Positive	BT4: Not Significantly Positive	BT2: Significantly Positive	BT2: Significantly Positive	BT2: Significantly Positive	-
UNH	Tot.	-	-	-	BT2: Significantly Positive	BT4: Not Significantly Positive	-

Note: "-" denotes "no data"

Cockroach Bay: Total copper removal was significantly positive (BT2). TSS removal was not significantly positive (BT4). A power value of <0.8 for this result indicates that, had larger sample sizes been available, removals may have been classified as statistically significant (BT2). Pond performances were monitored during a study funded by the South West Florida Water Management District in 2002. It was reported that the copper, lead and zinc mass removals percentages were positive for all the years of the study (1998-2001).

De Bary: Copper (all fractions) and total lead removals were generally unresponsive (BT1). Total and dissolved zinc as well as TSS removals were significantly positive (BT2). Particulate zinc removal was not significantly positive (BT4), but a power result of <0.8 indicates a possible change in classification to BT2 had a larger sample size been available. The results therefore indicate that pond behaviour was generally (1) efficient in terms of zinc (total, dissolved and possibly particulate) and TSS removals and (2) inefficient in terms of copper (all fractions) and total lead removals.

Pond performances were monitored during a study funded by the St Johns River Water Management District from June to November 1992 by Harper & Herr (1993). They reported that the total mass percentage removals were positive for copper (< 50%), lead, zinc and TSS (> 50%). These efficiency indications do not contradict the above stated results.

Greens Bayou: Copper (all fractions) and total lead removals were generally unresponsive (BT1). Zinc (all fractions) removals were not significantly negative (BT5), but power values of <0.8 for the dissolved and particulate fractions indicate that these classifications may have changed to BT3 had a larger sample size been available. TSS removal was not significantly positive (BT4), but a power value of <0.8 indicates that this classification may have changed to BT2 had a larger sample size been available.

Therefore the results indicate that pond behaviour (1) was generally inefficient in terms of copper (all fractions) and total lead removals, (2) had negative zinc (all fraction) removals and (3) a better efficiency classification may have been obtained for TSS removals had larger sample sizes been available.

Pond performances were monitored during a study done by Wetland Solutions Inc. (2010) from January to December 2009. The study was broadly focussed on the wetland project as a whole, and did not provide insight into the functioning of the Greens Bayou retention pond as a sole entity. However, it was indicated that the Greens Bayou pond may have received inflows from a separate wetland for which data was not included in the International Stormwater BMP Database. This may account for the seemingly poor and negative pond removal efficiencies found above.

Heritage Estates: Total copper and zinc removals were significantly positive (BT2). Total cadmium, lead and TSS removals were not significantly positive (BT4), but power of <0.8 for all these results indicate that these classifications may have been changed to BT2 had larger sample sizes been available.

Pond performances were monitored in a study by the Stormwater Assessment Monitoring and Performance (SWAMP) Program (2005) from between 1995 and 2002. High concentration removal efficiencies (>70%) were reported for total copper, zinc and TSS . These efficiency indications do not contradict the above stated results.

I5 La Costa East WB: Total and particulate cadmium, copper, lead and zinc, TSS as well as dissolved lead removals were significantly positive (BT2). Dissolved cadmium removals were generally unresponsive (BT1). Dissolved copper and zinc removals were not significantly positive (BT4), but power values of <0.8 indicate that these classifications may have changed to BT2 had larger sample sizes been available.

Therefore the results indicate that pond behaviour was generally (1) efficient in terms of total and particulate cadmium, copper, lead, zinc, TSS as well as dissolved lead removals, (2) possibly efficient in terms of dissolved copper and zinc removals and (3) inefficient in terms of dissolved cadmium removals.

Pond efficiencies were monitored during a pilot study by the California Department of Transportation (2004). Percentage removals for the concentrations of total and dissolved fractions were positive for zinc, copper, lead and TSS. An ANOVA ($p<0.05$) indicated that all of the removals were statistically significant.

Lake Ellyn: Total and particulate copper, lead, zinc, TSS as well as dissolved zinc removals were significantly positive (BT2). Dissolved copper removals were generally unresponsive (BT1). Dissolved lead removals were significantly negative (BT3).

The results therefore indicate that pond behaviour was generally (1) efficient in terms of total and particulate copper, lead, zinc, TSS and dissolved zinc removals, (2) inefficient in terms of dissolved copper removals. Additionally dissolved lead sources to the pond other than from the inflow stream were indicated. Such sources may include external dissolved lead inputs or speciation of lead substances into dissolved form within the lake from previous sediment deposits.

Pond performances were monitored during a study by Striegl & Cowan (1987) for the U.S. Geological Survey (USGS). Percentage removals for the concentrations of total and dissolved substances were positive for dissolved copper (< 50%), dissolved zinc (> 50%); and total copper, total lead, total zinc and TSS (> 70%). Dissolved lead percentage removals varied between highly negative and highly positive. These efficiency indications do not contradict the above stated results.

Lake Ridge: Total lead, TSS and TVS removals were significantly positive (BT2). Pond performances were monitored during a study by Walker (1993) for the U.S. Geological Survey (USGS). The Mann-Whitney U test indicated statistically significant differences between inflow and outflow total lead and SS masses. These efficiency indications are support the above stated results.

Lakeside: Total zinc and TSS removal behaviour was not significantly positive (BT4). Power values of <0.8 indicate that this classification may have changed to BT2 had larger sample sizes been available. Pond performances were monitored during a study by Wu (1989) for the Water Resources Research Institute of Norch Carolina. Percentage removals for concentrations were reported as positive for total zinc and TSS (> 70%). These efficiency indications do not contradict the above stated results.

Madison Monroe str.: TSS and TVS removals were significantly positive (BT2). Total lead removals were not significantly positive (BT4), but a power value of <0.8 indicates that this classification may have changed to BT2 had a larger sample size been available. Pond performances were monitored during a study by House et al. (1993) from February 1987 to April 1988 for the U.S. Geological Survey. Percentage removals for concentrations and masses were reported as positive for total lead and TSS (> 70%). These efficiency indications do not contradict the above stated results.

McKnight Basin: Total lead, TSS and TVS removals were significantly positive (BT2).

Phantom Lake pond A: Total copper, lead, zinc and TSS removals were significantly positive (BT2). Pond performances were monitored during a study by Comings et al. (2000) from October 1996 to March 1997. Percentage removals for masses were reported as positive for total copper, zinc (< 50%), total lead and TSS (> 50%). These efficiency indications do not contradict te above stated results.

Pinellas: Total copper removals were significantly positive (BT2). Total zinc removal was not significantly positive (BT4), but a power value of <0.8 indicates that this classification may have changed to BT2 had a larger sample size been available. Total lead, TSS and TVS removal behaviour was generally unresponsive (BT1).

The results therefore indicate that (1) pond behaviour was generally efficient in terms of total copper and possibly zinc removal, (2) inefficient in terms of total lead, TSS and TVS removal. Pond performances were monitored during a study by Kantrowitz & Woodham (1995). Percentage removals for masses were reported to be positive for total copper, total lead and total zinc (> 50%), and negative for TSS. These efficiency indications are not directly in accord with the above stated results, but neither are they contradictory.

Pittsfield: TSS removal was significantly positive (BT2). Total lead removal was not significantly positive (BT4), but a power value of <0.8 indicates that this classification may have changed to BT2 had a larger sample size been available.

Runaway Bay: Total zinc and TSS removals were not significantly positive (BT4), but power values of <0.8 indicate that these classifications may have changed to BT2 had larger sample sizes been available. Pond performances were monitored during a study by Wu (1989). Percentage removals for concentrations were reported as positive for total zinc (< 50%) and TSS (> 50%). These efficiency indications do not contradict the above stated results.

Silver Star rd.: This pond showed curious behaviour, which was not observed in any other case studies. Dissolved lead removal was significantly positive (BT2) while all other substance fraction removals were either generally unresponsive (BT1) (total lead, total zinc, dissolved zinc, particulate zinc, TVS) or even significantly negative (BT3) (particulate lead, TSS). This behaviour indicates sources of lead, zinc and other solids other than the influent stream.

A report produced by Gain (1996) for the U.S. Geological Survey illustrated changes in performance of the pond after it was modified in 1998. The data obtained from the International Stormwater BMP Database, however, limited the use of these findings to those of the original pond. Percentage removals for concentrations were reported to be (1) low for total and TSS (> 50%), and (2) negative for total zinc. These efficiency indications are not in general accord with the above stated results, possibly due to the pond modification. They do, however, also indicate a propensity to negative removals.

<u>Tampa Office Pond 1:</u> Total zinc removal was significantly positive (BT2). TSS removals was not significantly positive (BT4), but a power value of <0.8 indicates that this classification may have changed to BT2 had a larger sample size been available. Pond performances were monitored during a study by Rushton et al. (1997). Percentage removals for masses were reported to as positive for total zinc (> 50%) and TSS (> 70%). These efficiency indications do not contradict the above stated results.

<u>Tampa Office Pond 2:</u> Total zinc and TSS removals were significantly positive (BT2). Total cadmium removal behaviour was generally unresponsive (BT1). Total copper removal was not significantly positive (BT4), but a power value of <0.8 indicates that this classification may have changed to BT2 had a larger sample size been available.

Therefore the results indicated that (1) pond behaviour was generally efficient in terms of total zinc, TSS and possible total copper removals, and (2) inefficient in terms of total cadmium removal. Pond performances were monitored during a study by Rushton et al. (1997). Percentage removals for masses were reported as positive for cadmium, copper, zinc (< 50%) and TSS (> 70%). These efficiency indications do not contradict the above stated results.

<u>Tampa Office Pond 3:</u> Total lead, zinc and TSS removals were significantly positive (BT2). Total cadmium and copper removals were not significantly positive (BT4), but power values of <0.8 indicates that these classifications may have changed had larger sample sizes been available. Therefore the results indicated that pond behaviour was generally efficient in terms of total lead, zinc, TSS and, possibly, total cadmium and copper removals.

Pond performances were monitored during a study by Rushton et al. (1997). Percentage removals for masses were reported to as positive for copper (> 50%), cadmium, lead, zinc and TSS (> 70%). These efficiency indications do not contradict the above stated results.

<u>University of New Hampshire:</u> Total zinc removals were significantly positive (BT2). TSS removals were not significantly positive (BT4), but a power value of <0.8 indicates that this classification may have changed to BT2 had a larger sample size been available.

4.3.2.4 General Discussion

Detention Ponds:

Dissolved and particulate data was available for most of the case studies (8 out of 10). Classifications given to particulate substances were also given to total substances in all cases. Classifications of dissolved substances, however, often differed with clear indications of significant removals or generally unresponsive behaviours. These classifications generally, therefore, had low probabilities of Type II error. This indicates that particulate removal efficiencies had the determining influence on total removal efficiencies in all these cases.

The Grant Ranch, Greenville, I5 Manchester East EDB, I15 SR78 EDB, I605 SR91 EDB, and Lexington Hills ponds had significantly positive removal efficiencies for nearly all measured total and particulate metals as well as TSS, with the exception of total cadmium removals in the Lexington Hills pond. These ponds had the following similar characteristics (See Addendum B):

(1) All ponds had squat (square, round, L – shaped) or triangular shapes. These shapes may have allowed the ponds to act as dams that allowed the capture of material.

(2) All ponds were earth lined. This may have allowed material to adhere to the bottom of the ponds and therefore be captured within the ponds.

Dissolved metal fraction removals were not significant in the majority of cases indicating that the detention ponds generally did not remove dissolved substances to any great degree. A similar result was found by Barrett (2008) and Lampe et al. (2005) for certain metals concentrations (see section 2.5.2).

Exceptions to this were found with the following data sets:

- I5 Manchester East EDB – copper and zinc
- I15 SR78 EDB – copper
- I605 SR91 EDB – copper, lead and zinc

These ponds were, as stated in 2. above, squat L-shaped and earth lined. The combination of squat shape and earth lining may have produced dam behaviour wherein the water was captured within the pond long enough for dissolved material to infiltrate into the soil.

The least efficient ponds in terms of metals, TSS and all measured fraction removals were the El Dorado, I5/I605 EDB and Mountain Park ponds. These were generally unresponsive or without statistically significant removals. Information on physical characteristics for the El Dorado and Mountain Park case studies were highly deficient, and no similar characteristics between the ponds were discovered. It was noted that the El Dorado pond had an elongated rectangular shape and the I5 I605 EDB had the same L-shape as the other California Department of Transportation

(2004) road ponds but was concrete lined. The smooth concrete lining of the I5 I605 EDB may have limited material adherence to the pond bottom or infiltration allowing it to be carried to the outflow stream rather than be captured within.

Retention Ponds:

Dissolved and particulate data was only available for 5 out of the 20 case studies. In these 5 case studies 13 metals subcases had dissolved and particulate data. The same classifications were given for all fractions (total, dissolved and particulate) in many cases (5 out of 13). 3 Subcases had classifications which may have changed to the classifications of the other fractions in their groups had larger sample sizes been available, viz. (1) De Bary particulate zinc and (2) I5 La Costa East WB dissolved copper and zinc. Statistically significant or generally unresponsive classifications for a particulate or dissolved fraction that was different to the other fraction classifications in its group were given in 5 out of the 13 sub cases, viz. (1) I5 La Costa East WB dissolved cadmium, (2) Lake Ellyn dissolved copper, dissolved lead and (3) Silver Star rd. dissolved and particulate lead. In general, dissolved classifications were more than twice as often poor (generally unresponsive, not significantly positive or significantly negative) than significantly positive. The opposite was found for particulate matter. Total classifications were also more often than not related to particulate classifications. Therefore, retention pond behaviour was mainly dictated by particulate matter behaviour and ponds were generally less efficient at dissolved matter removal.

The I5 La Costa East WB, Lake Ellyn, Lake Ridge, McKnight Basin and Phantom Lake Pond A ponds had significantly positive efficiencies for all measured total metals as well as TSS. The Central Park, Cockroach Bay, Heritage Estates, Lakeside, Madison Monroe str., Pittsfield, Runaway Bay and Tampa Office Ponds (1, 2 and 3), had positive efficiencies for all measured metals (except for cadmium, see 4. below) and TSS. These ponds had the following similar characteristics (See Addendum B):

(1) All ponds were either squat (round or square) or triangular shaped, or were composed of a series of smaller squat shapes such as compartmentalised rectangular shapes.

(2) All ponds were earth lined.

The Greens Bayou and Silver Star road ponds had no positive efficiencies for any of the measured metals or fractions, except for significantly positive dissolved lead removals for the Silver Star rd. pond. From outside reports (Wetland Solutions Inc. 2010) the Greens Bayou pond may have had large unmeasured influent from a wetland and the results are therefore not decisive. The Silver Star road pond had a long rectangular shape and was earth lined. The long rectangular shape characteristic is as was seen in the poorly performing El Dorado detention pond, indicating that elongated shapes may have played a part in poor pond performance for both types of ponds.

Total cadmium removal efficiencies were poor compared to other metals in the Central Park pond (total fraction), I5 La Costa East WB (dissolved fraction and Tampa office pond 2 (total fraction). This may indicate that cadmium removal processes differ from other metals removal processes, inflow masses were too low to result in significant removals or data sets were too small to result in representative results.

4.3.3 Conclusion

The Grant Ranch, Greenville, I5 Manchester East EDB, I15 SR78 EDB, I605 SR91 EDB and Lexington Hills detention ponds were determined to have the greatest total fraction removal efficiencies across all metals. Characteristics that these ponds all shared were squat (round, L – shaped) or triangular shapes and earth linings. The least efficient detention ponds in terms of total fraction removals were the El Dorado and I5/I605 EDB ponds. It was noted that the El Dorado pond had a long rectangular shape and the I5 I605 EDB was concrete lined. These characteristics may have reduced pond settling and/or infiltration abilities.

The I5 La Costa East WB, Lake Ellyn, Lake Ridge, McKnight Basin and Phantom Lake Pond A retention ponds were determined to have significantly positive efficiencies for the total fractions of all measured metals. Characteristics that these ponds all shared with each other and with the efficient detention ponds were that they had squat (round or square) or triangular shapes and were earth lined. The least efficient retention ponds in terms of total metals removals was the Silver Star road pond.

The following additional observations were made:

1. The results indicated that long rectangular shaped ponds were prone to poor efficiencies e.g. the El Dorado detention and Silver Star rd. retention ponds. Although these were only 2 ponds out of 30, they were also the only ponds that had long, rectangular shapes. This is in contrast to prescriptive design guidelines (Addendum A) that prescribe length to width ratios of at least 2:1 and the results of Dufresne, et al. (2010) (section 2.5.2) that indicated longer ponds to have better sediment removals. The reasons for poor efficiencies in these ponds could not be ascertained at this time. The I5/I605 EDB classifications also indicated very poor efficiencies across all measured metals, but had a squat L-Shape as was often seen in ponds with generally good efficiency classifications. This pond was, however, concrete-lined, and it is postulated that this lining was responsible for the poor general efficiency of the pond. There were other ponds in the study, that had generally good overall efficiency classifications, with long rectangular shapes, but on closer examination of these ponds it can be seen that they all contained compartments, e.g., the Phantom Lake pond A was broken up into 3 smaller squat shapes.

2. Generally unresponsive, not significantly positive and significantly negative classifications occurred more often for dissolved than for particulate metals. In detention ponds, such classifications occurred more than twice as many times for dissolved metals (20) than for particulate metals (8). In retention ponds, this phenomenon was less pronounced with 9 occurrences of such classifications in dissolved fractions compared to 6 occurrences in the particulate fractions.
3. For 7 out of 62 detention ponds, and 23 out of 72 retention ponds, positive classifications were not significant (BT4) with power <0.8, indicating that these classifications may have changed to BT2 had larger sample sizes been available. For 2 out of 7 retention pond negative classifications were not significant (BT5) with power <0.8, indicating that these classifications may have changed to BT3 had larger sample sizes been available. This result indicates the importance of investigations into sample size determination before embarking on data measurements. It is therefore recommended that such investigations be done as a standard in stormwater quality research enterprises in future.

5. Relationships between physical pond parameters and efficiencies

5.1 Introduction

This section contains results of correlational analyses and logistic regression between metal substance (As, Cd, Cu, Pb, Zn and TSS) removals and pond physical characteristics of the previously selected 10 stormwater detention and 20 retention pond case studies. Additionally an investigation of cross correlations between metals and solids substances in pond inflow, outflow and removals was included.

Although the 30 case studies included large amounts of data overall, small individual data sets and associated limitations (see Section 3.2.5) negated detailed investigations. Therefore, the methodology was focussed on elucidating data trends rather than specifics.

In the past, the use of the concentration parameter has been favoured in general stormwater structure efficiency determinations (see Greb & Bannerman (1997), Strecker et al. (2001), Hossain et al. (2005), Barrett (2008), Chen et al. (2009), Geosyntech Consultants Inc. & Wright Water Engineers Inc. (2011), Fassman (2012)). This prompted its inclusion in this analysis.

The term “concentration removal” has been used in this section. Concentration is a compound variable and can, strictly speaking, not be removed. This term must therefore be understood to refer to the mathematical definition of the variable C_{rem} as defined in Eqn. 5.1 below, and not to its linguistic definition.

This section contributed towards fulfilment of research objective 1 (Chapter 1, section 1.4) through identification of pond parameters with a notable influence on efficiency. In addition, the results provided context for development of pond conceptual models (Chapter 6) from which design recommendations were ultimately made (Chapter 7).

5.2. Methods

5.2.1 Pond efficiencies over different data ranges

Literature pertaining to stormwater detention and retention pond removals have alluded to different removals at different concentrations i.e., discharge concentrations may be a function of influent concentrations (Lampe et al., 2005). This prompted an investigation into pond removals over different data ranges. The purpose of this was the determination of inflow data sub-sections that have similar removals. Data from identified sub-sections were grouped and averaged to provide input into correlational analyses between substance removals and pond parameters.

1. Concentration and mass inflow data for all case studies were combined, ordered per storm event and ranked with associated fraction removal values:

   $$C_{rem} = (C_{in} – C_{out}) / C_{in} \quad (5.1)$$

   $$M_{rem} = (M_{in} – M_{out}) / M_{in} \quad (5.2)$$

   Where C_{in} is the inflow EMC per storm event, C_{out} is the outflow EMC value associated with C_{in} per storm event, C_{rem} is the fraction of concentration “removed” per storm event, M_{in} is the inflow mass value per storm event, M_{out} is the outflow mass value associated with M_{in} per storm event and M_{rem} is the fraction of mass removed per storm event.

2. Ranked inflow data sets (with associated C_{rem} or M_{rem} values) were split into two sub-sections at the following inflow data values: First Quartile (Q1), Third Quartile (Q3), and Median. Small sample sizes per case-study meant that data could be grouped into a maximum of two sub-sections to enable as much data overlap as possible between case studies in subsequent correlational analyses.

3. The Mann-Whitney U test was used to determine significant differences in C_{rem} or M_{rem} between the different groups at $p \leq 0.05$. Where significant differences were found, groups were averaged. These average values were used as input into the correlational analysis between substance removals and pond parameters.

5.2.2 Cross correlations between substances

Metals and solids data form all case studies were grouped together and averaged. The non-parametric Spearman correlation coefficient was used. Strong correlations ($R_s \geq 0.8$) that were statistically significant at $p \leq 0.05$ were reported.

5.2.3 Relationships between substance removals and pond parameters

Correlation analysis was used to measure the strength of association between substance fraction removals and physical pond parameters. Logistic regression was used to find predictor variables in terms of physical pond parameters for statistically significant efficiencies and negative removals.

5.2.4 Correlation analysis

1. Fraction removals were calculated. Inflow concentrations and masses were ranked with their associated fraction removal values.

2. Fraction removal values were then split into two groups according to the chosen Q1, Q3 or median split. The average fraction removal was calculated for each split group.

3. Information on physical pond parameters was compiled from the International Stormwater BMP Database and literature referenced in the database.

4. Data was ordered into three sections to investigate pond functioning in cases, viz. (1) All Data, (2) Positive Data Only and (3) Negative Data Only.
5. The results of Spearman correlation between fraction removal values and physical pond parameters significant at $p \leq 0.05$ were reported.

5.2.5 Logistic regression

A. Possible relationships between pond physical parameters and efficiencies were investigated as follows:

1. Pond efficiencies for masses were classified according to the Effluent Probability Method and coded as shown in Table 5.1.
2. The data was used as input to the software program STATISTICA v.10 (Copyright© StatSoft, Inc. 1984-2011). Logistic regression modelling was employed to determine parameters of the best predictor models ($p \leq 0.05$).

Table 5-1 Efficiency coding

Cumulative Frequency Plot Classification	Statistical Significance between Inflow and Outflow Values	Pond Efficiency Classification	Code
Generally positive efficiency	Yes	Significantly Positive	1
Not generally positive efficiency	Yes / No	Not Significantly Positive	0

B. Possible relationships between pond physical parameters and negative average fraction mass removal were investigated as follows:

1. Average fraction removals for all substances were grouped according to the case study and coded as shown in Table 5.2.
2. The data was used as input to the software program STATISTICA v.10 (Copyright© StatSoft, Inc. 1984-2011). Logistic regression modelling was employed to determine parameters of the best predictor models.

Table 5-2 Substance removal codes

Average substance mass removal	Code
negative	1
positive	0

5.3 Detention ponds results and discussion

5.3.1 Pond efficiencies over different data ranges

The results of the investigation into pond efficiencies over the substance data ranges are displayed in Table 5.3. Values statistically significant at $p \leq 0.05$ are displayed in bold.

Table 5-3 DP sub-range p-values (Mann-Whitney U test) for 2 independent groups

Fraction	**Total**						**Dissolved**						**Particulate**					
Split	**Q1**		**Q3**		**Median**		**Q1**		**Q3**		**Median**		**Q1**		**Q3**		**Median**	
Sub - Case	Conc.	Mass	Conc.	Mass	Conc.	Mass	Conc.	Mass	Conc.	Mass	Conc.	Mass	Conc.	Mass	Conc.	Mass	Conc.	Mass
Arsenic	0.111	0.604	0.324	**0.014**	**0.005**	0.675	0.323	0.701	0.294	0.574	0.116	0.177	0.099	0.983	0.319	0.447	**0.029**	0.386
Cadmium	**0.000**	**0.042**	**0.008**	0.661	**0.000**	0.248	0.860	0.478	0.700	0.309	0.316	0.829	0.164	0.630	0.329	0.726	0.104	0.704
Copper	**0.000**	**0.019**	**0.000**	0.629	**0.000**	0.696	0.838	0.373	0.544	0.915	0.118	0.753	**0.000**	0.099	**0.000**	**0.024**	**0.000**	**0.009**
Lead	**0.000**	0.442	**0.001**	0.356	**0.000**	0.109	**0.025**	0.595	**0.008**	0.163	**0.001**	0.142	0.060	0.447	**0.007**	0.236	**0.009**	0.058
Zinc	**0.001**	0.147	**0.000**	1.000	**0.000**	0.288	0.123	0.169	**0.047**	**0.002**	**0.003**	0.204	**0.000**	0.151	**0.000**	**0.003**	**0.000**	**0.026**
TSS	**0.000**	0.236	**0.000**	0.679	**0.000**	0.661	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

Note: ID = Insufficient Data, NA = Not Applicable

As was alluded to in the literature (see Lampe et al. (2005)), there were statistically significant differences between upper and lower concentration and mass removals groups. This information was used to group data for input into the correlational analysis between substance removals and pond parameters. The split statistics at which significant differences between groups were found are summarised in Table 5.4. The split statistics employed in subsequent correlational analyses are displayed in bold.

Table 5-4 DP data splits within data sets for correlational analysis

Fraction	**Total**		**Dissolved**		**Particulate**	
Sub - Case	**Conc.**	**Mass**	**Conc.**	**Mass**	**Conc.**	**Mass**
Arsenic	**Median**	**Q3**	**None**	**None**	**Median**	**None**
Cadmium	Q1, Q3,**Median**	**Q1**	**None**	**None**	**None**	**None**
Copper	Q1, Q3,**Median**	**Q1**	**None**	**None**	Q1, Q3,**Median**	Q3, **Median**
Lead	Q1, Q3,**Median**	**None**	Q1, Q3,**Median**	**None**	Q3, **Median**	**None**
Zinc	Q1, Q3,**Median**	**None**	Q3, **Median**	**Q3**	Q1, Q3,**Median**	Q3, **Median**
TSS	Q1, Q3,**Median**	**None**	NA	NA	NA	NA

Note: ID = Insufficient Data, NA = Not Applicable

It can be seen from table 5.4 that the most common statistic at which data could be split to find statistically significant differences between the split groups was the median. This general dominance of the median motivated the choice of this statistic as the default split statistic in all cases in which it appeared. In general, no single split statistic was found to appear in all data sets and an investigation into the required split for a specific data set is recommended in situations where the methodology used in this project is applied.

5.3.2 Cross correlations between substances

Association groups in concentration correlations often differed from mass correlations. This indicates that (1) the influence of inflow volume affected correlation results for the compound parameter concentration in such a way that correlations between substances were confounded, or (2) the mass data was insufficient to show correlations in some cases. If the second scenario is to be accepted, it would stand to reason that fewer correlations would be seen in the mass data. This was not the case and therefore, it was accepted that mass data correlations provided the most accurate information on relationships between substances.

Table 5-5 DP concentration/mass cross correlation ($p \le 0.05$, $R_s \ge 0.8$) groups

Location	Concentrations	Masses
Inflow		
Total	1. Cadmium and copper (0.86), lead (0.82), zinc (0.83) 2. Copper and lead (0.83), zinc (0.92) 3. lead and zinc (0.87)	1. Cadmium and copper (0.86), lead (0.80), zinc (0.86), TSS (0.79) 2. Copper and lead (0.94), zinc (0.97), TSS (0.87) 3. Lead and zinc (0.94), TSS (0.80) 4. Zinc and TSS (0.85)
Dissolved	1. Zinc and copper (0.94)	1. TSS and copper (0.86)
Particulate	1. TSS and copper (0.82) 2. Zinc and arsenic (0.90) 3. Copper and arsenic (0.90)	1. Zinc and copper (0.83)
Outflow		
Total	1. Zinc and copper (0.81), lead (0.81)	1. Arsenic and cadmium (0.89), copper (0.87), zinc (0.79), TSS (0.89) 2. Cadmium and copper (0.91), lead (0.90), zinc (0.93), TSS (0.87) 3. Copper and lead (0.93), zinc (0.98), TSS (0.90) 4. Lead and zinc (0.94), TSS (0.84) 5. Zinc and TSS (0.88)
Dissolved	1. Zinc and copper (0.94)	1. TSS and arsenic (0.90), copper (0.93) 2. Zinc and copper (0.83)
Particulate	1. TSS and copper (0.79) 2. Zinc and copper (0.94)	1. TSS and copper (0.96), zinc (0.96)
Fraction Removed		
Total	1. Zinc and copper (0.80), lead (0.84)	1. Cadmium and zinc (0.80) 2. Copper and lead (0.89), zinc (0.90), TSS (0.84) 3. Lead and zinc (0.93), TSS (0.84)
Dissolved	None	1. TSS and copper (0.89) 2. Zinc and copper (0.83)
Particulate	1. TSS and copper (0.79)	1. Copper and lead (0.95), zinc (0.89), TSS (0.84) 2. Lead and zinc (0.96), TSS (0.88)

Note: Values in brackets denote Spearman R_s results

All total metals (masses) except for arsenic showed strong ($R_s \ge 0.8$) and significant ($p \le 0.05$) correlations with each other and with TSS in the inflow, outflow and fraction removed sections. This indicates that these substances were associated in surface runoffs and were similarly removed within ponds.

Dissolved metals (masses) correlated with TSS in the inflow mass section (TSS and copper), outflow mass section (TSS, arsenic and copper) and fraction removals section (TSS and copper). This may have been due to an external relationship between substances and flow volumes i.e. when flow volumes increased then the masses of materials they carried increased proportionally, regardless of whether they were in particulate or dissolved form. Dissolved zinc and copper correlated in the outflow and fraction removed sections, indicating that these substances were similarly removed within ponds.

Particulate zinc and copper masses correlated in the inflow, outflow and fraction removed sections, indicating that these substances were associated in surface runoffs and similarly removed within ponds. Correlations in outflow and fraction removed sections indicated that TSS was associated with particulate copper, lead and zinc removals within ponds. A similar result was found by Hossain, et al. (2005) for a highway detention pond in the USA (see section 2.5.2).

5.3.3 Relationships between substance removals and physical pond parameters

The results of correlation analysis and logistic regression are summarised in Tables 5.6 – 5.8. Physical pond parameters used in the analysis included brim full emptying time (BFET), water quality detention basin mean length (Lwq), water quality detention surface area (SAwq), water quality detention volume (Vwq), pond surface area (SAd), water quality detention volume + forebay volume (Vwq + Vfb), water quality surface area + forebay surface area (SAwq + SAfb), flood control volume (Vfc), watershed area (WA) and the estimated percentage of the watershed that was impervious (%Imperv.). Combinations of these parameters were also used, viz. Vwq/WA, Vwq/SAwq, SAwq/SAd, SAwq/WA, SAwq/Lwq and Lwq/(SAwq/Lwq).

Table 5-6 DP statistically significant correlations ($p \le 0.05$)

Parameter (Nr. of case studies correlated)	Fraction	ALL DATA			POSITIVE DATA ONLY			NEGATIVE DATA ONLY		
		Substance	Split	R_s	Substance	Split	R_s	Substance	Split	R_s
Vwq (9)	Total	-	-	-	Cu	Above Q1	- 0.76	-	-	-
Vwq/ SAwq (8)	Dissolved	Zn	Above Q3	- 0.83	-	-	-	-	-	-
Lwq (8)	Total				Cu	Above Q1	-0.77			
SAd (8)	Total	TSS	None	-0.75						
	Dissolved				As	None	-0.90			
SAwq/Lwq (6)	Dissolved				Cu	None	-0.90			
Lwq / (SAwq/ Lwq) (6)	Dissolved	-	-	-	Zn	Above Q3	+ 0.83	-	-	-
BFET (9)	Total	TSS	None	+ 0.68	-	-	-	-	-	-

Note: Values in brackets denote data set size.

Table 5-7 DP significant ($p \le 0.05$) physical pond parameter efficiency predictors

Substance	Total Fraction	Dissolved Fraction	Particulate Fraction
Arsenic	Vwq/SAwq, -SAwq/WA, SAwq/Lwq	-	Vwq/SAwq, -SAwq/WA, SAwq/Lwq
Cadmium	Vwq/SAwq, -SAwq/WA, SAwq/Lwq	-	-
Copper	-	Vwq/SAwq	-
Lead	-	SAwq/SAd, -SAwq/Lwq, % Imperv.	-
Zinc		-Lwq	
TSS	-SAwq/WA	-	-

Table 5-8 DP significant ($p \le 0.05$) physical pond parameter average negative removals predictors

Substance	Total Fraction	Dissolved Fraction	Particulate Fraction
Arsenic	-	-	-Vwq/SAwq, SAwq/WA, -SAwq/Lwq
Copper	-	-Vwq/SAwq, SAwq/WA, Lwq	-
Lead	-	-SAwq/WA, -Lwq/(SAwq/Lwq), SAwq/Lwq	-
Zinc	Vwq/WA, SAwq/WA, -BFET, SAwq/SAd, -% Imperv.	Vwq/WA, Lwq	-
TSS	-BFET, SAwq/Lwq	-	-

In most cases concentration removal correlations did not have corresponding mass removal correlations. This illustrates that concentration and mass parameters were not interchangeable. Only mass results were therefore reported and further discussed.

In Table 5.6 it can be seen that correlated substances differed between the All Data and Positive Data Only sections. This indicates that, although no correlations were found in the Negative Data Only section, the influence of different pond parameters differed between normal functioning events and events where wash out or large unmonitored inflows, resulting in abnormal pond behaviour, occurred. It is evident; therefore, that negative fraction removal data from such events may influence investigations into pond behaviour if included in the data sets.

Patterns in the types of substances removed per parameter were not observed. The cross correlational analysis between substances indicated that (1) total TSS, cadmium, copper, lead and zinc, (2) dissolved copper and zinc and (3) particulate copper, lead, zinc and TSS masses were associated in pond removals. Paucity in correlation results for some of these mass substances were therefore taken to indicate a lack of data rather than a lack of relationships.

Correlations with data in different split groups i.e. above or below the median, Q1 or Q3 indicate that removals may have been differently influenced by pond parameters over different data ranges.

In general, larger ponds had poorer efficiencies. Correlation results in table 5.6 showed: (1) water quality volume (Vwq) and length (Lwq) negatively correlated with total copper removal in the Positive Data Only section for values above Q1, (2) pond surface area (SAd) negatively correlated to TSS in the ALL Data section and to dissolved arsenic in the Positive Data Only section and (3) pond width (SAwq/Lwq) negatively correlated with dissolved copper in the Positive Data Only section. Logistic regression results in tables 9 and 10 showed: (1) the ratio of water quality surface area to watershed area (SAwq/WA) was a significant predictor for negative removals of particulate arsenic, dissolved copper and total zinc; as well as a significant predictor of decreased probability of arsenic (total and particulate), cadmium (total) and TSS efficiency, (2) the ratio of water quality volume to watershed area (Vwq/WA) was a significant predictor for negative removals of total and dissolved zinc; as well as a significant predictor for decreased probability of dissolved zinc efficiency and (3) the ratio of water quality surface area to pond area (SAwq/SAd) was a significant predictor for negative removal of total zinc.

Therefore, negative correlations, decreased probability of significantly positive efficiencies and increased probability of negative removals were indicated in ponds with larger water quality surface areas and volumes for total, particulate and dissolved substances. This result can be explained by assuming a mechanism of deposition and re-suspension in ponds for particulate material and larger sources of unmeasured inflow for dissolved material (direct rainfall, overland flow, baseflow etc.). Evidence of possible re-suspension and wash out was found in raw data where outflow masses were greater than inflow masses (negative data). Increasing probability of re-suspension in larger ponds may have been due to many factors such as larger storm events with fast and high volume runoffs (the reason for the ponds being large), increased amounts of loose material deposition at pond bottom during normal functioning times resulting in more material available for re-suspension etc.

An exception to this result was that of dissolved lead in Tables 5.7 and 5.8, where SAwq/SAd was a significant predictor for removal efficiency and decreased probability of negative removals through increased SAwq/WA was indicated. Lead was not correlated with dissolved copper and zinc fraction removals. This result therefore indicates that dissolved lead in these case studies were possibly more efficiently removed in ponds with larger surface areas indicating infiltration as a removal mechanism. The reason for this result may be that unmeasured inflow sources were less likely to contain additional lead. Lead pollution is mainly associated with household, industrial and road use activities making it more likely to be captured in formal stormwater systems (pipes, channels etc.). Arsenic, copper and zinc are used in pesticide and herbicides and are therefore more likely to become part of overland runoff and baseflow.

Length to width ratio relationships with pond efficiencies were only found for dissolved substances, viz.(1) Lwq/(SAwq/Lwq) positively correlated with zinc for values above Q3 in the Positive Data Only section and (2) decreased probability of negative dissolved lead removals were indicated by increases and Lwq/(SAwq/Lwq). This indicates that dissolved lead and zinc substance removals were positively influenced by increases in length to width ratios, but in the zinc case this was only seen for higher fraction removals (above Q3).

Brim full emptying time (BFET) was positively correlated with TSS removals. In addition, decreased probability of negative TSS and total zinc removals were indicated by increases in this parameter. Therefore, increased BFET was associated with increased substance removals during normal functioning and decreased negative removals at times in which they occurred. Since most particulate substance removals were correlated with TSS removals, this indicates that detention times of inflow volumes were critically important, possibly due to the allowance of increased settling times for particulate matter.

Basic pond parameters depth, length and width showed unclear and varied relationships to overall pond efficiencies. Increased pond depth was associated with improved and diminished pond efficiencies, viz.: (1) Vwq/SAwq was a significant predictor of total and particulate arsenic and dissolved copper removal efficiencies and (2) decreased probability of average negative particulate arsenic and dissolved copper fraction removals were indicated by increases in Vwq/SAwq. However, Vwq/SAwq was negatively correlated with dissolved zinc removals in the All Data section above Q3. Dissolved zinc and copper removals were correlated. Lampe et al. (2005) also found no clear relationship between TSS concentration removals and basin depth (see section 2.5.2)..

Water quality length (Lwq) was negatively correlated with total copper in the Positive Data Only section for removals above Q1. It was also a significant predictor of decreased dissolved zinc removal efficiency, dissolved zinc negative removal efficiency and dissolved copper negative removal efficiency.

Water quality width (SAwq/Lwq) was a significant predictor of total and particulate arsenic efficiency, total cadmium efficiency and decreased negative particulate arsenic removal efficiency. However, it was also a significant predictor of decreased dissolved lead efficiency; increased negative dissolved lead removal efficiency and increased negative TSS efficiency. No clear pattern was therefore observed. This may have been due to intricate interactions when part of compound parameters such as surface area, volume, BFET etc.

5.3.4 Conclusion

Pond efficiencies over different data ranges

Statistically significant differences between upper and lower data ranges for inflow data indicated that pond efficiencies, defined as fraction removals, differed between high and low inflow concentrations and masses. This provides support to the notion of different removals at different concentrations i.e., that discharge concentrations may be a function of influent concentrations (see Lampe et al (2005)) and adds the knowledge that this also applies to masses.

Cross Correlations between metals and solids

1. Concentration was found to be an inaccurate indicator of correlations between substances in pond inflow and outflow streams as well as the fractions of substances removed within ponds.
2. Mass results indicated that total cadmium, copper, lead, zinc and TSS were associated in surface runoff and were similarly removed within ponds. Some dissolved substances correlated with TSS in the inflow (copper), outflow (arsenic and copper) and fraction removals section (copper). This may have been due to an external relationship between these substances and flow volumes. Results also indicated that dissolved zinc and copper were similarly removed within ponds. Particulate zinc and copper were associated in surface runoffs. Correlations in outflow and fraction removed sections indicated that TSS was associated with particulate copper, lead and zinc removals within ponds.

Relationships between pond efficiencies and pond physical characteristics

1. Indications were found that the influence of different pond parameters differed between normal functioning events and events where negative removals occurred.

2. Indications were found that removals were differently influenced by pond parameters over different data ranges.
3. Patterns in the types of substances removed per parameter were not observed. Paucity in correlation results for mass substances cross-correlated in pond fraction removals were taken to indicate a lack of data rather than a lack of relationships.
4. Mechanisms of substance deposition and re-suspension were indicated. Ponds with larger volumes and surface areas had poorer removal efficiencies and increased probability of negative removals. Increasing probability of re-suspension in larger ponds may have been due to many factors such as larger storm events with fast and high volume runoffs (the reason for the ponds being large) or increased amounts of loose material deposition at pond bottom during normal functioning times resulting in more material available for re-suspension.
5. Length to width ratio relationships with pond efficiencies were only found for dissolved substances zinc (positive correlation for values above Q3) and lead (decreased probability of negative removals).
6. Increased BFET was associated with increased solids removals during normal functioning and decreased probability of negative removals. This indicates that detention times of inflow volumes were key to particulate substance removals. This also indicates settling as a removal mechanism since increased BFETs allow longer settling times.
7. No clear patterns were observed with basic parameters length, width and depth. This may have been due to intricate interactions when part of compound parameters such as surface area, volume, BFET etc.

5.4 Retention ponds results and discussion

5.4.1 Pond efficiencies over different data ranges

The results of the investigation into pond efficiencies over substance data ranges are displayed in Table 5.9. Values statistically significant at $p \leq 0.05$ were displayed in bold. As was alluded to in the literature (see Lampe et al. (2005)) there were statistically significant differences between upper and lower concentration and mass removals groups. This information was used to group data for input into the correlational analysis between substance removals and pond parameters. The split statistics at which significant differences between groups were found are summarised in Table 5.10. The split statistics employed in subsequent correlational analyses are displayed in bold.

Table 5-9 RP sub-range p-values (Mann-Whitney U test) for 2 independent groups

Fraction	**Total**						**Dissolved**						**Particulate**					
Split	**Q1**		**Q3**		**Median**		**Q1**		**Q3**		**Median**		**Q1**		**Q3**		**Median**	
Sub - Case	Conc.	Mass	Conc.	Mass	Conc.	Mass	Conc.	Mass	Conc.	Mass	Conc.	Mass	Conc.	Mass	Conc.	Mass	Conc.	Mass
Cadmium	**0.001**	0.616	**0.025**	0.575	**0.014**	0.098	ID	ID	ID	ID	ID	ID	ID	ID	ID	ID	ID	ID
Copper	**0.000**	**0.026**	**0.000**	**0.000**	**0.000**	**0.029**	**0.000**	**0.012**	**0.000**	0.890	**0.000**	0.083	**0.027**	0.082	0.129	0.443	0.083	**0.005**
Lead	**0.000**	0.149	**0.000**	0.131	**0.000**	**0.036**	0.429	0.556	**0.000**	**0.009**	**0.000**	0.248	0.473	**0.012**	0.089	0.185	0.093	**0.005**
Zinc	**0.005**	0.648	**0.000**	0.082	**0.000**	**0.014**	0.359	**0.001**	0.177	**0.040**	0.080	0.695	0.584	**0.019**	**0.000**	0.825	**0.001**	0.756
TSS	**0.000**	0.146	**0.000**	**0.018**	**0.000**	0.092	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
TVS	**0.018**	0.586	**0.008**	0.913	**0.019**	0.477	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

Note: ID = Insufficient Data, NA = Not Applicable

Table 5-10 RP data splits within data sets for correlational analysis

Fraction	**Total**		**Dissolved**		**Particulate**	
Sub - Case	**Conc.**	**Mass**	**Conc.**	**Mass**	**Conc.**	**Mass**
Cadmium	Q1, Q3,**Median**	**None**	ID	ID	ID	ID
Copper	Q1, Q3,**Median**	Q1, Q3,**Median**	Q1, Q3,**Median**	**Q1**	**Q1**	**Median**
Lead	Q1, Q3,**Median**	**Median**	Q3, **Median**	**Q3**	**None**	Q1, **Median**
Zinc	Q1, Q3,**Median**	**Median**	**None**	**Q1**, Q3	Q3, **Median**	**Q1**
TSS	Q1, Q3,**Median**	**Q3**	NA	NA	NA	NA
TVS	Q1, Q3,**Median**	**None**	NA	NA	NA	NA

Note: ID = Insufficient Data, NA = Not Applicable

5.4.2 Cross Correlations between substances

Table 5-11 RP concentration/mass cross correlation ($p \leq 0.05$, $R_s \geq 0.8$) groups

Fractions	**Concentrations**	**Masses**
Inflow		
Total	1. TSS and TVS (0.85) 2. Copper and lead (0.83), TVS (0.82)	1. Cadmium and copper (0.89), zinc (0.84), TVS (0.87) 2. Copper and lead (0.89), zinc (0.92), TSS (0.84), TVS (0.96) 3. Lead and zinc (0.86), TSS (0.79), TVS (0.80) 4. Zinc and TSS (0.88), TVS (0.90) 5. TSS and TVS (0.93)
Dissolved	1. Cadmium and TSS (0.81) 2. TSS and TVS (0.93)	1. Cadmium and lead (0.90), zinc (0.79), TSS (0.86) 2. Copper and lead (0.91), zinc (0.83), TSS (0.85) 3. Lead and zinc (0.85) 4. Zinc and TSS (0.83), TVS (0.89)
Particulate	1. Copper and zinc (0.86) 2. Lead and zinc (0.82) 3. TSS and TVS (0.79)	1. Cadmium and copper (0.90), lead (0.95), zinc (0.96) 2. Copper and lead (0.89), zinc (0.92), TSS (0.86) 3. Lead and zinc (0.81) 4. Zinc and TSS (0.86), TVS (0.83) 5. TSS and TVS (0.91)
Outflow		
Total	None	1. Cadmium and copper (0.88), lead (0.87), zinc (0.86), TSS (0.86), TVS (0.92) 2. Copper and lead (0.96), zinc (0.90), TSS (0.89), TVS (0.89) 3. Lead and zinc (0.88), TSS (0.89) 4. Zinc and TSS (0.94)
Dissolved	None	None
Particulate	1. Lead and zinc (0.81) 2. Zinc and TSS (0.82)	1. Copper and lead (0.94), zinc (0.87), TSS (0.85) 2. Lead and zinc (0.95), TSS (0.93) 3. Zinc and TSS (0.90)
Fraction Removed		
Total	None	None
Dissolved	None	None
Particulate	1. Zinc and TVS (-0.90)	1. Zinc and copper (0.84), lead (0.88)

Note: Values in brackets denote Spearman R_s results.

It can be seen from Table 5.10 that the most common statistic at which data could be split to find statistically significant differences between the split groups, was the median. This general dominance of the median motivated the choice of this statistic as the default split statistic in all cases in which it appeared. No single split statistic was found to appear in all data sets and an investigation into the required split for a specific data set is recommended in situations where the methodology used in this project is applied.

Association groups in concentration correlations often differed from mass correlations. As for detention ponds, this indicates that (1) the influence of inflow volume affected correlation results for the compound parameter concentration in such a way that correlations between substances were confounded, or (2) the mass data was insufficient to show correlations in some cases. If the second scenario is to be accepted, it would stand to reason that fewer correlations would be seen in the mass data. This was not the case and therefore, once again, it was accepted that mass data correlations provided the most accurate information on relationships between substances.

All total masses showed strong ($R_s \geq 0.8$) and significant ($p \leq 0.05$) correlations with each other, with TSS, and with TVS in the inflow and outflow sections. These substances were therefore associated in surface runoffs and pond outflows, indicating similar removals within ponds.

All dissolved metals masses correlated with TSS in the inflow mass section indicating some relationship between particulate and dissolved matter in runoff streams. This may have been due to an external relationship between substances and flow volumes i.e. when flow volumes increased then the masses of materials they carried increased proportionally, regardless of whether they were in particulate or dissolved form. No correlations were found in the outflow or fraction removed sections.

All particulate metals masses correlated with TSS in the inflow mass section. Zinc correlated with TVS as well, indicating zinc content in the organic particulate material. Particulate copper, lead, zinc and TSS correlated in the outflow section as well, indicating similar removals of these materials within the pond. Particulate zinc, copper and lead also correlated in the fraction removed section, lending support to this indication.

5.4.3 Relationships between substance removals and pond parameters

The results of correlation analysis and logistic regression are shown in Tables 5.12 – 5.14. Physical pond parameters used in the analysis included permanent pool volume (Vpp), forebay volume (Vfb), surcharge detention volume (Vsd), flood control volume (Vfc), permanent pool surface area (SApp), forbay surface area (SAfb), surcharge detention surface area (SAsd), littoral zone surface area (SAlz), permanent pool average length (Lpp), permanent pool average width (Wpp), permanent pool average depth (dpp), percent imperviousness of the watershed area (%

Imperv.), surcharge brim full emptying time (SBF) and hydraulic retention time (Rh). Combinations of these parameters were also used, viz. Vfb + Vpp, Vpp/Vfc, Vpp/Vsd, Vpp/WA, SAfb + SApp, SAlz/SApp, SApp/SAsd, SApp/WA, Vpp/SApp, SApp/Lpp and Lpp:Wpp.

In no cases did concentration removal correlations have corresponding mass removal correlations. This illustrates that concentration and mass parameters were not interchangeable. Only mass results were therefore reported and further discussed. No correlations with dissolved or particulate data were found. This indicates insufficient data for these fractions since correlations were found for total substances, which was composed of dissolved and particulate material.

The results contained few correlations with basic pond parameters such as Vpp, SApp (a similar result for TSS concentrations was found by Lampe et al. (2005), section 2.5.2), Lpp and Wpp in relation to combinations of parameters such as Vpp/Vfc, Vpp/Vsd etc. This possibly indicates that the ponds functioned as a system without significant direct influences from the basic parameters. No correlations with Vpp in the All Data section was in accordance with the findings of Barrett (2008) and Lampe et al. (2005) for metals and TSS concentrations (see section 2.5.2). In his research this was found to be the case when volume equals or exceeds the mean runoff from the mean storm of the area.

Table 5-12 RP statistically significant correlations ($p \leq 0.05$)

Parameter (Nr. of case studies correlated)	Fraction	ALL DATA			POSITIVE DATA ONLY			NEGATIVE DATA ONLY		
		Substance	Split	R	Substance	Split	R	Substance	Split	R
Vpp (19)	Total	-	-	-	-	-	-	Zn	None	+0.68
Vpp / Vfc (7)	Total	-	-	-	Cu TSS	None Below Q3	+ 0.90 + 0.79	-	-	-
Vpp / Vsd (8)	Total	Cu	None	+0.89	Cu Zn	None Above Median	+ 0.89 + 0.90	-	-	-
Vpp / WA (17)	Total	Cu	Above Median	+0.82	Cu	None	+ 0.79	-	-	-
SAlz (7)	Total	-	-	-	Cu	Below Median	- 0.90	-	-	-
SAlz / SApp (7)	Total	-	-	-	-	-	-	TSS	None	+0.94
SApp / SAsd (5)	Total	Cu	Above Median	+0.90	Cu	Above Median	+ 0.90	-	-	-
SApp/Lpp (8)	Total	TSS	Above Q3	- 0.90	TSS	Above Q3	-0.90			
Vpp / SApp (17)	Total	Cu	Above Median	+0.67	Cu	None	+ 0.71	-	-	-
Vpp/dpp (12)	Total							TSS	None	+0.86
Dpp (12)	Total	Pb Zn	Below Median Above Median	- 0.96 - 0.82	Pb	Below and Above Median	- 0.94, - 0.79	-	-	-
% Imperv. (12)	Total							Zn	None	+0.89
SBF (5)	Total	TSS	Below Q3	- 0.90	-	-	-	-	-	-

Note: Values in brackets denote data set size.

Table 5-13 RP significant ($p \leq 0.05$) physical pond parameter efficiency predictors

Substance	Total Fraction	Dissolved Fraction	Particulate Fraction
Copper	Vpp/Vfc	-	-
Lead	-dpp, -SBF	-	-
Zinc	SApp/SAsd, -dpp	-	Vpp/WA, SApp/WA
TVS	-Vpp/WA	-	-

Table 5-14 RP Significant ($p \leq 0.05$) physical pond parameter negative removals predictors

Substance	Total Fraction	Dissolved Fraction	Particulate Fraction
Cadmium	-Vpp/WA, -Vpp/SApp	-	-
Copper	%Imperviousness	-	-Vpp/SApp
Lead	-SApp/SAsd, dpp	-	-
Zinc	-Vpp/Vfc, -SApp/SAsd, Wpp	-SApp/WA	-SApp/WA
TSS	SApp/SAsd, dpp, SBF	-	-

Patterns in the types of substances removed per parameter were not often observed. Copper had the highest number of correlations. The cross correlational analysis between substances indicated that TSS, copper, lead, zinc and TVS masses were associated in pond removals. Paucity in correlation results for some of these mass substances were therefore taken to indicate a lack of data rather than a lack of relationships.

Correlations with data in different split groups i.e. above or below the median, Q1 or Q3 indicate that removals may have been differently influenced by pond parameters over different data ranges.

Increased permanent pool volume in relation to the surcharge detention and flood control volumes (Vpp/Vsd and Vpp/Vfc) were associated with improved pond efficiencies, both during normal functioning and cases where average negative removals occurred viz.:(1) total copper and TSS correlated positively with Vpp/Vfc in the Positive Data Only section, (2) total copper and zinc masses correlated positively with Vpp/Vsd in the Positive Data Only section, (3) increased probability of significant positive total copper efficiencies were indicated by increases in Vpp/Vfc, (4) decreased probability of average negative total zinc removals were indicated by increases in Vpp/Vfc.

This indicates that the volume within the permanent pool was of greater importance to pond efficiencies than the volume captured during storm events, which may simply have drained out of the ponds carrying material not removed within the retention times of the draining volumes.

The same indications were found for pond surface areas, probably through relationships with pond volumes, viz.: (1) total copper mass correlated positively with SApp/SAsd in the All Data and Positive Data Only sections, (2) increased probability of significantly positive total zinc removals were indicated by increases in SApp/SAsd, (3) decreased probability of negative total lead and zinc fraction removals were indicated by increases in SApp/SAsd.

Increased permanent pool volume and surface areas in relation to the watershed area (Vpp/WA and SApp/WA) were also associated with increased pond efficiencies, viz.(1) total copper correlated positively with Vpp/WA in the All Data and Positive Data Only sections, (2) increased probability of significantly positive particulate zinc efficiencies were indicated by increases in Vpp/WA and SApp/WA, (3) decreased probability of average negative total cadmium removals was indicated by increased Vpp/WA and (4) decreased probability of average negative dissolved and particulate zinc removals was indicated by increased SApp/WA.

Exceptions were (1) an increase in the probability of average negative TSS removals with increases in SApp/SASd and (2) decreased probability of significantly positive TVS efficiencies indicated by increases in Vpp/WA. These results may be associated with biological matter growth within ponds between storm events and therefore the results were not indicative of clear relationships.

Inflow volumes may have facilitated mixing of material within the permanent pool with reduced efficiency as a result. Such a phenomenon was possibly indicated by (1) a negative TSS mass correlation with the SBF parameter, (2) decreased probability of significantly positive total lead removal efficiencies with increases in SBF and (3) increased probability of average negative TSS removals with increases in SBF. The results therefore indicated worsening functioning with increased surcharge brim full emptying times possibly due to increased mixing time.

Littoral zone surface area (SAlz) was negatively correlated with total copper mass removals in the Positive Data Only section. The ratio of littoral zone surface area to permanent pool surface area (SAlz/SApp) was positively correlated to TSS in the Negative Data Only section. This indicates that increases in littoral zone negatively affected pond efficiencies during normal pond functioning, possibly through reduction of effective capture volume and effects on pond hydraulics. However, during events where negative removals occurred, littoral zones decreased such removals, possibly by acting as a mechanical hindrance to wash out of particulate material.

Apparent contrasting results for pond depth were found. Total copper removals correlated positively with the Vpp/SApp parameter in the All Data and Positive Data Only sections. In apparent contrast to this, total lead (All Data and Positive Data Only sections) and zinc (All Data section) correlated negatively with the given Dpp parameter. In the logistic regression results, (1) decreased probability of significantly positive total lead efficiencies was indicated by increases in dpp, (2) decreased probability of average negative total cadmium and particulate copper removals were indicated by increased Vpp/SApp and (3) increased probability of average negative total lead and TSS removals were indicated by increased dpp.

Therefore, it was indicated that total copper mass removals were higher and the probability of total cadmium and particulate copper negative removals were lower in ponds with increased depth.

Conversely, total zinc and lead removals, the probability of significantly positive total lead efficiencies and decreased probability of average negative total lead and TSS removals were higher in ponds with decreased depth. Total copper was associated with total zinc, lead and TSS removals in the cross correlation section. Therefore, these results may indicate complexity in the effect of pond depth on metals removals not illuminated here.

The percentage imperviousness of the site was positively correlated with total zinc in the negative data only section. This indicates that negative removals became less with increases in % imperviousness of the watershed. In apparent contrast to this, % imperviousness was a significant predictor for negative total copper removals. Therefore, these results may indicate complexity in the relationship between watershed imperviousness and metals removals not illuminated here.

5.4.4 Conclusion

Pond efficiencies over different data ranges

Statistically significant differences between upper and lower data ranges for inflow data indicated that pond efficiencies, defined as fraction removals, differed between high and low inflow concentrations and masses. This provides support to the notion of different removals at different concentrations i.e., that discharge concentrations may be a function of influent concentrations and adds the knowledge that this also applies to masses.

Cross Correlations between metals and solids substances

1. Concentration was found to be an inaccurate indicator of correlations between substances in pond inflow and outflow streams as well as the fractions of substances removed within ponds.
2. Mass results indicated that total cadmium, copper, lead, zinc and TSS were associated in surface runoff and were similarly removed within ponds. All dissolved substances correlated with TSS in the inflow section. Dissolved zinc also correlated with TVS. This may have been due to an external relationship between these substances and flow volumes. Correlations in outflow and fraction removed sections indicated that TSS was associated with particulate copper, lead and zinc removals within ponds.

Relationships between pond efficiencies and pond physical characteristics

1. In no cases did concentration removal correlations have corresponding mass removal correlations, illustrating that concentration and mass variables were not interchangeable in this study.
2. It was indicated that removals may have been differently influenced by pond parameters over different data ranges.

3. It was indicated that the volume within the permanent pool was of greater importance to pond efficiencies than the volume captured during storm events. However, correlations with this parameter were not found directly, indicating that the ponds operated as complex systems. Therefore, the permanent pool volume was important to the functioning of the ponds, but was only one part of complex systems. For example, it was also indicated that increases in the littoral zone negatively affected pond efficiencies during normal pond functioning, possibly through reduction of effective capture volume and effects on pond hydraulics. However, during events where negative removal occurred, littoral zones decreased such removals, possibly by acting as a mechanical hindrance to wash out particulate material.
4. Negative correlations with surcharge brim full emptying times possibly indicated that inflow volumes may have facilitated mixing of material within the permanent pool with reduced efficiency as a result possibly due to increased mixing times.
5. Apparently contrasting results for pond depth and % imperviousness of the site were found. This may indicate complexity in the relationship between these parameters and metals removals not illuminated here.

6. Modelling

6.1 Introduction

The thesis of this project is that investigations into the relationships between stormwater pond efficiencies and physical pond parameters can be used to augment current pond design methodology towards satisfying South African water requirements for metal toxins as relates to primary food production. Investigations into said relationships entailed descriptive statistics, efficiency evaluations, correlational analysis and logistic regression (Chapters 3, 4 and 5). Application of the project results first required compilation into a comprehensive and illustrative format.

The development of mechanistic conceptual models for pond functioning was possible with the available data and information. Theoretical examination of conclusions relating to the applicable pond processes of sedimentation, scour and re-suspension, was done by means of regression analysis and computer modelling.

This section therefore includes the development of theoretical conceptual models for metals and solids removals in detention and retention ponds as an illustrative means to describe and further examine behavioural trends observed in the data analysis results of previous chapters. It serves to inform the direction that, the author recommends, future design guidelines should take and depicts areas where knowledge is lacking.

Key results from Chapters 4 and 5 indicated both detention and retention ponds to have been generally less efficient at dissolved matter removal than particulate matter removal. In addition, total efficiencies were usually dictated by particulate efficiencies. Most of this section therefore focussed on the processes of particulate matter removal.

6.2 Conceptual models for detention and retention pond functioning

Chapra (2008:13) explains that mechanistic water quality models are based on the principle of conservation of mass, which can be stated as follows for a finite period of time and a segmented volume of water:

Accumulation = loadings ± transport ± reactions

In mathematical terms, and for the water phase, this can be expressed in the following way for retention ponds:

$$\frac{\Delta M}{\Delta t} = M_{in} - M_{out} - M_{settling} - M_{reaction} - M_{infiltration} + M_{resupension} \qquad (6.1)$$

where M = mass, t = time

This philosophy was used as the basis for development of the detention and retention pond conceptual models.

6.2.1 Supporting research

6.2.1.1 Case study model reviews

Models used in the design of the investigated case studies were reviewed for possible application in this project. Information was obtained mainly from internet sources referenced in the International Stormwater BMP Database (Water Environment Research Federation, Federal Highway Administration, American Public Works Association, Environmental and Water Resources Institute, 2011). Results are displayed in Tables 6.1 and 6.2.

Retention ponds:

Table 6-1 RP case study design information

Case Study	**Approximate Shape**	**Design Basis**	**Reference**	**General Efficiency (Total Fraction)**
Central Park	3 areas: Triangle, Squat Rectangle and Long Rectangle	-	International Stormwater BMP database, v.07.07.11	Medium
Cockroach Bay	2 areas: Triangle and Squat Rectangle	-	(Rushton, 2002)	Good
De Bary	Squat Rectangle	Florida Administrative Code Chp. 40C-42: capture specified volume and have specified draw down time	(Harper & Herr, 1993)	Medium
Greens Bayou	Squat Rectangle	Surge Basin	(Wetland Solutions Inc., 2010)	Poor
Heritage Estates	L-Shape	Pre-development flow rates for 5 and 100yr storms	(SWAMP Program, 2005)	Medium
I5 La Costa East	Triangle	Water quality volume approach	(California Department of Transportation, 2004)	Good
Lake Ellyn	Rectangle	n/a	(Striegl & Cowan, 1987)	Good
Lakeside	Long Triangle	Runoff quantity control	(Wu, 1989)	Medium
Lake Ridge	Long Triangle	According to EPA guidelines	(Walker, 1993)	Good
Madison Monroe str.	Triangle (curved sides)	Water quality (design method unknown)	(House et al., 1993)	Good
McKnight Basin	2 areas: Triangle and Indeterminable shape	-	(Oberts et al., 1989)	Good
Phantom Lake Pond A	3 areas: Triangle, Squat Rectangle, Rectangle	King County Water Quality Design Manual (King County 1990) : Assumed 80% TSS removal with design volume at least 3 times mean annual storm runoff volume	(Comings et al., 2000)	Good
Pinellas	L-Shape	Runoff quantity control and water quality improvement (design method unknown)	(Kantrowitz & Woodham, 1995)	Poor
Pittsfield	Irregular rounded	-	International Stormwater BMP database, v.07.07.11	Medium
Runaway Bay	Long Triangle	Runoff quantity control	(Wu, 1989)	Medium
Silver Star rd.	Rectangle	-	(Martin & Smoot, 1986)	Poor
Tampa Office Pond 1	Irregular L-Shape	Treatment volume – 0.5 inch watershed runoff	(Rushton et al., 1997)	Medium
Tampa Office Pond 2	Irregular L-Shape	As above, but with greater pool fluctuation allowed	(Rushton et al., 1997)	Medium
Tampa Office Pond 3	Irregular Rectangle	Permanent pool with 1 inch watershed runoff volume and 14 d residence time	(Rushton et al., 1997)	Good

Note: "-" denotes areas where information was not found.

Table 6.1 shows that design methodologies were in all cases based on flood control, water quality volume approaches or prescriptive approaches. This was similar to the results found for detention pond data.

These approaches are discussed in detail in Chapter 7. In summary, water quality volume (WQV) approaches are usually similar in the parameters that they incorporate e.g. water quality volume, % site imperviousness, basin drain time, storm rainfall depth, watershed area and soil classification. They are simplistic and easy to apply. However, such models are deficient in the amount of information that they use and can provide. The WQV approaches investigated in this project (Refer to Addendum A) included parameters for which information is easy to obtain, but did not encompass the range parameters that influence pond efficiency, e.g. % imperviousness of a site is easy to calculate, but was not found to have a clear relationship with pond efficiency in Chapter 5. Other parameters that were found to possibly influence pond efficiencies such as Vpp/Vsd, Vpp/Vfc and littoral zone area were not included as parameters in these models.

Prescriptive approaches often incorporate the removal of a TSS fraction, are based on site specific rainfall statistics and prescribe design elements such as draw down times, pond depth, littoral zone coverage area etc. The focus of many such methods is done on the claim that specified TSS removals may be achieved simply by following prescribed design methods. Debo and Reese (2003) have stated that detention of storms more frequent than about 6 months for minimum 24h can effect a long term TSS removal rate of about 80% but criteria may differ between different regions. These methods therefore do not incorporate mechanistic modelling elements.

Although the general efficiency of many ponds designed with these methods was relatively good, the approaches followed were deficient in accurately describing the functioning of retention ponds and were not useful in this project.

Detention Ponds:

Table 6.2 shows that design methodologies were in all cases, where information was obtained, based on flood control, water quality volume approaches or prescriptive approaches. This was similar to the results found for retention pond data.

As discussed previously, water quality volume (WQV) and prescriptive approaches are simplistic and easy to apply but are deficient in the amount of information that they use and can provide. Therefore, although the general efficiency of many ponds designed with these methods was relatively good, the approaches followed were deficient in accurately describing the functioning of detention ponds and were again not useful to this project.

Table 6-2 DP case study design information

Case Study	**Approximate Shape**	**Design Basis**	**Reference**	**General Efficiency (Total Fraction)**
El Dorado	Segmented Rectangle	Runoff Quantity Control: 100 year flood event	(PBS&J, 2004)	Poor
Grant Ranch	Triangle	WQCV approach	(Piza & Eisel, 2009)	Good
Greenville	Irregular Square	Treatment volume – 1.3 cm watershed runoff	(Stanley, 1994)	Good
I5/I605 EDB	L-Shape	WQV approach	(California Department of Transportation, 2004)	Poor
I5/SR56 EDB	L-Shape	WQV approach	(California Department of Transportation, 2004)	Medium
I5 Manchester East EDB	L-Shape	WQV approach	(California Department of Transportation, 2004)	Good
I15/SR78 EDB	L-Shape	WQV approach	(California Department of Transportation, 2004)	Good
I605/SR91 EDB	L-Shape	WQV approach	(California Department of Transportation, 2004)	Good
Lexington Hills	Irregular Triangle	-	-	Good
Mountain Park	-	-	-	Poor

Note: "-" denotes areas where information was not found.

6.2.1.2 Data trends indicative of pond functioning

Previous chapters focussed on relationships between pond efficiencies and physical parameters. Modelling required additional information and the following where investigated:

A. The relationship between outflow mass and (1) inflow mass, (2) outflow volume and (3) inflow volume:

1. Inflow and outflow mass and volume data was compiled in tabular form. Data was grouped by case study and substance.
2. Outflow mass data was plotted against (1) inflow mass, (2) outflow volume and (3) inflow volume data with the software program Excel 2010 (Copyright© Microsoft Corporation). The plots were used to identify and remove outliers from the data sets. Extreme events were therefore not included. The functioning of ponds during such events was considered extraneous to the purposes of the project at this point.
3. Data entries where outflow mass was greater than inflow mass were removed. These entries possibly represent storm events where re-suspension and wash out occurred and were removed to limit confounding of the results by these events.
4. The cleaned data sets were used as input into the software program STATISTICA v.11 (Copyright© StatSoft, Inc. 1984-2012). Due to small sample sizes ($N < 50$) normality was not assumed and the Spearman correlation coefficient was calculated.

B. The relationships between volume gains or losses and mass gains or losses:

1. The differences between inflow and outflow volumes as well as masses were calculated per storm events and tabulated. Mass gains were grouped with volume gains and mass losses were grouped with volume losses. Calculations were as follows:

$$fM_{loss/gain} = \frac{(M_{in} - M_{out})}{M_{in}} \qquad (6.2)$$

$$V_{loss/gain} = |V_{in} - V_{out}| \qquad (6.3)$$

2. where $fM_{loss/gain}$ = the fraction of mass lost or gained per storm event (a positive value denotes mass lost and a negative value denotes mass gained), M_{in} = the mass calculated from the Event Mean Concentration (EMC) measured in the inflow during a storm event, M_{out} = the mass calculated from the EMC measured in the outflow during a storm event, $V_{loss/gain}$ = the volume lost or gained during a storm event, V_{in} = the total volume measured in the inflow during a storm event and V_{out} = the total volume measured in the outflow during a storm event.
3. The grouped data sets were used as input into the software program STATISTICA v.11 (Copyright© StatSoft, Inc. 1984-2012). Due to small sample sizes (N < 50) normality was not assumed and the Spearman correlation coefficient was calculated.

Tables 6.3 – 6.10 contain the results. Values in bold denote data sets with a correlation p-value ≤ 0.05. Values in italics denote data sets with a correlation p-value ≤ 0.01. The results of efficiency classifications in Chapter 4 were overlaid. Data sets with negative efficiencies were too small to provide useable information in this section. The following key applies:

🟪	Generally Unresponsive Efficiency
🟦	Not Significantly Positive Efficiency
🟩	Significantly Positive Efficiency

Retention Ponds:

The majority of case studies had statistically significant ($p \leq 0.05$) strong ($R \geq 0.8$) monotonic correlations between suspended solids outflow mass data and (1) inflow mass data (a similar result was found for TSS concentrations by Barrett (2008) (see section 2.5.2,) (2) outflow volume data as well as (3) inflow volume data. Useable data for particulate and dissolved metals fractions was scarce, obtained only from the De Bary, I5 La Costa East and Lake Ellyn case studies. Data for cadmium was not obtained. These data trends followed the same general patterns as seen in the total suspended solids data.

A comparison of the results with the pond efficiency classifications indicated that the monotonic relationships were not related to pond efficiencies. Significant and strong correlations were found for case studies classified as generally unresponsive, not significantly positive as well as significantly positive for a range of substances. This indicates that pond efficiencies as classified in Chapter 4 were independent of the relationships between the correlated data groups, i.e. ponds with poor substance removals showed similar monotonic trends to ponds with good substance removals in some cases. This was also indicated for both dissolved and particulate substances. Although it must be remembered that only 3 case studies had useable dissolved and particulate data.

Weak correlations (R < 0.6) between masses removed/ gained and volume loss/gain were found for all substances as shown in Table 6.6. Statistically significant (p ≤ 0.05) results were found in some cases, viz. (1) mass removed vs. volume losses for particulate cadmium, lead and TSS substances and (2) mass added vs. volume gain for TSS. These correlations, however, had low R-values and no conclusions were made.

It was indicated that the ponds had similar behaviour in general in terms of TSS removal. In Chapter 5 it was found that particulate copper, lead, and zinc masses were associated in pond removals. Particulate cadmium also significantly correlated with copper, lead, zinc, TSS and TVS in the pond outflows. The Department of Water Affairs and Forestry (1996c) has stated that cadmium strongly interacts with zinc and is strongly adsorbed by clay minerals. Therefore it was concluded that cadmium matter was affected similarly to the other included metals within the ponds during physical removal processes.

Table 6-3 RP spearman correlations between pond inflow and outflow mass data

Case Study	**TSS**		**TVS**		**Part. Copper**		**Part. Lead**		**Part. Zinc**		**Diss. Copper**		**Diss. Lead**		**Diss. Zinc**	
	R	p	R	p	R	p	R	p	R	p	R	p	R	p	R	p
Central Park	*0.8*	***0.01***	0.7	**0.05**	-	-	-	-	-	-	-	-	-	-	-	-
Cockroach Bay	*0.8*	***0.00***	-	-	-	-	-	-	-	-	-	-	-	-	-	-
De Bary	0.3	0.46	-	-	-	-	-	-	-	-	0.90	**0.04**	-	-	0.6	0.11
Greens Bayou	0.5	0.22	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Heritage Estates	0.4	0.21	-	-	-	-	-	-	-	-	-	-	-	-	-	-
I5 La Costa East	*0.9*	***0.00***	-	-	*0.9*	***0.00***	*1.0*	***0.00***	*0.8*	***0.00***	*0.8*	***0.00***	0.5	0.09	*0.8*	***0.01***
Lake Ellyn	0.5	**0.04**	-	-	0.4	0.11	0.5	**0.04**	0.3	0.27	0.5	0.13	-	-	0.5	**0.04**
Lake Ridge	0.6	**0.02**	*0.9*	***0.00***	-	-	-	-	-	-	-	-	-	-	-	-
Lakeside	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Madison Monroe str.	0.8	**0.00**	*0.6*	***0.01***	-	-	-	-	-	-	-	-	-	-	-	-
McKnight Basin	0.6	0.06	*0.8*	***0.00***	-	-	-	-	-	-	-	-	-	-	-	-
Phantom Lake	*1.0*	***0.00***	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pittsfield	*0.9*	***0.01***	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Runaway Bay	*0.9*	***0.01***	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Tampa Office Pond 1	0.5	**0.02**	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Tampa Office Pond 2	*0.9*	***0.00***	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Tampa Office Pond 3	*0.6*	***0.00***	-	-	-	-	-	-	-	-	-	-	-	-	-	-
UNH	0.8	0.07	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Note: R = Spearman correlation coefficient, p = p value, “-“ denotes insufficient data available.

Table 6-4 RP spearman correlations between pond outflow volume and mass data

Case Study	**TSS**		**TVS**		**Part. Copper**		**Part. Lead**		**Part. Zinc**		**Diss. Copper**		**Diss. Lead**		**Diss. Zinc**	
	R	p	R	p	R	p	R	p	R	p	R	p	R	p	R	p
Central Park	*0.8*	***0.00***	*0.9*	***0.00***	-	-	-	-	-	-	-	-	-	-	-	-
Cockroach Bay	*0.9*	***0.00***	-	-	-	-	-	-	-	-	-	-	-	-	-	-
De Bary	*0.8*	***0.03***	-	-	-	-	-	-	-	-	-	-	-	-	*0.9*	***0.00***
Greens Bayou	*0.9*	***0.00***	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Heritage Estates	*0.9*	***0.00***	-	-	-	-	-	-	-	-	-	-	-	-	-	-
I5 La Costa East	*0.7*	***0.01***	-	-	*0.8*	***0.00***	*0.9*	***0.00***	*0.8*	***0.00***	*0.8*	***0.00***	*0.9*	***0.00***	*0.9*	***0.00***
Lake Ellyn	*0.7*	***0.00***	-	-	0.5	0.09	*0.7*	***0.00***	0.4	**0.20**	*0.9*	***0.00***	-	-	*0.8*	***0.00***
Lake Ridge	0.4	0.17	0.6	0.08	-	-	-	-	-	-	-	-	-	-	-	-
Lakeside	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Madison Monroe str.	*0.9*	***0.00***	*0.9*	***0.00***	-	-	-	-	-	-	-	-	-	-	-	-
McKnight Basin	0.0	0.96	*0.8*	***0.00***	-	-	-	-	-	-	-	-	-	-	-	-
Phantom Lake	0.5	0.11	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pittsfield	0.8	**0.05**	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Runaway Bay	*0.9*	***0.01***	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Tampa Office Pond 1	*0.9*	***0.00***	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Tampa Office Pond 2	*0.8*	***0.00***	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Tampa Office Pond 3	*0.9*	***0.00***	-	-	-	-	-	-	-	-	-	-	-	-	-	-
UNH	0.8	**0.04**	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Note: R = Spearman correlation coefficient, p = p value, "-" denotes insufficient data available.

Table 6-5 RP spearman correlations for outflow mass vs. inflow volume

Case Study	**TSS**		**TVS**		**Part. Copper**		**Part. Lead**		**Part. Zinc**		**Diss. Copper**		**Diss. Lead**		**Diss. Zinc**	
	R	p	R	p	R	p	R	p	R	p	R	p	R	p	R	p
Central Park	*0.8*	***0.00***	*0.9*	*0.00*	-	-	-	-	-	-	-	-	-	-	-	-
Cockroach Bay	*0.9*	***0.00***	-	-	-	-	-	-	-	-	-	-	-	-	-	-
De Bary	0.6	0.10	-	-	-	-	-	-	-	-	0.9	**0.04**	-	-	0.5	0.14
Greens Bayou	0.6	0.11	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Heritage Estates	*0.9*	***0.00***	-	-	-	-	-	-	-	-	-	-	-	-	-	-
I5 La Costa East	*0.7*	***0.01***	-	-	*0.8*	***0.00***	*0.9*	***0.00***	*0.8*	***0.00***	*0.8*	***0.00***	*0.9*	***0.00***	*0.9*	***0.00***
Lake Ellyn	*0.7*	***0.00***	-	-	*0.7*	***0.01***	*0.7*	***0.00***	*0.8*	***0.00***	*0.9*	***0.00***	-	-	*0.6*	***0.01***
Lake Ridge	0.4	0.17	0.6	0.07	-	-	-	-	-	-	-	-	-	-	-	-
Lakeside	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Madison Monroe str.	*0.9*	***0.00***	*0.9*	***0.00***	-	-	-	-	-	-	-	-	-	-	-	-
McKnight Basin	0.0	0.88	*0.8*	***0.00***	-	-	-	-	-	-	-	-	-	-	-	-
Phantom Lake	0.5	0.11	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pittsfield	0.8	**0.05**	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Runaway Bay	*0.9*	***0.01***	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Tampa Office Pond 1	*0.6*	***0.00***	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Tampa Office Pond 2	*0.8*	***0.00***	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Tampa Office Pond 3	*0.7*	***0.00***	-	-	-	-	-	-	-	-	-	-	-	-	-	-
UNH	*0.9*	***0.00***	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Note: R = Spearman correlation coefficient, p = p value, "-" denotes insufficient data available.

Table 6-6 RP spearman correlations between masses and volumes

Substance	Mass Removed vs. Volume Loss						Mass Added vs. Volume Gain					
	Dissolved			Particulate			Dissolved			Particulate		
	N	R	p	N	R	p	N	R	p	N	R	p
Cadmium	5	-0.5	0.39	12	0.6	0.03	-	-	-	5	0.0	1.00
Copper	28	0.3	0.15	32	0.1	0.77	16	0.0	0.88	3	1.0	-
Lead	25	0.1	0.73	28	0.4	0.04	17	-0.4	0.13	-	-	-
Zinc	42	0.2	0.32	39	0.2	0.16	13	0.0	0.96	8	-0.5	0.26
TSS	-	-	-	*234*	*0.2*	*0.00*	-	-	-	47	0.3	0.02
TVS	-	-	-	56	0.2	0.21	-	-	-	10	-0.1	0.83

Note: N = number of data points, R = Spearman correlation coefficient, p = p value.

Detention Ponds:

Significant ($p \leq 0.05$) and strong ($R \geq 0.8$) correlations were found for many case studies for all correlated data groups, viz. outflow mass vs. (1) inflow mass, (2) outflow volume and (3) inflow volume, as well as across metals and solids substances. A comparison of these results with the pond efficiency classifications indicated that the found monotonic relationships were not related to pond efficiencies. Significant and strong correlations were found for case studies classified as generally unresponsive, not significantly positive as well as significantly positive for a range of substances. This indicates that pond efficiencies as classified in Chapter 4 were independent of the relationships between the correlated data groups, i.e. ponds with poor substance removal efficiencies showed similar trends (monotonic) to ponds with good substance removal efficiencies in many cases. This was indicated for both dissolved and particulate substances. These results are similar to retention pond results.

The results indicate that many case studies had monotonic relationships between outflow masses and inflow masses, inflow volumes and outflow volumes for both particulate and dissolved substances regardless of the classified efficiency of the case study. Varying results made distinguishing between different substances difficult; however, arsenic notably had the least number of correlations. This lack of information for arsenic was also seen in cross correlations between metals in Chapter 5. This may indicate that arsenic behaved differently to other metals or that the data sets were too small to elucidate significant relationships.

Table 6-7 DP spearman correlations between pond inflow and outflow mass data

Case Study	TSS		Part. Arsenic		Part. Cadmium		Part. Copper		Part. Lead		Part. Zinc		Diss. Arsenic		Diss. Cadmium		Diss. Copper		Diss. Lead		Diss. Zinc	
	R	p	R	p	R	p	R	p	R	p	R	p	R	p	R	p	R	p	R	p	R	p
El Dorado	0.5	0.13	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Grant Ranch	*0.9*	***0.00***	-	-	-	-	-	-	-	-	0.2	0.64	-	-	-	-	-	-	-	-	0.7	**0.02**
Greenville	*0.9*	***0.01***	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
I5/I605 EDB	*0.8*	***0.01***	-	-	-	-	*0.8*	***0.01***	0.6	0.12	0.8	**0.02**	-	-	0.9	**0.04**	-	-	*0.9*	***0.00***	*0.9*	***0.00***
I5/SR56 EDB	0.2	0.58	-	-	-0.5	0.30	0.4	0.29	0.6	0.12	0.4	0.24	-	-	-	-	0.4	0.34	0.6	0.09	0.4	0.40
I5 Manchester East EDB	*0.9*	***0.00***	*0.9*	***0.00***	*0.8*	***0.00***	*0.9*	***0.00***	*0.9*	***0.00***	*0.8*	***0.00***	-	-	*0.9*	***0.00***	*0.8*	***0.00***	*0.9*	***0.00***	*0.9*	***0.00***
I15/SR78 EDB	*1.0*	***0.00***	0.6	0.10	-	-	*0.7*	***0.00***	-	-	*0.8*	***0.00***	0.8	0.07	-	-	*0.9*	***0.00***	-	-	*1.0*	***0.00***
I605/SR91 EDB	0.5	0.14	-	-	-	-	0.8	**0.04**	0.8	**0.04**	0.8	**0.04**	-	-	-	-	0.4	0.40	0.9	**0.04**	0.6	0.21
Lexington Hills	0.7	**0.02**	*0.8*	***0.01***	-	-	*0.9*	***0.00***	-	-	*0.7*	***0.01***	0.1	0.70	-	-	0.7	**0.03**	-	-	0.7	0.07
Mountain Park	0.2	0.75	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

<u>Note:</u> R = Spearman correlation coefficient, p = p value, “-“ denotes insufficient data available.

Table 6-8 DP spearman correlations between pond outflow volume and mass data

Case Study	TSS		Part. Arsenic		Part. Cadmium		Part. Copper		Part. Lead		Part. Zinc		Diss. Arsenic		Diss. Cadmium		Diss. Copper		Diss. Lead		Diss. Zinc	
	R	p	R	p	R	p	R	p	R	p	R	p	R	p	R	p	R	p	R	p	R	p
El Dorado	*0.8*	***0.00***	-	-	-	-	0.8	0.10	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Grant Ranch	*0.9*	***0.00***	-	-	-	-	-	-	-	-	0.6	0.15	-	-	-	-	-	-	-	-	0.8	**0.02**
Greenville	0.7	0.09	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
I5/I605 EDB	*0.9*	***0.00***	-	-	-	-	0.8	**0.02**	*0.9*	***0.01***	*0.9*	***0.01***	-	-	-	-	*0.9*	***0.00***	*1.0*	***0.00***	*0.9*	***0.00***
I5/SR56 EDB	*0.9*	***0.00***	-	-	0.5	0.30	0.7	**0.04**	0.8	**0.02**	*0.9*	***0.00***	-	-	-	-	*0.9*	***0.01***	*1.0*	***0.00***	0.8	0.07
I5 Manchester East EDB	*0.8*	***0.00***	0.4	0.39	0.6	0.07	*0.7*	***0.01***	*0.7*	***0.00***	0.6	**0.02**	0.2	0.70	*0.8*	***0.01***	*0.7*	***0.01***	*0.8*	***0.00***	*0.8*	***0.00***
I15/SR78 EDB	*0.9*	***0.00***	0.6	0.14	-	-	*0.8*	***0.00***	-	-	*0.8*	***0.00***	0.5	0.33	-	-	*0.9*	***0.00***	-	-	*0.9*	***0.00***
I605/SR91 EDB	0.7	**0.05**	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.8	**0.04**	0.9	**0.04**	*0.9*	***0.00***
Lexington Hills	*0.9*	***0.00***	*0.9*	***0.00***	-	-	*0.9*	***0.00***	-	-	*0.7*	***0.01***	*0.9*	***0.00***	-	-	0.8	**0.02**	-	-	0.8	**0.05**
Mountain Park	0.3	0.62	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

<u>Note:</u> R = Spearman correlation coefficient, p = p value, “-“ denotes insufficient data available.

Table 6-9 DP spearman correlations for outflow mass vs. inflow volume

Case Study	TSS		Part. Arsenic		Part. Cadmium		Part. Copper		Part. Lead		Part. Zinc		Diss. Arsenic		Diss. Cadmium		Diss. Copper		Diss. Lead		Diss. Zinc	
	R	p	R	p	R	p	R	p	R	p	R	p	R	p	R	p	R	p	R	p	R	p
El Dorado	0.6	**0.04**	-	-	-	-	0.8	0.10	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Grant Ranch	*1.0*	***0.00***	-	-	-	-	-	-	-	-	0.8	**0.05**	-	-	-	-	-	-	-	-	*0.9*	***0.00***
Greenville	0.7	0.09	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
I5/I605 EDB	*0.9*	***0.00***	-	-	-	-	0.8	**0.02**	*0.9*	***0.01***	*0.9*	***0.01***	-	-	-	-	*0.9*	***0.00***	*1.0*	***0.00***	*0.9*	***0.00***
I5/SR56 EDB	*0.8*	***0.00***	-	-	-	-	0.7	**0.04**	0.7	**0.03**	0.5	0.22	-	-	-	-	0.5	0.25	0.8	**0.03**	0.4	0.40
I5 Manchester East EDB	*0.8*	***0.00***	0.4	0.29	0.6	0.11	*0.7*	***0.00***	*0.7*	***0.00***	*0.7*	***0.01***	0.6	0.21	*0.9*	***0.01***	*0.7*	***0.01***	*0.7*	***0.01***	*0.9*	***0.00***
I15/SR78 EDB	0.4	0.31	0.6	0.14	-	-	*0.8*	***0.00***	-	-	*0.7*	***0.00***	0.5	0.33	-	-	*0.9*	***0.00***	-	-	*0.9*	***0.00***
I605/SR91 EDB	0.5	0.15	-	-	-	-	0.8	**0.04**	0.8	**0.04**	0.8	**0.04**	-	-	-	-	0.6	0.21	0.6	0.28	0.7	0.16
Lexington Hills	0.0	0.88	-0.3	0.40	-	-	0.1	0.66	-	-	-0.2	0.54	-0.2	0.65	-	-	0.4	0.24	-	-	0.4	0.43
Mountain Park	0.4	0.49	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

<u>Note:</u> R = Spearman correlation coefficient, p = p value, “-“ denotes insufficient data available.

Table 6-10 DP spearman correlations between masses and volumes

Substance	**Mass Removed vs. Volume Loss**						**Mass Added vs. Volume Gain**					
	Dissolved			Particulate			Dissolved			Particulate		
	N	R	p	N	R	p	N	R	p	N	R	p
Arsenic	*27*	*0.7*	*0.00*	*33*	*0.5*	*0.00*	9	-0.5	0.13	3	0.0	1.00
Cadmium	19	0.5	0.02	18	0.3	0.27	5	-0.7	0.18	1	-	-
Copper	*59*	*0.4*	*0.00*	*68*	*0.4*	*0.00*	*24*	*-0.7*	*0.00*	12	-0.5	0.09
Lead	33	0.2	0.21	*34*	*0.5*	*0.01*	11	-0.6	0.04	8	-0.5	0.23
Zinc	60	0.5	0.00	*72*	*0.4*	*0.00*	24	-0.4	0.04	8	0.3	0.51
TSS	-	-	-	*109*	*0.4*	*0.00*	-	-	-	22	-0.4	0.08

Note: N = number of data points, R = Spearman correlation coefficient, p = p value.

In Table 6.10, weak correlations ($R < 0.6$) were found for all substances, except for dissolved arsenic removal via volume loss and dissolved copper and lead addition via volume gain. Statistically significant ($p \leq 0.05$ and $p \leq 0.01$) results were found in many cases indicating that the correlations were significantly different from 0. Notably such results were found for the majority of (1) dissolved and particulate substance removed correlations with volume loss and (2) dissolved mass added correlations with volume gain. (1) May indicate that dissolved and particulate material was lost with volume losses such as infiltration and spill. Interestingly, significant correlations between all dissolved mass added and volume gains were negative. The reason for this result remains unclear.

6.2.1.3 Processes

A lack of detailed data within the case study data sets necessitated the use of information re. metals chemistry and biological uptake within surface waters from outside sources. In addition:

1. Descriptive statistics for pH were compiled with the software program Excel 2010 (Copyright© Microsoft Corporation). Data was obtained from the International Stormwater BMP database (Water Environment Research Federation, Federal Highway Administration, American Public Works Association, Environmental and Water Resources Institute, 2011).
2. Correlational analysis results between (1) substances and (2) substance removals and pond physical parameters (Chapter 5) were used to provide indications towards the most likely processes that played a role in general pond functioning.
3. Logistic regression between (1) general pond efficiencies and physical pond parameters and (2) negative removals and physical pond parameters (Chapter 5) were used to provide indications towards the most likely processes that played a role in general pond functioning.

Retention Ponds:

It is likely that stormwater ponds have two different functioning periods, viz. (1) functioning during a storm event and (2) functioning between storm events. Storm events are here defined as encompassing the time between when flows into the pond begin and flows out of the pond end. During storm events, therefore, pond hydraulics were accepted to play a major role in pond functioning. Between storm events were accepted to be dominated by quiescent settling processes with the possible inclusion of chemical and biological processes in retention ponds.

Chemical processes:

It is unlikely that any of the included metals were removed during storms, or even during quiescent conditions, by chemical processes. Arsenic removal requires conversion, coagulation and subsequent settlement. Cadmium, copper and zinc removal requires high pH (>8.5) and subsequent precipitation. Copper removal also requires high pH and precipitation. Lead removal requires chemical coagulation and subsequent settlement (Department of Water Affairs and Forestry, 1996a,b,c).

Metals are also known to precipitate in sulphur rich sediment during anoxic conditions (Chapra, 2008:763), however, no evidence of such conditions was observed in the data. Therefore, assuming no outside addition of chemical coagulants to the system during storm events, pH was postulated to be the main factor controlling possible chemical precipitation in the studied ponds.

The international Stormwater BMP database, v.07.07.11, available on www.bmpdatabase.org. contained influent and effluent pH data for approximately 340 events for 19 detention and retention pond case studies. These included case studies used in this project viz. I5/SR56, I5 Manchester East, I15/SR78 EDB, I5/I605 EDB, I605/SR91 EDB, Lexington Hills and Mountain Park. A combined analysis of all the data (N = 678) provided the following statistics: arithmetic mean = 7.4, range = 4.3 to 9.6, IQR = 7.1 to 7.5 and Q3 = 7.85. This indicates that the pond pH of these case studies rarely rose above the required 8.5. Therefore, assuming similar behaviour in the other case studies, chemical precipitation is deemed to have been an unlikely metal removal process in the studied stormwater ponds.

Biological processes:

Littoral zone surface area (SAlz) was negatively correlated with total copper mass removals during normal pond functioning. The ratio of littoral zone surface area to permanent pool surface area (SAlz/SApp) was positively correlated to TSS in the Negative Data Only section. This indicates that increases in littoral zone negatively affected pond efficiencies during normal pond functioning, possibly through reduction of effective capture volume and effects on pond hydraulics. However, during events where negative removal occurred, littoral zones decreased such removals, possibly by acting as a mechanical hindrance to wash out of particulate material. A comparative result was found by Winston et al. (2013) during a study into the effect on stormwater pond efficiency through floating treatment wetland retrofits. They found that surface area coverage appeared to affect treatment performance positively. In addition, they found statistically significant TSS reductions post retrofit for one of the studied ponds, which had greater surface area coverage than the correspondingly studied pond. They therefore postulated that increased hydraulic resistance by the plants themselves influenced sedimentation.

Studies on metals (Cd, Cu, Zn) uptake of macrophytes in wetlands have indicated that retained metals were stored mainly in the sediment compartment with biological uptake being comparatively small and slow uptake of metals by rooted plants due to immobilisation of metals in the sediment (Hadad et al., 2006) (Yeh et al., 2009) (Galletti et al., 2010). Biological uptake of metals by plants occur in the root zone, which is located within pond sediment. Therefore, the uptake of metals from particulate material requires such material to be settled to the root zone first, i.e. through physical processes. Similarly, dissolved material must diffuse to the root zone before it can be absorbed. Therefore, biological processes from the littoral zone are unlikely to have significantly influenced particulate metals or solids removal from the water column during storm events. This was not negated by the monotonic relationships between inflow and outflow dissolved masses.

Portele et al. (1982) performed a study on the impact of stormwater runoff in Washington, USA on aquatic biota. They found that negative impacts on algae and zooplankton due to the presence of high levels of metal contaminants in runoff. They suggested dilution of stormwater to protect aquatic areas from highways with traffic of more than 10 000 vehicles per day. Although the study included lead, a metal now mostly phased out in petrol, it also included copper and zinc which are present as much today as during the 80’s, if not more so. This study indicates that biological uptake of metals within ponds by organisms other than macrophytes at any time may be negatively affected by toxicity of the metals to the biota.

Physical processes:

Characteristics required by a hypothetical pond, based on findings in Chapter 5, which should improve efficiency during storm events, were:

1. Increased permanent pool volume in relation to the surcharge detention and flood control volumes.
2. Increased permanent pool volume in relation to the watershed area.
3. Increased littoral zone area in relation to the permanent pool surface area. This parameter must be designed so as not to negatively affect normal pond functioning through hydraulic effects.
4. Increased permanent pool surface area in relation to the surcharge detention area.

In general, therefore, the results indicate that pools with large storage capacity and large littoral zones performed best in stormwater TSS and the studied metals’ removals. Geosyntech Consultants Inc. & Wright Water Engineers Inc. (2011) have stated that structures with large retention times, laminar flow, shallow depths and the presence of vegetation can improve sedimentation. Elliot (2000) found that vegetation with a horizontal component can increase the sediment removal rate from the water column through settling directly onto the vegetation. Furthermore, he found that vegetation induces vertical mixing. Yousef et al. (1990) found evidence to indicate that the majority of particulate cadmium, copper, lead and zinc metals from highway runoff may settle out quickly upon entering a pond. Yousef et al. (1994) found a strong correlation between pond surface area and sedimentation for 9 different ponds. These results therefore provide support to the notion that sedimentation was a major particulate substance removal process during storm events.

In Chapter 3 it was shown that across numerous case studies outflow masses were greater than inflow masses for particular storm events. Re-suspension of sediment from pond bottoms and subsequent wash out was therefore indicated as another physical process that influenced pond efficiency.

Detention ponds:

Chemical and biological processes:

It is unlikely that any of the included metals were removed during storms by chemical processes, for the same reasons as discussed for retention ponds above.

Detention ponds remain dry between storm events and are usually maintained to prevent plant growth. Therefore plant coverage is usually minimal. Biological processes relating to plant uptake of metals were therefore accepted to be negligible.

Physical processes:

Investigations into the relationships between pond efficiencies and physical parameters (Chapters 3 and 5) indicated (1) mechanisms of deposition and re-suspension in ponds, (2) increased Brim Full Emptying Times (BFETs) was associated with improved TSS removals during normal functioning and decreased probability of negative TSS and total zinc removals and (3) dissolved zinc, copper and TSS were correlated in pond removals.

6.2.2 Conceptual model for detention ponds

It has been shown that chemical and biological processes are unlikely to influence substance masses in the water phase during storm events. Further discussions were therefore focussed on physical processes. In the absence of chemical or biological processes and from correlations between substances in pond outflows and fraction removals (Chapter 5), it was concluded that the main factors influencing substance removals were whether they were in dissolved or particulate form and the available mechanism of removal, e.g. infiltration for dissolved substances and sedimentation for particulates. Therefore, no distinction was made between substance types in further modelling.

The apparent importance of Brim Full Emptying Times for total substance removals and water quality surface area for dissolved lead removal indicated that sedimentation and infiltration were important removal processes for these two fractions respectively. Due to the possibility of dissolved matter infiltration into pond bottoms, a process not possible for particulate matter removals, different modelling approaches were followed for the different fractions.

6.2.2.1 Dissolved substances

During storm events, in the absence of chemical or biological processes, it was previously concluded that dissolved masses were conservative. It is postulated that, in the absence of volume spill, mass reduction in ponds was a result of volume capture and infiltration (refer to section 5.3.3) within the ponds and increases a result of sediment re-suspension with release of dissolved matter trapped in the bottom sediment layer; or additions due to sources other than the measured influent such as direct rainfall or overland flow, viz.:

$$M_{d,out} = f_{d,out}\, M_{d,in} + \mathrm{M}_{\mathrm{d,res,out}} + \mathrm{M}_{\mathrm{d,other,out}} \tag{6.4}$$

where $\mathrm{M}_{\mathrm{d,out}}$ = the total outflow mass per storm event, $\mathrm{f}_{\mathrm{d,out}}$ = the fraction of total inflow dissolved mass ($\mathrm{M}_{\mathrm{d,in}}$) that leaves the pond via the outflow, $\mathrm{M}_{\mathrm{d,res,out}}$ = the dissolved mass re-suspended from the pond during the storm that leaves the pond via the outflow, $\mathrm{M}_{\mathrm{d,other,out}}$ = the dissolved inflow mass other than that measured in the inflow (indications of this occurrence were seen in Chapter 3). Additionally:

$$M_{d,in} = f_{d,out} M_{d,in} + f_{d,cap} M_{d,in} \tag{6.5}$$

$$f_{d,out} + f_{d,cap} = 1 \tag{6.6}$$

where $\mathrm{f}_{\mathrm{d,cap}}$ = the fraction of total inflow mass captured in the pond during the storm event and possibly leaves the pond via infiltration.

The monotonic relationship between outflow mass and outflow volume indicated increased outflow volumes carried increased outflow masses. This may be explained by visualising pond functioning, for active zones, akin to a mixed reactor. The following volumetric equation applies:

$$V_{storm} = V_{in} + V_{other} \tag{6.7}$$

where $\mathrm{V}_{\mathrm{storm}}$ = the total volume influent to the pond, i.e. the direct inflow volume V_{in}, plus $\mathrm{V}_{\mathrm{other}}$ (rainfall directly onto the pond, overland flow, baseflow etc.).

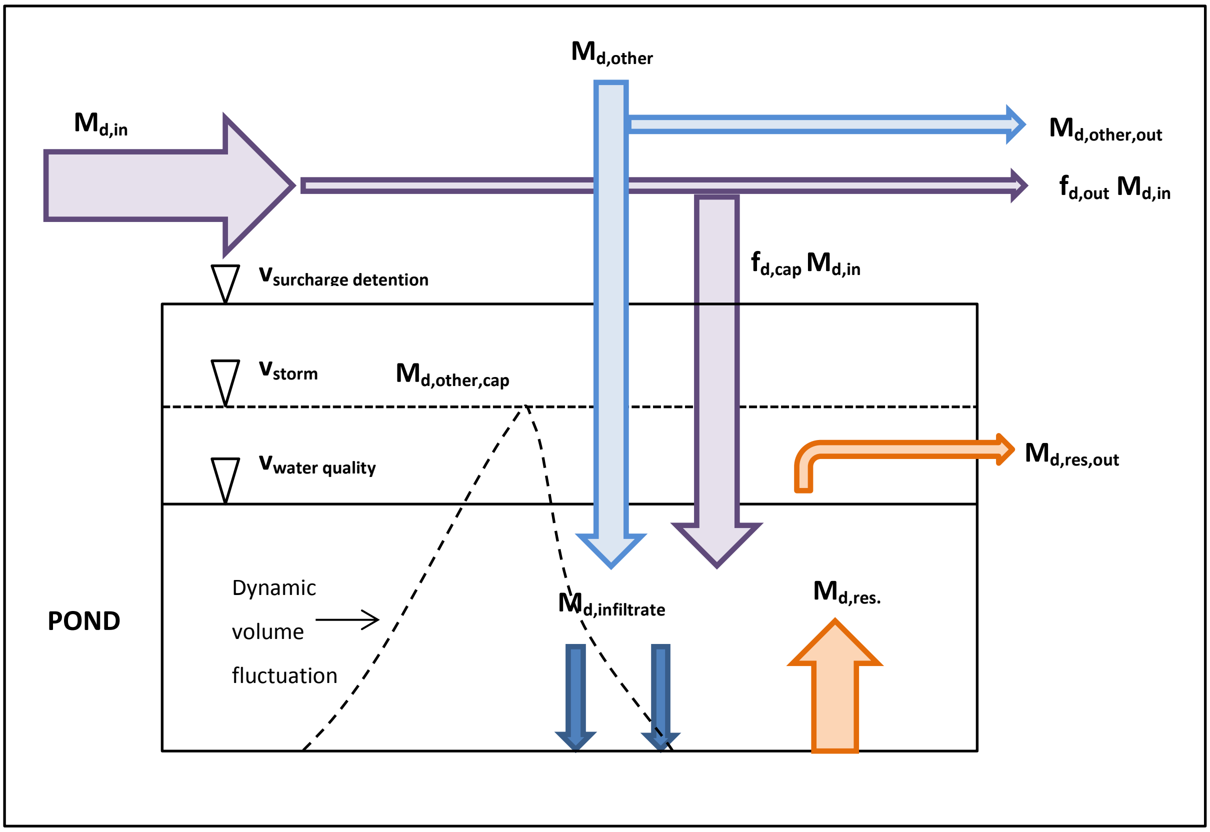


Figure 6-1 DP conceptual model for dissolved metals removal during storm events

6.2.2.2 Particulate substances

According to Ji (2008:118), in a pond with through flow during a storm event, particles with higher settling velocities are expected to settle closer to the inflow point and slow settling particles might be expected to have insufficient time to settle before being wash out via the outflow stream.

If it is accepted that suspended solids contained unchanging ratios of fast settling particles to slow settling particles between storm events, i.e. the catchment area produces consistent material over different storm events, it may be accepted that an unchanging fraction of suspended sediment will be found in pond outflows during storms, hence and in the absence of re-suspension, resulting in a monotonic relationship between inflow and outflow mass values as was indicated previously, i.e.

$$M_{p,out} = f_{ns,out}\ M_{p,in} + M_{p,other,out} + M_{p,res,out} \tag{6.8}$$

where $M_{p,in}$ is the inflow mass of particulate matter, $f_{ns,out}$ is the non-settleable fraction of the total inflow particulate mass ($M_{p,in}$) during storm events not captured in the pond, $M_{p,other,out}$ is particulate input from sources other than the influent during the storm which becomes part of the outflow stream and $M_{p,res,out}$ is the re-suspended particulate matter in the outflow stream.

The monotonic relationships between the outflow masses and inflow volumes indicated that both small and large storms carried material with very similar compositions, i.e. the fraction of non-settleable material not captured in the pond from the watershed remained comparable regardless of the runoff volumes and increased in amount with increasing volumes, i.e.

$$(f_s M_{p,in} + f_{ns} M_{p,in}) \text{ is monotonically related to } V_{in} \tag{6.9}$$

$$f_s + f_{ns} = 1 \tag{6.10}$$

where f_s is the settleable, and f_{ns} the non-settleable fraction of $M_{p,in}$ during storm events.

The monotonic relationship between outflow mass and outflow volume indicated increased outflow volumes carried proportionally increased outflow masses. This may be explained by visualising pond functioning akin to a mixed reactor.

In Chapter 5, it was found that total cadmium, copper, zinc, lead and TSS mass removals were positively correlated for the studied ponds. A similar result for copper and TSS correlations was found by Banas et al.(2010) who found a significant ($p < 0.001$) strong ($r^2 = 0.79$) correlation in a detention basin receiving runoff water from a vineyard. There were relatively few particulate arsenic and cadmium data entries for metals cross correlational analysis. The Department of Water Affairs and Forestry (1996c) has stated that cadmium strongly interacts with zinc. This therefore supported the indication that cadmium matter was affected similarly to the other included metals within the ponds during physical removal processes. If it is further accepted that particulate arsenic was physically removed similarly to other particulate materials in the absence of biological or chemical processes, then each metal type can be categorised in terms of a fraction of the TSS, viz.

$$M_{p,x} = f_x MTSS \tag{6.11}$$

where f_x = the fraction of metal mass in TSS mass. Althouth data trends indicated that, theoretically the above stated relationships exist, practically determining the fractions of metals that are included in TSS can be challenging because TSS measurements are relatively crude (e.g. gravimetric methods), when compared to metals measurements (e.g. mass spectrometry) in water quality samples. However, the possibility remains that particulate metal removals in ponds could be modelled only in terms of TSS.

As for dissolved matter, the following volumetric equation applies:

$$V_{storm} = V_{in} + V_{other} \tag{6.12}$$

where V_{storm} = the total volume influent to the pond, i.e. the direct inflow volume V_{in}, plus V_{other} (rainfall directly onto the pond, overland flow, baseflow etc.).

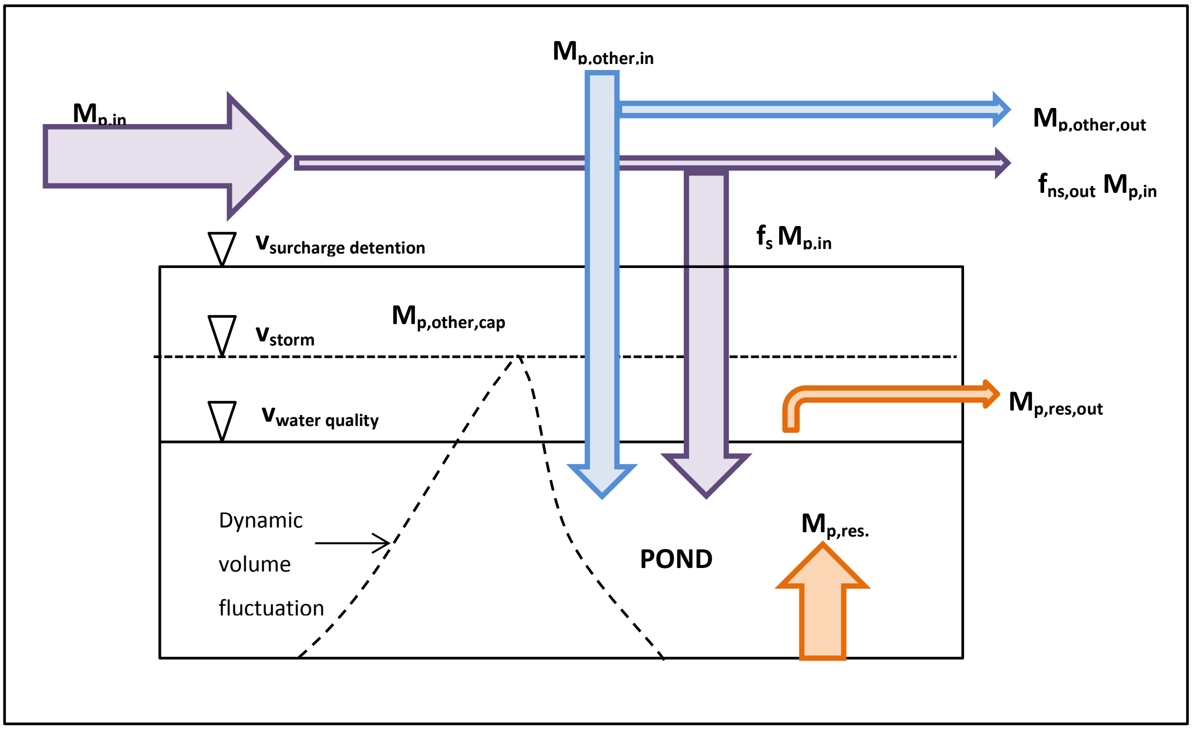


Figure 6-2 DP conceptual model for particulate metals removal

6.2.3 Conceptual model for retention ponds

6.2.3.1 Dissolved substances

Data for dissolved matter was scarce and a framework within which a conceptual model could be produced was not established. In the absence of chemical or biological processes during storm events, it was inferred that dissolved masses were conservative with reduction in efluents being a result of dilution within the ponds and sorption to particulate matter. Increases were accepted to have been a result of sediment re-suspension with release of dissolved matter trapped in the bottom sediment layer or due to unmeasured outside sources. It is possible that dissolved matter was removed from the water between storm events via biological or chemical processes. This could not be confirmed with the available data.

6.2.3.2 Particulate substances

The sedimentation philosophy provided by Ji (2008:118) and discussed in section 6.2.2.2 above applies. Barrett (2008) found indications in his investigation of 12 retention and 6 detention ponds that settling occurrs rapidly after which small suspended particles remain, which will not settle with increased time (see section 2.5.2). If it is accepted that suspended solids contained unchanging ratios of fast settling particles to slow settling particles, it may be further accepted that a generally consistent fraction of suspended sediment will be found in pond outflows during storms, hence, in the absence of re-suspension, resulting in a monotonic relationship between inflow and outflow mass values as previously found, i.e.

$$M_{out} = f_{ns,out}\, M_{in} + M_{ini,out} \qquad \text{(Eqn. 6.13)}$$

where $f_{ns,out}$ is the non-settleable fraction of M_{in} during storm events not captured in the pond and $M_{ini,out}$ is the initial suspended matter in the pond at the start of the storm and which becomes part of the outflow stream. $M_{ini,out}$ was further postulated to be comparatively small enough not to have affected the monotonic relationship between inflow and outflow masses. Unmeasured sources of material such as from overland flow were unlikely due to generally high surface friction terrain around ponds.

The monotonic relationships between the outflow masses and inflow volumes indicated that both small and large storms carried material with very similar compositions, i.e. the fraction of non-settleable material not captured in the pond from the watershed remained similar regardless of the runoff volumes and increased in amount with increasing volumes, i.e.

$$\left(f_{cap} M_{in} + f_{ns,out} M_{in} \right) is\ monotonically\ related\ to\ V_{in} \qquad \text{(Eqn. 6.14)}$$

where f_{cap} is the capturable fraction of M_{in} during storm events which remained constant for different storm events and f_{cap} + $f_{ns,out}$ = 1. In addition, f_{cap} can consist of material that is settleable ($f_s f_{cap}$) and non-settleable ($f_{ns} f_{cap}$) material between storm events.

The monotonic relationship between outflow mass and outflow volume indicated increased outflow volumes carried proportionally increased outflow masses. This may be explained by visualising pond functioning in active areas akin to a mixed reactor. This result supports the statement by Barrett (2008) that plug flow conditions were not achieved in ponds as was assumed by designers (section 2.5.2).

If it is accepted that physical processes played a dominant role in substance removal efficiencies and chemical or biological processes did not alter chemical fractionation during storm events, then each metal type could be categorised in terms of a fraction of the TSS, viz.

$$f_x\, MTSS_{out} = f_{x1}\, f_{ns}\, M_{in} + f_{x2} M_{ini,out} \qquad \text{(Eqn. 6.15)}$$

where f_x = the fraction of metal mass in TSS mass in the outflow, f_{x1} = the fraction of metal mass in the influent non-settleable TSS and f_{x2} = the fraction of metal mass in the suspended TSS within the pond before the storm. However, as discussed in previously, practically determining the fractions of metals that are included in TSS can be challenging.

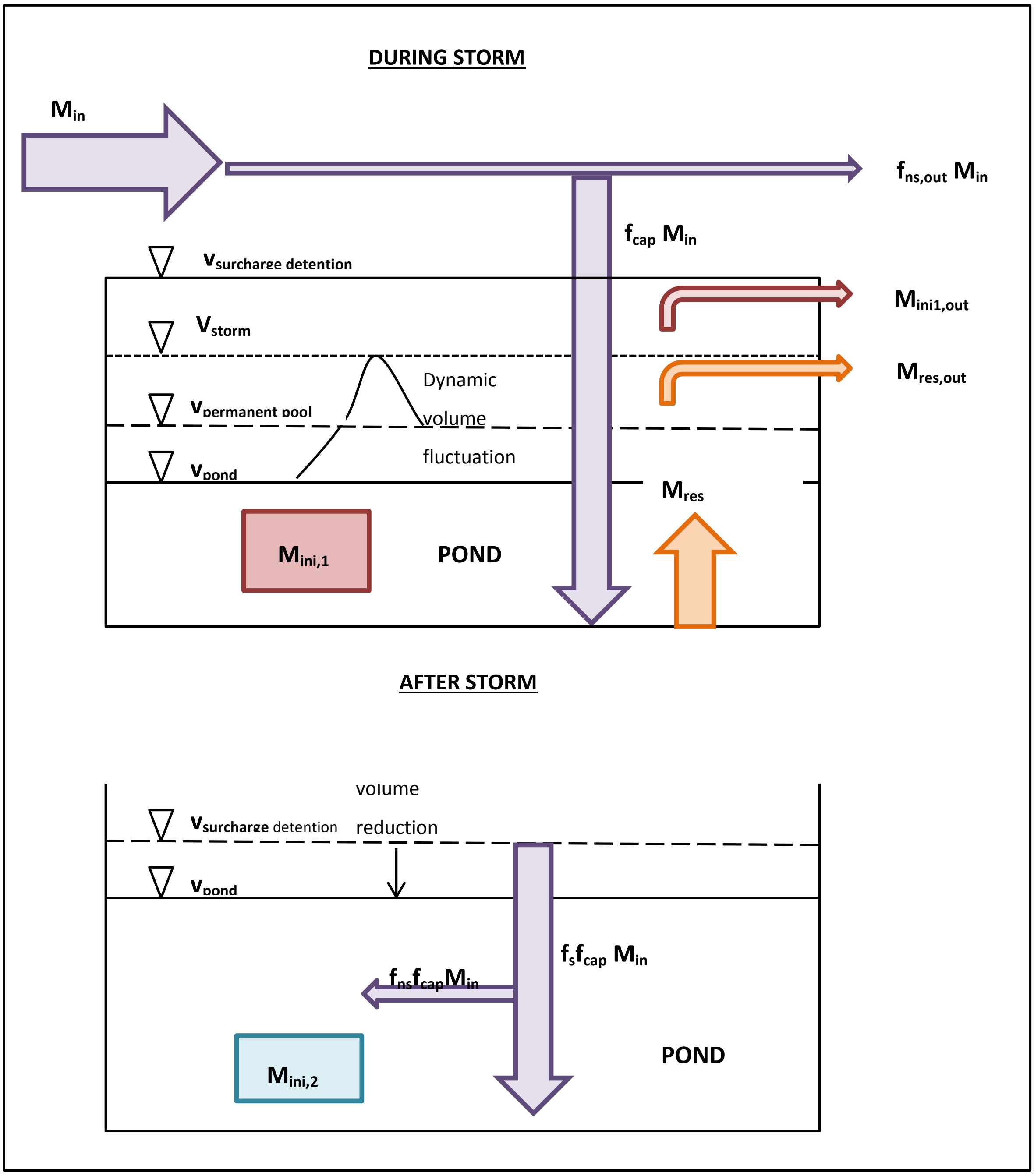


Figure 6-3 RP conceptual model for particulate metals removal

The following equations additionally apply:

$$V_{storm} = V_{in} + V_{other} + V_{pond} \qquad \text{(Eqn. 6.16)}$$

Where the maximum water volume in the pond during a storm, V_{storm} is a consequence of V_{in} (the direct inflow volume), V_{other} (the volume of outside sources into the ponds) and V_{pond} (the water volume within the pond at the start of the storm). Also,

$$M_{ini1} = f_{ns,cap,prev}\, M_{cap,prev} + M_{other} \qquad \text{(Eqn. 6.17)}$$

Where $f_{ns,cap,prev}M_{cap,prev}$ = the non-settleable fraction from previous storm inputs and re-suspensions not previously washed out from the pond and M_{other} = other suspended inputs such as windblown sediment. Therefore,

$$M_{out} = f_{ns,out}M_{in} + M_{ini1,out} + M_{res,out} \qquad \text{(Eqn. 6.18)}$$

where $M_{res,out}$ is the fraction of re-suspended material in the outflow. Between storms it may be expected that fractions of inflow sediment will remain within the pond and settle ($f_s f_{cap}$) or won't settle ($f_{ns} f_{cap}$). Non settleable material will form part of outflow material during the next storm and settled material may re-suspend to add to the wash out mass. Additionally added loads such as wind driven sediment may add to the material within the ponds during and between storms.

6.2.4 Discussion

The complexity of detailed modelling of stormwater ponds were illustrated in the conceptual models. Many parameters require vast data inputs and experimental investigations to accurately predict. Volumetric input parameters may be predicted with hydrology and runoff models, but change dynamically thereby increasing model complexity. This complexity, however, is manageable and can be performed with software applications, but may have substantial design time and cost implications.

If filtration, sedimentation and re-suspension processes are to be accepted to play a role in the removal of metals during storm events, then the greatest obstruction to detailed modelling is the prediction of sediment behaviour during three dimensionally dynamically fluctuating pond hydraulic conditions. Dufresne et al. (2010) showed that even under controlled experimental conditions, sediment discharge exhibited significant variations with time. These were attributed to unsteadiness of flow, unsteadiness of sediment input and the nature of dominant bed-load sediment transport.

Many sediment processes are not yet completely understood, especially for cohesive sediments. Particle settling velocity is the most fundamental parameter that determines particle settling. A function of particle size, shape and density it can also be influenced by the viscosity of the medium through which it falls. In addition, particle settling can be influenced by turbulence, inter particle action such as flocculation or collision, temperature etc. These parameters are so highly variable in reality that settling velocities are usually determined empirically. However, a sample of the inflow sediment may not give representative results when studied in a laboratory setup because the effect of turbulence within the studied water body may not be represented within the laboratory (Ji, 2008:122).

Filtration of dissolved substances can be modelled on the assumption that dissolved material discharges from the pond in direct relation to volume discharges. However, metals are easily bound to sediment (Department of Water Affairs and Forestry, 1996a) and one cannot ignore the possibility of dissolved matter sorption to the pond sediment layers with possible re-suspension of these materials at a later stage, complicating removal predictions.

Re-suspension results from shear stresses imposed by currents and begin when these are more than the shear strength of the sediment surface layer. For cohesive sediments, this process can be highly complex and depends, additionally, on the electrochemical properties of the sediments. Erosion can be affected by many parameters, such as hydrodynamic conditions and vegetation. Like for sedimentation processes, variability in the parameters means that theory and practice of re-suspension is based on laboratory work and empirical formulations (Ji, 2008:122).

For the presented conceptual models, data may be obtained to satisfy the physical, biological and chemical process model requirements for quiescent conditions in-between storm events. Settling velocities and chemical compositions of typical runoff matter and plant uptake of dissolved metals may be determined in laboratory setups.

The determination of the model parameters can be highly complex e.g. fractions of inflow sediment that will remain non-settleable and leave the pond via the outflow stream ($f_{ns,out}$), remain within the pond and settle ($f_s f_{cap}$), remain within the pond and do not settle ($f_{ns} f_{cap}$) during storm events, are remnant in the water phase from previous storms (M_{ini}) and become re-suspended and washed out ($M_{res,out}$). Dependable and predictable information regarding hydrological conditions, three-dimensional pond hydraulic behaviour and the settling and re-suspension responses of matter is required.

The determination of the required information may require substantial cost and time inputs. The complexity of the modelling and subsequent design processes can be greatly reduced if a high level of control is exerted over the pond hydraulic behaviour. The ponds studied in this research were irregularly shaped and had unregulated plant growth. This rendered the prediction of hydraulic processes impossible without large and relevant data variety. In future modelling enterprises aimed towards design; however, much of the variability may be reduced by exercising control over the hydraulic behaviour of ponds. Therefore, design efforts should aim to create designs that can mimic model concepts such as fully mixed reactors, plug flow, laminar flow etc., rather than trying to apply models to ponds whose functioning is highly complex due to high three-dimensional variability.

6.3 Investigations into sedimentation type

The results of investigation into the relationships between detention and retention pond efficiencies and design (Chapters 4 and 5) have indicated that sedimentation was a key process in particulate metals removals for the studied ponds. Sedimentation process behaviour can take different forms.

These include flocculent, non-flocculent, zone and compression settling (Ekama, 1986:160). Different settling behaviours require different design approaches. Establishment of the type of settling behaviour seen within the studied ponds can therefore guide future metals removal design philosophy.

This section contains modelling of pond behaviour with a polynomial time function more often seen in ideal laboratory settling studies. The aim of this investigation was to establish the degree to which pond outflow particulate masses were dependent on the time allowed within the pond for settling per storm. Non- flocculent (Class 1) settling behaviour is mainly dependent on time allowed for settling in idealised scenarios (Ekama, 1986:161) and a large degree of dependence of non-settled mass in pond outflows on time allowed was deemed to be an indication of this type of settling.

6.3.1 Methodology

The methodology followed and information on the general behaviour of Class 1 settling was sourced from (Ekama, 1986:83).

6.3.1.1 Data

Data required in this section included outflow masses as well as storm start and end times. As was discussed previously, many ponds showed evidence of re-suspension. The most obvious sign of this was outflow masses that were greater than inflow masses per storm (Chapter 3, section 3.3.2). The occurrence of re-suspension within a pond would confound efforts to model outflow masses as a function of time. Only data with no obvious indication of re-suspension was therefore used.

Not many case studies included storm start and end time data. Such data was usually logged by data loggers in volumetric measuring devices at pond inlets and outlets. Only case studies where such data was reported could therefore be used in this analysis.

6.3.1.2 Analytical Procedure – Polynomial curve fitting

A standard polynomial curve with independent variable time was used. This took the form:

$$M_{out} = a + bt + ct^2 + dt^3 \qquad \text{(Eqn. 6.19)}$$

where: M_{out} is the particulate mass of substance in the outflow per storm event. A,b,c and d are calibrated curve fitting constants. And t is the total time allowed for particles to settle within a pond. In this case the time between the first recorded inflow and last recorded outflow measurement in the pond per storm.

The constants a, b, c and d were calibrated from the data by multiple least squares regression. All calculations were performed with the software program Excel 2010 (Copyright© Microsoft Corporation). Calibration was done as follows:

The values of a, b, c and d were determined such that the sum of the squares of errors (SSE) between the measured and calculated masses were a minimum with the following relationship:

$$SSE = Sigma\ from\ i = 1\ to\ n\ (M_{out} - a - bt - ct^2\ - dt^3)\text{^}2 \qquad \text{(Eqn. 6.20)}$$

The partial derivatives of Eqn. 6.4.2 with respect to a, b, c and d were therefore set to 0 and four equations were generated as shown below:

$$\frac{\partial SSE}{\partial a} = Sigma\ from\ i = 1\ to\ n\ \{-2t_i^0(M_i - at_i^0 - bt_i^1 - ct_i^2 - dt_i^3)\} = 0 \qquad \text{(Eqn. 6.21)}$$

$$\frac{\partial SSE}{\partial b} = Sigma\ from\ i = 1\ to\ n\ \{-2t_i^1(M_i - at_i^0 - bt_i^1 - ct_i^2 - dt_i^3)\} = 0 \qquad \text{(Eqn. 6.22)}$$

$$\frac{\partial SSE}{\partial c} = Sigma\ from\ i = 1\ to\ n\ \{-2t_i^2(M_i - at_i^0 - bt_i^1 - ct_i^2 - dt_i^3)\} = 0 \qquad \text{(Eqn. 6.23)}$$

$$\frac{\partial SSE}{\partial d} = Sigma\ from\ i = 1\ to\ n\ \{-2t_i^3(M_i - at_i^0 - bt_i^1 - ct_i^2 - dt_i^3)\} = 0 \qquad \text{(Eqn. 6.24)}$$

The four equations were solved simultaneously with matrix manipulation.

Statistical evaluation of the goodness of fit of the polynomial function to the measured data was done by comparing the error sum of squares (SSE) of the regression to the total sum of squares (SST). The regression sum of squares (SSR) was calculated for this purpose as follows:

$$SSR = 1 - SSE/SST \qquad \text{(Eqn. 6.25)}$$

6.3.2 Results and discussion

Results are displayed in Tables 6.11 and 6.12. Land use types for the case studies was summarised in Table 6.13.

Only 6 detention pond and 2 retention pond case studies had the required data available for this analysis. The regression sum of squares (SSR) varied from 0.37 to 1.00. This parameter indicates the percentage of variance in the observed data that is explained by the calibrated function. A value of 1.00 indicates that 100% of variance in substance outflow mass was explained only by the time variable in the calibrated polynomial function. This indicates that time allowed for settling was the most important factor in outflow mass results in such a case. By extension, a high SSR value for a polynomial that contains only the time variable indicates a mechanism of non-flocculant (Class 1) type settling.

Table 6-11 DP polynomial curve fitting results

Case Study	Fitted Function Coefficients				Sum of Squares			Max. Fraction Outflow
Particulate Arsenic								
	a	b	c	d	SSE	SSR	SST	Fr out
I5 Manchester East EDB	0.0057	9.61636E-05	-4.81389E-08	6.0E-12	7.8E-04	0.87	0.0059	0.41
I15 SR78 EDB	-1.3	0.0028	-1.94155E-06	4.42474E-10	6.10E-04	0.96	0.015	0.39
Particulate Cadmium								
	a	b	c	d	SSE	SSR	SST	Fr out
I5 Manchester East EDB	0.0041	1.58E-05	-4.43546E-09	5.12771E-13	0.0023	0.72	0.0081	0.24
Particulate Copper								
	a	b	c	d	SSE	SSR	SST	Fr out
El Dorado	0.044	0.019	-5.10039E-05	3.37637E-08	0.37	0.90	3.8	0.83
I5 I605 EDB	6.5	-0.0090	3.6E-06	-3.4E-10	54	0.56	123	0.68
I5 Manchester East EDB	0.072	0.0011	-3.6E-07	3.7E-11	1.0	0.89	9.6	0.12
I15 SR78 EDB	268	-0.54	0.00036	-7.8E-08	1.7	0.54	3.7	0.13
Particulate Lead								
	a	b	c	d	SSE	SSR	SST	Fr out
I5 I605 EDB	30	-0.043048398	1.8E-05	-1.7E-09	1310	0.56	2995	0.92
I5 Manchester East EDB	-9.0	0.0087	-2.3E-06	1.9E-10	6.6	0.92	86	0.18
Particulate Zinc								
	a	b	c	d	SSE	SSR	SST	Fr out
Grant Ranch	6.6	-0.010	4.2E-06	-3.6E-10	0.22	1.00	346	0.42
I5 I605 EDB	108	-0.14	5.1E-05	-4.9E-09	2185	0.72	7861	0.74
I5 Manchester East EDB	5.8	0.001104661	-9.07592E-07	1.285E-10	46	0.82	254	0.11
I15 SR78 EDB	18	-0.043	3.3E-05	-6.3E-09	144	0.29	203	0.07
TSS								
	a	b	c	d	SSE	SSR	SST	Fr out
El Dorado	-18	0.14	-1.2E-04	2.5E-09	898	0.45	1619	0.19
Grant Ranch	-33	0.050	-2.0E-05	2.3E-09	40	0.92	490	0.16
I5 I605 EDB	-20	0.022	-3.84614E-06	1.77697E-10	94	0.70	316	0.55
I5 Manchester East EDB	2.9	-0.007180295	4.1007E-06	-5.1E-10	5.6	0.82	32	0.16
I15 SR78 EDB	25	-0.028960605	1.7E-05	-3.9E-09	111	0.37	176	0.16
I605 SR91 EDB	-0.78	0.0039	-3.21901E-06	7.23359E-10	0.018	0.73	0.068	0.14

It was evident that sedimentation of particulate forms of metals behaved as Class 1 type settling for most detention pond and both retention pond case studies. Particulate arsenic SSR values were above 0.87 for both included case studies. A particulate cadmium SSR value was 0.72 for the one included case study. Particulate copper SSR values were above 0.80 for two (out of four) detention pond and the one retention pond case study. Particulate lead SSR values were above 0.90 for one (out of two) detention pond and the one retention pond case studies. Particulate zinc SSR values were above 0.80 for two (out of four) detention pond and the one included retention pond case study. Total suspended solids (TSS) behaviour followed a similar Class 1 type pattern with SSR values above 0.80 for two (out of six) detention pond and both included retention pond case studies. Two more detention pond case studies had TSS SSR values above 0.70. These results indicate that metals sedimentation not only behaved as Class 1 type settling across metal types, but also across detention and retention pond types.

Table 6-12 RP polynomial curve fitting results

Case Study	Fitted Function Coefficients				Sum of Squares			Max. Fraction Outflow
Particulate Copper								
	a	b	c	d	SSE	SSR	SST	Fr out
I5 La Costa East WB	-0.60	9.9E-04	-4.7E-07	7.4E-11	0.0058	0.81	0.031	0.02
Particulate Lead								
	a	b	c	d	SSE	SSR	SST	Fr out
I5 La Costa East WB	1.2	-0.0018	8.3E-07	-1.1E-10	0.00041416	0.99	0.081	0.009
Particulate Zinc								
	a	b	c	d	SSE	SSR	SST	Fr out
I5 La Costa East WB	3.9	-0.0053	2.2E-06	-2.7E-10	0.0023	1.00	0.60	0.009
TSS								
	a	b	c	d	SSE	SSR	SST	Fr out
Central Park	1209	-12	0.033	-1.8E-05	14028	0.85	91772	0.22
I5 La Costa East	3.4	-0.0044	1.7E-06	-1.8E-10	0.0041	1.00	5.1	0.03

Table 6-13 Case study land use types

Case Study	Open Space	High Density Residential	Low-Medium Density Residential	Industrial / Commercial	Roads / Highways	Agriculture	Unknown	
Detention Ponds								International BMP Stormwater Database (available at www.bmpdatabase. org)
El Dorado	30%	40%	25%	-	-	-	5%	
Grant Ranch	-	-	100%	-	-	-	-	
I5 I605 EDB	-	-	-	-	100%	-	-	
I5 Manchester East EDB	-	-	-	-	100%	-	-	
I15 SR78 EDB	-	-	-	-	100%	-	-	
I605 SR91 EDB	-	-	-	-	100%	-	-	
Retention Ponds								
Central Park	35.5%	-	25%	37.5%	-	2%	-	
I5 La Costa East	-	-	-	-	100%	-	-	

Low SSR values occurred in a few cases. I5 I605 EDB and I15 SR78 EDB had SSR values of 0.56 and 0.54 respectively for particulate copper. The I5 I605 EDB also had a SSR value of 0.56 for particulate lead. In contrast to this the I5 I605 EDB had relatively high SSR values for particulate zinc (0.72) and TSS (0.70).The I15 SR78 EDB had very low SSR values for particulate zinc (0.29) and TSS (0.37). The El Dorado pond also had a low SSR value for TSS (0.45). Perusal of other data indicators such as calibrated coefficients, SSE and SST showed no clear difference in the scale or variation of values of these poorly fitted modelling cases to other cases where the polynomial time function was well fitted. The fraction of inflow mass in the outflow (Fr out) also showed no clear relationship to cases where the time polynomial was poorly fitted. Further investigation of land use types in the watershed did not indicate a clear trend in land use type for poorly or well fitted model cases, i.e. cases where the time polynomial was well fitted had a range of land use types as did cases where the time polynomial was poorly fitted. It was therefore concluded that these results could have been due to a number of reasons ranging from watershed runoff material to unmeasurable re-suspension within ponds that confounded outflow mass data.

6.3.3 Summary of results

Class 1 type settling was indicated across metal types viz. arsenic, cadmium, copper, lead and zinc as well as for TSS for the majority of ponds. It is therefore recommended that future pond design philosophy focus on non-flocculent settling for particulate metals removal in detention and retention ponds, pending the results of catchment runoff sampling within a watershed.

Class 1 type settling was indicated in both detention and retention ponds. A few cases had data to which the time polynomial function could not be well calibrated. No clear reason for this occurrence could be determined.

6.4 Sediment transport computer modelling

A one dimensional computer model was used to investigate the theoretical tendency of metals and TSS to be transported and re-suspended within three different pond configurations. This was done to support or negate the indication of these processes as important for metals removals in ponds in previous chapters. The software program Mike 11, a subsection of Mike Zero by DHI (Release 2012, Copyright 1995-2012) was used.

6.4.1 Methodology

6.4.1.1 Model Setup

Hydrodynamic model:

The hydrodynamic (HD) model simulated detention (DP) and retention ponds (RP) with parameters applicable to the Cape Metropol (South Africa). To this end, a triangular inflow hydrograph with a peak of 2m³/s and a time of concentration of 30 minutes was calculated for an urban area of around 500 m x 500 m. The rational method was used to calculate peak storm runoff for a 1:100 year return period with a Mean Annual Precipitation for the Cape Town area (1000 mm).Three configurations of variable length (L = 27, 54 and 108 m) were investigated. Pond side slopes were kept at 1:5, resulting in pond configurations as shown in Figure 6.4.

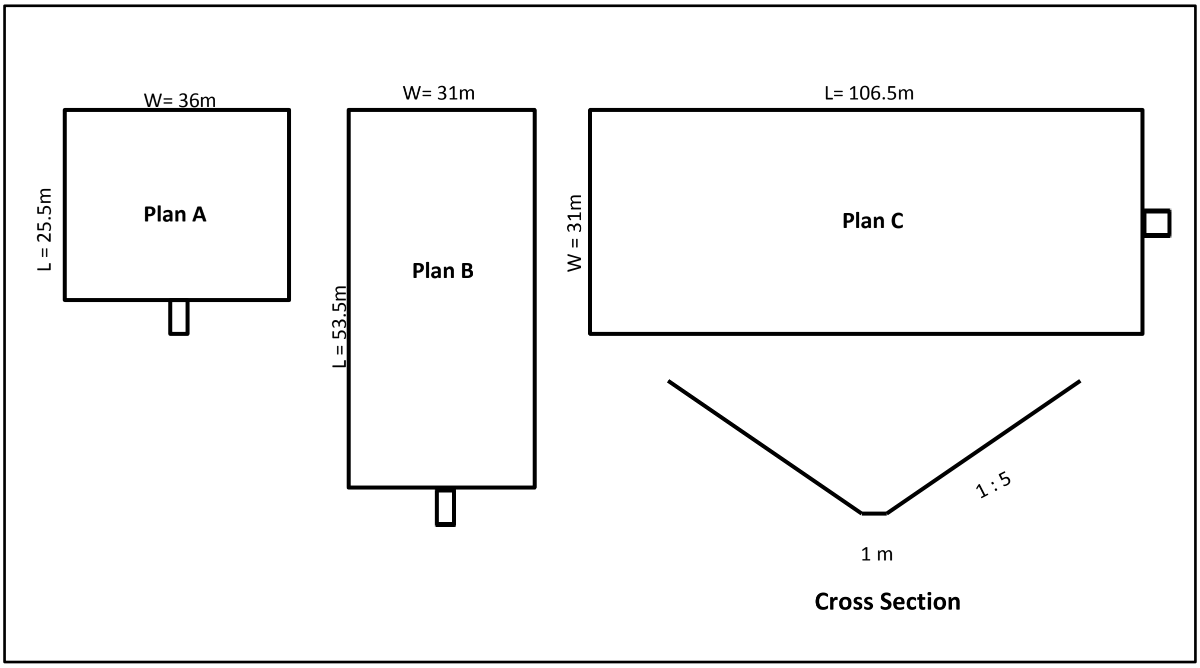


Figure 6-4 Pond configurations

The pond outlets were modelled as a pipe culvert placed 1.5m before branch end, i.e. at 25.5, 52.5 and 106.5 m for the respective branch lengths. The pipe culvert was set at pond bottom for detention pond simulations. Retention pond simulations included an initial water depth of 2m and an outflow pipe culvert at that level.

Sediment Transport model:

The Engelund & Hansen (1967) transport model for total load was used. Calculation of bottom level was included. Non scouring bed level was set to a depth of 0 for sediment transport simulation runs and set to the default value for investigation of scour.

A sediment grain diameter of 8µm was used. Literature reviews have indicated around 80% of particles from urban runoff to be greater than this (See section 2.6.4). Particle density was changed according to the substance under investigation.

6.4.1.2 Simulation Runs

Densities of arsenic, cadmium, copper, lead, zinc and TSS were used as input to separate simulation runs for of all three pond configurations for both detention and retention ponds. Total sediment transport was recorded. Simulations included both scouring and non-scouring bed levels.

6.4.1.3 Sensitivity Analysis

Sensitivity analyses were performed for sediment transport and scour. The analysis was performed on pond configuration B (length 52.5m) for TSS. Input parameters were increased by 10% while all other parameters remained unchanged. Tested parameters included peak concentration of substance (m^3/s), grain diameter (m) and substance density (kg/m^3). Additionally the Shields dimensionless parameter (theta critical) was included for scour results.

6.4.2 Results and discussion

The Engelund & Hansen (1967) model was developed for particle sizes much larger than the 0.8 µm used. It was cautioned that smaller particle sizes might effect under prediction of sedimentation. The results discussed here, however, were theoretical comparisons of different pond designs and not attempts at accurate modelling of real ponds. Under prediction of sedimentation for all outcomes, therefore, were not deemed significant to conclusions of relative efficiencies.

6.4.2.1 Sediment Transport

Both detention and retention pond results showed all substances settled soon after entry to the ponds in most cases. For the detention pond configurations, sediment transport values fell to less than 0.1% of inflow peaks within 11.1 m for pond configurations A (L = 27m) and B (L = 54m) for all substances except copper, lead and zinc in the case of pond configuration A. Here, these substance transport peaks were significantly reduced within 5.6 m (See Table 6.14). In detention pond configuration C (L = 108m), transport values fell to less than 0.1% of inflow peak within 47.1

m. Pond configurations A and B (L = 54m) therefore performed best in terms of sediment transport reduction by removing all substances within less than 22% of pond length. These results indicate, in ideal situations, ponds of squat shape to be better suited to removal of the investigated substances than elongated rectangular shapes. This supports the conclusions of better behaviour in squat pond shapes in Chapter 4.

Retention ponds had no sediment transport at pond inflow points. These results can be attributed to comparably milder velocity profiles for retention ponds (See Table 6.15). Detention ponds had maximum velocity peaks more than 10 times higher than retention ponds and peaked much faster during the simulated storms. Minimum velocities, however, were only around three or four times higher for detention ponds and peaked at roughly the same times as those of retention ponds.

Peak sediment transport values for detention ponds showed an increasing trend in peak transport rates and longer transport times with increase in pond length (See Table 6.16 and graphical illustrations in Addendum D). This trend followed the trend of increase in peak velocities with increase in pond length. This again indicates that pond configuration C (L = 108 m) carried higher amounts of sediment due to relatively higher velocities, indicating this type of configuration to be ill suited to removal of metal sediment.

Table 6-14 DP chainage at which sediment transport is < 0.1% inflow peak

Pond Configuration	Arsenic	Cadmium	Copper	Lead	Zinc	TSS
A (L=27m)	11.1	11.1	5.6	5.6	11.1	5.6
B (L=54m)	11.6	11.6	11.6	11.6	11.6	11.6
C (L=108m)	47.1	47.1	47.1	47.1	47.1	47.1

Table 6-15 Pond velocity profiles at chainage 0

Pond Configuration	Max v (m/s)	Time	Min v (m/s)	Time
Detention Pond				
A (L=27m)	0.40	1min11s	0.00052	90min1s
B (L=54m)	0.59	3min12s	0.00050	90min1s
C (L=108m)	0.63	6min12s	0.00068	90min1s
Retention Pond				
A (L=27m)	0.029	23min37s	0.00013	90min1s
B (L=54m)	0.041	29min47s	0.00016	90min12s
C (L=108m)	0.059	29min27s	0.00021	90min18s

Table 6-16 DP peak sediment transport (m3/s) and Chainage 0

Pond Configuration	Arsenic	Cadmium	Copper	Lead	Zinc	TSS
A (L=27m)	2.3E-14	5.8E-15	1.6E-11	1.7E-12	7.5E-12	1.4E-07
B (L=54m)	1.4E-13	3.5E-14	9.5E-11	1.0E-11	4.5E-11	8.2E-07
C (L=108m)	3.2E-13	8.2E-14	2.2E-10	2.3E-11	1.0E-10	1.9E-06

6.4.2.2 Scour

Simulations showed greater scour in detention than retention ponds. Retention ponds showed no significant decrease in bed level in any of the simulations at any investigated points. Decreases in bed level at pond inflows (chainage 0) showed an increasing trend with increases in pond length for detention ponds (See Figures 6.5, 6.6 and 6.7).

Scour was reduced along the length of flow within detention ponds. For pond configuration A (L = 27m), scour was slight at chainage 0 and more pronounced at chainage 2.7, while no indication of changes in bed level were seen at chainage 5.6. For pond configuration B (L = 54m), scour was pronounced at chainage 0 and chainage 5.8, while bed level rises were seen at chainage 11.6. For pond configuration C (L = 108m), scour was comparably very high at chainage 0, non-existent at chainage 11.8 and large amounts of deposition were indicated at chainage 23.6. These results indicate trends of increasing amounts of scour at pond entrance with longer lengths of sediment transport downstream with increasing pond length.

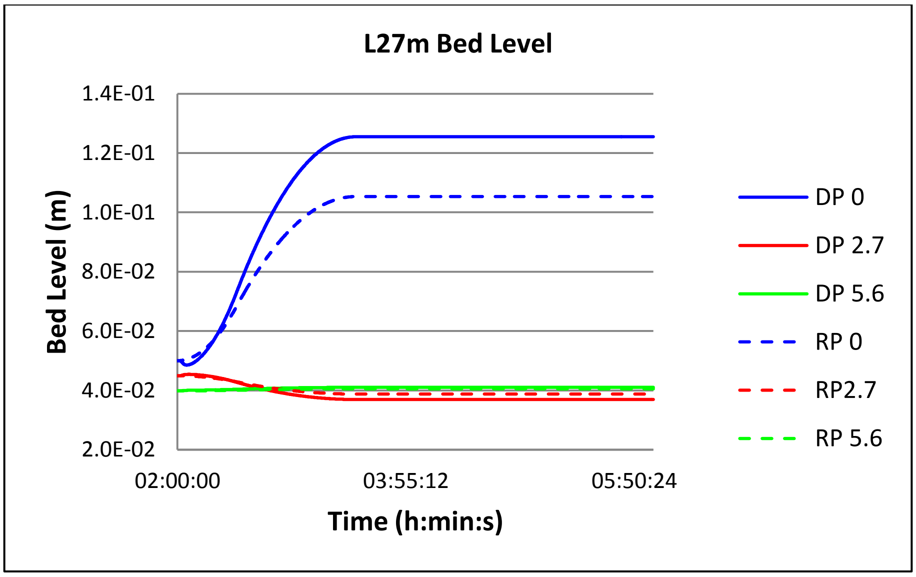


Figure 6-5 Bed levels at different DP and RP chainages for pond configuration A

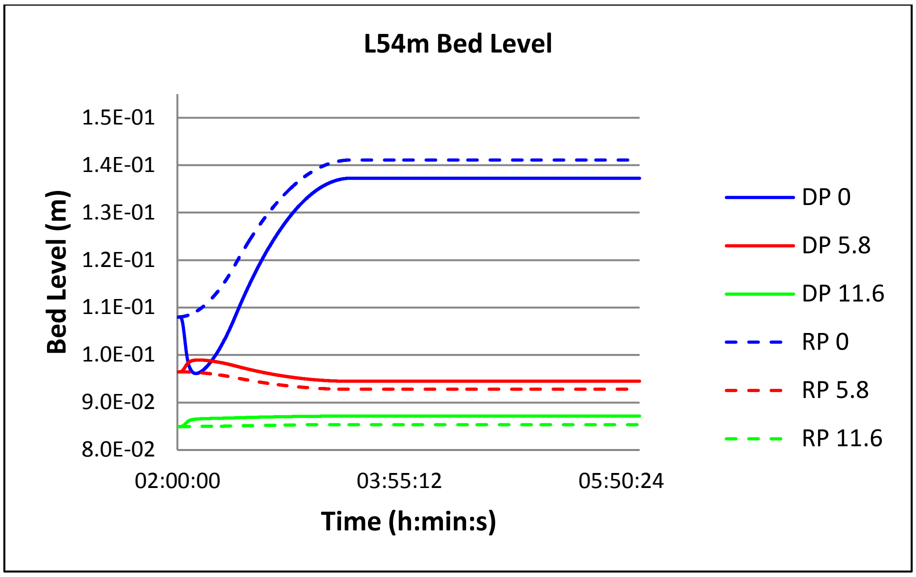


Figure 6-6 Bed levels at different DP and RP chainages for pond configuration B

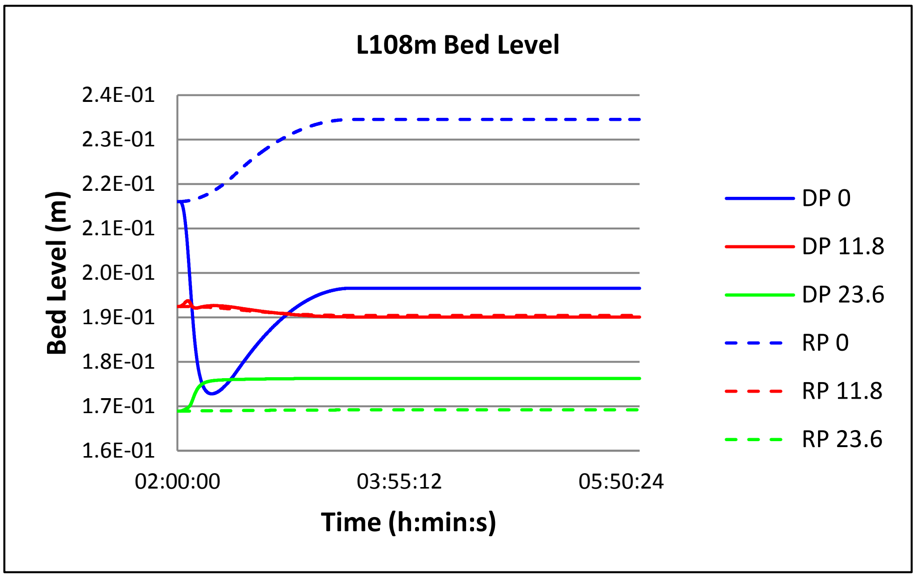


Figure 6-7 Bed levels at different DP and RP chainages for pond configuration C

6.4.2.3 Sensitivity Analysis

The sensitivity analysis showed sediment transport results to be highly sensitive to changes in grain diameter (as cautioned by Engelund & Hansen (1967)) and substance density for both sediment transport and scour results (See Table 6.17). Substance density was the most relevant factor for changes in results with negative change of over 30% in results with only 10% increase change in input values. The model was insensitive to changes in peak concentration and the dimensionless critical shields parameter for scour results. A slight sensitivity to changes in peak concentration was seen for sediment transport results.

Table 6-17 Sensitivity analysis results (sediment transport, m^3/s)

Parameter	No scour		
	First Resultant Value	Second Resultant Value	%Change
Peak Concentration TSS (m3/s)	8.2E-07	9.01E-07	9.9%
Grain Diameter (m)	8.2E-07	7.46E-07	-9.0%
Substance Density (kg/m3)	8.2E-07	6.11E-07	-25.4%
	Scour enabled		
Peak Concentration TSS (m3/s)	0.002837	0.002839	0.1%
Grain Diameter (m)	0.002837	0.002612	-7.9%
Substance Density (kg/m3)	0.002837	0.002184	-23.0%
Theta Critical	0.002837	0.002837	0.0%

6.4.3 Summary of results

Squat shapes were better suited to removal of substances than elongated rectangular shapes. This echoes the results seen in the efficiency evaluations in Chapter 5.This result is once in again in contrast to prescriptive design length to with ratios within ponds of at least 2:1 and the results of Dufresne, et al. (2010) (section 2.5.2). This supports the indication that settling Type 1 was applicable to metals and TSS within the examined ponds.

The retention pond configurations were better suited to substance removal than detention pond configurations. The retention pond configurations showed no significant indications of scour. In contrast, detention pond configurations showed increases in scour at pond inflow and longer lengths of sediment transport with increasing pond length. This result can be attributed to the buffering effect on inflow pond velocities of the initial water within ponds. This result echoes previous results which indicated retention ponds to be more efficient in metals removals.

The model was highly sensitive to changes in substance density for both sediment transport and scour investigations.

In all, the results supported theoretically the indications of sedimentation and re-suspension of metals within ponds from the previous analytical work.

7. Design

7.1 Introduction

Detention and retention pond functioning for metals removal was illustrated in Chapter 6 to be complex; making descriptive detailed modelling enterprises difficult for in-situ irregularly shaped ponds. It was therefore recommended that future design philosophy should aim to mimic established design theory, including high levels of control and focussed on the identified processes of importance.

The indicated physical processes volume capture, sedimentation and re-suspension (particulates) as well as infiltration (dissolved matter) were shown to have been the main processes governing metals removals in the studied ponds. In addition, possible external loading mechanisms such as polluted rainfall, windblown sediment and polluted overland flow should not be ignored.

The practical extent of stormwater treatment is constrained by the diffuse nature of the runoff and, because it is expected that in most cases the runoff from catchment areas cannot be conveyed to a central treatment plant, end of pipe treatments such as ponds are geographically remote. This means that specialised operation is not feasible and ponds must be designed as self-regulating systems without inclusion of mechanical or chemical metals removal aids. Design recommendations were therefore focussed on realistic applications in within the South African environment.

7.2 Current design methodologies

Prominent and pertinent design methodologies as well as the parameters they included, in international literature, were compared with the research results. The comparisons elucidated advantages and shortcomings of the included methodologies.

7.2.1 Water quality volume (WQV) approaches

Water quality volume (WQV) approaches were prevalent in design methodologies used for the investigated ponds (refer to Tables 6.1 and 6.2). Two general approaches used in the USA and UK were summarised in Chp. 2, section 2.7.1 and Addendum A1.

Water quality volume:

The results of Chapter 5 did not indicate water quality volume to be a sole determinant of detention and retention pond efficiencies. This was in accordance with the findincs of Barrett (2008) who found that mean TSS and metals discharge concentrations where not significantly correlated with retention pond permanent pool volume, even though this is a prominent design element. The water quality volume can therefore not be used as the sole design parameter in stormwater pond design for both pond types, but was indicated in Chapter 5 to be an important element.

% Imperviousness:

This parameter was used to directly calculate the water quality capture volume in all WQV approaches. For detention and retention ponds, the correlation results were very sparsely populated. Although the results cannot deny the existence of a possible relationship between the parameter and pond efficiencies, they did not support the assumption that this parameter has a major direct influence on pond efficiency.

Basin drain time:

A coefficient for this parameter was provided prescriptively from a choice of 3 drain times, viz. 12 hrs, 24 hrs and 40 hrs and was used to directly calculate the WQV in the approach presented by the Urban Drainage and Flood Control District (2010). In detention ponds, indications of relationships between the Brim Full Emptying Time parameter and efficient metals removals were found. Therefore, this parameter is important to pond efficiencies, but it is uncertain whether the use of rigid prescriptive drain times is advisable.

Storm depth**:**

This parameter was used to directly calculate the WQV in the approaches presented by the Urban Drainage and Flood Control District (2010) and Woods-Ballard et al. (2007). Design storm depth data was not available for comparison.

Watershed area:

This parameter was directly used in all approaches to calculate the required design volume of the structure. Although it undoubtedly influences watershed runoff quantities, pollutant loads are determined by the use of the area, e.g. the occurrence of industry, traffic etc., which were considerations not included in this study. No clear relationship trends between efficiencies and watershed area were found in Chapter 5.

Soil classification:

This parameter was used in the methodology presented in the SUDS manual (Woods-Ballard et al., 2007) to directly calculate the required design volume of the structure. Soil classification data was not available for comparison.

WQV approaches are simplistic in nature. Simplicity of models can make them easy to apply in industry. However, such models can be deficient in the amount of information that they use and can provide. The WQV approaches researched included parameters for which information is easy to obtain, but did not encompass the range parameters that influence pond efficiency, e.g. %

imperviousness of a site is easy to calculate but was not found to have major direct influence on pond efficiencies. Other parameters found to possibly influence pond efficiencies such as water quality surface area and littoral zone areas were not included in these models. Such models are therefore not recommended for use in design of ponds that are specifically used for the removal of the metals investigated in this research project.

7.2.2 Routing

The pollutant routing methodology compared here is discussed in Chapter 2, section 2.7.2 and 2.7.3 and technical details are summarised in Addendum A 2 and A 3.

The methodologies for detention and retention pond chemical routing contained the assumption that dissolved chemicals are conservative. Results of efficiency analysis in Chapter 4 indicated that dissolved metals efficiencies were not significantly positive / generally unresponsive for the majority of metals removed in detention and retention ponds, lending support to the notion of conservative dissolved chemicals. Exceptions in results such as significantly positive efficiencies for dissolved copper (I5 Manchester East EDB, I15 SR78 EDB, I605 SR91 EDB), lead (I605 SR91 EDB, I5 La Costa East WB) and zinc (I5 Manchester East EDB, I605 SR91 EDB, Lake Ellyn) were attributed to mass loss via volume loss (Chapter 6 section 6.2) for detention ponds. Dissolved substance removal mechanisms for retention ponds could not be directly determined from the data, however, postulation based on outside literature in Chapter 6 indicated such mechanisms were physical in nature, e.g. unmeasured volume additions or loss with subsequent infiltration or dilution within the permanent pond volume.

Two processes for trapping of chemical substances were modelled in this design methodology, viz. settling and sorption. The philosophies behind the equations for both detention and retention ponds were identical.

All parameters, exept trapping efficiencies (TE) were empirical in nature. These parameters are dependent only on the characteristics of watershed and rainfall, relating to characteristics of the influent material. They are therefore separate from pond design characteristics and could provide no further information to this research project. The TE parameter was the only parameter in the chemical routing equations that was influenced by pond design characteristics.

Design parameters were limited to pond surface area, depth and detention times for both detention and retention pond models. Although these parameters have been found to influence pond efficiencies in terms of sediment removal (Chapter 5), they do not encompass other design parameters that may have an effect such as pond shape and littoral zone area.

These methodologies are therefore difficult to apply in practice due to difficulties in obtaining the amount of empirical information that is required, and are limited in the amount of design parameters that they include. They also have no consideration of possible hydraulic effects such as short circuiting and streaming problems commonly found in sedimentation basins. They do, however, include more parameters than were included in the WQV approaches, include consideration of pond processes such as settling and sorption and consideration of dynamic and quiescent conditions in retention ponds.

7.2.3 Prescriptive detention pond design guidelines

The methodology compared here was discussed in Chapter 2, section 2.7.4 and Addendum A 4.

Basin forebay:

General design guidelines have recommended a forebay volume of 10% of the total volume (United States Environment Protection Agency, 2004b) or 10% of total basin area (Woods-Ballard et al., 2007) for improved maintenance ease. No data for detention pond forebays were available for statistical analysis. However results for water quality volume and surface areas indicated that increases in these parameters with inclusion of forebays may improve pond efficiencies.

Micropool and outlet structure:

Brim full emptying time (BFET) was positively correlated with TSS removals in detention ponds. In addition, decreased probability of negative TSS removal was indicated by increases in this parameter. Therefore, increased BFET was associated with increased substance removals during normal functioning and decreased negative removals. This indicates that outlet structure design, as the main control of pond emptying times, was of high importance, however it is doubtful whether such times can be simply prescribed if specific numerical efficiency targets are to be met.

Surcharge volume:

Insufficient data was obtained and therefore comparisons between the results of this research project and design guidelines could not be made.

7.2.4 Prescriptive retention pond design guidelines

The methodology compared here was discussed in Chapter 2, section 2.7.4 and Addendum A 5.

Surcharge volume:

General design guidelines have recommended a surcharge volume above the permanent pool volume calculated from the maximum event volume and a drain time of 12 hours. This parameter is not directly included in the design for water quality purposes, but for flood control. In Chapter 5 it was indicated that permanent pool volume is of greater importance to pond efficiencies than the volume captured during storm events, i.e. surcharge detention, which simply drains out of the pond carrying material not removed within the retention times of the draining volumes.

Basin shape and depth:

Design guidelines recommended maximised lengths between inlets and outlets, large length to width ratios (> 2:1) and a mean permanent pool depth of 1-3 m (Urban Drainage and Flood Control District, 2010) (United States Environment Protection Agency, 2004b). In addition, Woods-Ballard et al. (2007) recommended a wedge plan shape to improve the sedimentation process.

Statistical analysis results (Chapter 5) did not find evidence of relationships between fraction removal efficiencies and pond length to width ratios for particulate substances. A positive detention pond dissolved zinc correlation with increased length to width ratios was found and may have been related to increased bottom surface area which improved infiltration of dissolved substances. In addition, results of the efficiency evaluations in Chapter 4 indicated that, conversely to design guidelines, long rectangular shapes ponds did not improve efficiency, but may have actively worsened it. The evidence for this was, however, limited (only 3 out of 19 case studies), and therefore the influence on this parameter on pond efficiency should considered as a possibility for further investigations. A wedge shaped pond structure was therefore better supported as a viable pond shape by the results of this research.

Statistical analysis results in Chapter 5 indicated complex relationships between pond depth and fraction removal efficiencies. Maximum pond depths are usually recommended for public safety reasons, but variations in depth may interact with other physical features in a complex fashion and therefore simple prescription of pond depths were not indicated to be advisable.

Basin forebay:

General design recommendations prescribe a volume of at least 3% of the WQV (Urban Drainage and Flood Control District, 2010). Insufficient data was obtained and therefore comparisons between the results of this research and design guidelines could not be made.

Outlet structure:

General design recommendations prescribe water quality volume drain time of at least 12 hours. The research results indicated poor efficiency with increased surcharge brim full emptying time (SBF) indicating that drain times should be designed as part of a complex system rather than being simply prescribed.

Vegetation:

Design guidelines recommended construction of a littoral shelf within the pool. In this research project it was indicated that increases in littoral zone negatively affect pond efficiencies during normal pond functioning, possibly through reduction of effective capture volume and effects on pond hydraulics. However, during events where negative removal occurred, littoral zones decreased such removals, possibly by acting as a mechanical hindrance to wash out of particulate material.

7.2.5 General discussion

- In general, design model parameters were limited and the focus of the models was overly simplistic. Parameters included in models provided in design guidelines were limited to pond volumes, pond depths, drain times and by extension detention times. There were a number of pond physical characteristics that were found to be possibly significant in pond efficiencies that were not included in the design models, e.g. littoral zone surface area. In addition, no consideration was given to the possible occurrence of re-suspension, a process indicated in the data to have commonly occurred in the studied ponds.

- Lack of focus on pollutants. Design methodology such as WQV approaches and prescriptive approaches included no consideration of pollutant loading. This was also noted by Scholes et al. (2008), who stated that the potential for specific types of BMPs to remove particular pollutants and their treatment effeciency in general was rarely, if ever, used as a discriminatory criterion for selection. Instead, catchment specific factors such as soil type and space available, capacity to store a design storm event, operation and maintenance requirements and cost were the basis for recommendations of BMP choice.

7.3 Design recommendations

The thesis stated that current water quality oriented stormwater pond design methods can be augmented towards satisfying SA water quality requirements for certain metal toxins through investigation into relationships between efficiency and design in existing stormwater pond case studies. In section 7.2.1 it was generally found that the discussed methodologies did not include the array of parameters found to be influential in the functioning of the studied ponds nor did they include consideration of all important processes e.g. re-suspension. These methodologies were therefore inadequate regarding metals removals in ponds.

The thesis statement further rested on the supposition that the results of investigations into international design methodologies and case studies could be applied in a South African context. The CSIR Building and Construction Technology Guidelines (2005:21) has stated that the use of detention ponds to remove pollutants in South Africa appears remote due to high clay content in South African runoff. Case studies used in this research project were existent in cities and agricultural areas within the USA and parallels with South Africa regarding metals source and behaviour were required to enable the transfer of knowledge gleaned from the research to South African scenarios. Such parallels hinged on a consideration of metals sources. Arsenic sources include industry (metallurgy, manufacture of glassware and ceramics), pesticides and wood preservatives. Cadmium sources included industry (alloy electroplating, solders, batteries, electronics, pigments, copper and zinc refineries), photography, pottery, phosphate fertilisers. Copper sources include industry (paper mills, steel works, electronics). Lead sources include industry (batteries), paints, gasoline. Zinc sources include industry (galvanizing, alloys, pharmaceuticals, dyes), paints and insecticides (Department of Water Affairs and Forestry, 1996c). All of these materials and industries are found in South African towns and cities. It is therefore maintained that surface runoff comparisons can be drawn for application in a South African context due to the existence of similar metals sources here.

The research results indicated that future design philosophy should contain the following characteristics:

- Hydraulic simplicity. Pond shape should be simple and should aim to mimic established modelling theory.

- Focus on sedimentation and re-suspension for particulate substances. Dissolved substance removal can possibly focus on infiltration or plant uptake. Not much data was available to ascertain the exact processes of dissolved metals removals and more research on these methods is warranted. If plant uptake can be shown to significantly reduce dissolved metals, then wetlands and reed beds might be more suited to this kind of stormwater purification.

- Control of additional sources of metals other than from the inflow. Such sources include polluted direct rainfall onto the pond, overland flow and wind blown sediment.

7.3.1 General design methodology

General mass balance theory (see Chapter 6) for pond design is as follows:

$$\frac{\Delta M}{\Delta t} = M_{in} - M_{out} - M_{settling} - M_{infiltration} + M_{resupension} \qquad (7.8)$$

where M = mass, t = time. No infiltration occurs in (1) retention ponds due to the design of ponds to retain water and (2) during particulate substance removals. The recommended general design methodology is therefore as follows:

7.3.1.1. Input loads

The determination of representative metal loads in catchment runoff may be done through on-site investigation or could be assumed from published values for watersheds with similar characteristics. Temporal and spatial watershed variations should be taken into account with appropriate weighting factors applied to combined results. Runoff pollution models are available. For example, Coleman & Simpson (1996) performed runoff pollution modelling on two catchment areas in Natal, South Africa with the WITQUAL model. They performed in-situ water quality and quantitity measurements for model input. The reality of undertaking such investigations for specific ponds, however, may prove to be impractical due to time and cost considerations.

A general lack of explicit research into the determination of pollutant loading rates for watershed areas was found. Future research towards establishing a summary of such information is warranted. Values published by the United States Environment Protection Agency (1983) and cited in Chen & Liew (2003:33-7) are displayed in Table 7.1. Values were based on an assumed 40 inches of rainfall a year as a long term average.

Table 7-1 Annual urban runoff loads (Kg/Ha/Year) (Chen & Liew, 2003:33-7)

Constituent	**Residential**	**Commercial**	**All Urban**
TSS	550	1460	640
Total Cu	0.13	0.35	0.15
Total Pb	0.55	1.48	0.65
Total Zn	0.62	1.64	0.72

Metals in particulate form are part of the TSS measurement. If it is accepted that particulate metals to TSS ratios remain unchanged between storm events, then metals removals can be defined in terms of TSS as was shown in Chapter 6. In detention ponds, it may be theorised that the pond is empty at the start of the storm. In retention ponds, quiescent settling between storms can be calculated from particulate material settling rates.

This approach illustrates the importance of control over the physical parameters of the structure. For the design to be realistically applicable, control over sources of material other than from the inflow stream must be absolute. In addition, measures must be taken to ensure that no re-suspension of material from previous storms occur.

7.3.1.2 Flood control detention volume determination

Detention and retention ponds designed for water quality control also usually has the dual function of flood control. Many different approaches towards the determination of inflow and outflow hydrographs exist and choice of methodology is at the discretion of the designer.

If a littoral zone is included in the design, care must be taken to estimate the volume of the basin occupied by the plant zone so as not to underestimate the flood control available volume. Additionally, if such a zone is not included, care must be taken in the physical pond design elements to ensure that natural growth does not occur, i.e. through the elimination of shallow zones where rooted plants may emerge. Additionally, local authorities should remove emergent vegetation not included in the design from both dry and wet ponds as a standard maintenance task.

7.3.1.3 Design for settling and re-suspension

Determination of particle settling velocities

The determination of particle settling velocities may be performed experimentally or published velocities may be used. Experimental determination of settling velocities requires a representative sample of particulate material from the watershed, but temporal and spatial watershed variations in such material may render such determinations very difficult to obtain and verify.

Clarifier design

It was concluded in Chapter 6 that practical modelling applications may be hindered by time and cost requirements to accurately model sedimentation and re-suspension in ponds with three dimensional variations in hydraulics due to irregular shapes and dynamic storm inflows. The complexity of the modelling and subsequent design processes can be greatly reduced if a high level of control is exerted over pond hydraulic behaviour. Therefore ponds with highly controlled hydraulic design elements, efficient sediment removal mechanisms and prevented re-suspension are preferable to other pond types for particulate metal removals. It is therefore recommended that settling tank design procedures, such as those commonly found in water quality treatment theory be used for pond design.

Two types of settling configurations are applicable to the design problem, viz. (1) conventional rectangular or circular settling basins and (2) plate or tube settlers. Problems associated with conventional clarifiers include (1) any particles entering the outlet zone either through inadequate time to reach the bottom or scour movement can be assumed to exit with the outflow, (2) short circuiting through density currents or streaming. Density currents are created when the density of the inflow stream is different to that of the clarifier, either due to differences in temperature or suspended solids. Small temperature differences can be significant. A possible effect of density currents that travel to the bottom of a pond is scouring (Chen & Liew, 2003:9-54). Streaming refers to the division of the water body into separate layers by density currents. This phenomenon can reduce efficiency (Fitch 1956 cited in Chen & Liew (2003), pg. 9-57). An example of these occurrences in practice was found by Hossain, et al. (2005) in a highway detention pond. They found that dead volume was approximately 38% of total volume. As a result, the actual residence time of the pond was approximately 64% of the theoretical residence time (see section 2.5.2). Indication of scour and re-suspension was observed in many of the investigated case studies in this research project. The accurate prediction of clarifier behaviour is therefore dependent on the elimination of re-suspension.

Therefore, the possibility of re-suspension in conventional clarifier design renders it non-ideal for application to the design problem especially in view of the difficulties of obtaining reliable information on metals or sorbed metals particle sizes, densities and settling velocities. If such designs are used, care must be taken to reduce hydrodynamic phenomena as described above. In particular, inflow and outflow velocities must be controlled. Research into this area is warranted.

Clarifiers with tube or plate settlers are known to water quality engineers, eliminate turbulence, density currents and streaming as well as the problems associated with them (Chen & Liew, 2003:9-60) making them a good candidate for application to particulate metals removal. The use of such technology has, however, been confined to highly specialised designs used in wastewater treatment, usually with addition of chemical aids (coagulants and flocculants) (Binnie & Kimber, 2011:127). In surface water treatment, proprietary designs may be used, but will require routing of stormwater from different areas to a central point and high costs not only for installation, but also for staff training and operation.

Simpler applications may possibly be used if the philosophy of design is one of self-regulating, remote installations for treatment of relatively small runoffs. In such scenarios, it is possible that lamellar plate or tubes may be installed in treatment basins, without application of chemical treatment, to function as sedimentation aids and prevent re-suspension. If such applications are envisioned, care must be taken in the choice of plate or tube material. It is recommended that plates or tubes be manufactured from plastic since metal theft is a possibility. Plastic must be UV stabilised and clear to prevent algal growth (Binnie & Kimber, 2011:120). Allowance for maintenance tasks such as sediment and plant removal must be made e.g. by allowing removal of plates or providing adequate area for maintenance tasks between plates. Material must therefore also be robust enough to withstand abuse during exercise of said maintenance tasks. Such simple application of lamellar or tube settlers for stormwater treatment has not yet been attempted in practice, and therefore warrants further research into optimisation of such systems.

7.3.1.4 Design for infiltration

Evidence was found in detention pond data analysis (Chapters 5 and 6) that dissolved metals were possibly removed through infiltration in the studied detention ponds. Infiltration should only be considered in ponds where the contaminated percolated water cannot be assumed to reach a natural water body. It may be uncertain which proportion of dissolved contaminants leave the pond with the percolated water and which proportion sorb to the bottom soils. Appropriate laboratory testing on in-situ material should be done to ascertain this if infiltration design is envisioned. If infiltration does not form part of the design philosophy, appropriate barriers must be installed to ensure a high level of control over the pond behaviour.

Infiltration rates of soils can be determined experimentally or determined from published values if existent. Many empirical equations for infiltration exist e.g. the Horton equation, Phillip’s infiltration equation and the Green and Ampt model (Chen & Liew, 2003:31-13). All the equations are not only dependent on the physical properties of the infiltration medium, but also on the time allowed for infiltration. Therefore, the longer the water volume remains in the pond, the more dissolved metals can be removed via infiltration.

7.3.1.5 Design for biological plant uptake in ponds during quiescent conditions

Retention ponds are not wetlands and plant uptake should therefore not be seen as a major substance removal mechanism. However, shallow side areas requirements for public safety and permanent water volumes within retention ponds often results in natural plant growth. Therefore, the designer may make use of this phenomenon and intentionally incorporate such elements into the whole pond design.

It is preferable to use water plants found locally. This has the advantage that the plants have a good chance of thriving in the local climate and maintains the integrity of indigenous species in the area. In the absence of published values for the envisioned plant species, laboratory studies may be performed to determine metal uptake rates. Examples of such studies can be found in Weiss et al. (2006), Hadad et al. (2006), Bragato et al. (2009) and Yeh et al. (2009).

7.3.1.6 Provide physical design elements to prevent inestimable sources of metals

Inestimable sources of metals to the pond may include runoff that flows directly into the pond, pollution captured in rainfall that falls directly onto the pond, windblown sediment and baseflow. It may be difficult in practice to estimate the loads provided to the pond by such sources and physical barriers, e.g. walls, ditches etc. should be installed to prevent inflows from these sources where possible. It may be argued that such inputs should not be prevented from reaching ponds so as to include them in treatment. If such inputs can be estimated, they should be included in the design. However, control over pond behaviour and the predictability of efficiency is lost if input elements cannot be estimated, rendering the exercise in pond design futile.

The removal of dissolved substances in detention and retention ponds can only be achieved (in the absence of chemical treatment) by plant removal or infiltration. Prevention of dissolved substance inputs may be redundant if ponds are not designed for dissolved substance removal.

7.3.2 Design example

A design example for a two basin system including a high rate settling pond and volume control pond was included in Addendum E. Practical testing of this type of design is, as previously mentioned, warranted in future research.

8. Conclusion

8.1 Introduction

This chapter serves to highlight the most important research findings and the conclusions thereof. The primary result of this investigation was the establishment of a focus area used for the determination of knowledge towards pond design improvement for metals removal. Although the main conclusions associated directly with the thesis of the research project, not all documented findings were so directly relevant. This summary of findings therefore also contains evidence deemed to be relevant to the objectives and significance of the research project; as well as being of general interest to environmental engineers. To this end, identification of the main processes that affected removals of the metals arsenic, cadmium, copper, lead and zinc in stormwater ponds and the subsequent establishment of a philosophical principle of design was a prominent result. This principle centres on enhanced control, not only during design, but also during operation and management of ponds.

8.2 Summary of findings

8.2.1 Findings of general interest

- Descriptive statistics showed different behaviours of substances, viz. (1) arsenic (detention ponds) and cadmium (detention and retention ponds) had similar inflow and outflow concentration and mass data ranges, medians and quartile ranges for all fractions, while (2) copper, lead and zinc had highly variable data.

These results indicate that (1) the ponds performed poorly with arsenic and cadmium removals, or (2) that the inflow values were relatively small and that the minimum achievable effluent concentrations and masses were achieved in these cases.

The similar inflow medians for masses and narrow quartile ranges indicate similarly loaded catchment areas. The narrow inflow quartile ranges indicate that catchment loading was generally subject to unchanging continuous loading without large shock load occurrences. The links between land use and runoff quality, however, did not form part of this research, but it is noted that the data that was compiled may possibly be used to investigate such links at a future time.

- Indications of resident material wash out in both detention and retention ponds were obtained in certain cases in the descriptive statistics analysis.

- Statistically significant differences between inflow and outflow values (concentration and mass) generally occurred less often in the dissolved fraction than in the total and particulate fractions. The CFPs for these cases often indicated generally unresponsive pond behaviour. Type

II error in the sign test results, which can be greatly dependent on sample size, was not accepted to be a likely reason for this result because the particulate fraction sample sizes were in all cases no larger than the dissolved sample sizes. Therefore, it was postulated that both detention and retention ponds were generally less efficient at dissolved fraction removal than at particulate fraction removal.

- The power of the sign test was low for the majority of detention and retention pond total (concentration and mass) cases where statistical significance between inflow and outflow values was not found. It is therefore possible that, due to effect size, these case studies may have produced significant results if larger sample sizes had been available.
- The favoured use of the concentration parameter in literature prompted an investigation into whether it may be used as a proxy parameter for mass, to ascertain the amount of substance removed by a structure. The results showed a noteworthy number of cases with contradictory concentration and mass efficiency classifications. This suggests that the use of the concentration parameter as a proxy parameter for mass is unfounded and, in addition, erroneous conclusions regarding pond efficiencies can be made if it is used within the Effluent Probability Method (EPM). It is therefore recommended that only the mass parameter be directly used for determination of pond efficiencies with the EPM.
- A notable number of detention pond and retention pond positive and negative classifications were not significant with power <0.8 indicating that these classifications may have changed had larger sample sizes been available. This demonstrations the importance of investigations into sample size determination before embarking on data measurements. It is therefore recommended that sample size investigations at the outset be done as a standard in stormwater quality research enterprises in future.
- Statistically significant differences between the upper and lower data range for both detention and retention ponds (inflow data) indicated that pond efficiencies, defined as fraction removals, differed between high and low inflow concentrations and masses. This provides support to the notion of different removals at different concentrations i.e., that discharge concentrations may be a function of influent concentrations.
- Concentration was found to be an inaccurate indicator of correlations between substances in inflow and outflow streams as well as the fractions of substances removed within ponds for both detention and retention ponds.
- In detention ponds, mass results indicated that (1) total cadmium, copper, lead, zinc and TSS were associated in surface runoff and were similarly removed within ponds, (2) dissolved zinc and copper were similarly removed within ponds, (3) particulate zinc and copper were associated

in surface runoffs and (4) TSS was associated with particulate copper, lead and zinc removals within ponds.

In retention ponds, mass results indicated that (1) total cadmium, copper, lead, zinc and TSS were associated in surface runoff and were similarly removed within ponds, (2) all dissolved substances correlated with TSS in the inflow section and (3) correlations in outflow and fraction removed sections indicated that TSS was associated with particulate copper, lead and zinc removals within ponds.

- Both detention and retention pond monotonic trends between outflow mass and inflow mass, outflow volume and inflow volume indicated that (1) the fraction of non-settleable material not captured in the pond from the watershed remained the same regardless of the runoff volumes i.e. consistent loadings over different storms and (2) increased outflow volumes carried proportionally increased outflow masses indicating mixing within ponds during storms. These results were regardless of pond efficiencies.

8.2.2 Findings relevant to the thesis

- The most efficient detention as well as retention ponds shared characteristic squat (round, L – shaped) or triangular shapes and earth linings. Long rectangular shaped ponds, although rare, were prone to poor efficiencies.

- Indications were found for both pond types that the influence of different pond parameters differed between normal functioning events and events where negative removals occurred and also that removals were differently influenced by pond parameters over different data ranges.

- In detention ponds, increasing probability of re-suspension in larger ponds was indicated and it is postulated that this was due to a number of factors such as larger storm events with fast and high volume runoffs (the reason for the ponds being large) or increased amounts of loose material deposition at pond bottom during normal functioning times resulting in more material available for re-suspension.

Length to width ratio relationships with pond efficiencies were only found for dissolved substances zinc (positive correlation for values above Q3) and lead (decreased probability of negative removals). This ratio is prescribed in prescriptive design methodology (see Chapter 7) and this result indicates that such a prescription is too simplistic to be used as a major design recommendation.

Increased BFET was associated with increased solids removals during normal functioning and decreased probability of negative removals. This result indicated that detention times of inflow volumes were key to particulate substance removals and also indicated settling as a removal mechanism since increased BFETs allow longer settling times.

- In retention ponds, the results indicated that the volume within the permanent pool was of greater importance to pond efficiencies than the volume captured during storm events. This parameter was deemed important to the functioning of the ponds, but was emphasised to be only one part of complex systems. For example, it was also indicated that increases in littoral zone negatively affected pond efficiencies during normal pond functioning, possibly through reduction of effective capture volume and effects on pond hydraulics. However, during events where negative removal occurred, littoral zones decreased such removals, possibly by acting as a mechanical hindrance to wash out of particulate material.

Negative correlations with surcharge brim full emptying times indicated that inflow volumes may have facilitated mixing of material within the permanent pool with reduced efficiency as a result.

- Physical processes of settling and re-suspension as well as infiltration in detention ponds were indicated as main functioning processes. Further consideration of chemical and biological functioning showed these processes to have been unlikely.
- Application of a polynomial time function to particulate data indicated non-flocculent settling across metal types viz. arsenic, cadmium, copper, lead and zinc as well as for TSS for the majority of detention as well as retention ponds.
- Computer hydrodynamic and sediment transport modelling with the MIKE 11 software program theoretically supported the indications of sedimentation and re-suspension of metals within ponds from the previous analytical work. In particular it was theoretically shown that (1) squat shapes were better suited to removal of substances than elongated rectangular shapes, and (2) retention pond configurations were better suited to substance removal than detention pond configurations.
- Pertinent and prominent international design methods were found to be limited, inadequately focussed and overly simplistic in view of the research results. They were therefore found to be unfeasible for metals removal in detention and retention ponds.

8.3 Conclusions

The thesis statement read:

“Current water quality oriented design methods used for stormwater pond structures can be augmented, towards satisfying SA water quality requirements for metal toxins as relates to primary food production, through investigation of the relationships between efficiency and design in existing international pond case studies”.

Relationships between efficiency and design were investigated by means of efficiency evaluations, correlational analysis and logistic regression. Data trends provided insight into the behaviour of arsenic, cadmium, copper, lead, zinc, TSS and TVS containing materials within the studied ponds. Identification of behavioural trends and processes informed the creation of a design philosophy. Modelling was employed to test indications of sedimentation and re-suspension, and these were thereby supported. The results were used to investigate the applicability of pertinent international design methodologies to pond removal of the studied metals. The investigated methodologies were found lacking in insight into processes that occurred within the ponds, overly simplistic and undefined. The developed design philosophy was therefore used to inform design recommendations for the studied metals removals.

Therefore, the thesis was deemed supported by the results.

8.4 Recommendations

8.4.1 General data measurement and handling

- Flow measurements coupled with water quality measurements at pond inlets and outlets should be included as a standard for all pond efficiency studies.

- Mercury, manganese and arsenic were under represented in the data. It is recommended that these substances be included as a standard in future data collection for pond efficiency studies.

- No method can claim to accurately predict the true concentration value of a non-detect measurement and different methods can produce variable mass results. Therefore it is recommended that *no* non-detect values be used to calculate mass data, where such data is directly used in case by case comparisons such as correlations between storm events, unless it can be shown that the result of data analysis is insensitive to the value of the concentration data for values below the MDL.

8.4.2 Statistical analysis

It is generally recommended that the assumption of normality in either untransformed or log transformed data be validated.

8.4.3 Efficiency evaluations of ponds

- It is recommended that assumptions be validated before choices on the statistical significance testing method to be used are made. Assumptions of improvements in symmetry through log-transformation of data are not recommended.

- It is recommended that the mass, and not the concentration, parameter be used for determination of pond efficiencies with the Effluent Probability Method.

8.4.4 Relationships between pond efficiencies and physical parameters

It is recommended that concentration data not be used in investigations into relationships between substance removals in stormwater ponds, since influence from the volume parameter may confound clear insights into such relationships. Mass data should be used instead.

8.4.5 Design of detention and retention ponds

All design recommendations were based on the principle of control. To this end, it is recommended that future design philosophy should aim to mimic established design theory with focus on particle sedimentation, re-suspension and infiltration. Specifically, future design philosophy should contain the following characteristics:

- Hydraulic simplicity. Pond shapes should be regular with predictable hydrodynamic fluctuations.

- Focus on sedimentation (in particular non-flocculent settling pending a runoff material analysis) and re-suspension for particulate material. In particular, flow velocities at pond inlets, outlets and within ponds must be carefully controlled. Focus on infiltration for dissolved material with consideration of groundwater pollution.

- Control of additional sources of metals other than from the inflow. Such sources include polluted direct rainfall onto the pond, overland flow and windblown sediment.

8.5 Summary of contributions

8.5.1 Theoretical contributions

1. Conceptual detention and retention pond models for metals removal were developed.
2. This research revealed that design methodologies for stormwater pond quality need not be accepted as final and that improvement can not only be made, but is needed. This is especially true for situations where there may be specific threats to future human well-being, such as the safeguarding of the South African (as well as international) food supplies.
3. It was shown that the concentration parameter cannot be used as a proxy to mass when determining pond efficiencies.
4. A novel classification system for pond efficiencies behavioural type that allows comparisons between ponds was developed (Addendum C2). This system may be used by researchers to perform comparative case study research into pond efficiencies.

8.5.2 Practical contribution

A philosophy of design for metals removal within ponds was developed based on pond behaviour in real applications. This provides a practical starting point for the practicing engineer in such design endeavours.

8.6 Future research

1. Standardisation: Stormwater quality research is currently being conducted worldwide. The growth of research into this subject is dependent on the ease with which researches can build on the work done be others. Internet based databases may become a standard tool for dissemination of data for researches worldwide in the future. Such databases are reliant on input from researchers all over the world, who may have developed country or discipline specific ways for dealing with stormwater quality information such as terms, data input standards, data handling standards etc. Such unmatched information can make interpretations of literature and data subjective. Therefore, scope exists for research that involves surveys among water quality professionals worldwide in order to come to agreements on specific terminology and data management techniques to be used as a standard in this area of study.
2. Runoff pollution data. It was discovered during the literature study that figures for runoff concentrations, masses and the characteristics thereof (settling velocities etc.) that could be expected from certain land use types were hidden in published literature. No standard reference document for such values was found. Costs and difficulties associated with on-site measurements of stormwater runoff concentrations may not be supported by the capital outlays of municipal projects. Therefore, a compilation of published and standard concentration values that may be expected from different land use types for general use by the civil engineer is warranted.

   Similarities and dissimilarities between inflow concentration and mass ranges and statistics between case studies may provide insight into the concentrations that may be expected from specific land uses. The links between land use and runoff quality did not form part of this research, but it was noted that the data that was compiled may possibly be employed in an investigation of such links at a future time.
3. Effect of the littoral shelf. General design guidelines recommend construction of a littoral shelf within the pool (see Addendum A). Results from this research project indicated that an increase in the littoral zone surface area when compared to the permanent pool surface areas may either improve or impair pond efficiencies for specific substances. This element of pond function therefore seems to be complex and more research into this area is warranted.

4. Pond design. It was recommended that future design philosophy should aim to mimic established design theory with focus of particle sedimentation, re-suspension and infiltration, which includes high levels of control. Sedimentation systems that include lamellar plates or tubes have been shown in wastewater treatment to improve sedimentation and prevent the occurrence of turbulence, density currents and streaming (Chen & Liew, 2003:9-60) making this type of design application theoretically ideal for removal of sediment associated metals in retention and detention ponds. No literature on the application of such systems to surface runoff has, however, been found and therefore research into this area is warranted.

ADDENDA

A. Technical summaries of international design methods

A 1 Water quality volume approaches

A 1.1. Methodology used in the United States of America

The Water Quality Capture Volume (WQCV)

A number of states in the United States of America use water quality volume approaches. These approaches are typically based on the philosophy of (1) the use of percent impervious area of a catchment and (2) chosen design storms to calculate the volume requirements for water quality improvement. An example taken from the Urban Drainage and Flood Control District's Urban Storm Drainage Criteria Manual Volume 3 (2010) is further discussed.

The Water Quality Capture Volume (WQCV) is based on the analysis of rainfall-runoff characteristics from 36 years of rainfall records from the Denver Stapleton rain gauge (1948-1984) conducted by (Urbonas et al. (1989) cited in Urban Drainage and Flood Control District (2010)). It was found that 61% of 75 storms that occured annually had less than 0.1 inches of precipitation in the Denver area. Such storms produced practically no runoff and therefore had no effect on the WQCV. It was also found that storms between 0.1 and 0.5 inches produced runoff and accounted for 76% of the remaining storm events.

Urbonas et al. (1989) cited in Urban Drainage and Flood Control District (2010) showed that the runoff produced from a precipitation event of 0.6 inches, corresponding to the 80th percentile of runoff producing storm events, is the target for the WQCV. The Water Environment Federation and American Society of Civil Engineers recommend that stormwater quality treatment facilities design be based on the capture and treatment of runoff generated by storms ranging in size from "mean" to "maximised" (70th and 90th percentile storms respectively). It is as a result of this recommendation that the runoff generated by the 80th percentile storm event is often used as a criteria for structure design. It is expected that the treatment of this volume will remove 80% - 90% of the annual TSS load. Doubling the volume is estimated to increase the removal rate by only 1% - 2% (Urban Drainage and Flood Control District, 2010).

A drain time of 24 hours was identified from a field study in Washington D.C. as being effective for a detention basin. A brim-full basin is generally allowed 40 hours to drain. Retention ponds are said to require only 12 hours because the hydraulic residence time of the effluent is increased due to mixing with the influent (Urban Drainage and Flood Control District, 2010).

Excess Urban Runoff Volume (EURV) and full spectrum detention

The Excess Urban Runoff Volume (EURV) represents the difference between the pre-developed and developed runoff volumes for the range of storms that produce runoff from pervious land surfaces (usu. greater than 1:2 years). The EURV is a larger volume than the WQCV and is detained over a longer time. It is used to replicate peak runoff for events that exceed those generating the WQCV (Urban Drainage and Flood Control District, 2010).

Calculation of WQCV and required storage

Step 1: Calculate the % imperviousness of the site

The total imperviousness is the weighted average of individual areas of like imperviousness. An area weighted average of all impervious and pervious areas are taken. The percent imperviousness of individual areas can be found in published literature, including Urban Drainage and Flood Control District (2010).

Effective imperviousness must be used where the unconnected (to the drainage system) impervious areas of the site are substantial. In such cases, the use of total imperviousness would result in over estimation of the peak runoff and storage volume. The term, effective imperviousness, referrs to the impervious areas which contribute surface runoff to the drainage system. This can be calculated as follows:

$$I_{effective} = \left(\frac{\mathrm{DCIA}+\mathrm{K}(\mathrm{UIA})}{\mathrm{DCIA}+\mathrm{UIA}+\mathrm{RPA}+\mathrm{SPA}}\right) 100 \qquad \text{(A.1)}$$

Where: DCIA = Directly Connected Impervious Area

K = Imperviousness Reduction Factor

UIA = Unconnected Impervious Area

RPA = Receiving Pervious Area

SPA = Separate Pervious Area

K is a factor, which includes considerations of pervious area infiltration loss, design rainfall depth, pervious area average infiltration rate, rainfall intensity and the WQCV.

Step 2: Calculate the WQCV

The WQCV is calculated with the following equation:

$$\mathrm{WQCV} = a\,(0.91I^3 - 1.19I^2 + 0.78I) \qquad \text{(A.2)}$$

Where: WQCV = Water Quality Capture Volume (watershed inches)

a = Coefficient corresponding to WQCV drain time (can be found in literature)

I = Imperviousness (%)

For areas outside the Colorado high plains, the following adjustment should be made:

$$\mathrm{WQCVother} = d_6\,(\mathrm{WQCV} / 0.43) \qquad \text{(A.3)}$$

Where: WQCV = WQCV calculated using equations above.

WQCVother = WQCV outside of Denver region (watershed inches)

d_6 = depth of average runoff producing storm from (can be found in literature)

Step 3: Calculate the required storage

For WQCV:

$$V = \frac{\mathbf{WQCV}}{\mathbf{12}}(1.2A) \quad (A.4)$$

For EURV:

$$V = \frac{\mathbf{EURV}}{\mathbf{12}}(A) \quad (A.5)$$

Where: V = design volume (acre ft.)

A = watershed area tributary to the extended detention basin (acres)

1.2 factor = multiplier to accommodate sediment accumulation

(Urban Drainage and Flood Control District, 2010)

A 1.2 Methodology used in the United Kingdom

The variable rainfall depth method

A treatment volume, which is greater than or equal to the runoff volume of 90% of storm events is given by this method:

$$Vt = 9\,D\,[\,SOIL/2 + (1 - SOIL/2)\,I\,] \quad (A.6)$$

Where: Vt = water quality treatment volume (m^3 / ha of total development area)

D = M5 – 60 minute rainfall depth (i.e. 5 year return period, 60 minute duration storm depth determined from Wallingford procedure), usu. ranging from 10 to 20mm

SOIL = soil classification (from Wallingford Procedure WRAP map)

I = fraction of area, which is impervious

(Lampe et al., 2005)

The fixed rainfall depth method

In England a fixed rainfall depth of 11 – 15 mm is used, applied to impermeable areas only (Lampe et al., 2005).

A 2 Sediment Routing

A 2.1 The simple rate approach for TSS routing

Total sediment trapping can be calculated with the following equation. However, this equation can not be used to predict the trapping of various size fractions (United States Environment Protection Agency, 2004b).

$V_c = D / T_d$ (A.7)

$TE_i = V_{s,I} / (q_{p,out} / A_a)Const_8 = V_{s,i} / V_c$ (A.8)

Where: TE_i = the trapping efficiency for particle class *i*

$V_{s,i}$ = the settling velocity in m/s (ft/s) for particle class *i*

$q_{p,out}$ = the peak outflow from the pond in m^3/s (ft^3/s)

A_a = the average surface area of pond in ha (acre) during the storm. This can be reduced to include the impact of dead storage by a factor of 0.18 for ponds with a length to width ratio of greater than 2:1 and 0.25 for ponds with a smaller ratio.

$Const_8$ = 10^{-4} for metric and $2.296\text{x}10^{-5}$ for English units

V_c = the overflow rate in m/s (ft/s)

D = liquid depth in the basin in m (ft)

Td = the detention time (s)

Further modification of the equation above for steady state conditions yields:

$TE = 1 – e^{(-kTd)}$ (A.9)

$K = V_s / h$ (A.10)

Where: h = basin depth

(United States Environment Protection Agency, 2004b)

A 2.2 Size distribution calculations for discharged and trapped sediment

The mass of sediment discharged or trapped in any size class, i, for detention ponds is given by:

$M_{D,i} = F_i Y_T (1 - TE_i)$ (A.11)

$M_{T,i} = F_i T_Y TE_i$ (A.12)

where: $M_{D,i}$ = mass of sediment discharged in kg (lb) for particle size classification i

$M_{T,I}$ = mass of sediment trapped in kg (lb) for particle size classification i

Y_T = the total sediment yield from the drainage area in a storm, in kg (lb)

F_i = the fraction of sediment in a given particle size classification i

TE_i = the trapping efficiency for particle size i

The mass of sediment trapped or discharged in any affluent size class, i, for retention ponds is given by:

$$F_{T,i} = F_i \, TE_{C,i} \tag{A.13}$$

$$F_{D,i} = F_i \, (1 - TE_{C,i}) \tag{A.14}$$

Where: $TE_{C,i}$ = combined trapping efficiency for a particle class

(United States Environment Protection Agency, 2004b)

A 2.3 Quiescent settling in retention ponds

The following equations for calculation of the quiescent settling rate of sediment are recommended by the USEPA.

$$R_{Q,i} = 8.64 \times 10^4 V_{S,i} \, A_Q \tag{A.15}$$

Where: RQ,i = quiescent removal rate in m^3/day (ac-ft/day) for particle class i

VS,i = the settling velocity in m/s (ft/sec) for particle class i

A_Q = surface area in m^2 (acre) for the permanent pool

The removal ration, RR_i, for average conditions and particle of class i is given by:

$$RRi = T_{IA} \, R_{Q,i} / V_R \tag{A.16}$$

Where: T_{IA} = the average time interval between storms in days

V_R = mean runoff volume in m^3 (ac-ft)

RR_i = the removal rate in the interval between storms for the average arrival time between storms

(United States Environment Protection Agency, 2004b)

Values for T_{IA} are tabulated by Driscoll et al. (1986) and are also given in Haan et al. (1994).

A 2.4 Dynamic settling in retention ponds

The trapping efficiency in the simple rate approach is only valid for a single storm event. For dynamic settling in a retention pond with varying flows the equation must be statistically averaged over all storms as described in USEPA (2004b).

A 2.5 Total removal efficiency:

The total removal efficiency of a retention pond is a combination of the quiescent and dynamic trapping efficiency. A complex computer model would be required to accurately estimate this. A simple alternative recommended by Driscoll (1986), found in United States Environment Protection Agency (2004b) is given below:

$$TE_{C,}i = 1 - (1 - D_{R,i})\ (1 - E_{Q,i}) \qquad (A.17)$$

Where: $TE_{C,i}$ = combined trapping efficiency for particle class i

$D_{R,i}$ = dynamic trapping efficiency for particle class i

$E_{Q,i}$ = fraction of sediment removed under quiescent conditions, determined from the figure above

$$D_{R,i} = [\ (1/CV_Q^2) / ((1/CV_Q^2) - \ln (TE_{M,i}))]^{[1/CV_Q + 1]} \qquad (A.18)$$

The trapping efficiency, $TE_{M,i}$, can be calculated with those presented in the simple rate approach above.

It must be noted that this equation fails at very low removal rates (values of $TE_{M,\ i} = 0.065$). These curves were also based on low density, single family residential developments. Curves were not developed for other land use patterns. No account was taken of variations in particle size, runoff volume or segregation of pervious and impervious area (United States Environment Protection Agency, 2004b).

A 3 Chemical pollutant routing

Calculation methodology for chemical pollutant routing has been discussed in the Stormwater Best Management Practice Design Guidelines (United States Environment Protection Agency, 2004b) as a method to be used when sizing detention and retention ponds for the purpose of chemical pollutant reduction. Dissolved chemicals are conservative. Trapping of chemicals is accepted to be as a result of settling of the particulate components and settling of particles sorbed to active clay particles.

A 3.1 Settleable fraction

Settleable chemicals are assumed to be part of the clay sized fraction and trapping is assumed to be calculated the same as for clay particles.

The total mass of inflow into the basin of a pollutant, k, is given by:

$$Ms_{,inf,k} = Y_T \sum_{i=1}^{5} (F_i \, CF_i \, F_{Pk,i}) \qquad \text{(A.19)}$$

Where: $M_{S,inf,k}$ = total mass of particulates in the inflow to the basin for a particular pollutant

Y_T = the total sediment yield from the drainage area in a storm, in kg (lb)

F_i = the fraction of sediment in a given particle size classification i

CF_i = the fraction of clay sized particles

$F_{Pk,i}$ = the fraction of clay sized particles that are chemical particulates or settleable particles, usu. a known quantitiy based on empirical data. If unknown, see calculation below:

$$F_{Pk\,,i} = [\gamma \, F_{S,k} \, EMC_k \, Q A \, Const_4] \; / \; Y_T \sum_{i=1}^{5} (F_i \, CF_i) \qquad \text{(A.20)}$$

(assumed to be constant over all size classes)

Where: γ = weight density of water in kg/m^3 (lb/ft^3)

$F_{S,k}$ = the fraction of an EMC for a given pollutant that is particulate

EMC_k = the EMC of pollutant k

Q = runoff volume in watershed cm (in.)

A = watershed area in ha (acre)

$Const_4$ = 10^{-4} for metric (0.00363 for English units)

The masses trapped and discharged are therefore given by:

$$M_{ST,k} = Y_T \sum_{i=1}^{5} (F_i \, CF_i \, F_{Pk,i} \; TE_i), \text{ and} \qquad \text{(A.21)}$$

$$M_{SD,k} = Y_T \sum_{i=1}^{5} (F_i \, CF_i \, F_{Pk,i} \; (1-TE_i)) \qquad \text{(A.22)}$$

(United States Environment Protection Agency, 2004b)

A 3.2 Sorbed and dissolved fraction

The masses of sorbed and dissolved fractions influent to the pond are defined by isotherm and active clay relationships and read as follows:

$C_{S,k} = K_{CD,k}$ $\qquad$ $C_{S,k} \leq CS_{max,k}$ (A.23)

$C_{DS,k} = C_{S,k} C_{AC} \times 10^{-6} + C_{D,k}$ (A.24)

Where: $C_{S,k}$ = the concentration on the solid phase in mg/g

$C_{D,k}$ = concentration in the liquid phase in mg/l

C_{AC} = concentration of active clay in mg/l, see equation below

$C_{DS,k}$ = dissolved and sorbed concentration of a pollutant in mg/l

K = the phase change constant in mg/g/mg/l

$C_{S\,max,k}$ = the maximum value for $C_{S,k}$

$C_{AC} = Y_{AC} / [\gamma\ QA\ Const_4]$ (A.25)

Where: Y_{AC} = yield of active clay size particles in kg (lb)

$Y_{AC} = Y_{CP} - \sum_{k=1}^{m}(Y_{S,k})$ (A.26)

Where: $Y_{S,k}$ = settleable yield in kg (lb) of a given chemical pollutant, k

S = refers to settleable

m = the number of chemical pollutants being considered

Y_{AC} = yield of clay-sized particles with an active charge that provides a surface for sorption of pollutants such as nutrients and other chemicals

The masses (kg) of pollutant trapped and discharged as a result of being sorbed to clay particles are calculated as follows:

$M_{DAT,k} = C_{S,k} Y_{AC} TE_{AC} \times 10^{-6}$, and (A.27)

$M_{DAD,k} = C_{S,k} Y_{AC} (1 - TE_{AC}) \times 10^{-6}$ (A.28)

(United States Environment Protection Agency, 2004b)

A 4 Prescriptive detention pond design guidelines

General guidelines for extended detention basin (EDB) design has been given in the Urban Storm Drainage – Criteria Manual Volume 3 (Urban Drainage and Flood Control District, 2010), and are discussed below along with input from other guidelines.

Step 1: Calculate the basin storage volume

This can be done with the water quality volume approaches previously discussed, or with sediment or chemical routing techniques. The US Environmental Protection Agency (USEPA) recommends that the design effluent TSS and chemical concentrations be checked against required water quality standards. If the effluent does not conform, an iterative process must be used to modify the design until the standards for water quality control as well as for peak flow reduction are met. It is also recommended that additional storage volume should be provided if high rates of sedimentation occur to account for deposition. A 20% increased allowance in volume is considered to be reasonable for less critical areas (United States Environment Protection Agency, 2004b).

Step 2: Determine the basin shape

It is often recommended in design guidelines that the distance between the inlet and outlet be maximised with a length to width ratio of at least 2:1. It is claimed that this will minimise short circuiting and improve the reduction of TSS (Urban Drainage and Flood Control District, 2010) (United States Environment Protection Agency, 2004b). The SUDS manual specifies a maximum depth of 3m and a length to width ratio of between 2:1 and 5:1 (Woods-Ballard et al., 2007).

Step 3: Determine the basin side slopes

Guidelines recommend that slopes should not be steeper than 3:1 with 4:1 being recommended for maintenance purposes (Urban Drainage and Flood Control District, 2010) (United States Environment Protection Agency, 2004b) (Woods-Ballard et al., 2007).

Step 4: Design the inlet

Guidelines recommend that the inlets should be designed to dissipate flow energy in order to reduce erosion and improve sedimentation (Urban Drainage and Flood Control District, 2010) (United States Environment Protection Agency, 2004b).

Step 5: Design the forebay

The forebay allows an opportunity for larger particles to settle out in an area that can be easily maintained (Urban Drainage and Flood Control District, 2010). The USEPA recommends a volume storage capacity of approximately 10% of total volume (United States Environment Protection Agency, 2004b). The SUDS manual recommends a forebay plan area that is 10% of the total basin area (Woods-Ballard et al., 2007).

Step 6: Design the trickle channel

This design aspect has little bearing on this research and further discussion is therefore not included.

Step 7: Design the micropool and outlet structure

Guidelines recommend that the permanent micropool should be located directly in front of the outlet structure. The well screen must be submerged into the bottom of the pool to prevent ponding, which provides a habitat for mosquitoes. A smaller, deeper pool is less likely to allow mosquitoes to breed. It is recommended that the micropool be at least 2.5 feet in depth and have a minimum surface area of 10 square feet (Urban Drainage and Flood Control District, 2010) . The USEPA recommends that the pool be designed to store 15% - 25% of capture volume (United States Environment Protection Agency, 2004b).

It is recommended that the outlet should be designed to release the WQCV over a 40 hour period. If the design is for full spectrum detention, a 72 hour drain time is required for the EURV. Reservoir routing techniques and orifice sizing equations are available in Urban Drainage and Flood Control District (2010).

The USEPA recommends that the outlet be allowed to empty less than 50% of the design volume in the first one third of emptying time (usu. 12 to 16 hours). It should also be designed to ensure TSS from small runoff events are adequately removed (United States Environment Protection Agency, 2004b).

Step 8: Provide an initial surcharge volume

The initial surcharge volume is additional volume provided outside of the micropool. It minimises standing water and sediment deposition in the remainder of the basin, necessary for turf maintenance and mosquito abatement. The volume begins at the surface of the micropool and extends upwards to a grade break in the basin, which is usually the invert of the trickle channel. The full area is usually the same as, or slightly larger than that of the micropool. It is recommended that it have a minimum depth of 4 inches and a volume of 0.3% that of the WQCV for watersheds greater than 5 impervious acres. This forms part of the WQCV and does not need to be provided additionally (Urban Drainage and Flood Control District, 2010).

Step 9: Provide a trash rack

It is recommended that a trash rack be provided at the outlet to provide sufficient hydraulic capacity when it is partially clogged (United States Environment Protection Agency, 2004b).

Step 10: Design the overflow embankment

The embankment must be designed to withstand at least the 100 year storm (Urban Drainage and Flood Control District, 2010) (United States Environment Protection Agency, 2004b).

Step 11: Provide vegetation

Guidelines recommend that basin berms, bottom and side plants should be planted with turf grass (Urban Drainage and Flood Control District, 2010) (Woods-Ballard et al., 2007), or native vegetation (United States Environment Protection Agency, 2004b).

Step 12: Provide access

Maintenance access must be provided to the forebay and outlet works (Urban Drainage and Flood Control District, 2010) (United States Environment Protection Agency, 2004b) (Woods-Ballard et al., 2007).

A 5 General prescriptive retention pond design guidelines

A retention pond contains a permanent pool of water and is also called a “wet” pond. It is designed to catch and release the WQCV over a period of 12 hours. Additionally, it has additional capacity above the permanent pool. It is expected that stormwater runoff mixes with the water in the pool during every runoff event, allowing for a reduced residence time compared to an EDB. It is claimed that the 12 hour drain time allows for better replication of pre-development flows for frequent events and reduces the potential for short circuiting treatment in smaller ponds. Ponds can also be designed for full spectrum detention (Urban Drainage and Flood Control District, 2010).

The USEPA has named two approaches to the design of retention ponds. The first is based on the assumption that all pollutants settle out with sediment. The second treats the pond like a lake and considers eutrophication processes to remove pollution. In practice most designs rely heavily on the assumption of pollutant removal via sedimentation (United States Environment Protection Agency, 2004b).

The following design procedure is recommended by the Urban Drainage and Flood Control District (2010) and is amended with design recommendations from other design guidelines:

Step 1: Consider baseflow

A perennial baseflow must be physically and legally available if the pool is not established by groundwater. Use conservative net influx calculations to account for significant annual variations. Low inflow in relation to the pond volume can result in poor water quality. Evaporation, evapotranspiration and seepage account for losses. A liner is recommended for ponds that lie above the groundwater table (Urban Drainage and Flood Control District, 2010).

Step 2: Calculate the surcharge volume

The Urban Drainage and Flood Control District (2010) recommends that the surcharge volume above the permanent pool should be based on a 12 hour drain time. The USEPA recommends that a surcharge volume be provided above the permanent pool whenever the VB/VR is less than 2.5. It is recommended that the maximum event based volume with a drain time of 12 hours be used. This should be checked with the sedimentation and chemical routing equations (United States Environment Protection Agency, 2004b).

Step 3: Determine the basin shape and depth

It is recommended by the UDFCD that the distance between the inlet and outlet be maximised with a length to width ratio of at between 2:1 and 3:1. This will minimise short circuiting and improve the reduction of TSS (Urban Drainage and Flood Control District, 2010) (United States Environment Protection Agency, 2004b). The USEPA (2004b) also recommendes a mean peremanent pool depth of 1-3 m. The SUDS manual recommends a length to width ratio of at least 3:1 and a wedge plan shape so that entering flow can spread out and in so doing improve the sedimentation process. A maximum depth of 2m is recommended to avoid stratification and anoxic conditions (Woods-Ballard et al., 2007).

Step 4: Calculate the volume of the permanent pool

This can be done with the water quality volume approaches previously discussed, or with sediment or chemical routing techniques. It is recommended by the UDFCD that two depth zones be included in the permanent pool:

Safety wetland bench: This area should be located around the perimeter of the pool with a depth of 6 to 12 inches and a minimum width of 4 feet. This allows aquatic plant growth that helps to strain surface flow, stabilizes the banks and provides a safety foothold for people who fell into the pond (Urban Drainage and Flood Control District, 2010). The USEPA recommends that this bench be 10 feet wide and 1 foot deep (United States Environment Protection Agency, 2004b). The SUDS manual recommends a maximum depth of 45 cm and a minimum width of 1 m (Woods-Ballard et al., 2007).

Open water zone: This is an open volume of water, which provides for sedimentation and nutrient uptake by organisms. It should not be deeper than 12 feet to prevent anoxic conditions (Urban Drainage and Flood Control District, 2010). The USEPA recommends a depth of 6 to 8 feet (United States Environment Protection Agency, 2004b).

The USEPA (United States Environment Protection Agency, 2004b) and SUDS (Woods-Ballard et al., 2007) approach philosophises that the permanent pool provides treatment during dry periods to runoff. A portion of this is displaced during subsequent storm events and the new influent is treated during the following dry periods. It is recommended that the pool be sized for a specific hydraulic retention time, where after the effluent quality is checked and the volume be modified in subsequent iterations.

$$T = VB / nVR \tag{A.29}$$

Where: T = hydraulic detention time in years

VB = volume of the permanent pool

n = number of runoff events per year

VR = volume of runoff for an average storm

Ponds with values of T greater than 2 to 3 weeks have a greater risk of thermal stratification and anaerobic bottom waters. Municipalities in the USA often require specific values of T or, alternatively, VB/VR or minimum total suspended sediment removal rate. It has been shown that ponds designed with $T \geq 2$ weeks and $VB/VR = 4$ achieve TSS removal rates of 80% to 90% (United States Environment Protection Agency, 2004b).

The USEPA recommends a pool depth of 3 to 6 feet to prevent thermal stratification and enable aerobic conditions (United States Environment Protection Agency, 2004b).

The SUDS manual recommends that the “treatment volume” be adjusted with a factor for different areas when calculating the storage volume (Woods-Ballard et al., 2007). Applicable factors are given in the literature.

Step 5: Determine the basin side slopes

It is recommended that slopes for the safety wetland bench should be no steeper than 4:1. Below the bench the slopes should be no steeper than 3:1. A deeper pond reduces penetration of sunlight and therefore algae growth (Urban Drainage and Flood Control District, 2010).

Step 6: Design the inlet

It is recommended that inlets should be designed to dissipate flow energy in order to reduce erosion and improve sedimentation. It should also be designed to diffuse the inlet plume (Urban Drainage and Flood Control District, 2010) .

Step 7: Design the forebay

The forebay allows an opportunity for larger particles to settle out in an area that can be easily maintained. It is recommended that, for maintenance purposes, solid linings be installed. The recommended volume is at least 3% of the WQV (Urban Drainage and Flood Control District, 2010).

Step 8: Design the outlet structure

It is recommended that the outlet should be designed to release the WQCV over a 12 hour period (Urban Drainage and Flood Control District, 2010).

Step 9: Provide a trash rack

It is recommended that a trash rack be provided at the outlet to provide sufficient hydraulic capacity when it is partially clogged (Urban Drainage and Flood Control District, 2010).

Step 10: Design the overflow embankment

It is recommended that the embankment must be designed to withstand at least the 100 year storm (Urban Drainage and Flood Control District, 2010).

Step 11: Consider maintenance

It is recommended that a means should be provided for draining the pond for maintenance. Gravity feed is preferred, but it can also be pumped (Urban Drainage and Flood Control District, 2010).

Step 12: Provide vegetation

It is recommended that basin berms should be planted with turf grass. The wetland bench should be planted with aquatic species (Urban Drainage and Flood Control District, 2010).

Step 13: Provide access

It is recommended that maintenance access must be provided to the forebay and outlet works (Urban Drainage and Flood Control District, 2010).

B. Case studies – Outside reports

B 1 Detention Ponds

B 1.1 El Dorado Detention Pond

The El Dorado Detention Pond (also named the B504-03-00 Detention Basin in the International Stormwater BMP Database) is located in the city of Houston, Texas in the USA. The detention pond consists of a rectangular basin with two inlets and one outlet. Three earthen pilot channels direct water towards a central pilot channels, from where water leaves the pond via a box culvert (PBS&J, 2004).

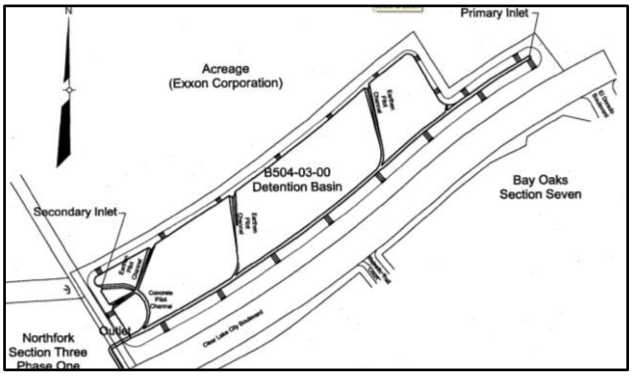


Figure B-1 El Dorado Detention Basin Layout (PBS&J, 2004)

B 1.2 Grant Ranch Detention Pond

The Grant Ranch Detention Pond (also named Orchard Pond in the International Stormwater BMP Database) Littleton, Colorado (USA). The pond is triangular shaped and contains one inlet and one outlet.

A performance evaluation on the pond was done by Piza & Eisel (2009). This report was not mentioned in the International Stormwater BMP Database as a report for this case study. Coordinates of the pond were, however, given in the database and therefore an image of the pond found with the software program Google Earth (Copyright© Google Inc.) was compared to the photos and layout included in the pond to ensure that the correct report was used.

Distinction is made between detention basins and EDBs in this report and the Grant Ranch Pond is classified as an EDB. Such distinction was, however, not made in this research project and the Grant Ranch Pond is hereafter simply classified as a detention pond.

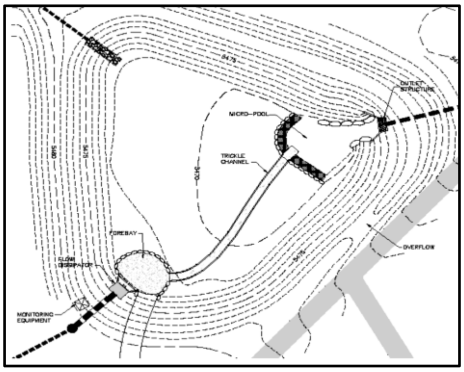


Figure B-2 Grant Ranch EDB Layout (Piza & Eisel, 2009)

The performance evaluation done by Piza & Eisel (2009) contained the following findings:

- Pond outflow volumes were found to be frequently higher than inflow volumes. A possibility of measurement error due to clogging in orifice plates was noted. It was also noted that runoff from 11 out of 18.7 acres entered the basin via the (measured) storm sewer.
- Total and dissolved copper and zinc as well as TSS data were subjected to the Wilcoxon signed rank test for statistical significance analyses (alpha = 0.05). Statistically significant differences between inflows and outflow were found for the total copper data group.
- Box plots were used for the display of descriptive statistics.

B 1.3 Greenville Detention Pond

The Greenville detention pond is located in Greenville, N.C. (USA). The pond was completed in 1991 and has a square shape with one inlet and one outlet.

A performance evaluation was done by Stanley (1994). Although this report was not directly listed in the International Stormwater BMP Database as the soure of information, it refers to a report by Belk et al. (1992) to APES as a source of its information. This same report is referred to as the source of information in the International Stormwater BMP Database. The report by Stanley (1994) was therefore accepted to contain the correct information. Pond efficiencies were reported as average percentage mass removals as listed below:

- Total Copper – 26%
- Total Lead – 55%
- Total Zinc – 26%
- TSS – 71%

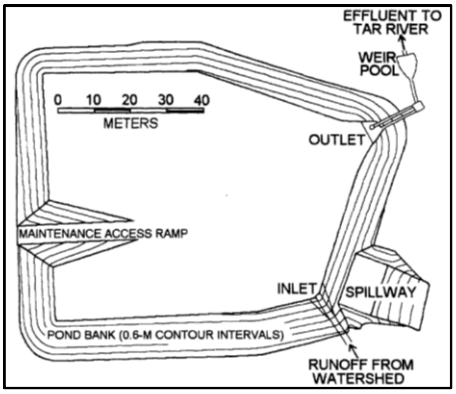


Figure B-3 Greenville detention pond Layout (Stanley, 1996)

B 1.4 Highway EDBs

I5/I605 EDB

The I5/I605 EDB is located within the I5/I605 highway right of way in Downey, CA (USA). T Pond performances were monitored during a pilot study by the California Department of Transportation (2004). The following was found:

- Percentage removals for concentrations and masses of copper, lead, zinc (total, particulate and dissolved) and TSS were positive.
- An ANOVA indicated that none of the removals were statistically significant.
- Inflow and outflow volumes were the same.
- Some TSS export occurred, indicating re-suspension of particles in four storm events.
- The pond is L-shaped.

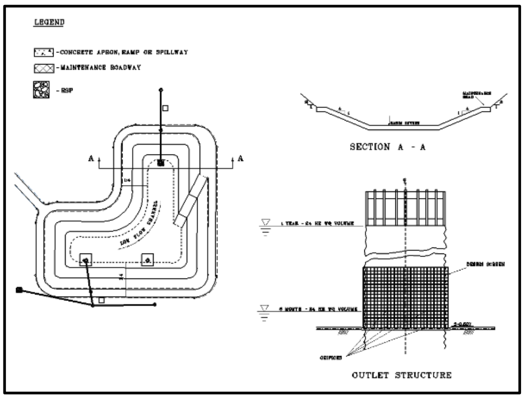


Figure B-4 I5/I605 EDB Layout (California Department of Transportation, 2004)

I5 Manchester East EDB

The I5 Manchester East EDB is located within the I5/I605 highway right of way in Downey, CA (USA). The pond design was identical to that of the I5/I605 EDB, i.e. it was L-shaped, and has one inlet and outlet. It was, however, earth lined rather than concrete lined (California Department of Transportation, 2004).

Pond performances were monitored during a pilot study by the California Department of Transportation (2004). it was found that percentage removals for concentrations and masses of total copper (63% and 72% respectively) and TSS (73% and 80% respectively) were positive.

I5/SR56 EDB

The I5/SR56 EDB is located within the I5/SR56 highway right of way in San Diego, CA (USA). The pond design was identical to that of the I5/I605 EDB, i.e. it was L-shaped, and has one inlet and outlet. It was, however, like the I5 Manchester East pond earth lined rather than concrete lined (California Department of Transportation, 2004).

Pond performances were monitored during a pilot study by the California Department of Transportation (2004). It was found that percentage removals for concentrations and masses of total copper (50% and 58% respectively) and TSS (55% and 62% respectively) were positive.

I15/SR78 EDB

The I15/SR78 EDB is located within the I15/SR78 highway right of way in Escondido, CA (USA). The pond design was identical to that of the I5/I605 EDB, i.e. it was L-shaped, and has one inlet and outlet. It was, however, like the I5 Manchester East and I5/SR56 ponds earth lined rather than concrete lined (California Department of Transportation, 2004).

Pond performances were monitored during a pilot study by the California Department of Transportation (2004). It was found that percentage removals for concentrations and masses of total copper (65% and 73% respectively) and TSS (74% and 80% respectively) were positive.

I605/SR91 EDB

The I605/SR91 EDB is located within the I605/SR91 highway right of way in Cerritos, CA (USA). The pond design was identical to that of the I5/I605 EDB, i.e. it was L-shaped, and has one inlet and outlet. It was, however, like the I5 Manchester East, I5/SR56 and I15/SR78 ponds earth lined rather than concrete lined (California Department of Transportation, 2004).

Pond performances were monitored during a pilot study by the California Department of Transportation (2004). It was found that percentage removals for concentrations and masses of total copper (36% and 76% respectively) and TSS (61% and 85% respectively) were positive.

General Discussion

The pilot study report produced by the California Department of Transportation (2004) included a general section on the earth lined ponds, in which the behaviours of the ponds were combined. The following results were presented:

- The ponds performed best with removal of particulate materials. Removal of dissolved metals was generally modest and not statistically significant.
- All earth lined ponds had significantly better removals than the concrete lined pond (I5/I605 EDB). It was believed that this was due to infiltration in the unlined ponds.
- The average TSS reduction was 73%.
- Approximately 40% of runoff infiltrated the soil in the unlined ponds. The percentages ranged from approximately 60% in the I605/SR91 EDB to about 8% in the I5/I56 EDB.
- Outflow volumes were greater than inflow volumes on many occasions.
- The I5/I605 EDB performed the best with an average TSS reduction efficiency of 85%.

B 1.5 Lexington Hills Detention Pond

The Lexington Hills detention pond is located within between 162nd Ave. and Flavel dr. in Portland, OR (USA). The pond is triangular in shape with one inlet and one outlet. No outside studies on pond performance were found.

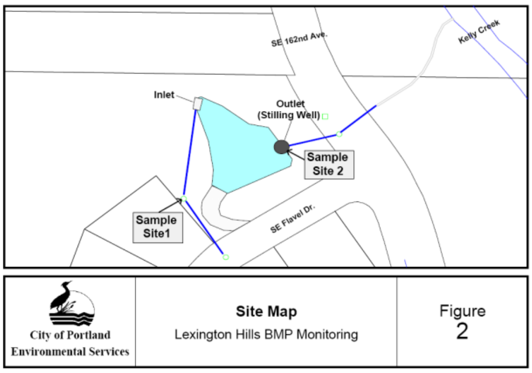


Figure B-5 Lexington Hills detention pond layout (International Stormwater BMP Database, accessed 14 October 2011)

B 1.6 Mountain Park Detention Pond

The Mountain Park detention pond is located in Lilburn, GA (USA). No pond images or outside studies on pond performance were found.

B 2 Retention Ponds

B 2.1 Central Park Retention Pond

The Central Park retention pond is located in Austin, TX (USA). The pond consists of 3 ponds in series, is linear in shape as a whole and has one inlet and one outlet (City of Austin, 1998). No outside studies on pond performance were found.

Information on pond performances was provided by the City of Austin (1998). The following information was provided:

- Percentage removals for concentrations were positive: TSS (85%), lead (98%) and zinc (76%).
- Median levels of zinc in sediment were 755mg/kg.

Figure B-6 Central Park retention pond layout (International Stormwater BMP Database, accessed 14 October 2011)

B 2.2 Cockroach Bay Retention Pond

The Cockroach Bay retention pond is located on an agricultural site in Ruskin, FL (USA). The pond consists of 2 ponds in series, which become connected when the water level is above 0.61m (Rushton, 2002).

Pond performances were monitored during a study funded by the South West Florida Water Management District in 2002. The following was found:

- An estimated 7% to 21% of water outflow was due to seepage. This is the result of inflow seepage – outflow seepage, the amounts of which are unknown.
- The cadmium, copper, lead and zinc percent removal of pollutant load efficiencies were positive for all the years of the study (1998-2001). The TSS percent removal efficiency was negative for the year 1999.

(Rushton, 2002)

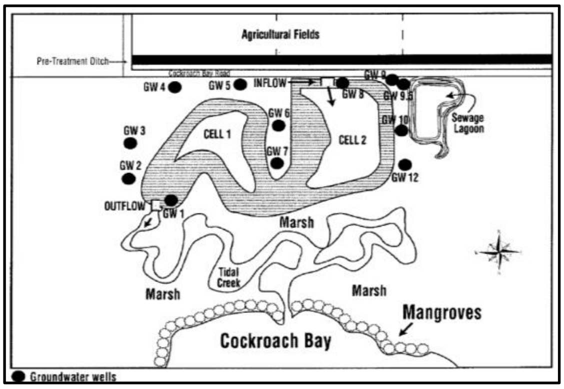


Figure B-7 Cockroach Bay retention pond layout (Rushton, 2002)

B 2.3 De Bary Retention Pond

The De Bary retention pond is located in De Bary, FL (USA). The pond is designed as a filtration pond, has a squat rectangular shape and has one inlet and outlet (Harper & Herr, 1993).

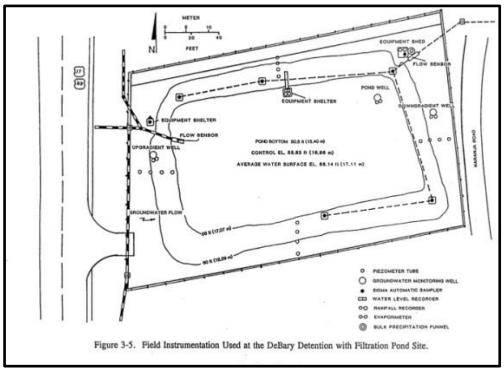


Figure B-8 De Bary retention pond layout (International Stormwater BMP Database, accessed 14 October 2011)

Pond performances were monitored during a study funded by the St Johns River Water Management District from June to November 1992 (Harper & Herr, 1993) . The following was found:

Flow inputs and outputs included seepage from or to groundwater.

The overall mass removal efficiencies of the system calculated as [Mass(out) – Mass(In)] / Mass(In) expressed as a percentage were published as:

- Total Cadmium: -47%
- Total Copper: -37%
- Total Lead: -71%
- Total Zinc: -89%
- TSS: -98%

It was observed that metals that predominantly occurred in the dissolved fraction (such as cadmium and copper) had lower removal efficiencies (40%-50%) then those that occurred predominantly in the particulate fraction (such as lead and zinc) (70%-90%). It was noted that a primary mechanism for removal might therefore be the settling process.

B 2.4 Greens Bayou Retention Pond

The Greens Bayou retention pond (also referred to in the International Stormwater BMP Database as the Greens Bayou Surge Basin) is located in Houston, TX (USA). The pond forms part of the Beltway 8 Wetland Water Quality Project, for which it serves as a surge basin for the stormwater inflow. The pond has a squat rectangular shape and has one main inlet and one outlet. Overflow from one of the wetlands also enters the pond on occasion (Wetland Solutions Inc., 2010).

Pond performances were monitored during a study done by Wetland Solutions Inc. (2010) and funded by the Harris County Flood Control District from January to December 2009. The study was broadly focussed on the wetland project as a whole, and did not provide insight into the functioning of the Greens Bayou retention pond as a sole entity.

Figure B-9 Greens Bayou retention pond located on the Beltway 8 Wetland Water Quality Project
(Wetland Solutions Inc., 2010)

B 2.5 Heritage Estates Retention Pond

The Heritage Estates retention pond is located in Richmond Hill, ON (Canada). The pond has a L-shape and has one main inlet and one outlet. Pond performances were monitored in a study by the Stormwater Assessment Monitoring and Performance (SWAMP) Program from between 1995 and 2002. The overall concentration removal efficiencies of the system were published as:

- Total Copper: 76%

- Total Zinc: 71%

- TSS: 84%

(Stormwater Assessment Monitoring and Performance (SWAMP) Programme, 2005)

Figure B-10 Heritage Estates retention pond location (International Stormwater BMP Database, accessed 14 October 2011)

B 2.6 I5 La Costa East WB

The I5 La Costa East retention pond (WB) is located within the I-5 highway right of way in Encinitas, CA (USA). The pond design is a long L-shape, and has one inlet and outlet (California Department of Transportation, 2004).

Figure B-11 I5 La Costa East retention pond image (California Department of Transportation, 2004)

Pond performances were monitored during a pilot study by the California Department of Transportation (2004). The following was found:

- Percentage removals for concentrations were:

  Total Copper: 89%, Dissolved Copper: 57%

  Total Lead: 98%, Dissolved Lead: 76%

  Total Zinc: 91%, Dissolved Zinc: 41%

  TSS: 94%

- An ANOVA ($p<0.05$)indicated that all of the removals were statistically significant.

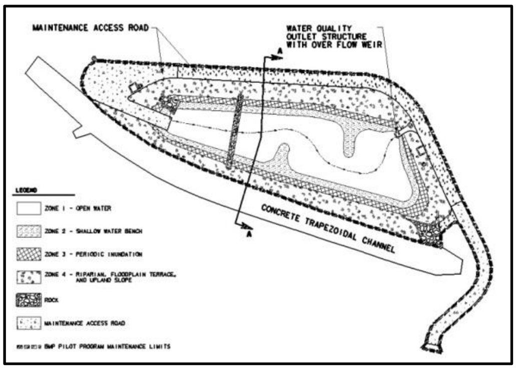


Figure B-12 I5 La Costa East retention pond layout (International Stormwater BMP Database, accessed 14 October 2011)

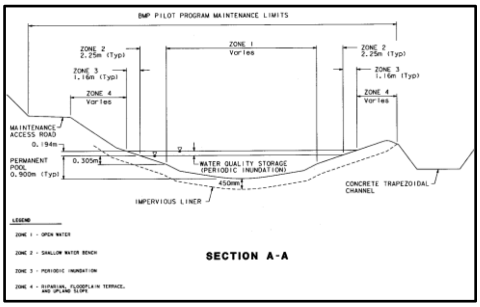


Figure B-13 I5 La Costa East retention pond cross section (California Department of Transportation, 2004)

B 2.7 Lake Ellyn

Lake Ellyn is located in Glen Ellyn, IL (USA). The pond has a rectangular shape with one main inlet and outlet.

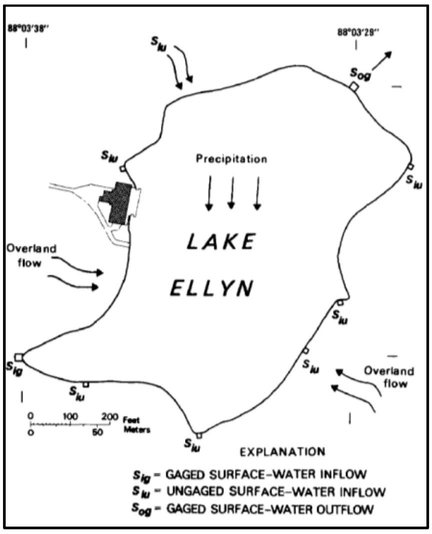


Figure B-14 Lake Ellyn inflows and outflows (Striegl & Cowan, 1987)

Pond performances were monitored during a study by Striegl & Cowan (1987) for the U.S. Geological Survey (USGS). Percentage removals for masses were estimated as:

- Total Copper: 77-88%, Dissolved Copper: 13-54%
- Total Lead: 84-92%, Dissolved Lead: -651—300%
- Total Zinc: 76-88%, Dissolved Zinc: 62-80%
- TSS: 88-94%

B 2.8 Lake Ridge

Lake Ridge is located in Woodbury, MN (USA). The pond has a long rectangular shape with one main inlet and outlet.

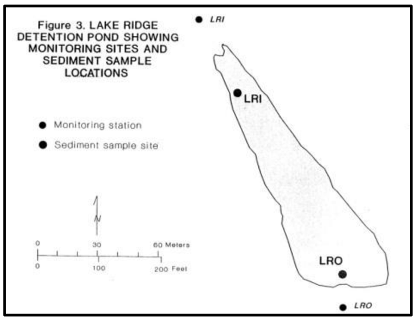


Figure B-15 Lake Ridge layout (International Stormwater BMP Database, accessed 14 October 2011)

Pond performances were monitored during a study by (Walker, 1993) for the U.S. Geological Survey (USGS). It was found that the Mann-Whitney U test for statistical significance was applied to inflow and outflow loads for the SS and Pb constituents, the resultant p-values were 0.015 and 0.025 respectively.

B 2.9 Lakeside Retention Pond

The Lakeside retention pond (also referred to as the Lakeside (LS) pond in the International Stormwater BMP Database) is located in Charlotte, NC (USA). The pond has a long rectangular shape with one main inlet and outlet.

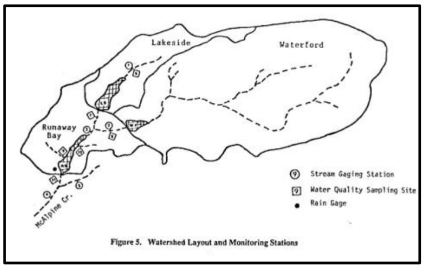


Figure B-16 Lakeside retention pond layout (International Stormwater BMP Database, accessed 14 October 2011)

Pond performances were monitored during a study by Wu (1989) for the Water Resources Research Institute of Norch Carolina. Percentage removals for concentrations were estimated as:

- Total Zinc: 80%
- TSS: 93%

B 2.10 Madison Monroe str. Retention Pond

The Madison Monroe str. retention pond (also referred to as the Wet detention pond, Monroe str. in the International Stormwater BMP Database) is located in Madison, WI (USA). The pond has a round shape with one main inlet and two outlets.

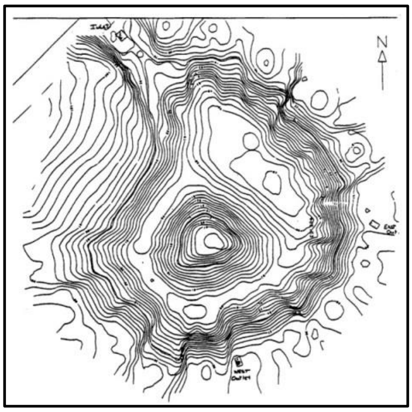


Figure B-17 Madison Monroe str. retention pond (International Stormwater BMP Database, accessed 14 October 2011)

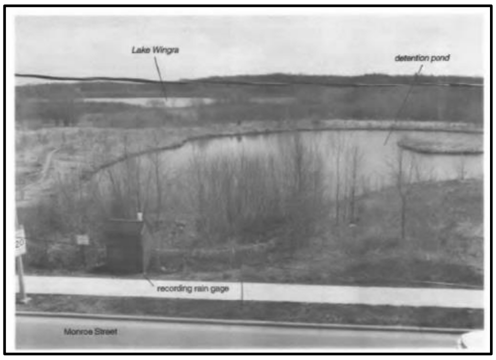


Figure B-18 Madison Monroe str. retention pond (House et al., 1993)

Pond performances were monitored during a study by (House et al., 1993) from February 1987 to April 1988 for the U.S. Geological Survey. The following was found:

- The median percentage decrease in outflow EMCs were reported as follows:

  Dissolved Copper: 29%

  Total Lead: 71%, Dissolved Lead: -16%

  SS: 88%

- The median percentage decrease in outflow loads were reported as follows:

  Total Copper: 97%, Dissolved Copper: 41%

  Total Lead: 93%, Dissolved Lead: 56%

  SS: 88%

B 2.11 McKnight Basin

The McKnight basin (also referred to as the McKnight basin detention pond in the International Stormwater BMP Database) is located in Maplewood, MN (USA). The pond system consists of three ponds with clearly defined inlet and outlet monitoring points. It is unclear from the available data how pond 3 forms part of the system. No outside studies on pond performance were obtained.

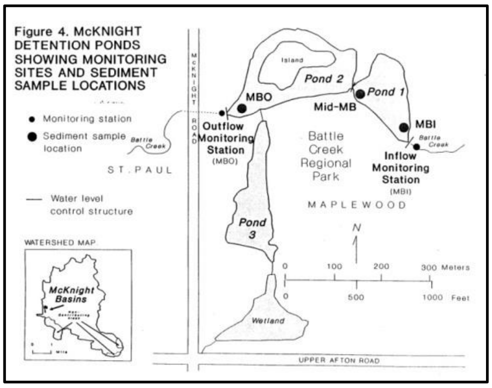
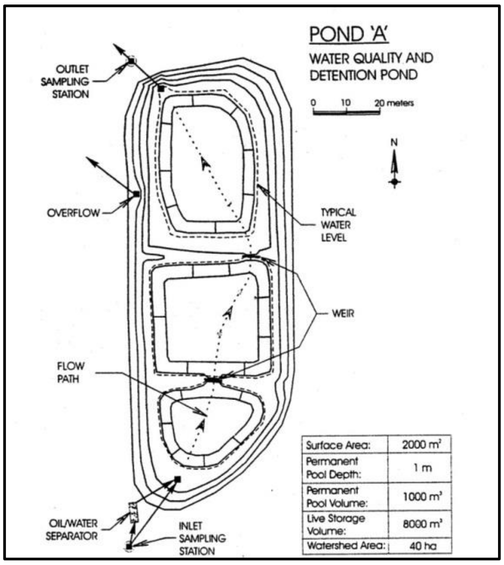


Figure B-19 McKnight basin layout (International Stormwater BMP Database, accessed 14 October 2011)

B 2.12 Phantom Lake Pond A

Phantom Lake Pond A (also referred to as Pond A in the International Stormwater BMP Database) is located in Bellevue, WA (USA). The pond forms part of the Phantom Lake system consists of three ponds with clearly defined inlet and outlet monitoring points.



Surface Area:	2000 m²
Permanent Pool Depth:	1 m
Permanent Pool Volume:	1000 m³
Live Storage Volume:	8000 m³
Watershed Area:	40 ha

Figure B-20 Phantom Lake Pond A layout (International Stormwater BMP Database, accessed 14 October 2011)

Pond performances were monitored during a study by Comings et al. (2000) from October 1996 to March 1997. The percentage removals for masses were reported as follows:

- Total Cadmium: 68%
- Total Copper: 37%
- Total Lead: 73%
- Total Zinc: 45%

- TSS: 61%

B 2.13 Pinellas Retention Pond

The Pinellas retention pond (also referred to as the Pinellas detention pond in the International Stormwater BMP Database) is located in Pinellas Park, FL (USA). The pond is located within the St Joe Creek water way, has a L-shape and a single inlet and outlet.

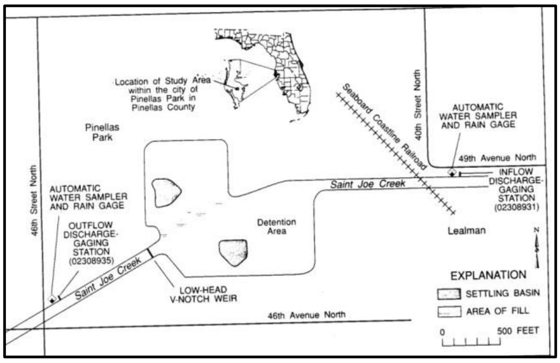


Figure B-21 Pinellas retention pond layout (International Stormwater BMP Database, accessed 14 October 2011)

Pond performances were monitored during a study by Kantrowitz & Woodham (1995). The percentage removals for masses were reported as follows:

- Total Copper: 21%
- Total Lead: 43%
- Total Zinc: 36%
- TSS: -20%

B 2.14 Pittsfield Retention Pond

The Pittsfield retention pond (also referred to as the Pittsfield retention basin in the International Stormwater BMP Database) is located in Ann Arbor, MI (USA). The pond is has a round shape and a single inlet and outlet. No outside studies on pond performance were found.

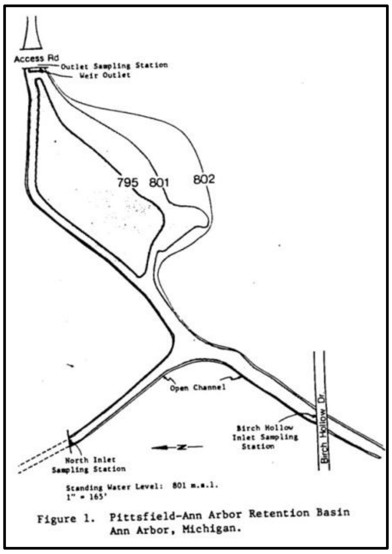


Figure B-22 Pittsfield retention pond layout (International Stormwater BMP Database, accessed 14 October 2011)

B 2.15 Runaway Bay Retention Pond

The Runaway bay retention pond (also referred to as the Runaway Bay (RB) pond in the International Stormwater BMP Database) is located in Charlotte, NC (USA). The pond connects with the Lakeside retention pond and has a long rectangular shape with one main inlet and outlet.

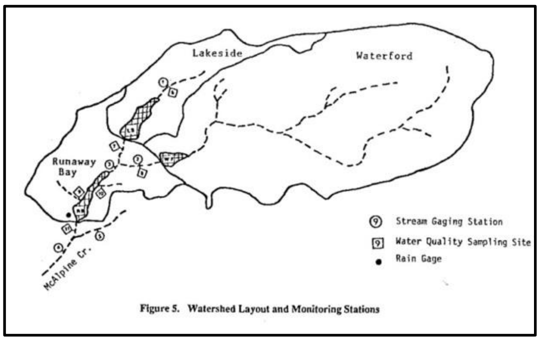


Figure B-23 Runaway Bay retention pond layout (International Stormwater BMP Database, accessed 14 October 2011)

Pond performances were monitored during a study by Wu (1989) for the Water Resources Research Institute of Norch Carolina. Percentage removals for concentrations were estimated as:

- Total Zinc: 32%
- TSS: 62%

B 2.16 Silver Star rd. Retention Pond

The Silver Star rd. retention pond (also referred to as the Silver Star rd. detention pond in the International Stormwater BMP Database) is located in Orlando, FL (USA). The pond connects with a wetland and has a rectangular shape with one main inlet and outlet (International Stormwater BMP Database).

A report produced by Gain (1996) for the U.S. Geological Survey illustrated changes in performance of the pond after it was modified in 1998. The data obtained from the International Stormwater BMP Database, however, limited the use of the findings to those of the original pond. Percentage removals for concentrations were estimated as:

- Total Lead: 19%
- Total Zinc: -15% , Dissolved Zinc: -32%
- TSS: 25%

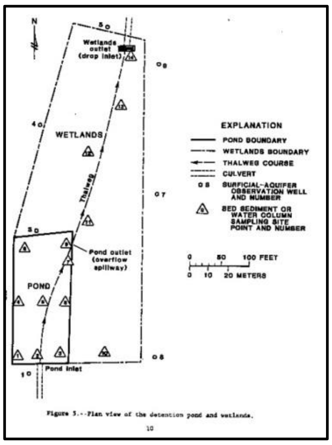


Figure B-24 Silver Star rd. retention pond layout (International Stormwater BMP Database, accessed 14 October 2011)

B 2.17 Tampa Office Ponds 1, 2 and 3

The Tampa Office Ponds 1 (1990-1991), 2 (1993-94) and 3 (1994-95) were located in Tampa, FL (USA). The Tampa Office Ponds 2 and 3 were created in succession due to modifications performed on the Tampa Office Pond 1 (Rushton et al., 1997). The Tampa Office Ponds 1 and 2 are L-shaped, while the Tampa Office Pond 3 has a rectangular shape. All ponds have one inlet and outlet. Pond performances were monitored during a study by Rushton et al. (1997) for the South West Florida Water Management District.

Table B-1 Mass removal efficiencies (%) of the Tampa Office Ponds (Rushton et al., 1997)

Constituent	Tampa Office Pond 1	Tampa Office Pond 2	Tampa Office Pond 3
Total Cadmium	55	42	87
Total Copper	-	1	55
Total Lead	-	-	92
Total Zinc	56	32	87
TSS	71	67	94

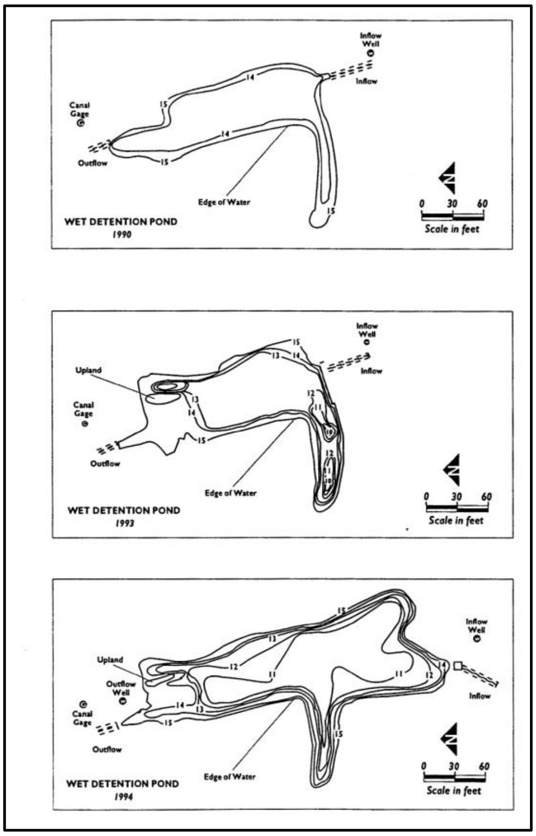


Figure B-25 Tampa office ponds 1, 2 and 3 layouts (Rushton et al., 1997)

B 2.18 UNH Retention Pond

The UNH retention pond (also referred to as the University of New Hampshire retention pond in the International Stormwater BMP Database) is located in Durham, NH (USA). No outside studies on pond performance were found.

C. Efficiency evaluations

C 1 Cumulative frequency plots

C 1.1 Detention ponds

C 1.1.1 DP Arsenic

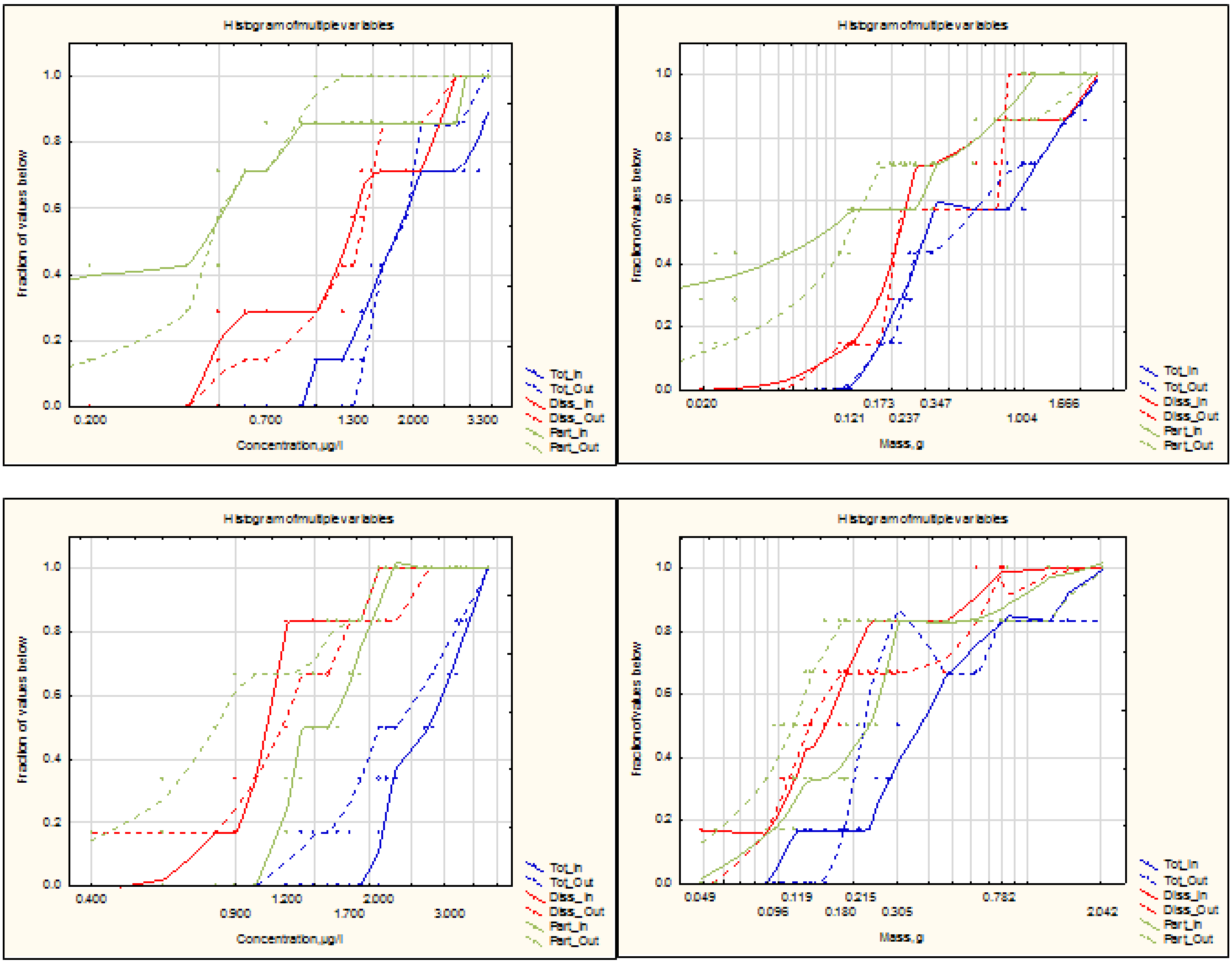


Figure C-1 Arsenic CFPs for I5/I605 EDB (top) and I5/SR56 EDB (bottom)

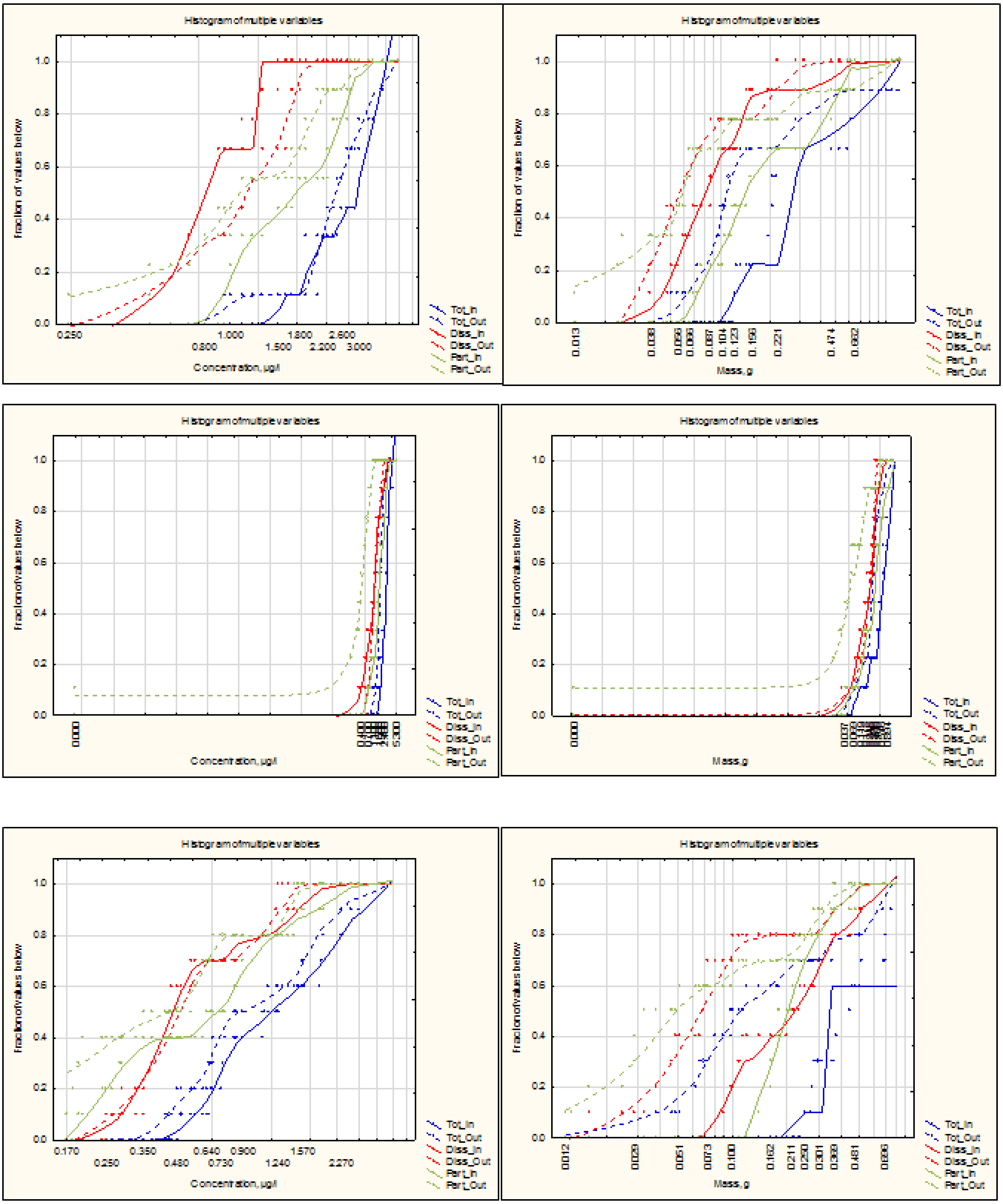


Figure C-2 Arsenic CFPs for I5/Manchester East EDB (top), I15/SR78 EDB (middle) and Lexington Hills (Bottom)

C 1.1.2 DP Cadmium

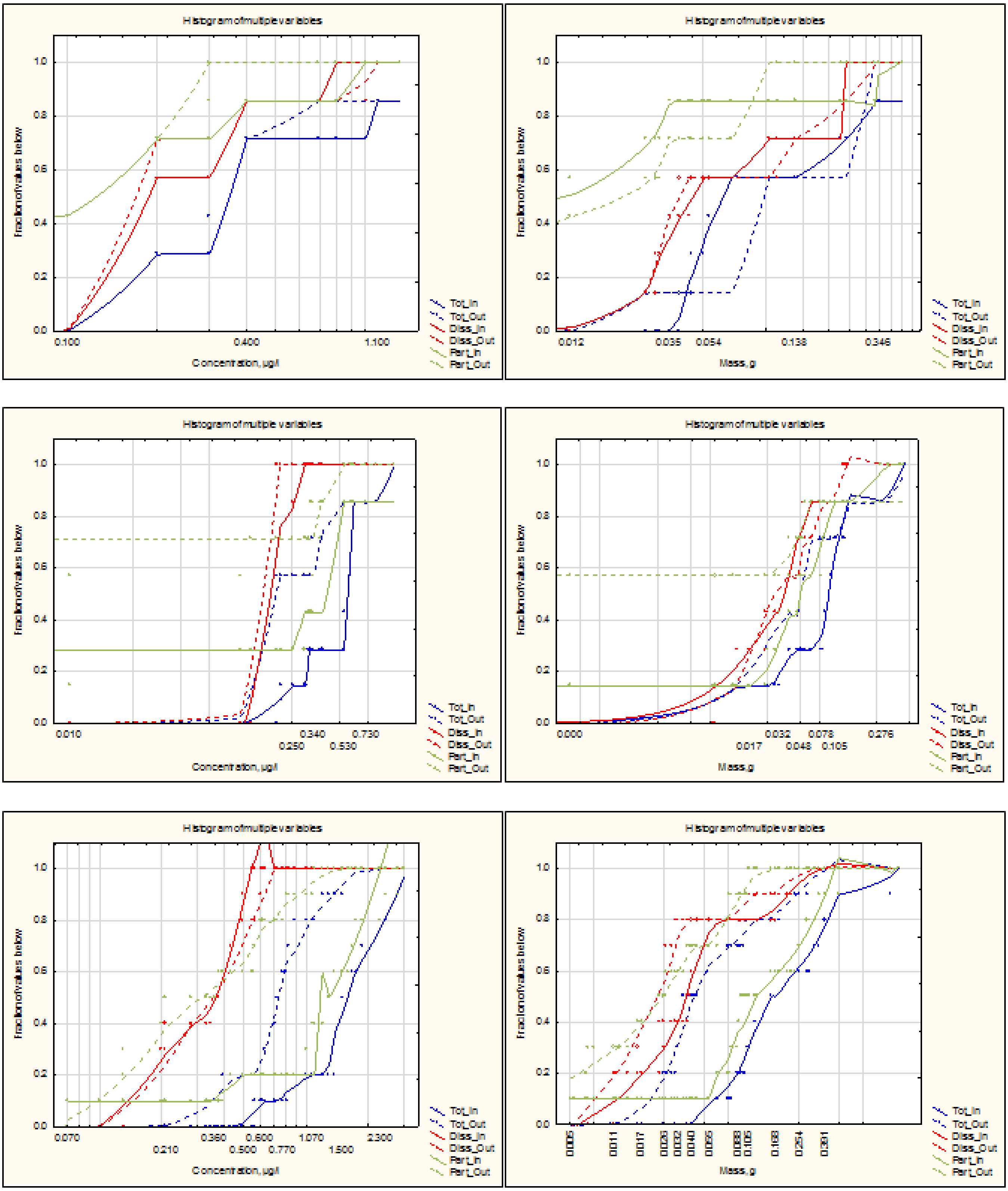


Figure C-3 Cadmium CFPs for I5/I605 East EDB (top), I5/SR56 EDB (middle) and I5 Manchester East EDB (Bottom)

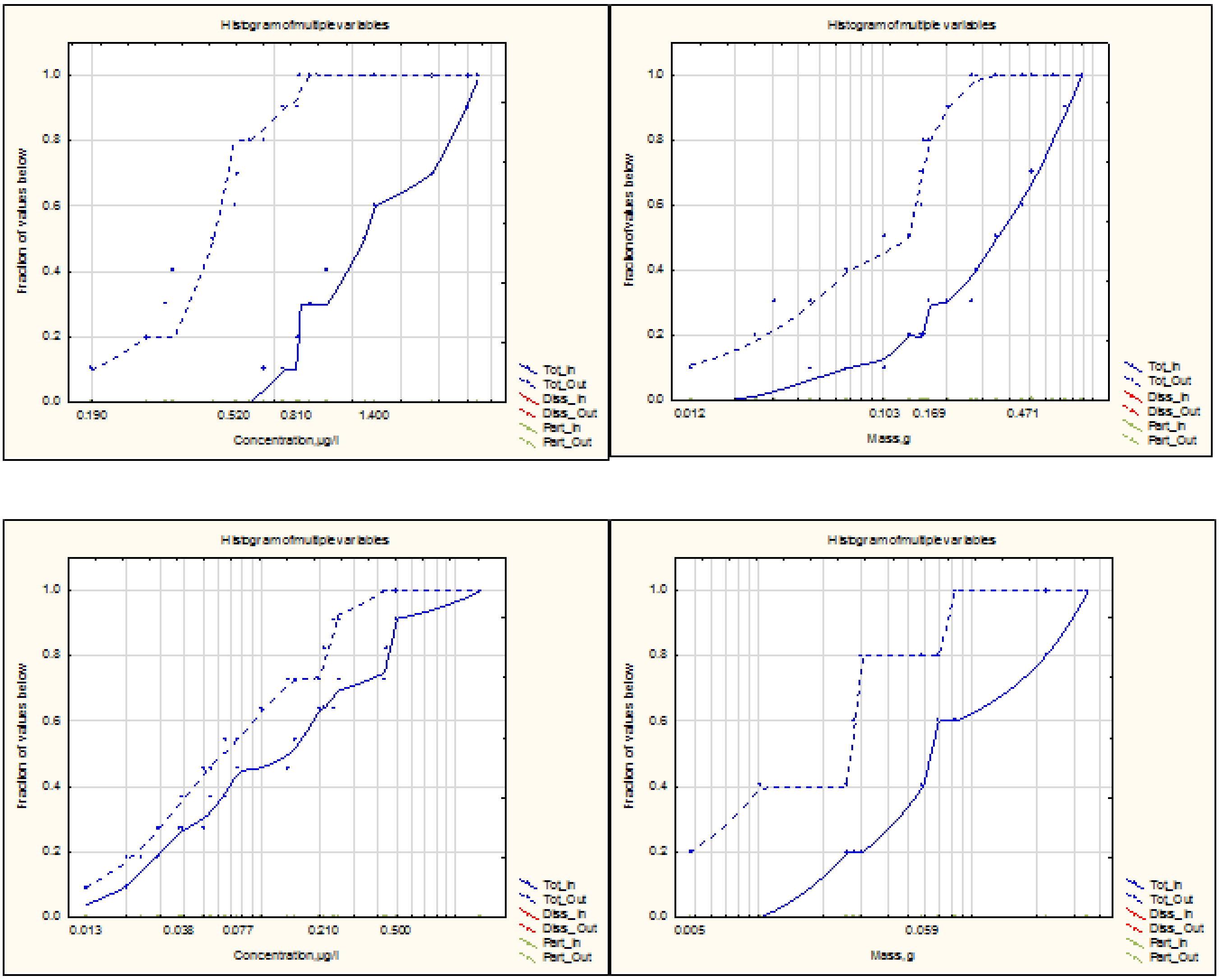


Figure C-4 Cadmium CFPs for I15/SR78 EDB (top) and Lexington Hills (Bottom)

C 1.1.3 DP Copper

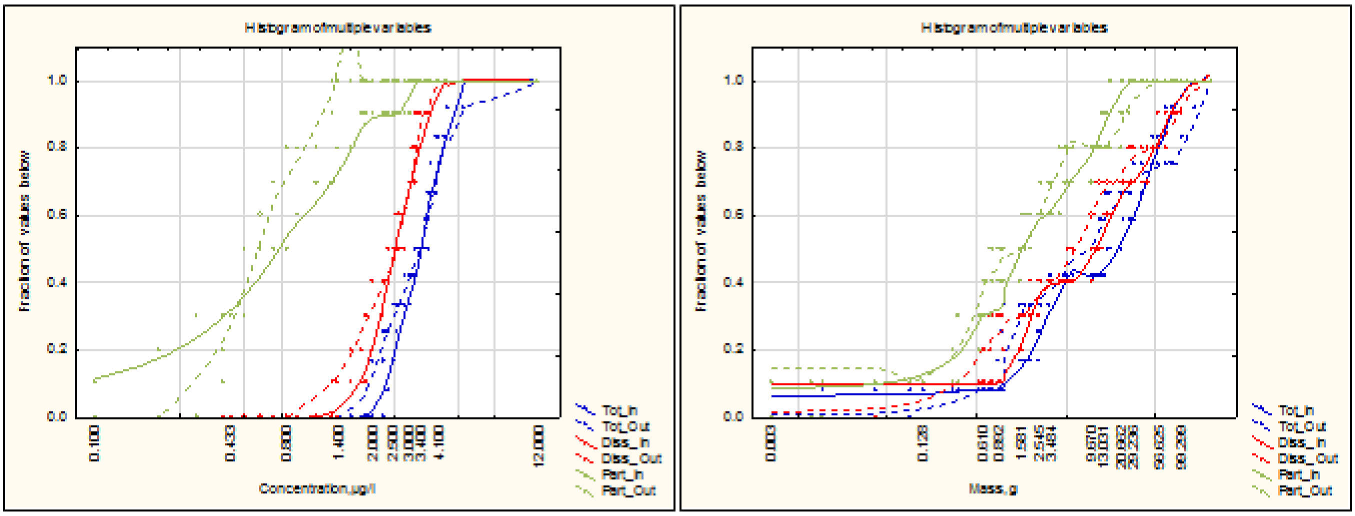


Figure C-5 Copper CFP for El Dorado

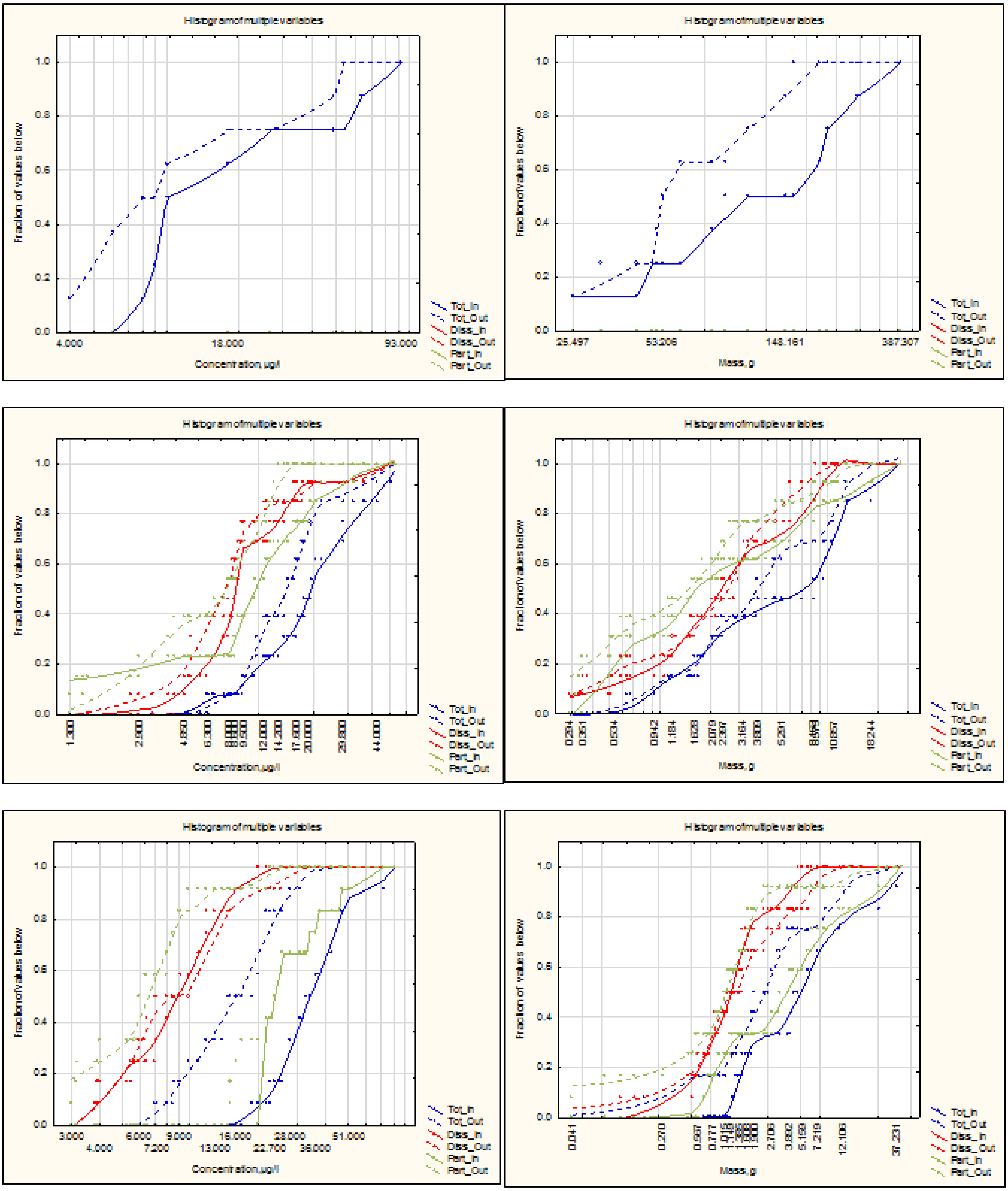


Figure C-6 Copper CFPs for Greenville (top), I5/I605 EDB (middle) and I5/SR56 EDB (Bottom)

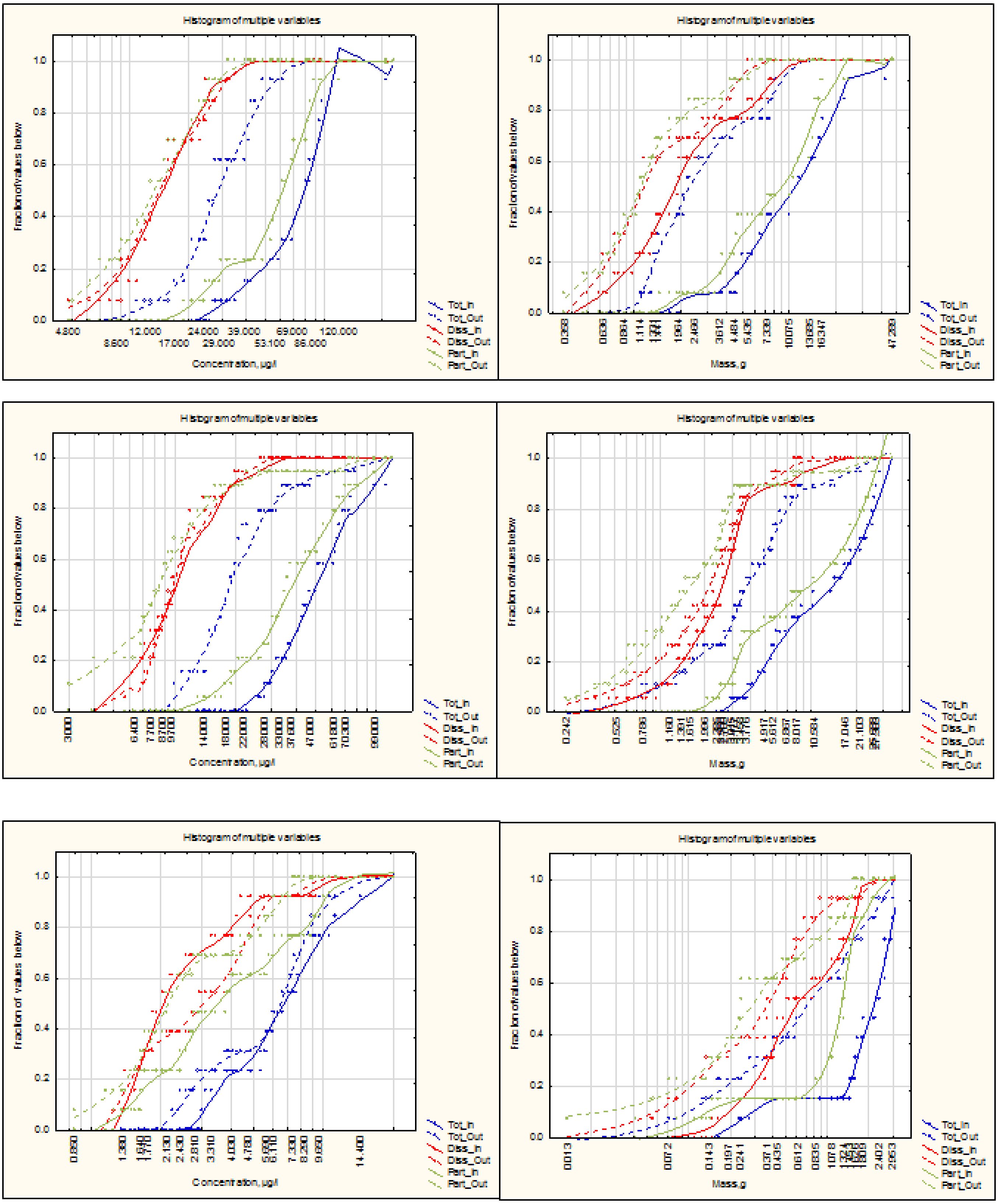


Figure C-7 Copper CFPs for I5 Manchester East EDB (top), I15/SR78 EDB (middle) and Lexington Hills (Bottom)

C 1.1.4 DP Lead

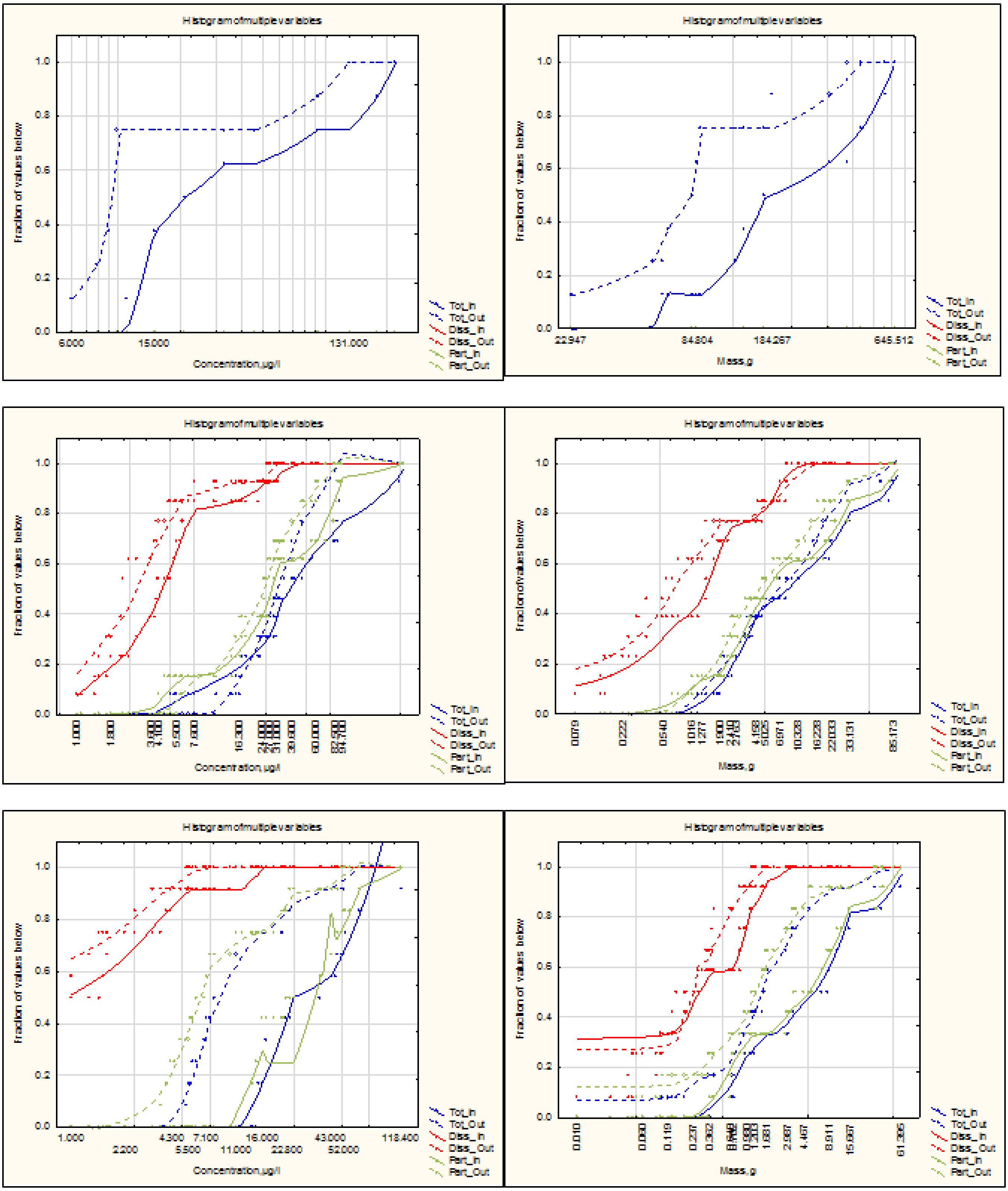


Figure C-8 Lead CFPs for Greenville (top), I5/I605 EDB (middle) and I5/SR56 EDB (Bottom)

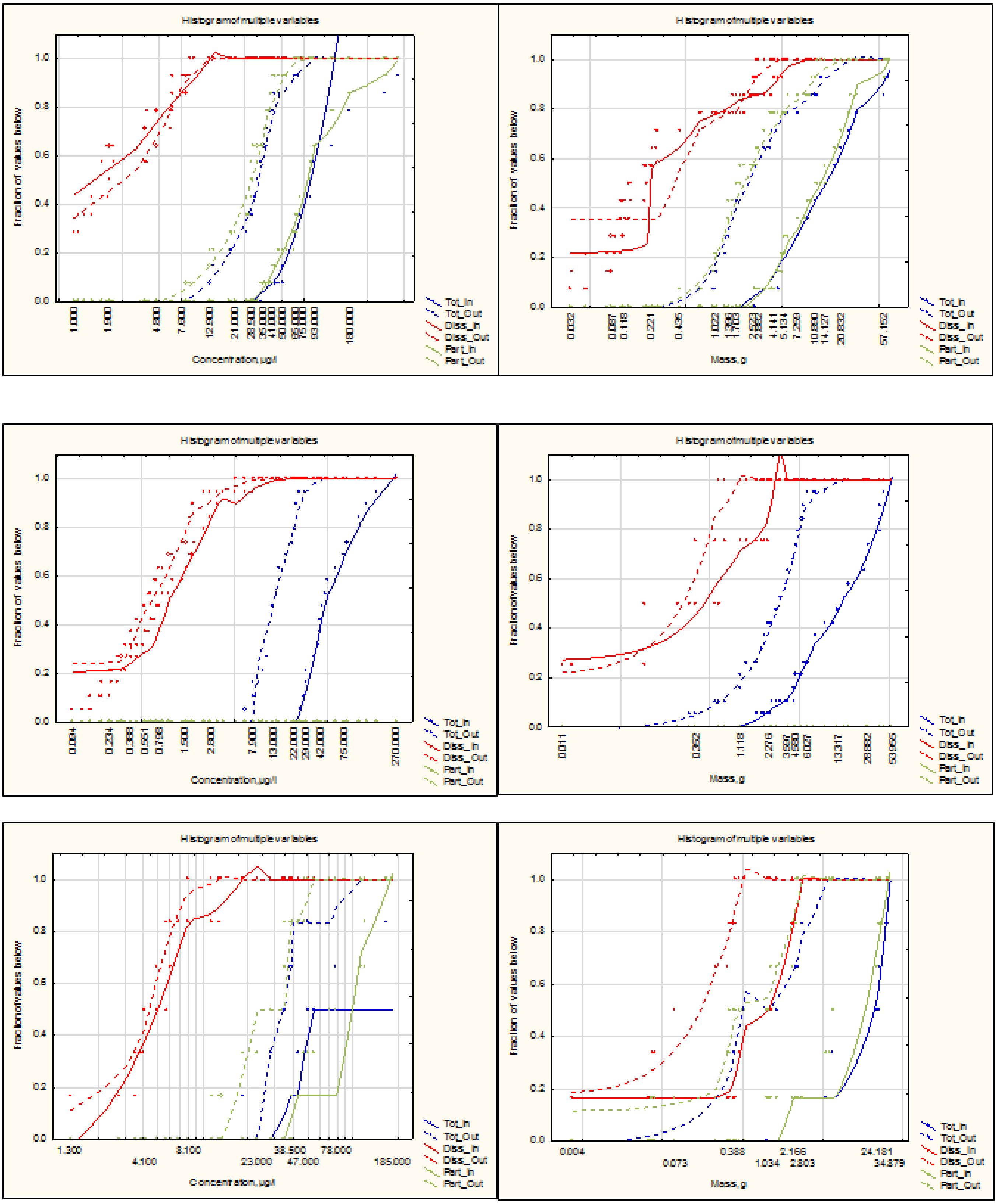


Figure C-9 Lead CFPs for I5 Manchester East EDB (top), I15/SR78 EDB (middle) and I605/SR91 EDB (Bottom)

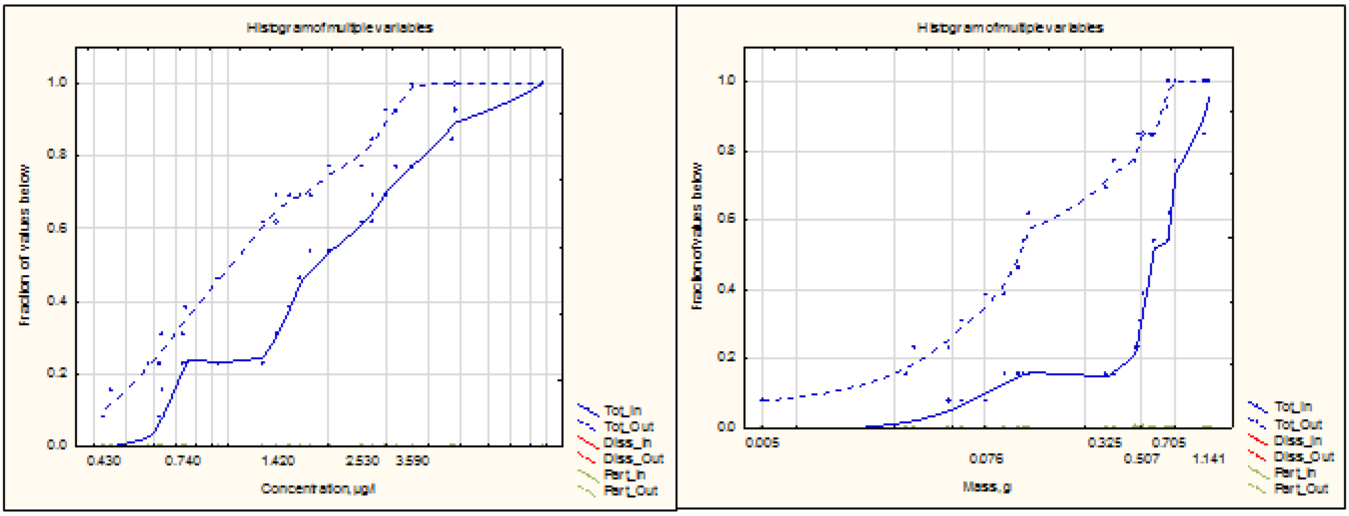


Figure C-10 Lead CFP for Lexngton Hills

C 1.1.5 DP Zinc

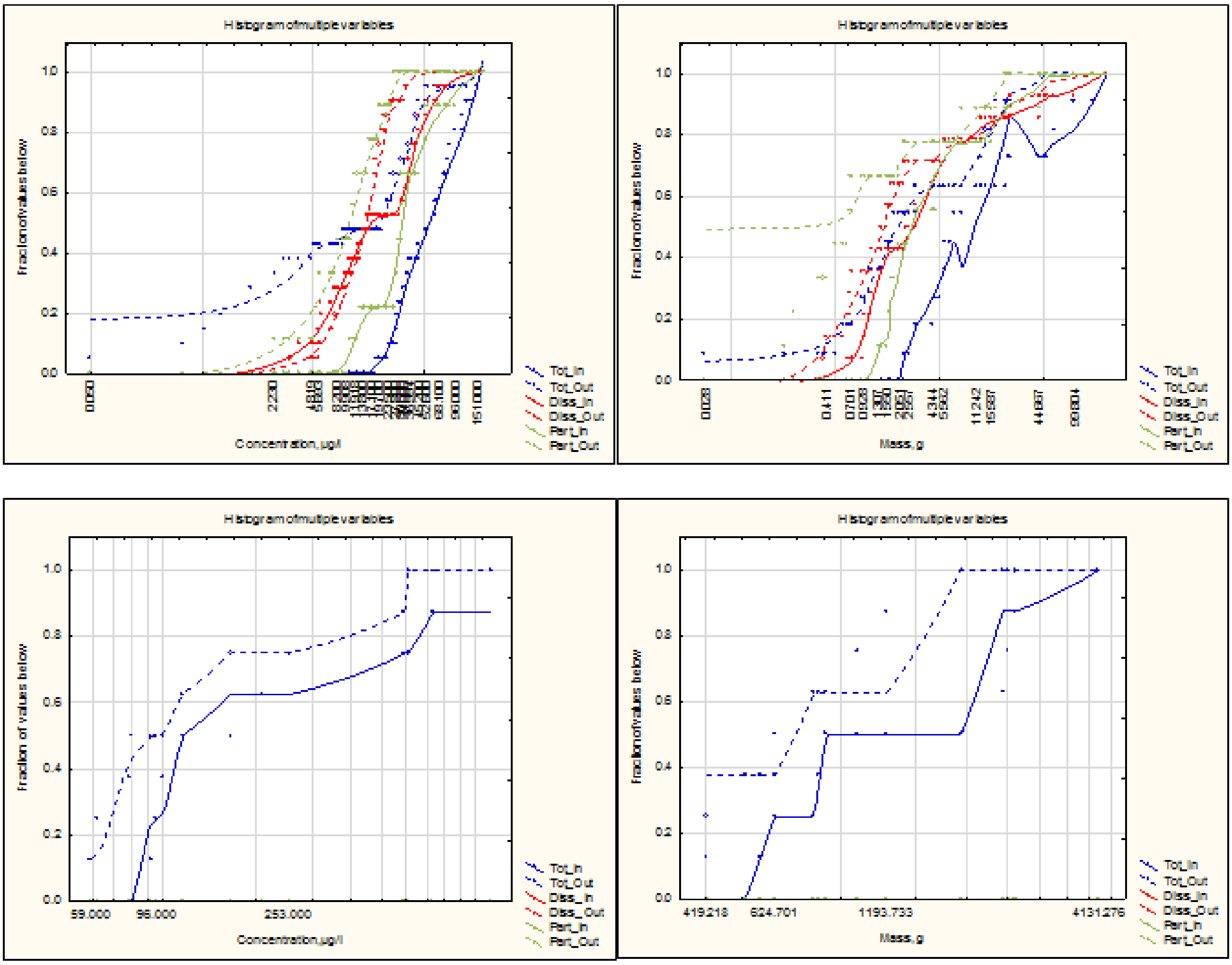


Figure C-11 Zinc CFP for Grant Ranch and Greenville

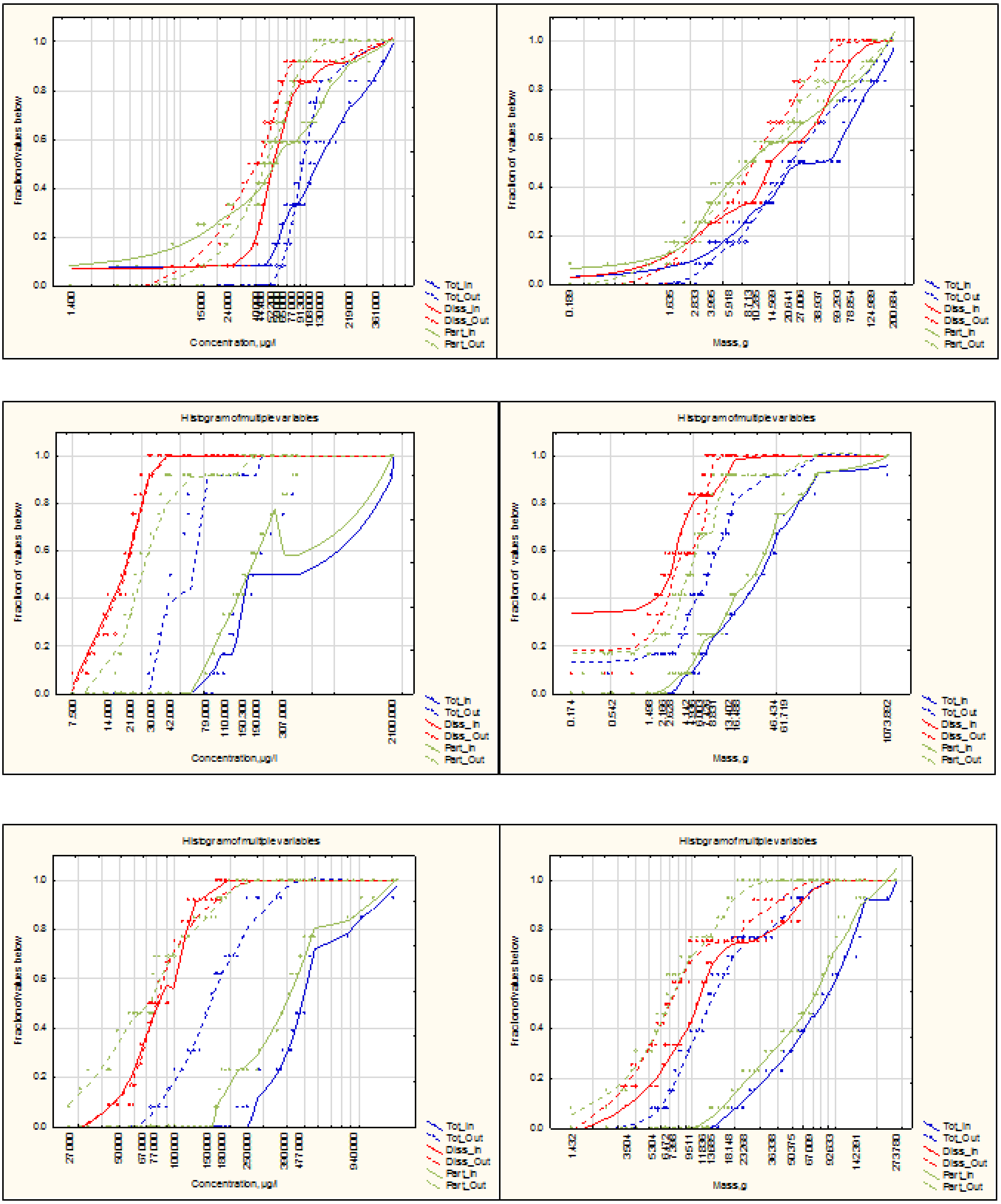


Figure C-12 Zinc CFPs for I5/I605 EDB (top), I5/SR56 EDB (middle) and I5 Manchester East EDB (Bottom)

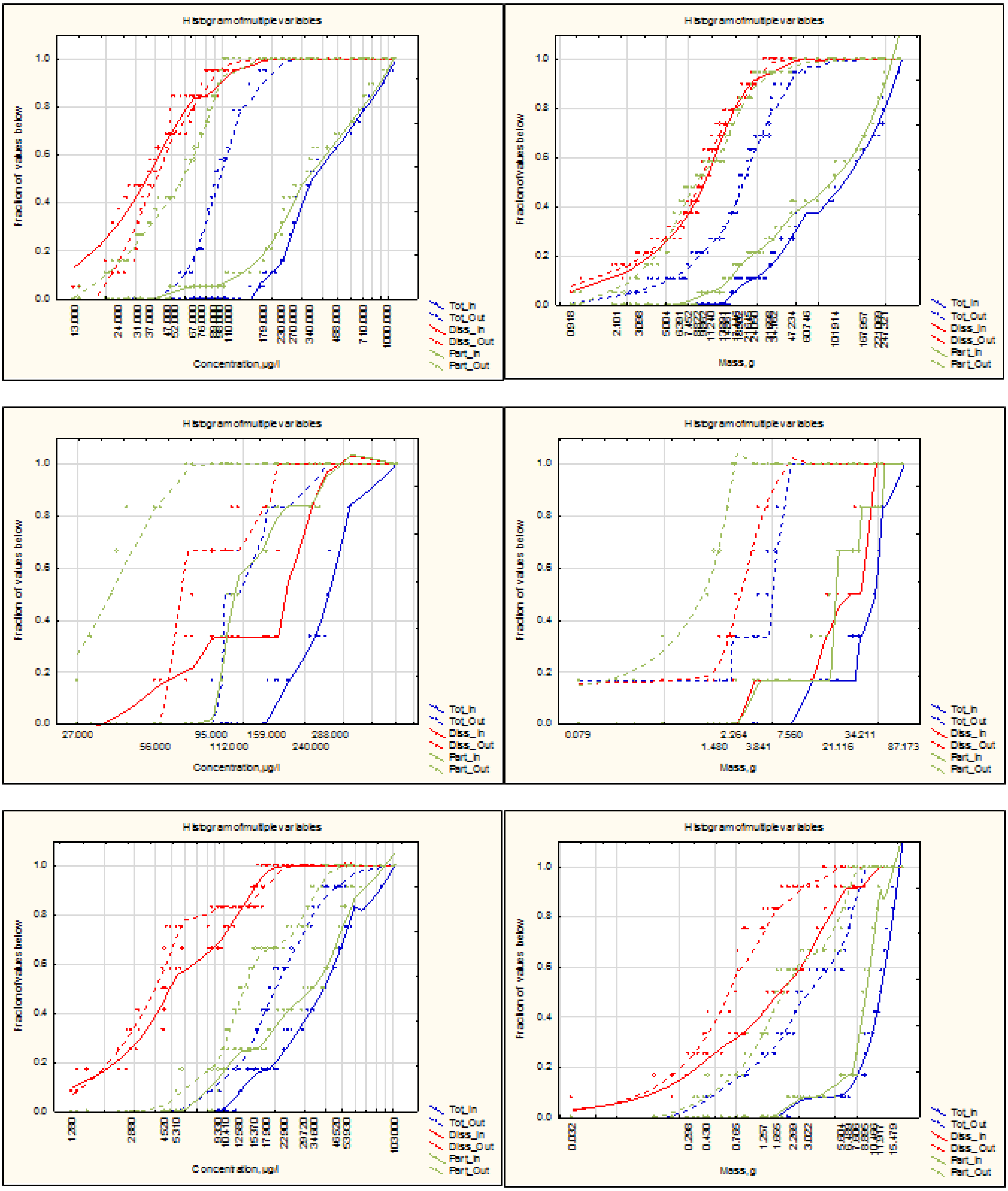


Figure C-13 Zinc CFPs for I15/SR78 EDB (top), I605/SR91 EDB (middle) and Lexington Hills (Bottom)

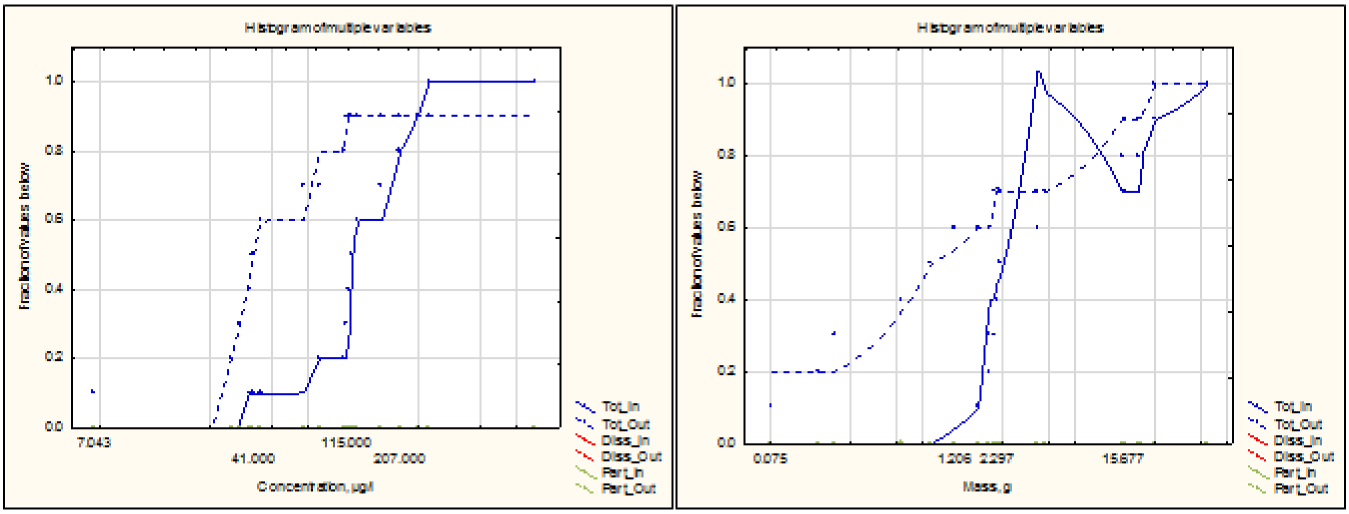


Figure C-14 Zinc CFP for Mountain Park

C 1.1.6 DP TSS

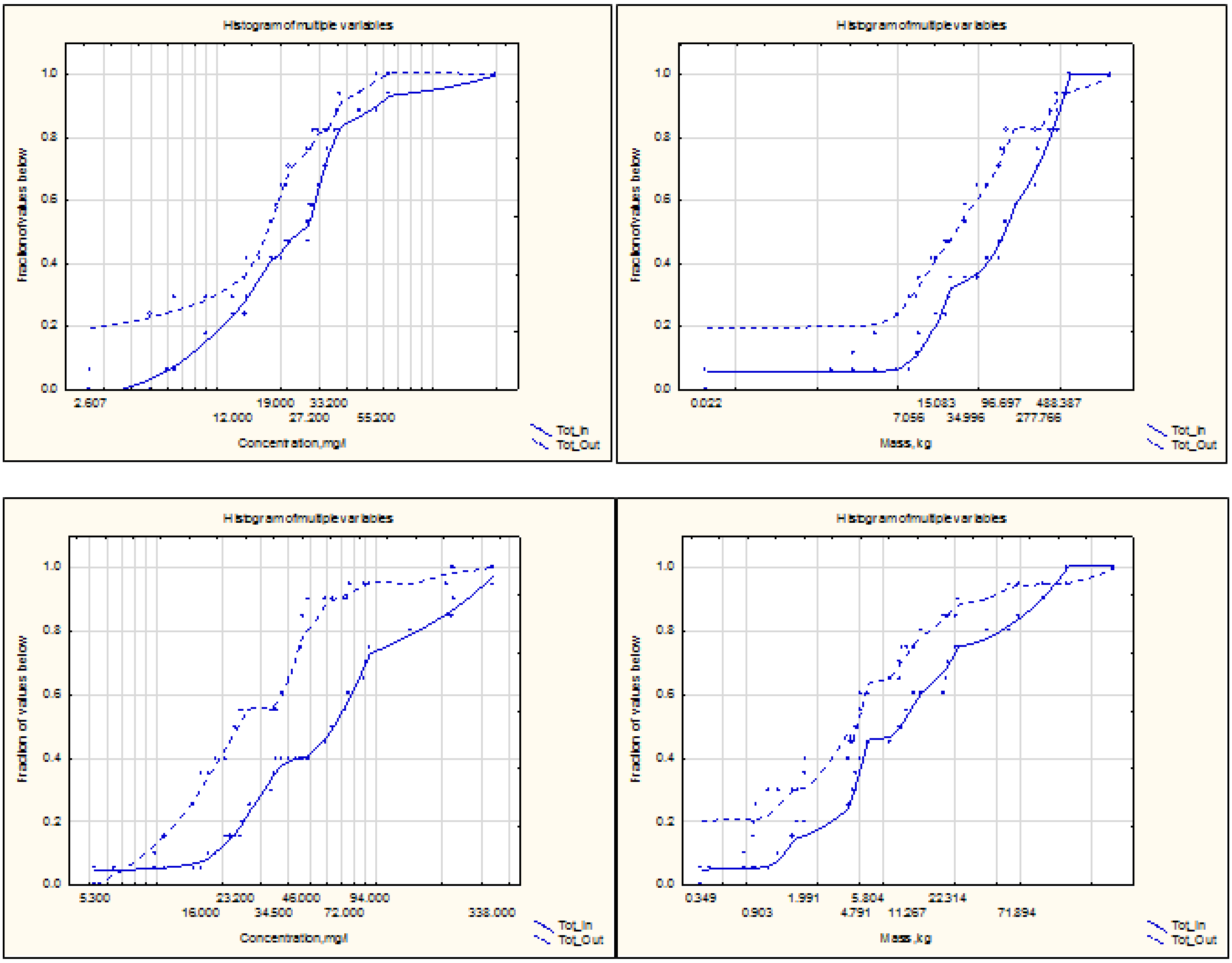


Figure C-15 TSS CFPs for El Dorado (top) and Grant Ranch (Bottom)

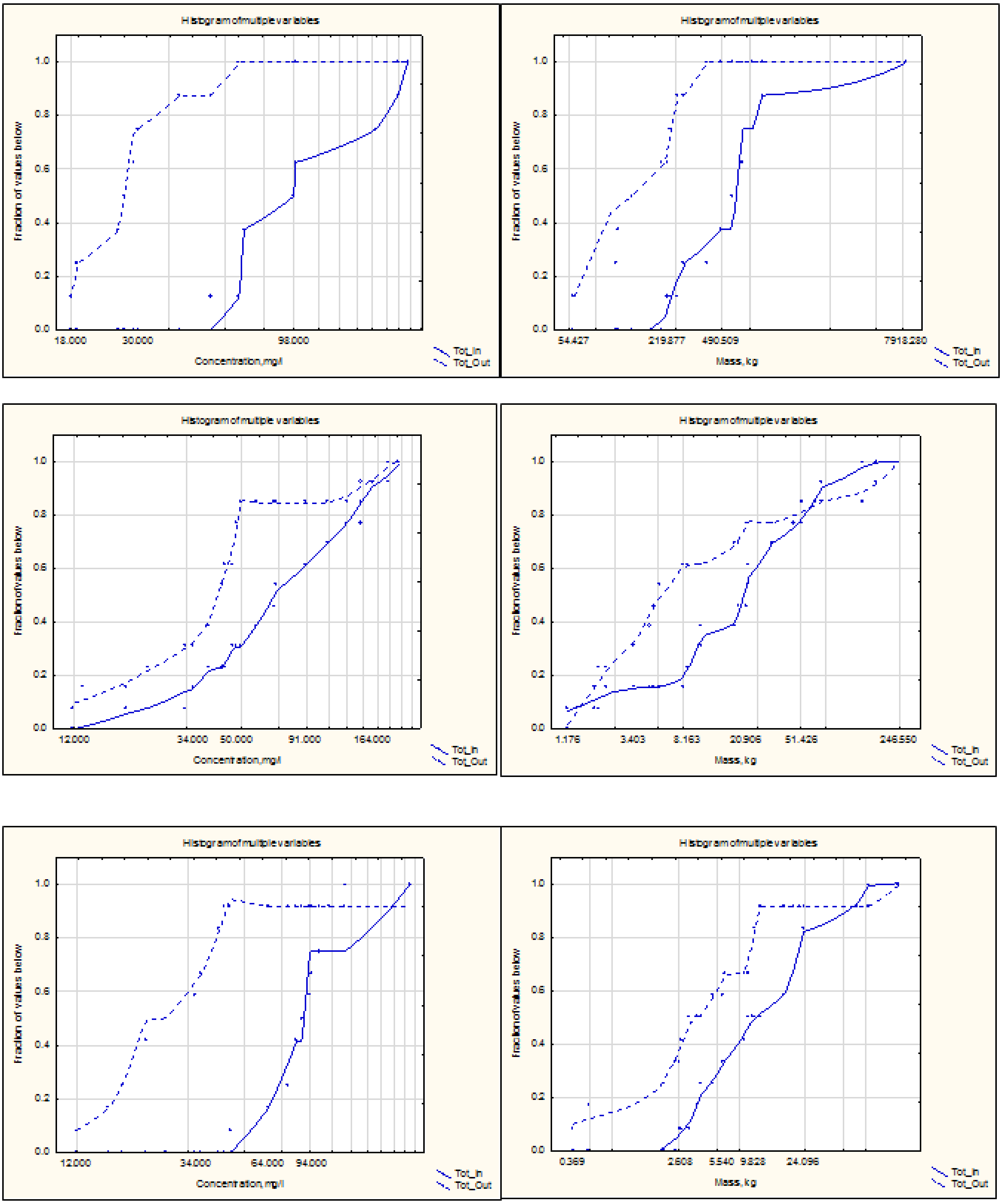


Figure C-16 TSS CFPs for Greenville (top), I5/I605 EDB (middle) and I5/SR56 EDB (Bottom)

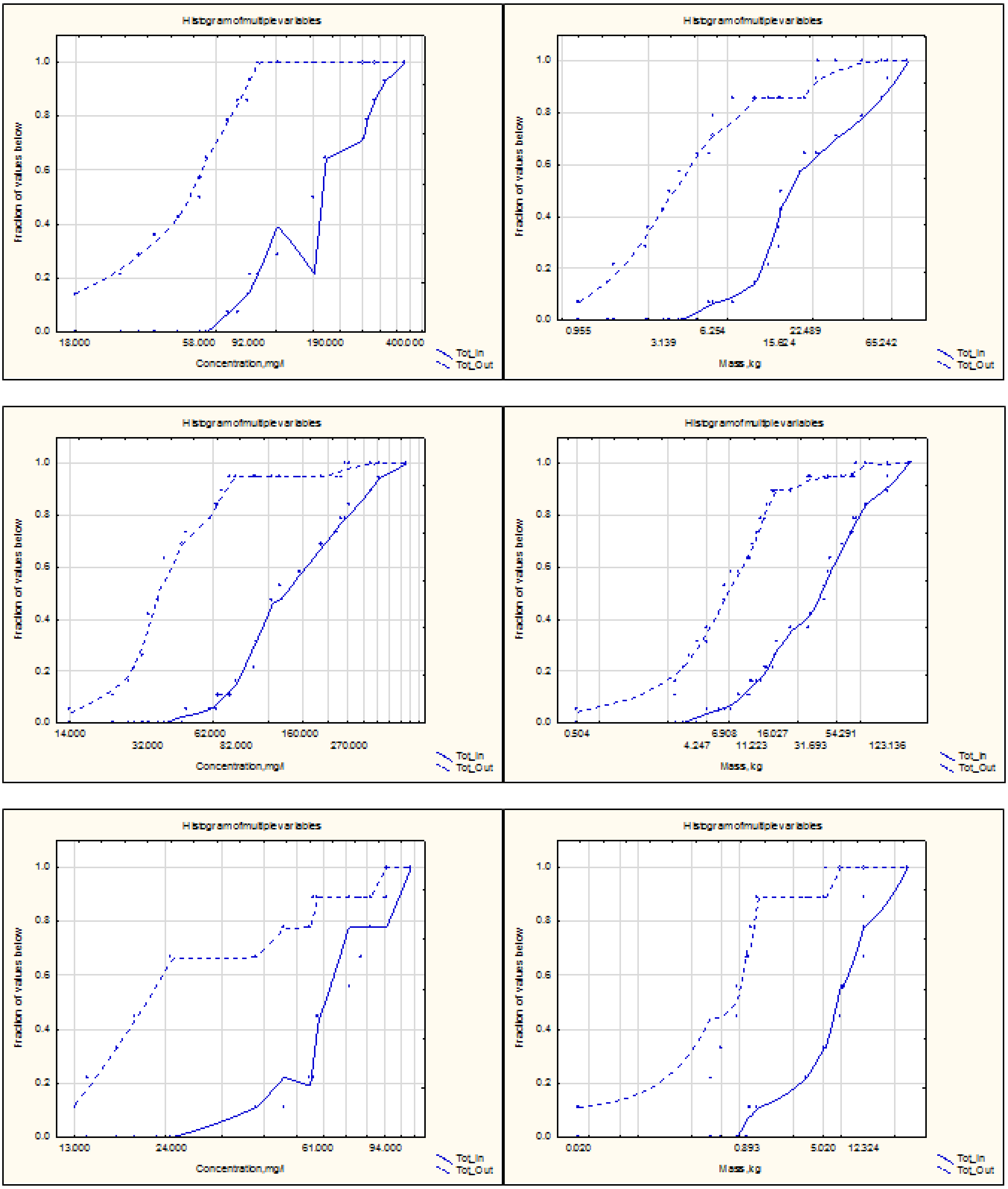


Figure C-17 TSS CFPs for I5 Manchester East EDB (top), I15/SR78 EDB (middle) and I605/SR91 EDB (Bottom)

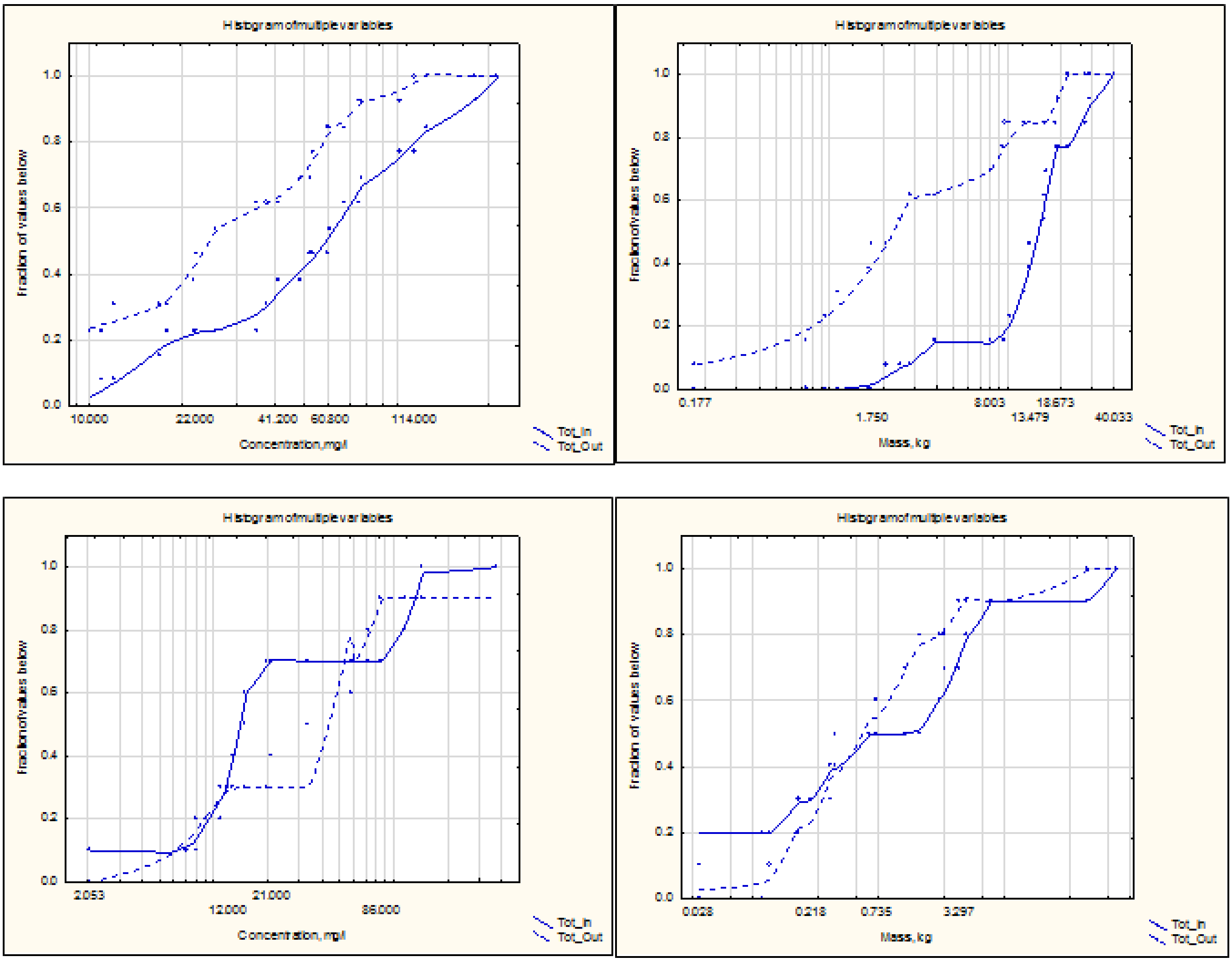


Figure C-18 TSS CFPs for Lexington Hills (top) and Mountain Park (Bottom)

C 1.2 Retention ponds

C 1.2.1 RP Cadmium

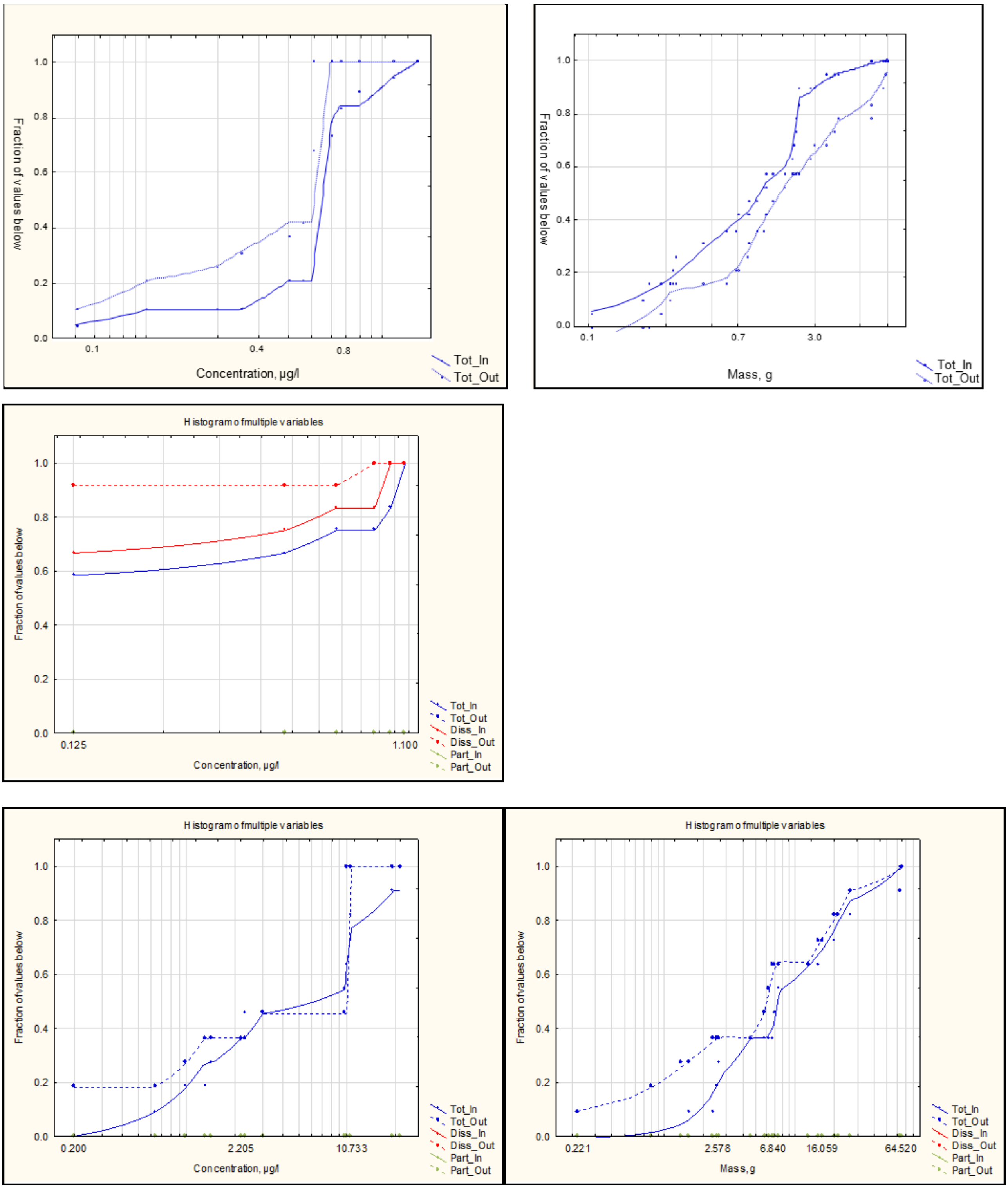


Figure C-19 Cadmium CFPs for Central Park (top), De Bary (middle) and Heritage Estates (Bottom)

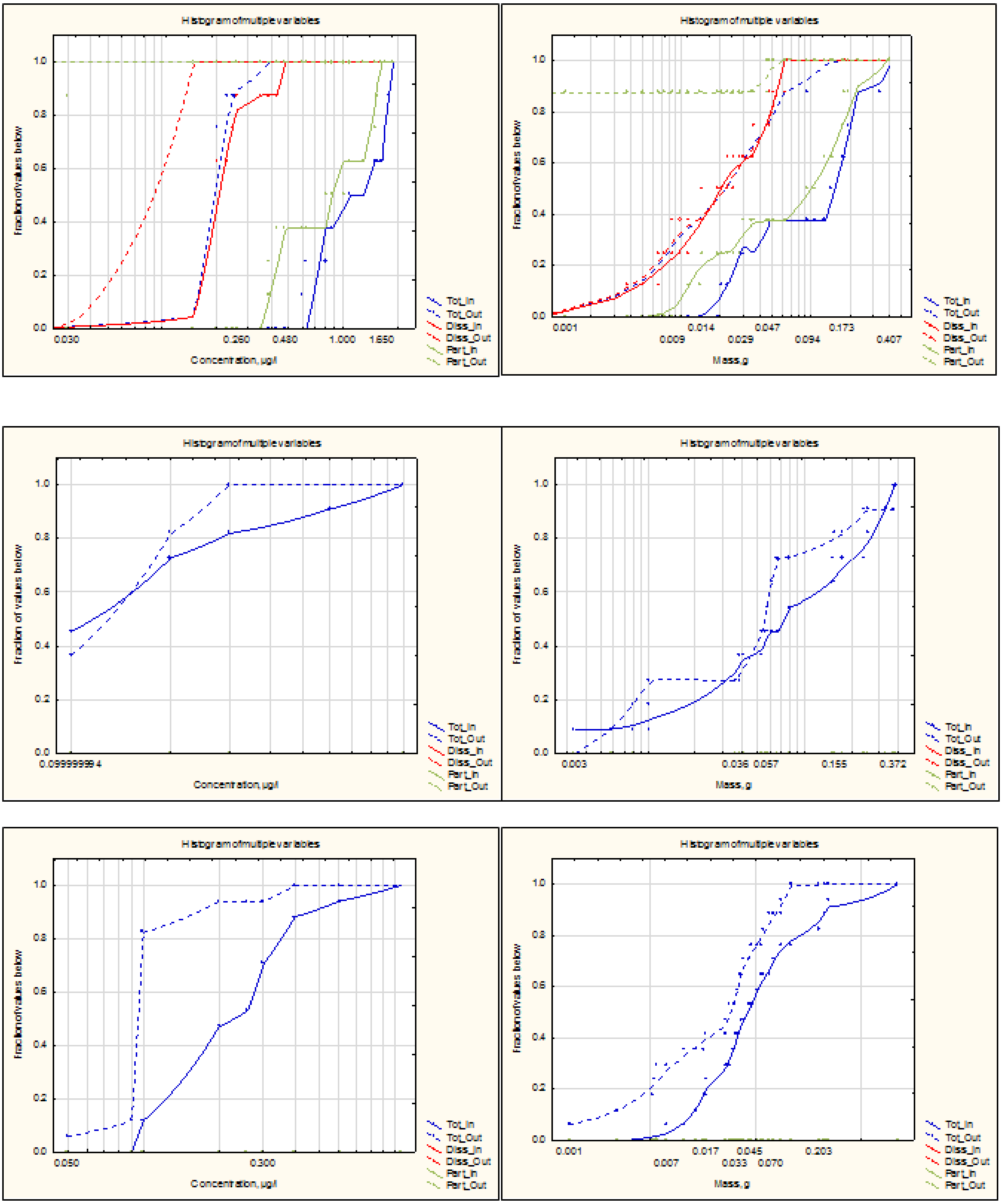


Figure C-20 Cadmium CFPs for I5 La Costa East (top), Tampa 2 (middle) and Tampa 3 (Bottom)

C 1.2.2 RP Copper

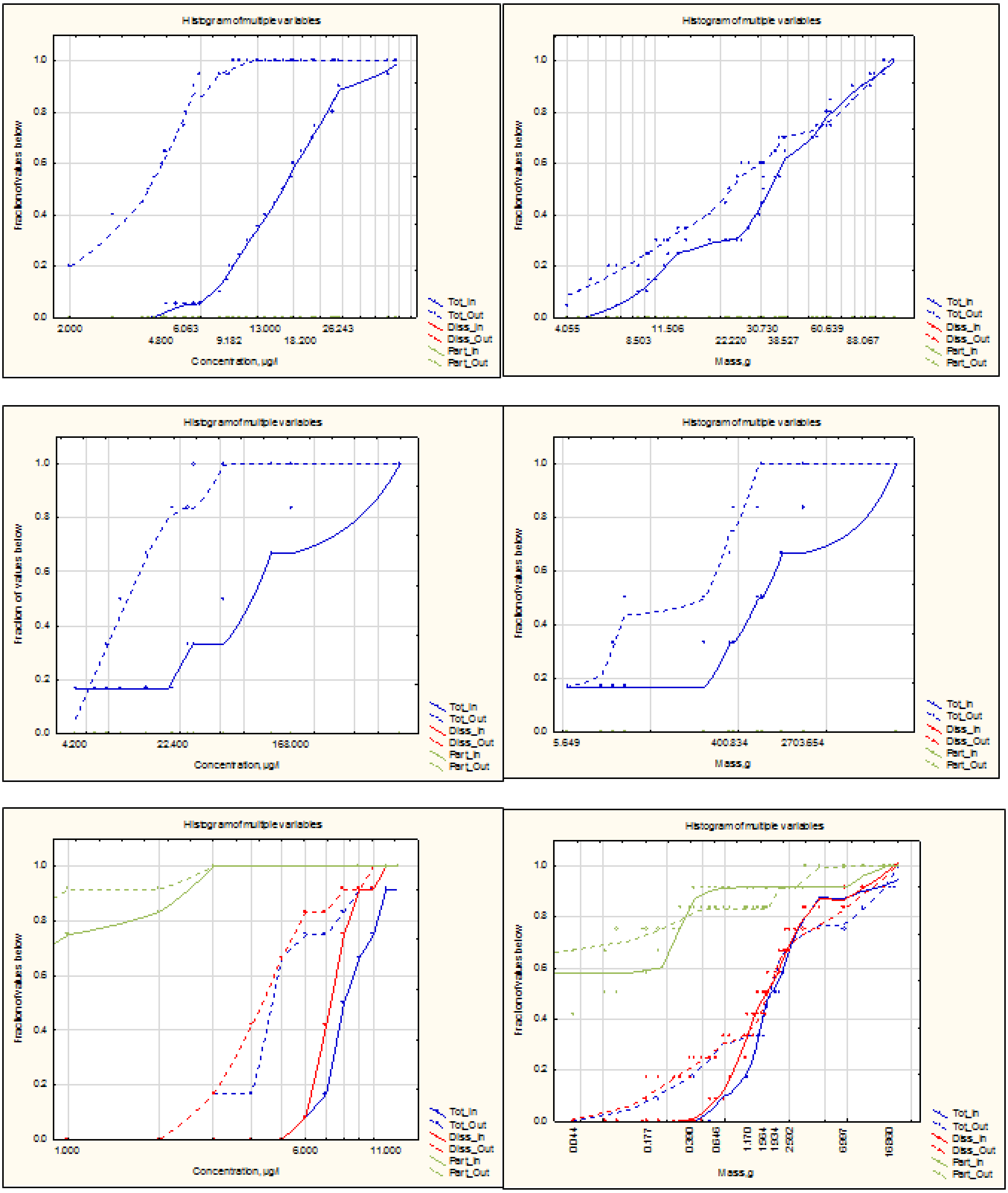


Figure C-21 Copper CFPs for Central Park (top), Cockroach Bay (middle) and De Bary (Bottom)

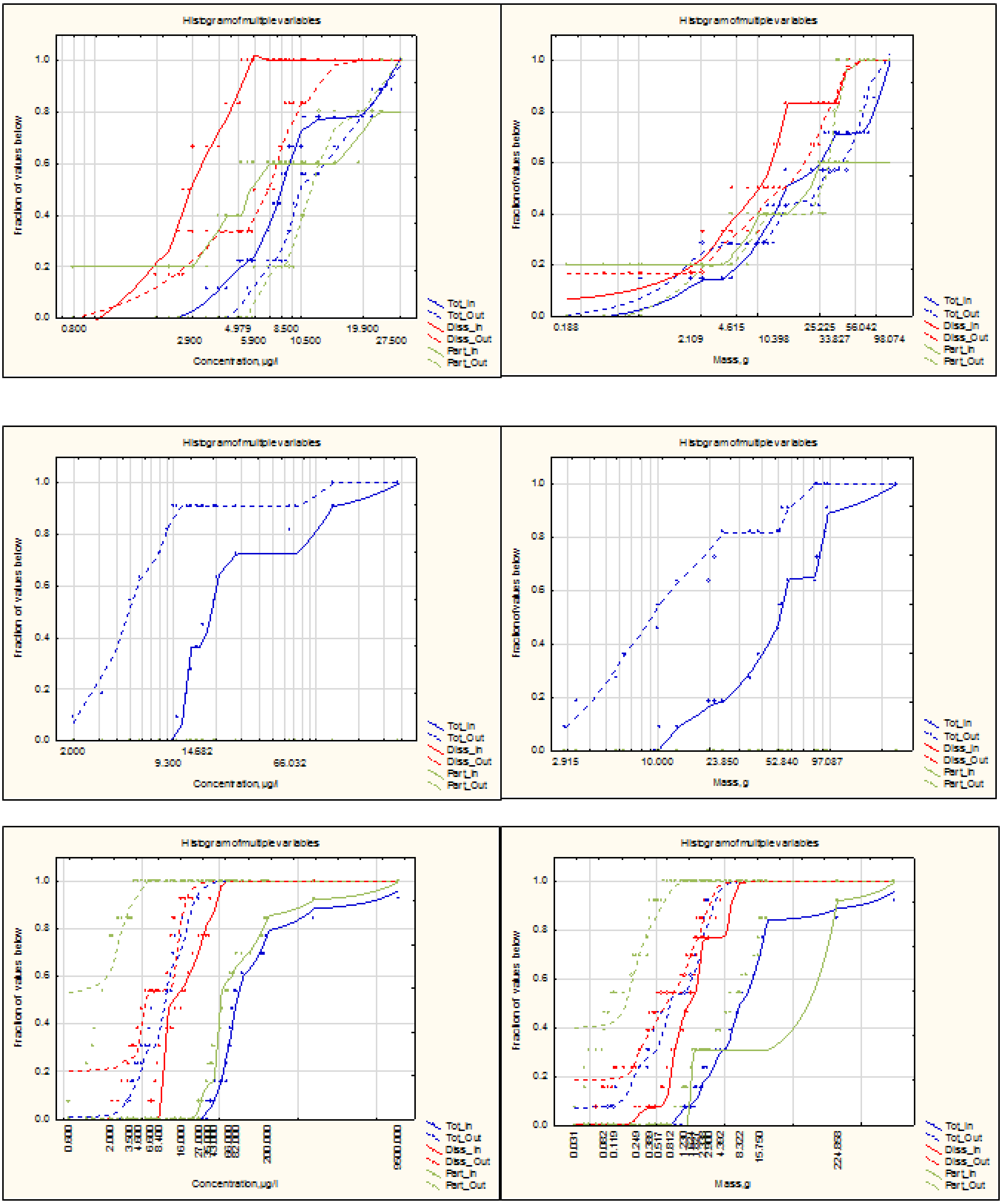


Figure C-22 Copper CFPs for Greens Bayou (top), Heritage Estates (middle) and I5 La Costa East (Bottom)

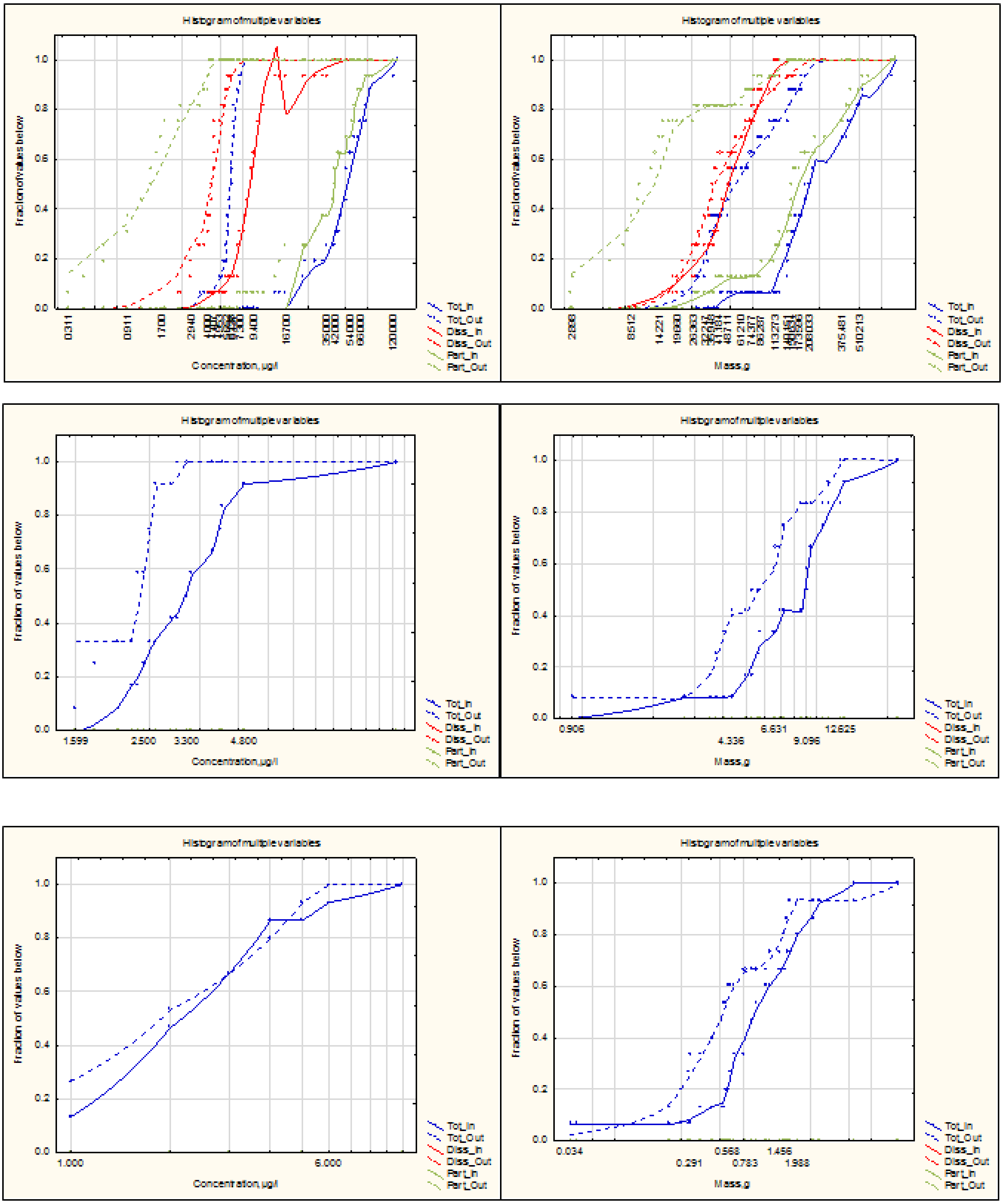


Figure C-23 Copper CFPs for Lake Ellyn (top), Phantom Lake Pond A (middle) and Tampa 2 (Bottom)

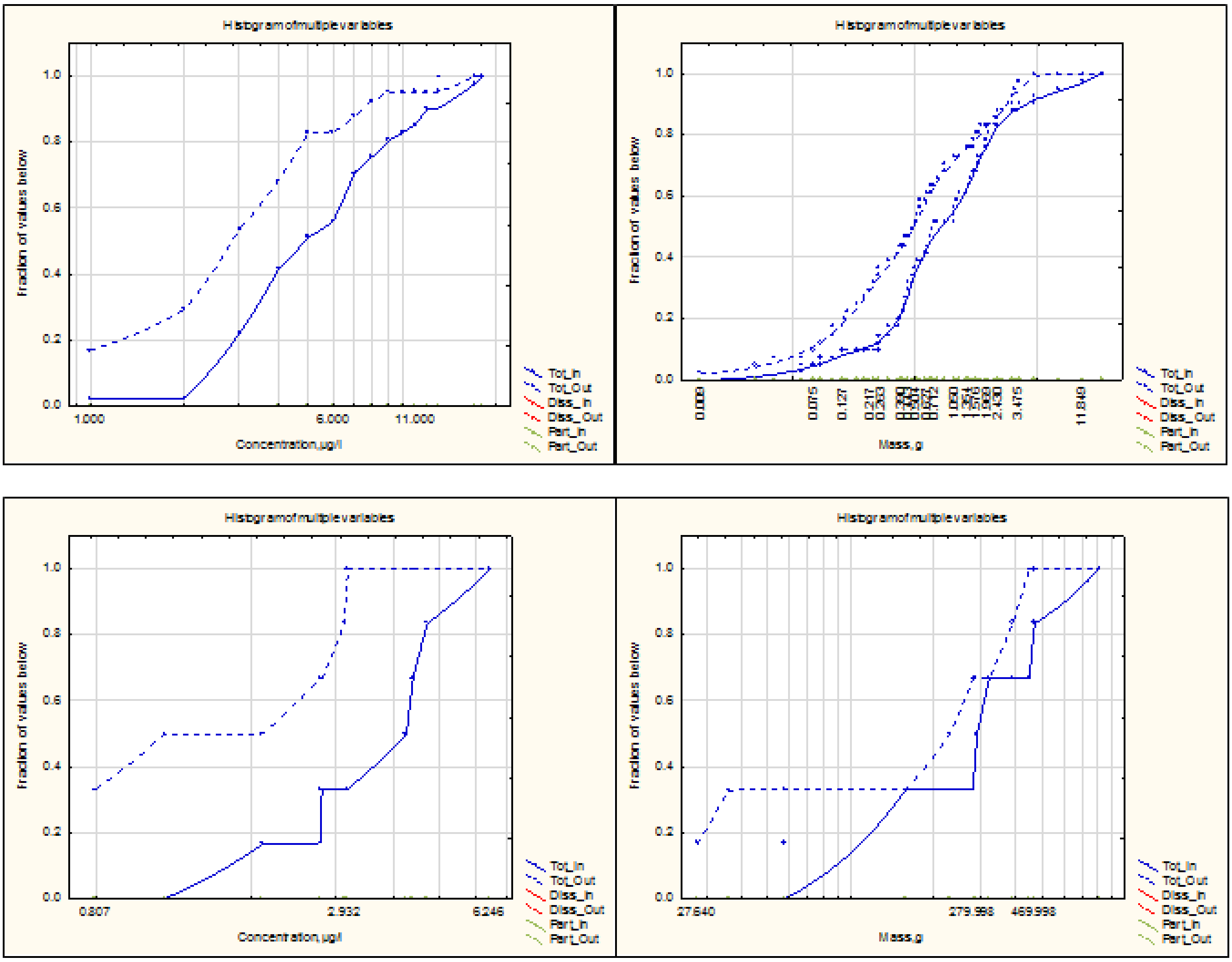


Figure C-24 Copper CFPs for Tampa 3 (top) and Pinellas (Bottom)

C 1.2.3 RP Lead

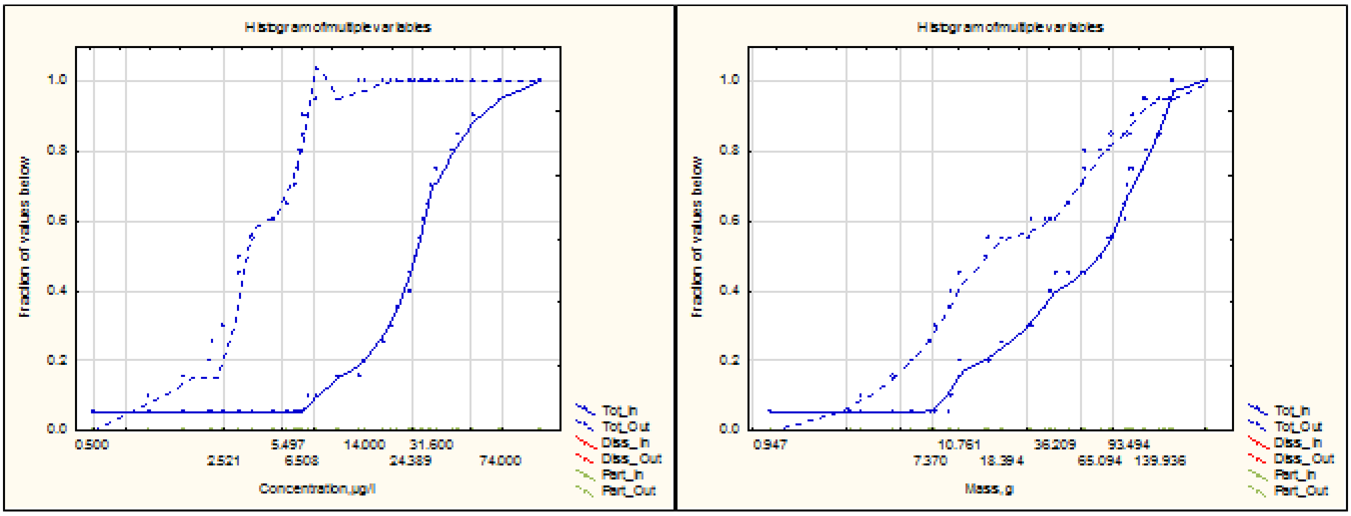


Figure C-25 Lead CFP for Central Park

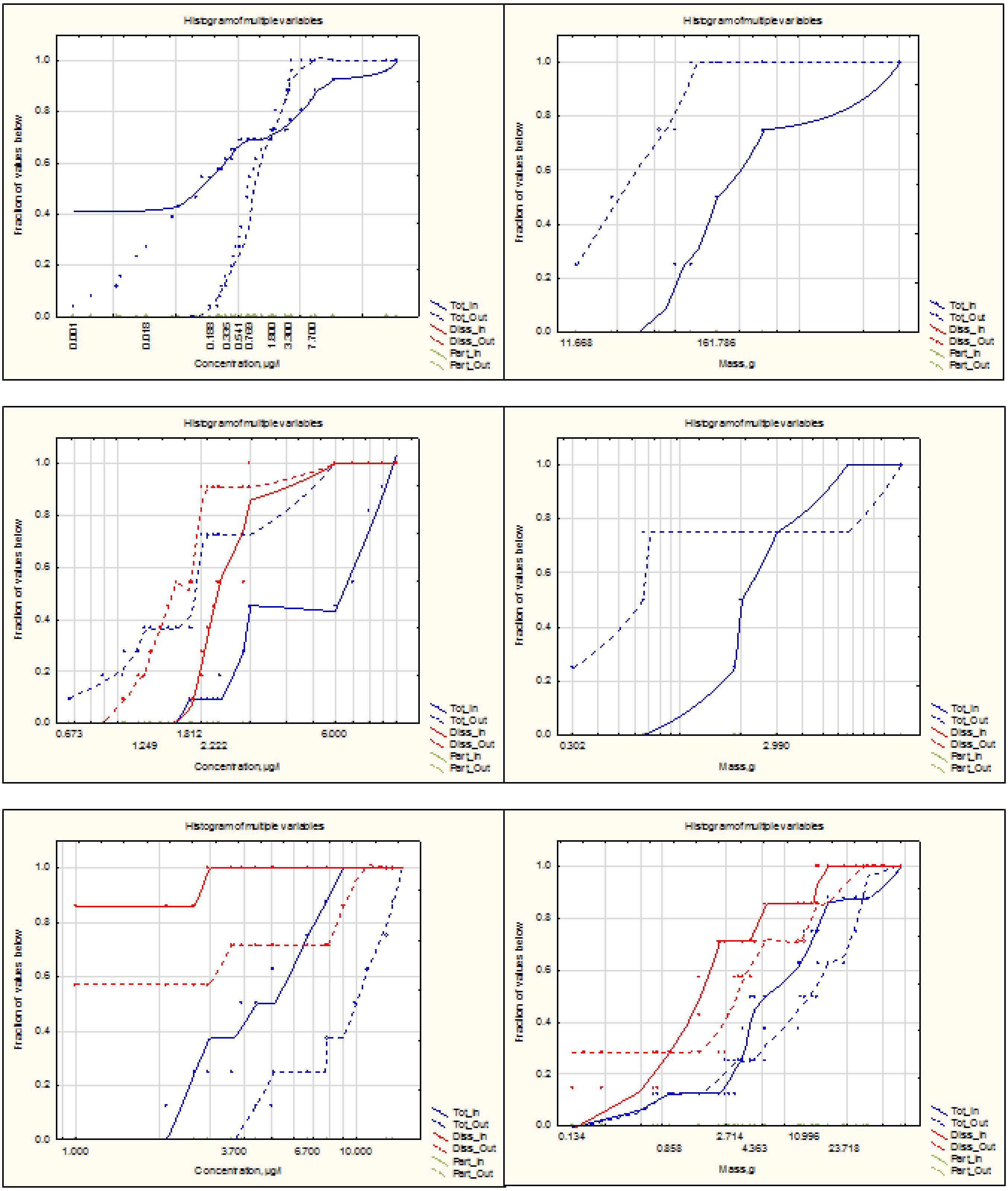


Figure C-26 Lead CFPs for Cockroach Bay (top), De Bary (middle) and Greens Bayou (Bottom)

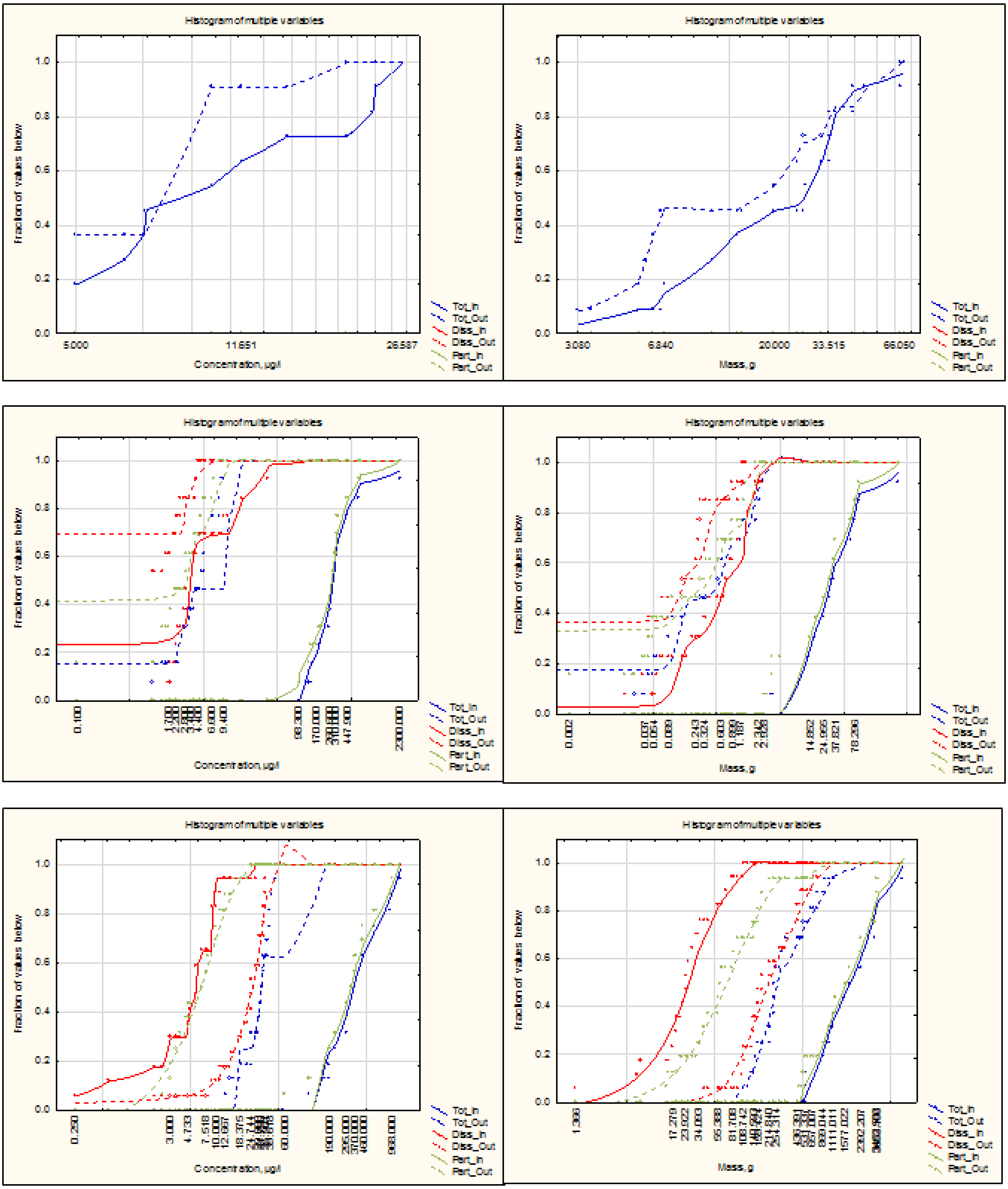


Figure C-27 Lead CFPs for Heritage Estates (top), I5 La Costa East (middle) and Lake Ellyn (Bottom)

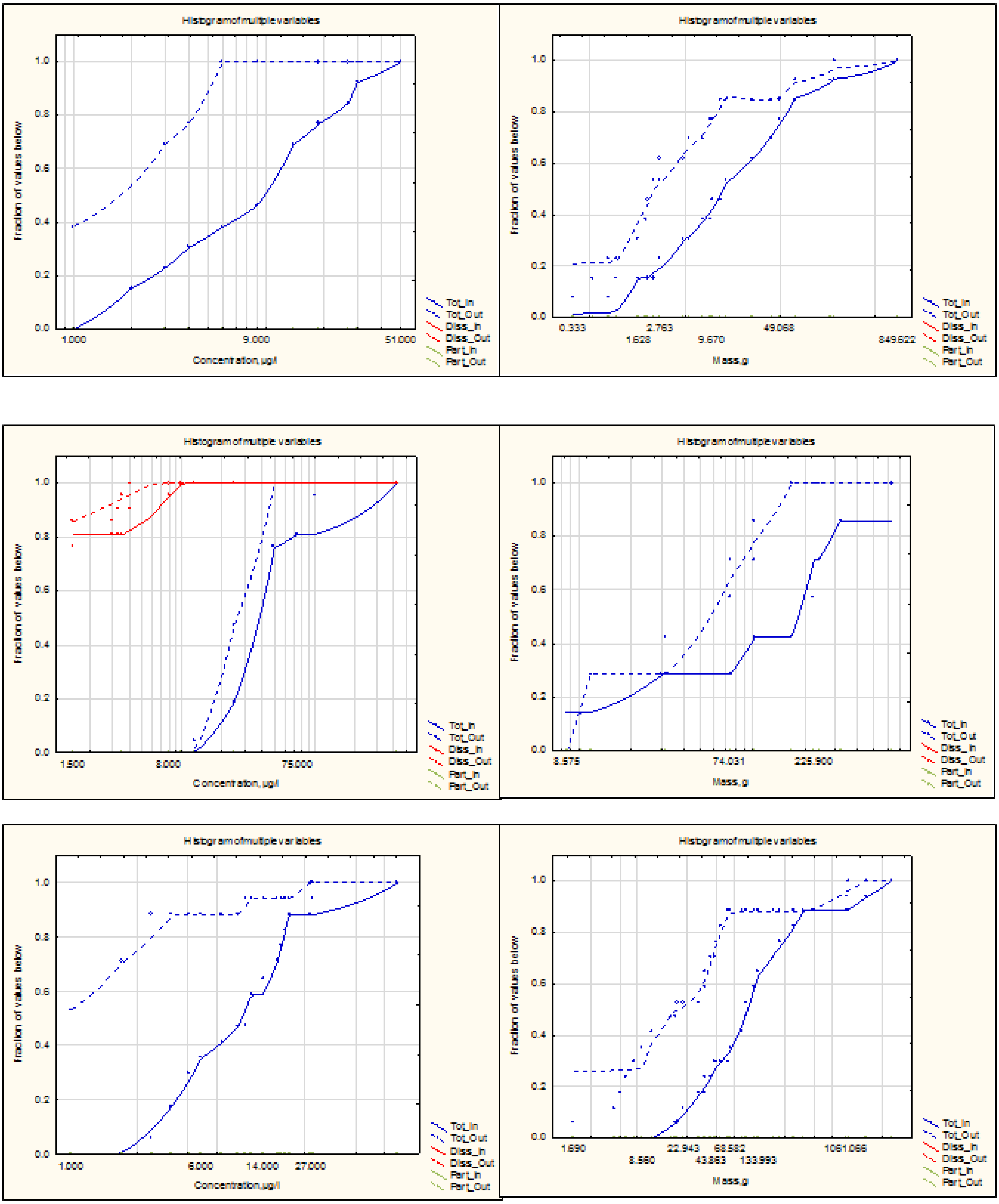


Figure C-28 Lead CFPs for Lake Ridge (top), Madison Monroe str. (middle) and McKnight Basin (Bottom)

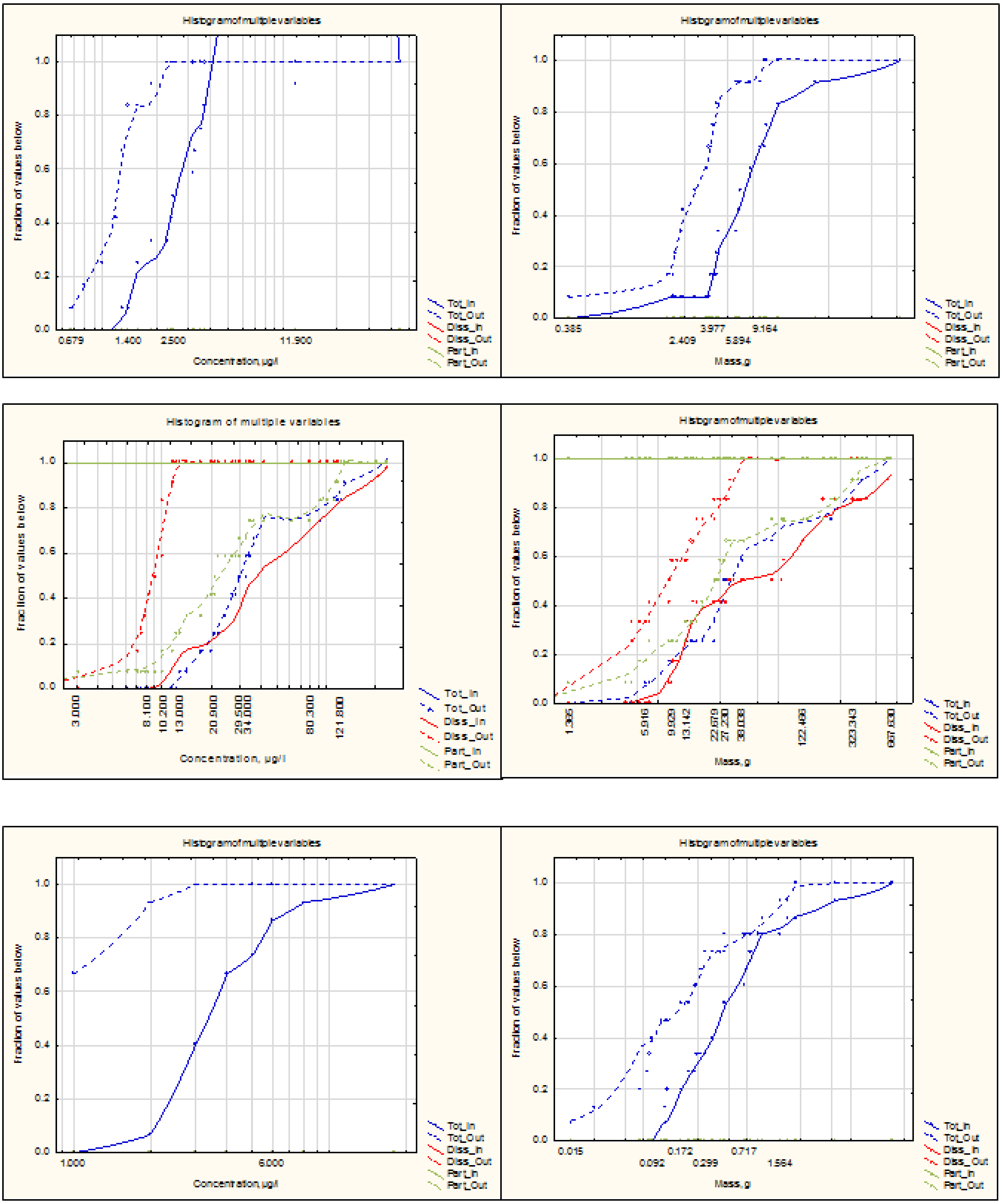


Figure C-29 Lead CFPs for Phantom Lake Pond A (top), Silver Star rd. (middle) and Tampa 3 (Bottom)

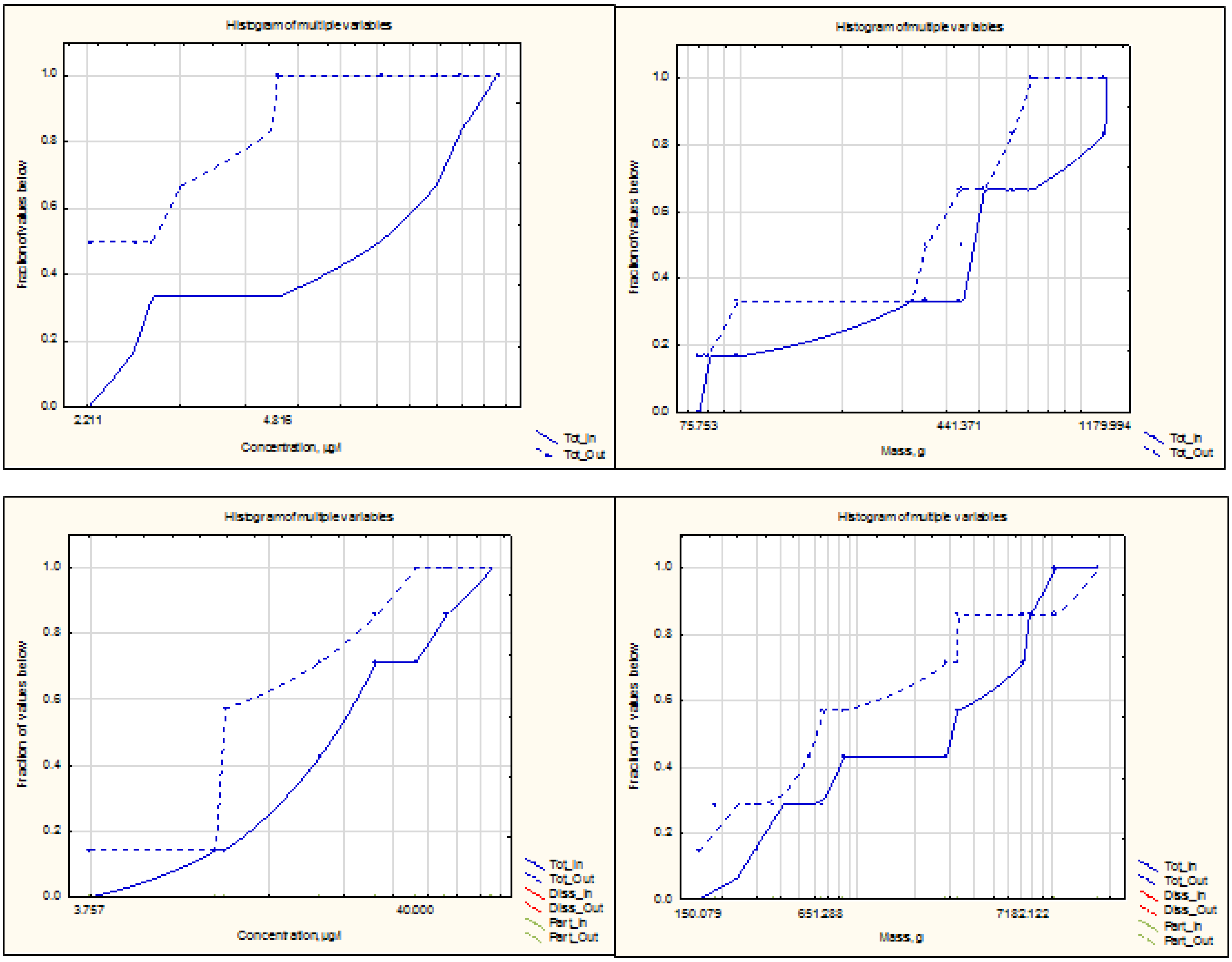


Figure C-30 Lead CFPs for Pinellas (top) and Pittsfield (Bottom)

C 1.2.4 RP Zinc

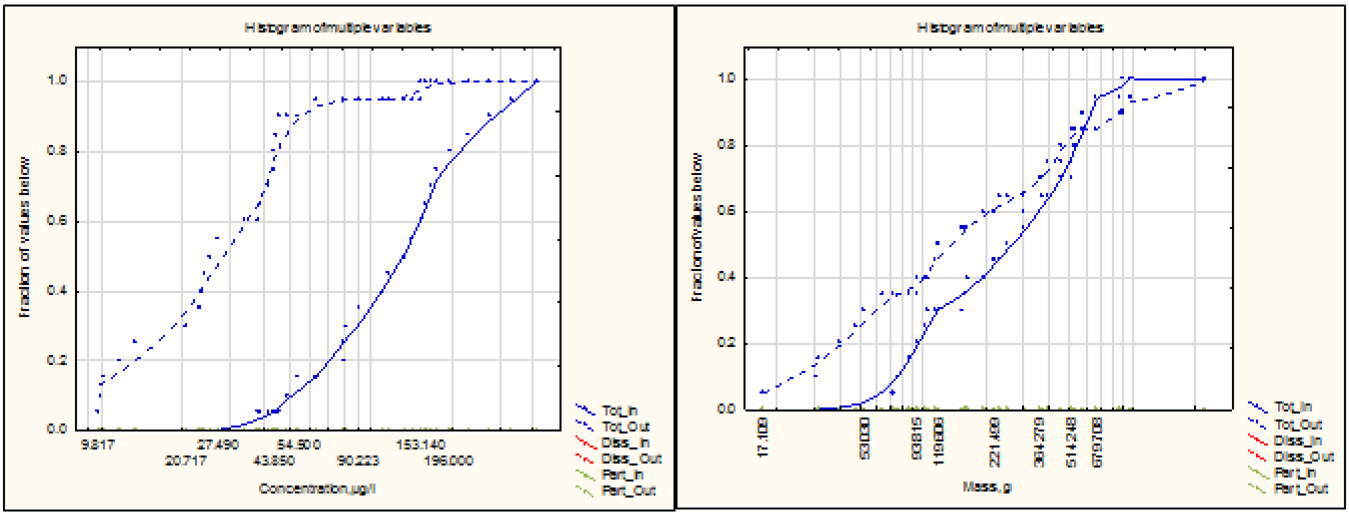


Figure C-31 Zinc CFP for Central Park

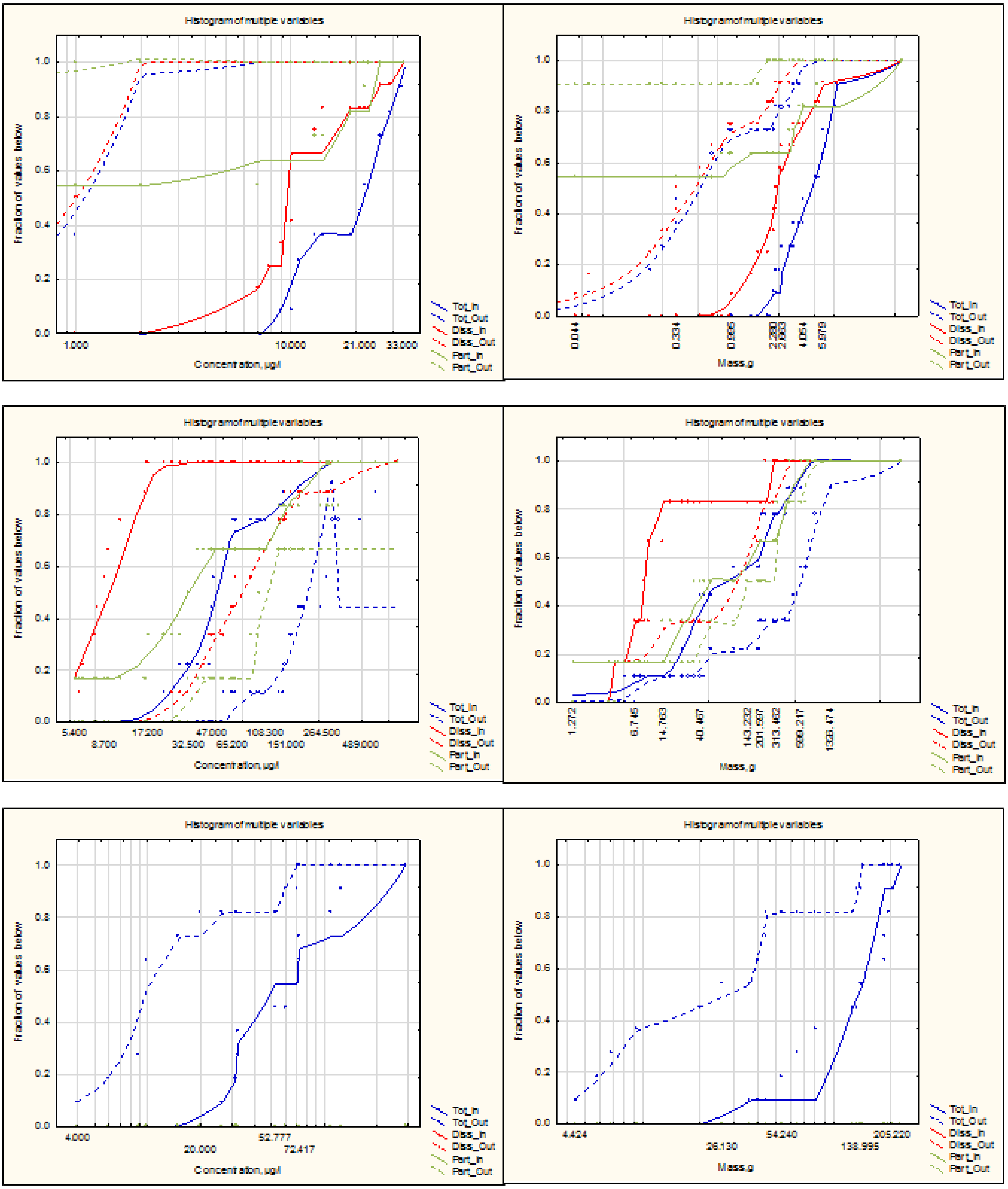


Figure C-32 Zinc CFPs for De Bary (top), Greens Bayou (middle) and Heritage Estates (Bottom)

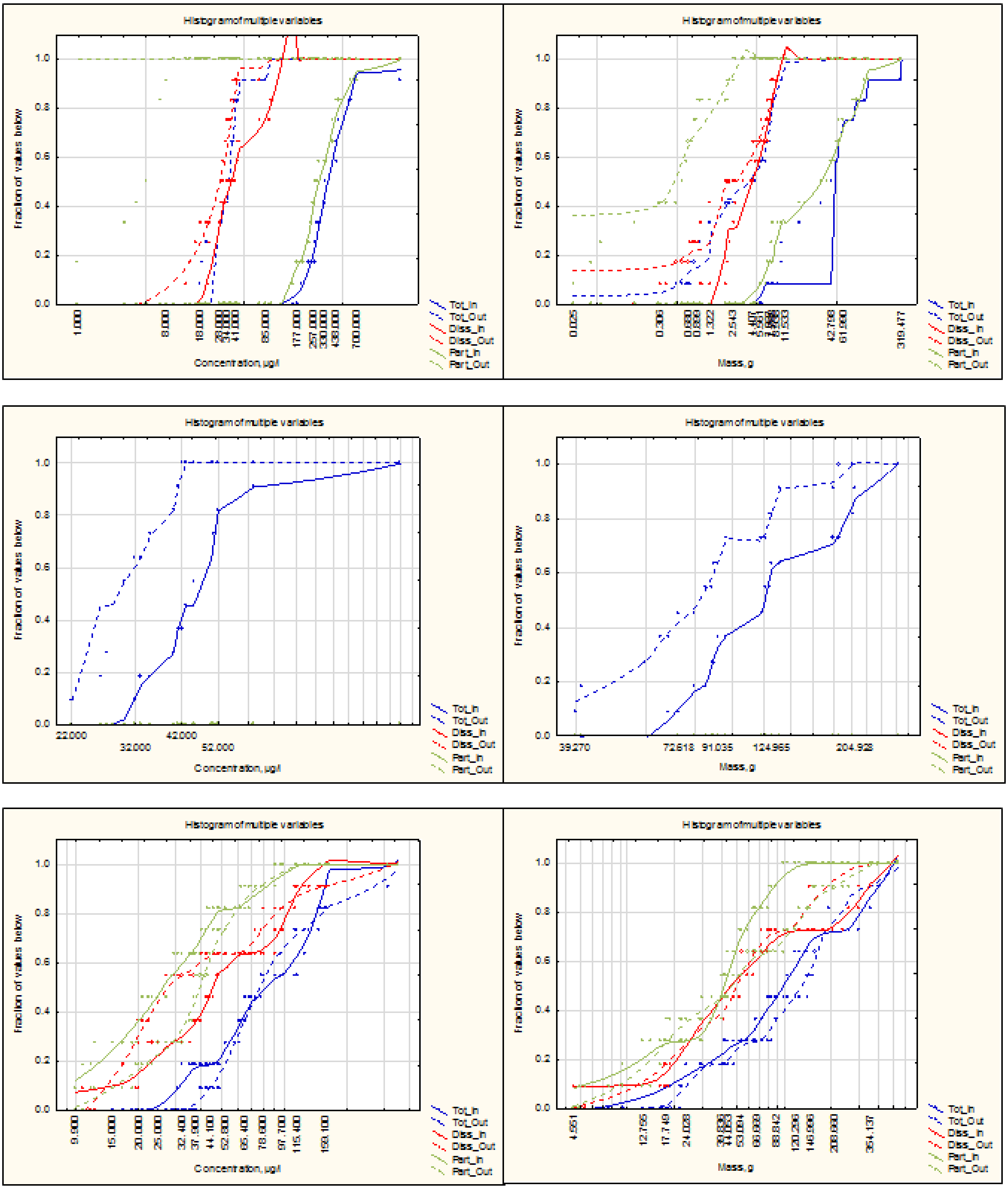


Figure C-33 Zinc CFPs for I5 La Costa East (top), Phantom Lake Pond A (middle) and Silver Star rd. (Bottom)

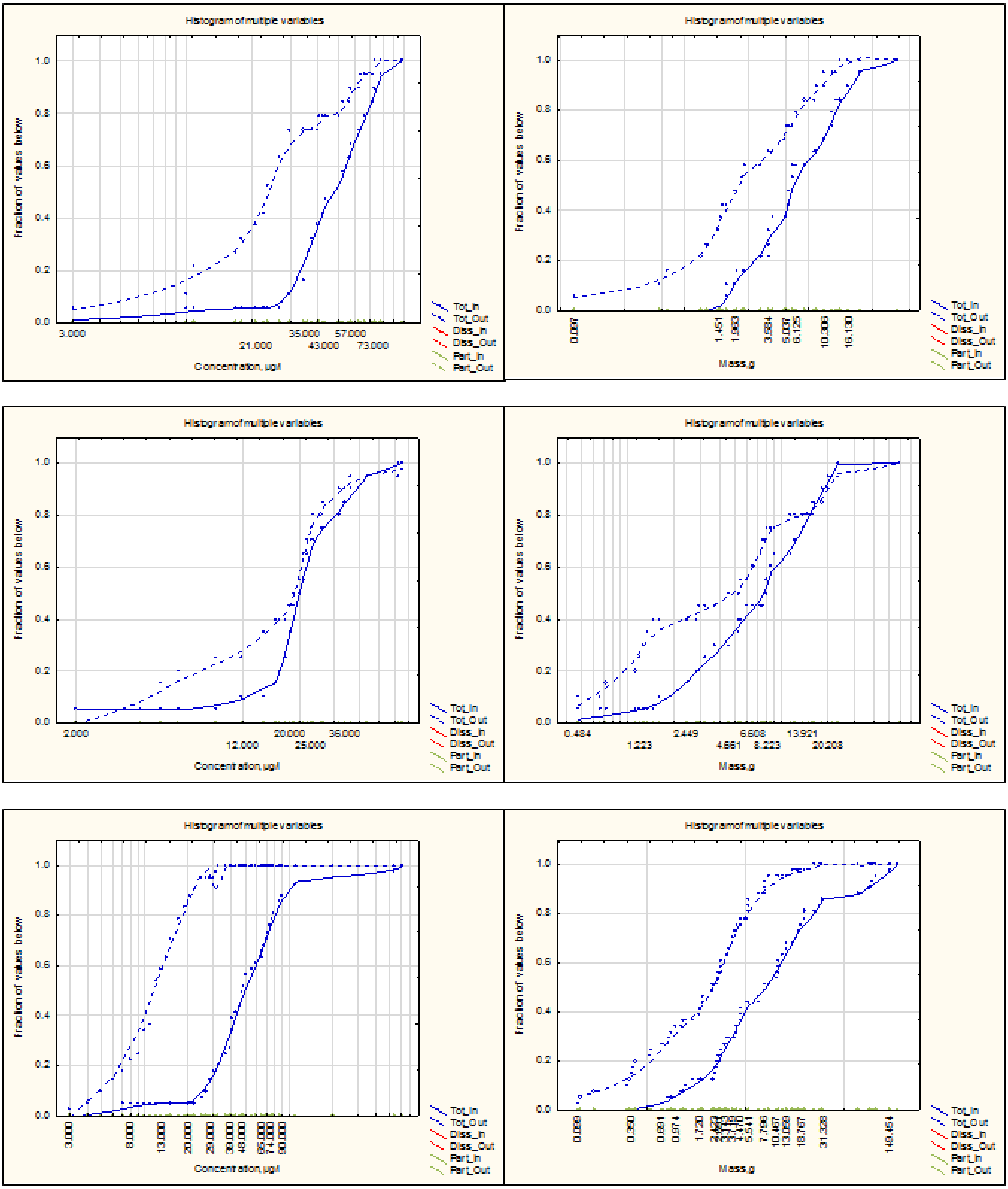


Figure C-34 Zinc CFPs for Tampa 1 (top), Tampa 2 (middle) and Tampa 3 (Bottom)

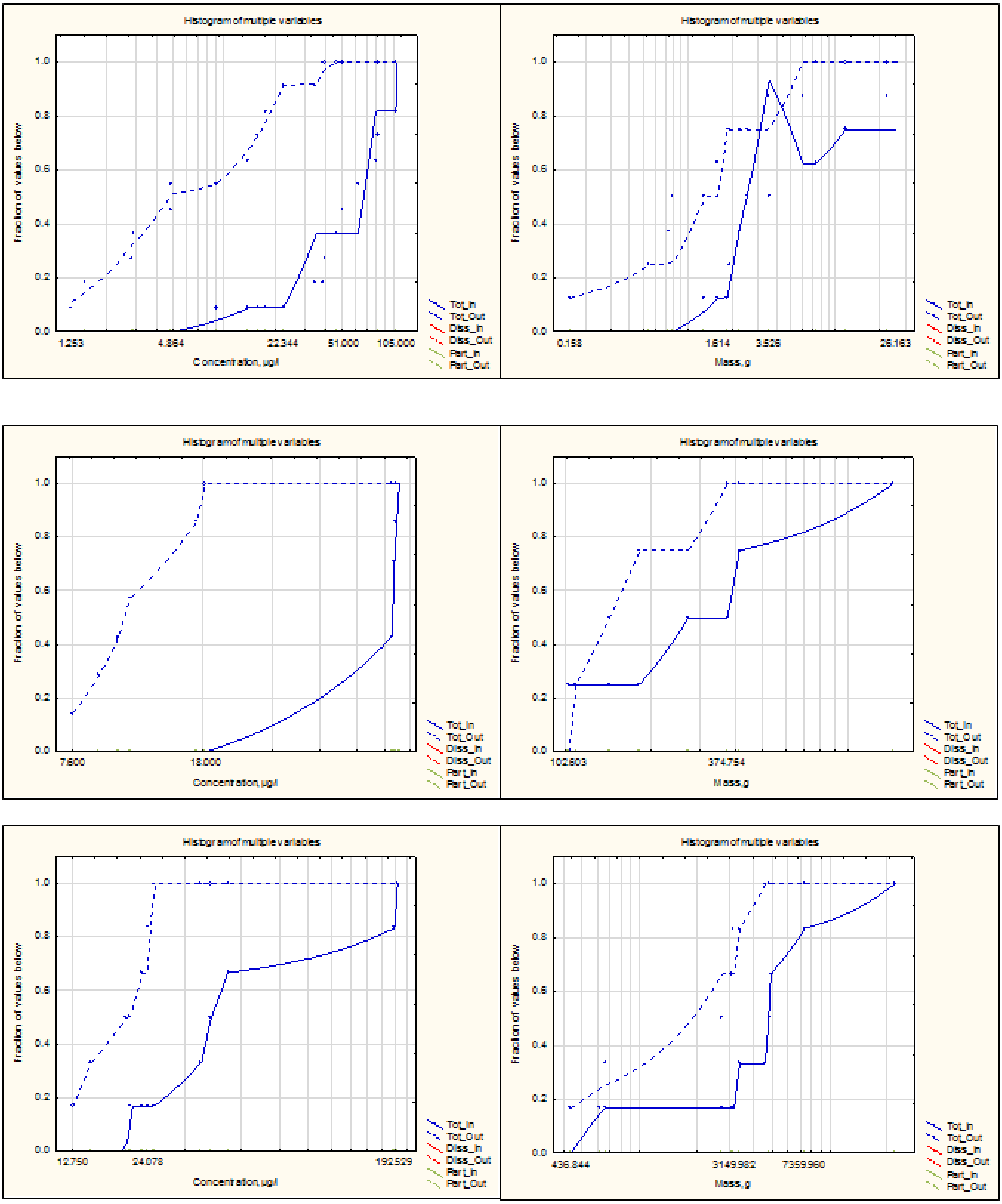


Figure C-35 Zinc CFPs for UNH (top), Lakeside (middle) and Pinellas (Bottom)

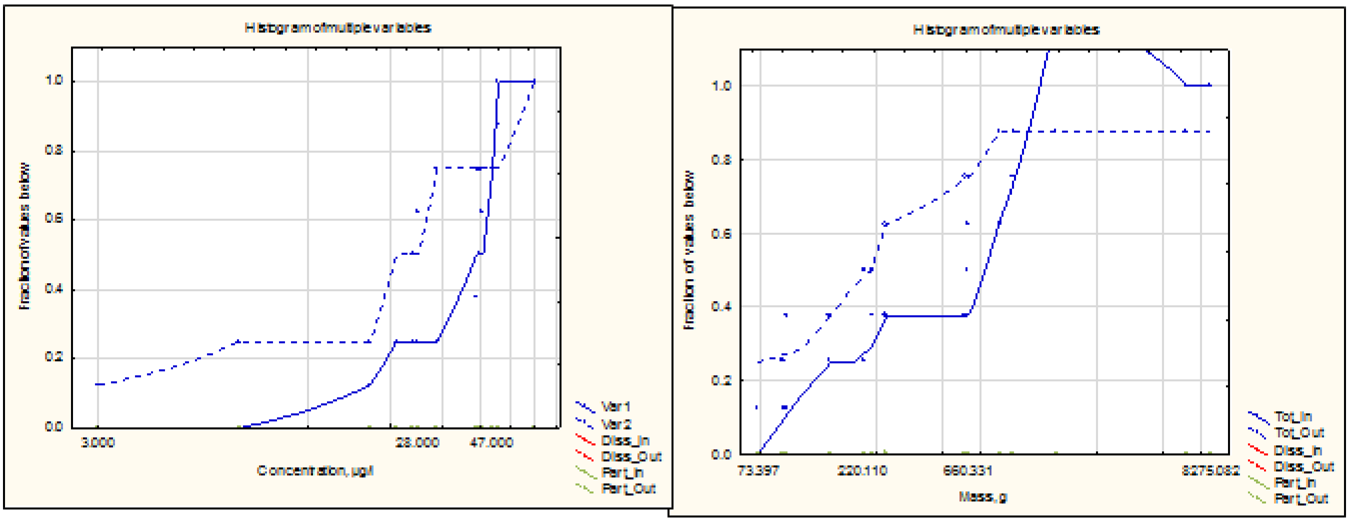


Figure C-36 Zinc CFP for Runaway Bay

C 1.2.5 RP TSS

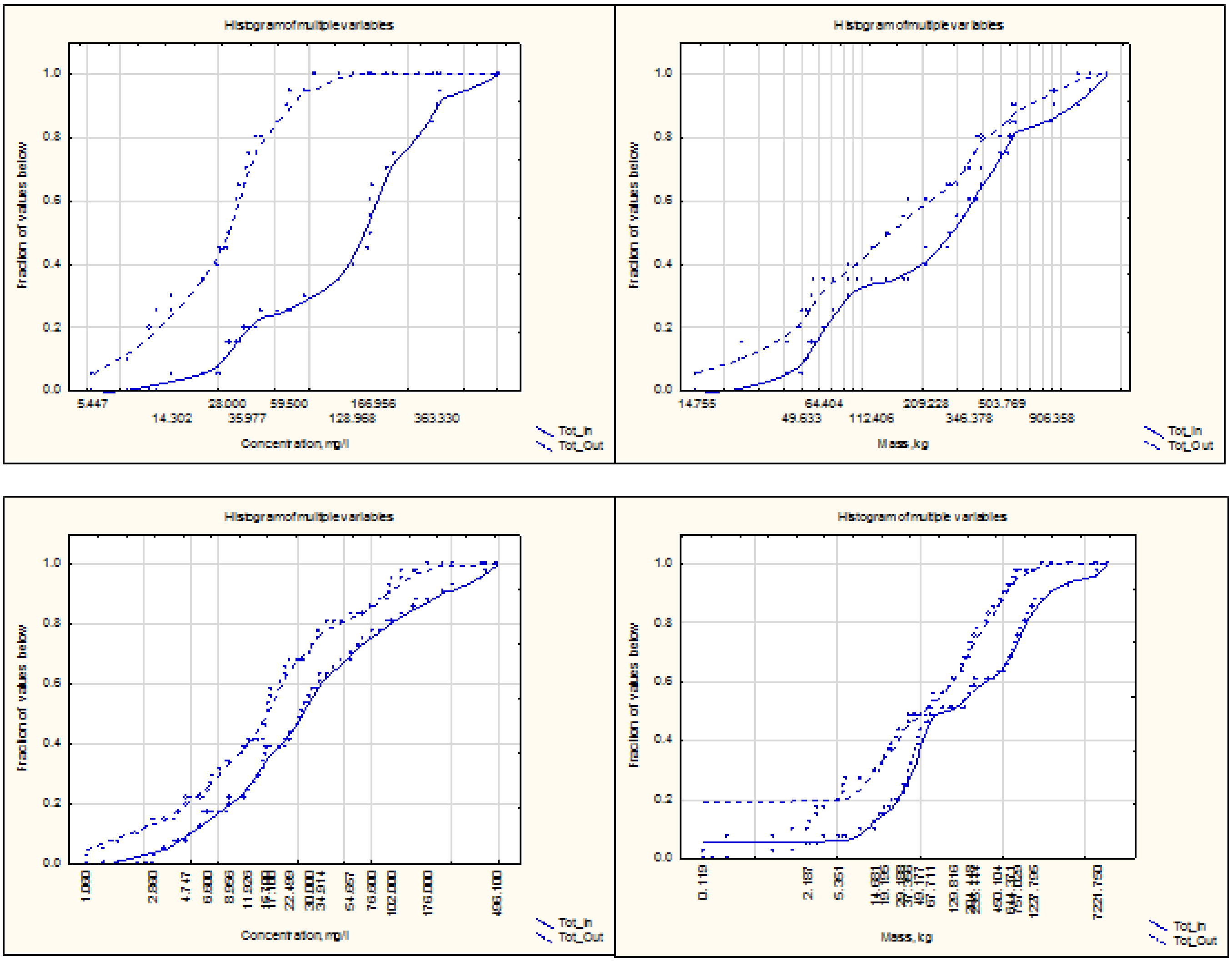


Figure C-37 TSS CFPs for Central Park (top) and Cockroach Bay (Bottom)

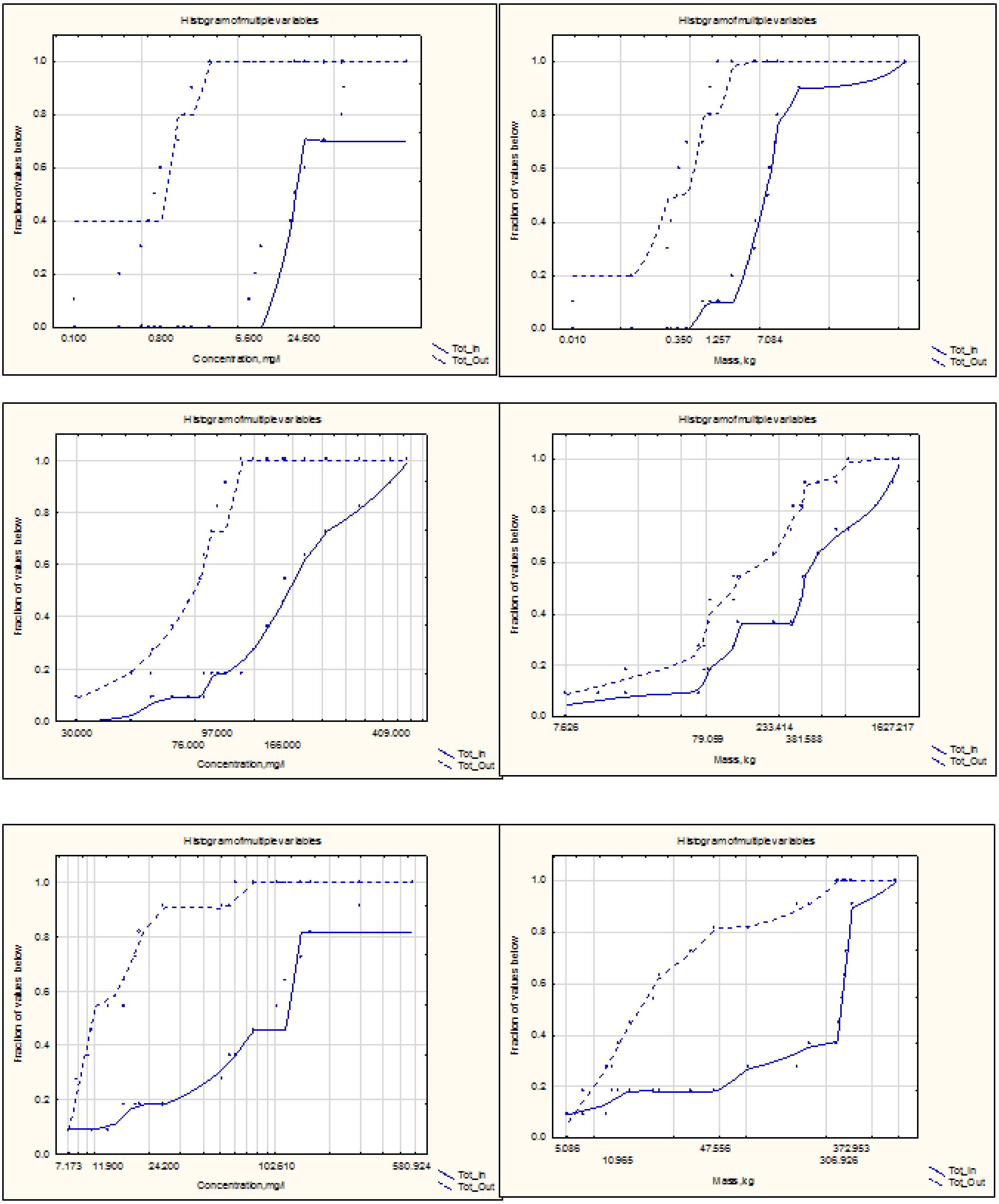


Figure C-38 TSS CFPs for De Bary (top), Greens Bayou (middle) and Heritage Estates (Bottom)

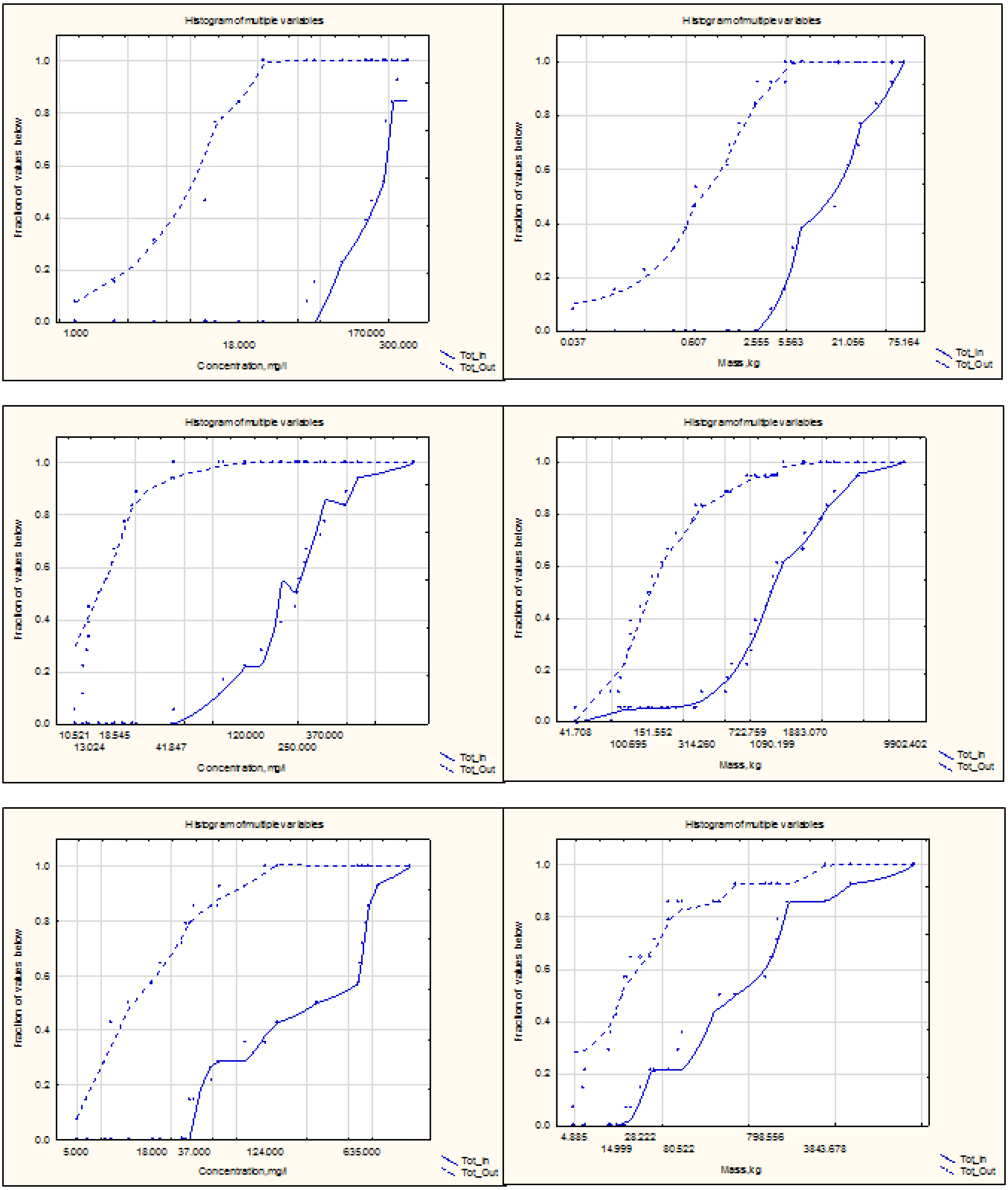


Figure C-39 TSS CFPs for I5 La Costa East (top), Lake Ellyn (middle) and Lake Ridge (Bottom)

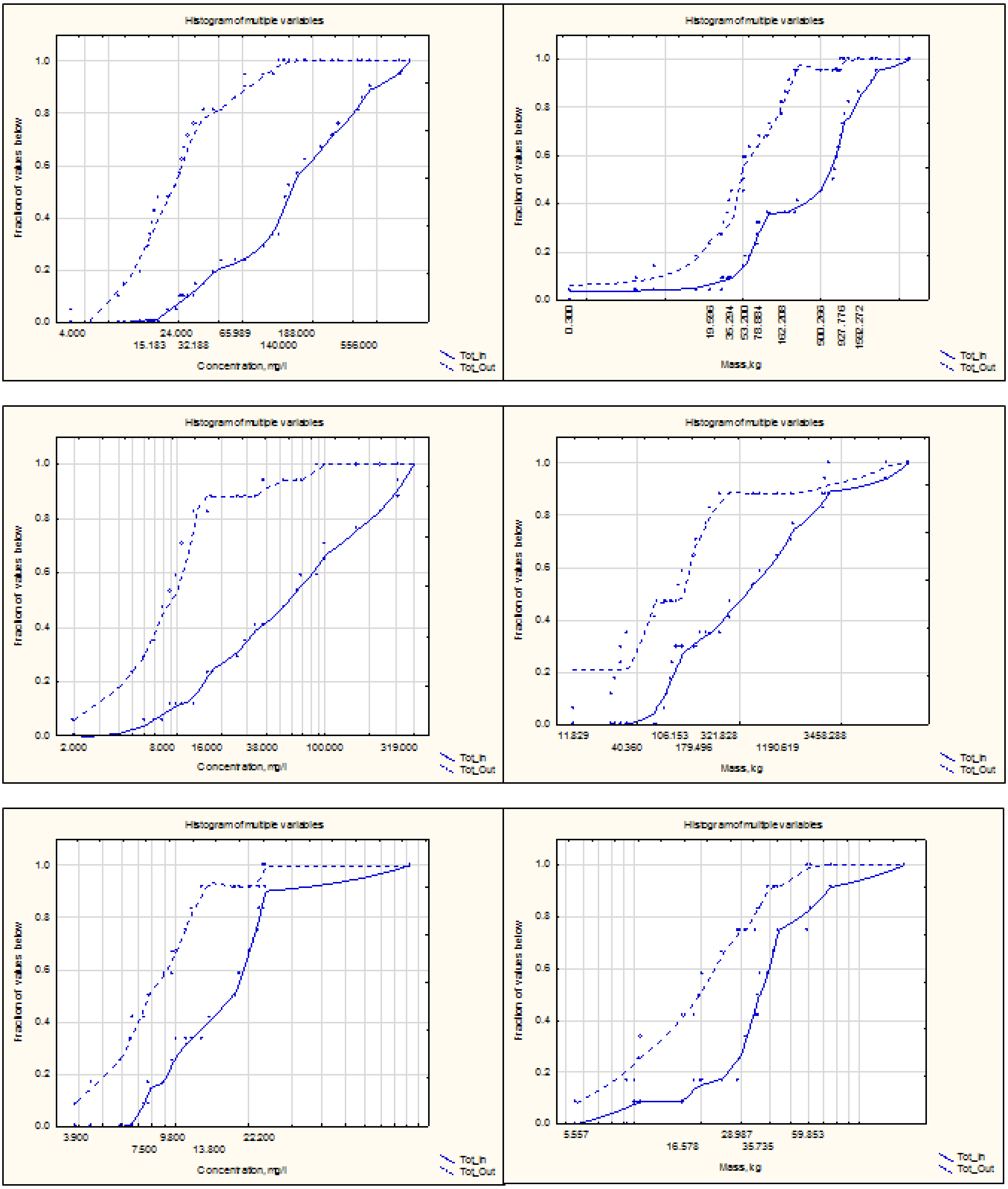


Figure C-40 TSS CFPs for Madison Monroe str. (top), McKnight Basin (middle) and Phantom Lake Pond A (Bottom)

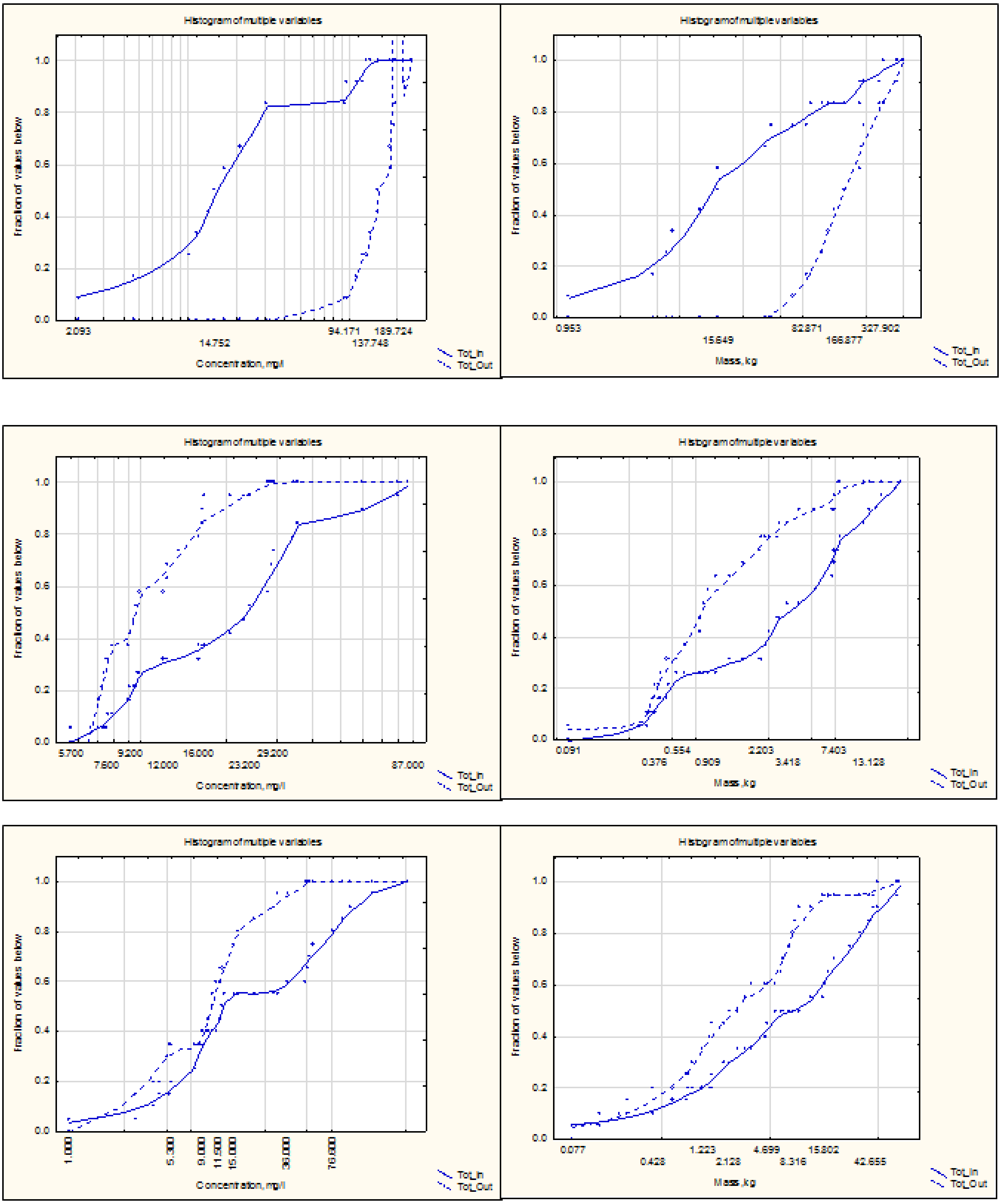


Figure C-41 TSS CFPs for Silver Star rd. (top), Tampa 1 (middle) and Tampa 2 (Bottom)

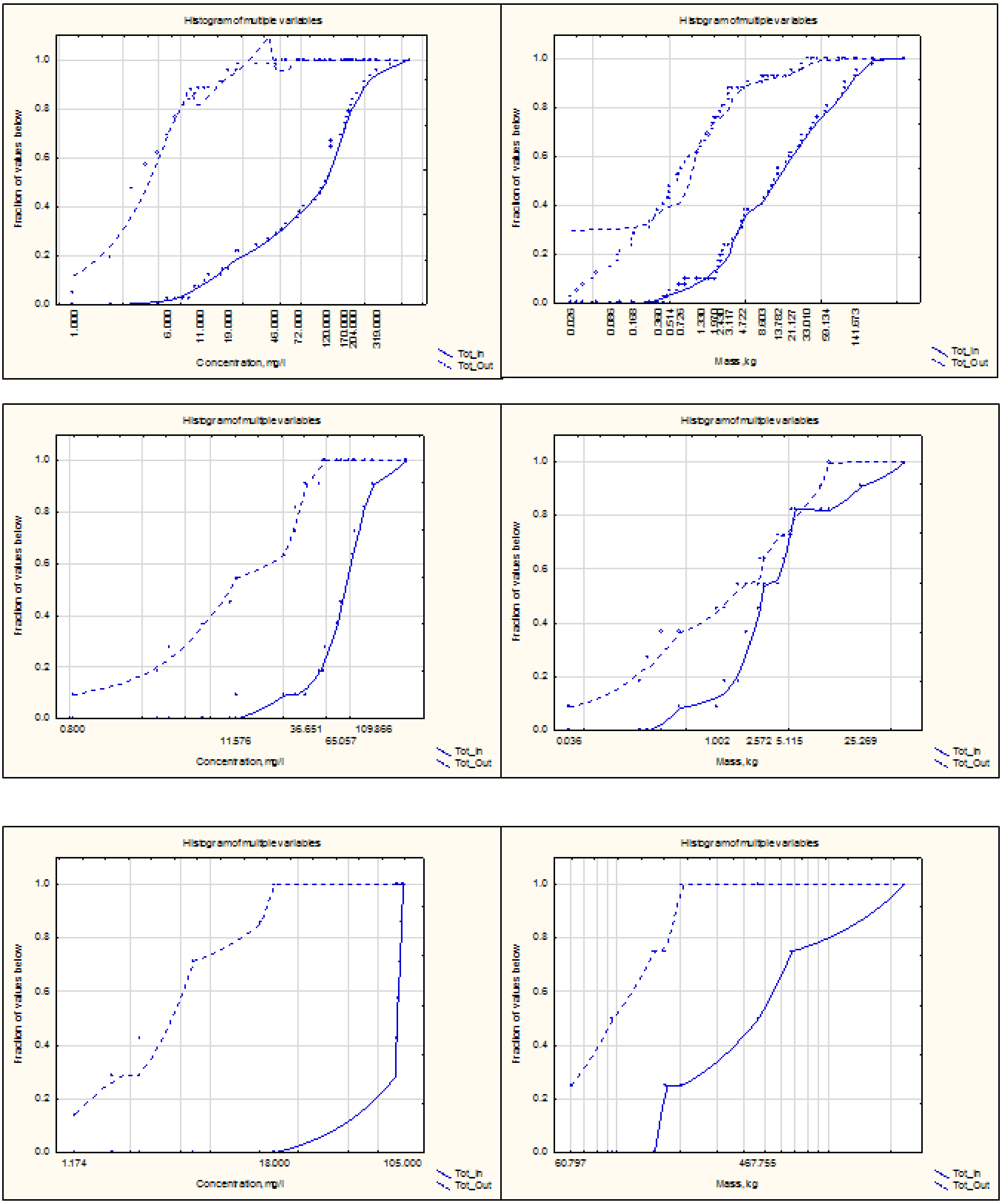


Figure C-42 TSS CFPs for Tampa 3 (top), UNH (middle) and Lakeside (Bottom)

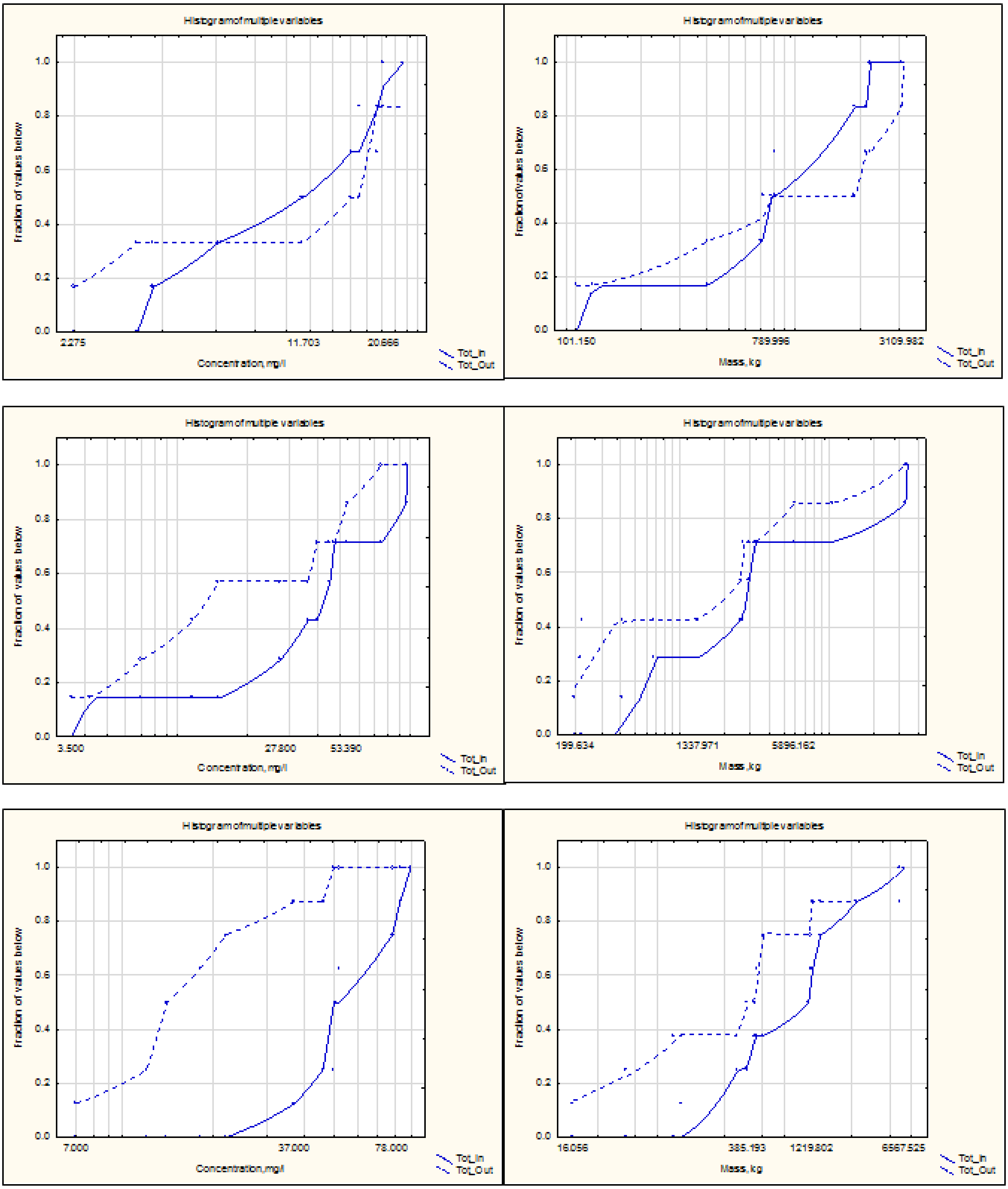


Figure C-43 TSS CFPs for Pinellas (top), Pittsfield (middle) and Runaway Bay (Bottom)

C 1.2.6 RP TVS

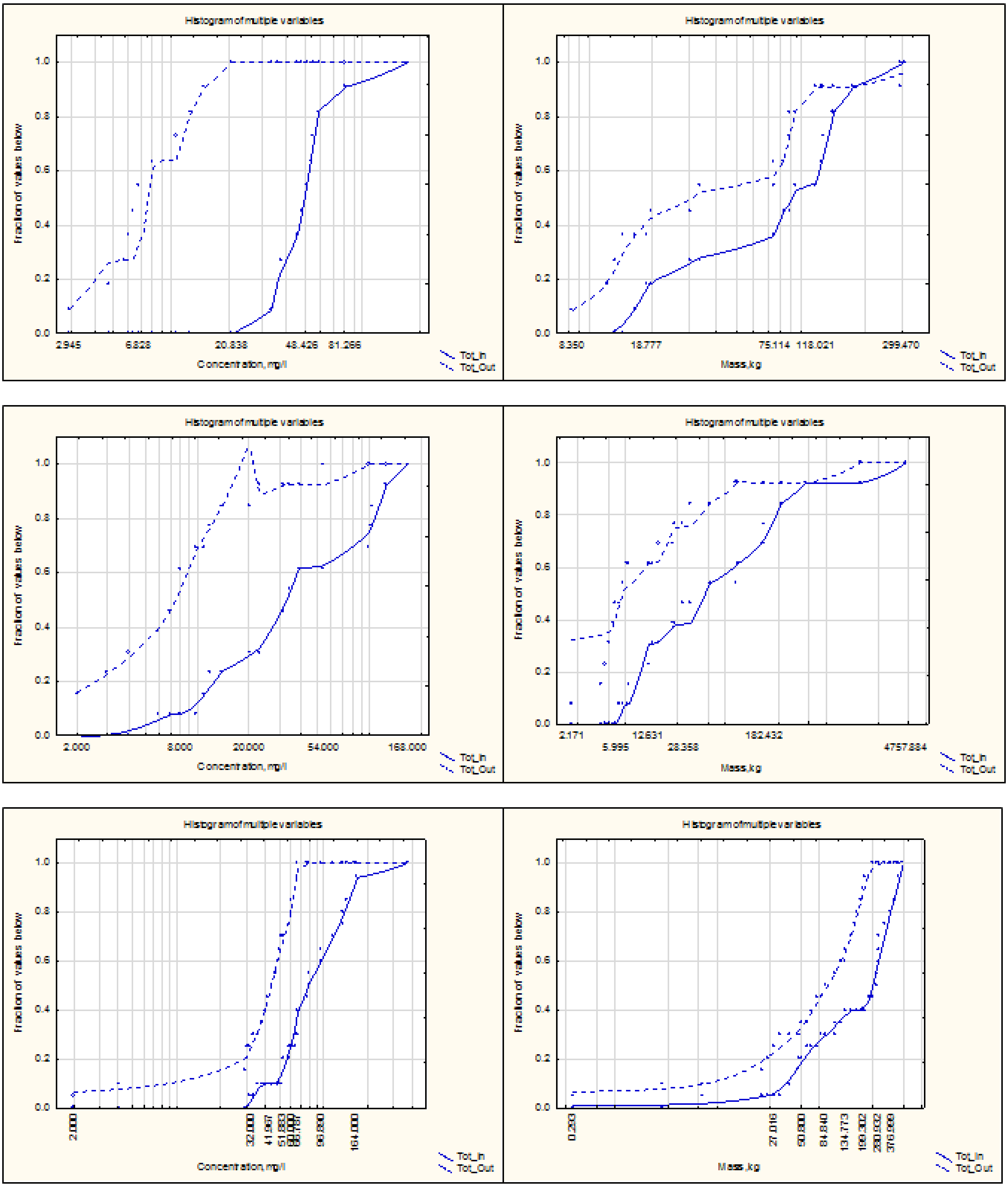


Figure C-44 TVS CFPs for Central Park (top), Lake Ridge (middle) and Madison Monroe str. (Bottom)

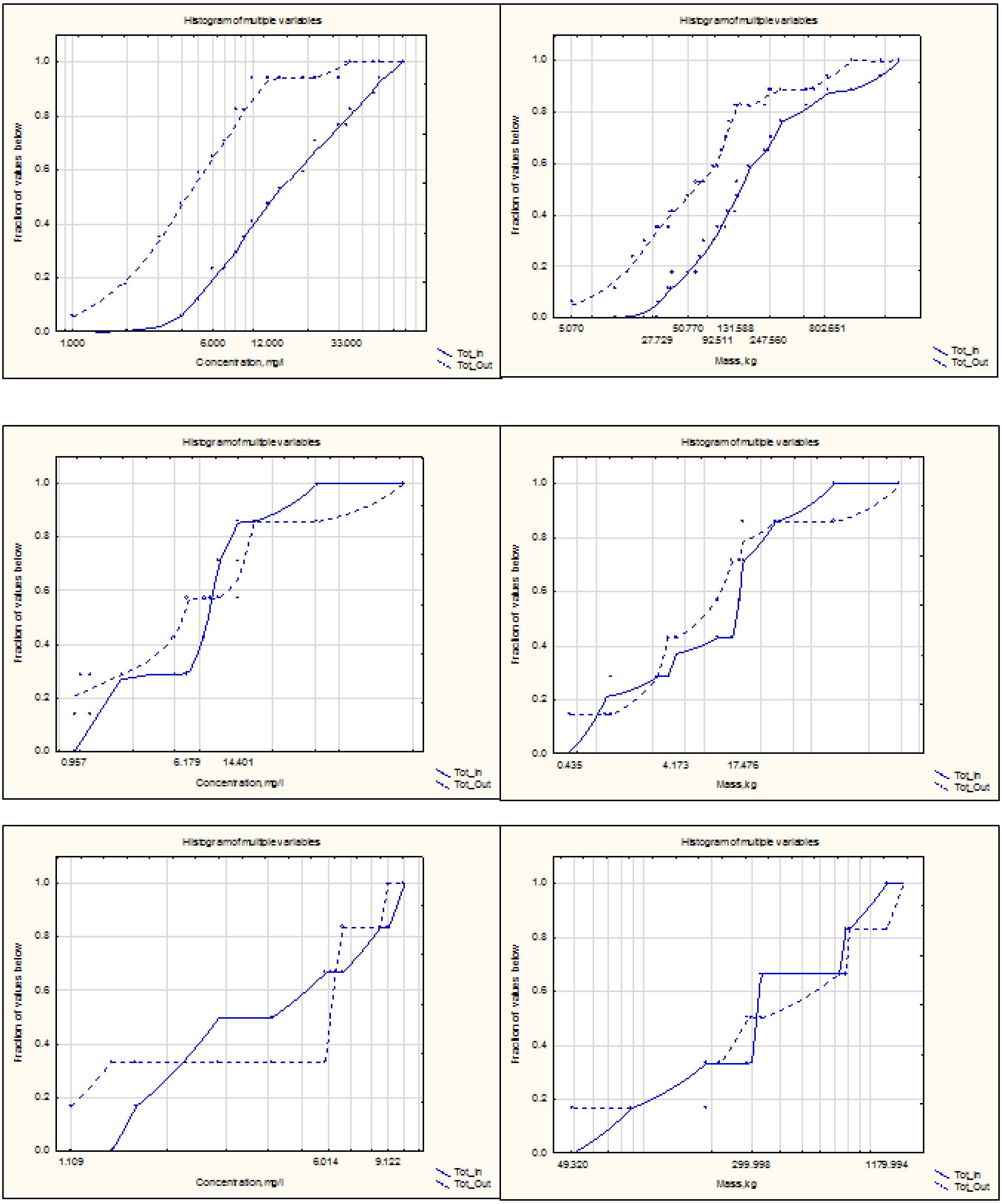


Figure C-45 TVS CFPs for McKnight Basin (top), Silver Star rd. (middle) and Pinellas (Bottom)

C2 Classification system technical note

C 2.1 Introduction

This technical note presents information on the development and application of a classification system for use as a supplement to the Effluent Probability Method (EPM). It is part of a larger research project into the determination of links between stormwater pond efficiency, in terms of metals removal, and design. It became apparent during the course of the research that a scheme that enabled the comparison of case studies in terms of efficiency was required. Extensive literature research yielded no such system, necessitating the development of the system presented here. The classification system was specifically designed to provide a scheme with which pond efficiencies could be compared across case studies.

The definition of stormwater pond efficiency used in this paper was adopted from literature provided by the United States of America Environmental Protection Agency (USEPA) and reads as follows:” Efficiency is a measure of how well a BMP (read Best Management Practice) or BMP system removes pollutants” (URS Greiner Woodward Clyde, Urban Drainage and Flood Control District, Urban Water Resources Research Council (UWRRC) of ASCE, 1999). In this paper, the term “efficiency” refers specifically to how well a stormwater pond removes metals and solids.

The EPM has been used in a number of studies to determine stormwater structure substance removal efficiencies, e.g. Chen et al. (2009), Wright Water Engineers Inc. & Geosyntech Consultants Inc., (2011), Fassman (2012). The findings of Chen et al. (2009) and Wright Water Engineers Inc. & Geosyntech Consultants Inc. (2011), are limited to graphical comparisons of influent and effluent data for specific substances with cumulative frequency plots. The findings of Fassman (2012) are limited to categorical (swales, wetlands etc.) graphical comparisons of substance effluent Event Mean Concentrations (EMCs).

The determinations of efficiency from these studies illuminate a shortcoming of the EPM, viz. determination of efficiency is performed on a graphical representation of differences in data for specific ponds or structure categories. It has the result that efficiency of specific structures can only be subjectively quoted, simply as “more efficient” or “less inefficient” in relation to other structures, with no scheme to suggest *how* “efficient” or “inefficient” a structure is. Moreover, such displays of data can show great variation in efficiency across data ranges, which make comparison of pond efficiencies across many case studies difficult.

A classification system for pond efficiency used as a supplement to the EPM was therefore developed. It provides a standardised methodology for the classification of stormwater pond efficiencies and serves as a scheme that can be used to compare pond efficiencies across different case studies.

C 2.2 The effluent probability method

The EPM provides a statistical view of influent and effluent quality and was recommended by GeoSyntec Consultants , Wright Water Engineers, Inc. (2009) under support from *inter alia* the Water Environment Research Foundation (WERF), the United States Environmental Protection Agency (USEPA) and the American Society of Civil Engineers (ASCE).

This methodology broadly comprises the following steps:

1. Determine whether a BMP is providing treatment by calculating statistical significance at 95% confidence level between influent and effluent values.
2. Examine a cumulative distribution function or standard parallel probability plot of influent and effluent quality.

   (GeoSyntec Consultants , Wright Water Engineers, Inc., 2009)

The advantages of the EPM are: (1) it is easy to apply and (2) it provides a clear picture of the effluent vs. influent water quality. Shortcomings of the method are: (1) The measure of statistical significance is only a measure that proves / disproves the null hypothesis that the influent and effluent data medians are equal at a predefined significance level. It cannot prove that influent concentration has got some impact on effluent concentration. (2) Graphical displays of data provide only a sense of pond performance. Personal and highly subjective judgement must be used to conclude whether a pond performs well or poorly in relation to other ponds.

Cumulative distribution functions (CDFs) can be approximated by cumulative frequency plots (CFPs) and can be displayed on CFPs to determine how well the data fits a theoretical (e.g. normal) distribution (GeoSyntec Consultants , Wright Water Engineers, Inc., 2009). CFPs are variations of histograms, in which the height of each bar represents the total number of observations that are less than or equal to the upper limit of the bin (Montgomery & Runger, 2003:205). These graphs are useful in pond efficiency evaluations because they can indicate variations in pond efficiencies over inflow/outflow data ranges. The establishment of pond efficiencies for comparative purposes in this research project did not require the establishment of theoretical distributions. Normality of data sets was established through the use of Normal Probability Plots in order to inform the choice between statistical tests. Therefore, the sample approximations of the cumulative distribution functions, i.e. CFPs, were deemed adequate for the graphical representations of data.

The use of statistical significance is controversial and has been criticised in literature. Dickson & Baird (2011:219) for example stated that although statistical significance testing has become the standard in many scientific explorations, the assumption that a significant difference is due to some causal relationship is currently “more an article of faith than a well-established principle”. On the choice of the significance level, Dickson & Baird (2011:224) stated that the choice of significance level is in itself statistically insignificant. It is arbitrary and unbased in theory. Statistical significance should therefore be used with cognisance of the criticisms raised against it. The EPM reduces the chance of drawing incorrect conclusions from the p-value by coupling its interpretation with that of graphical displays of data. In this way, the use of the p-value forms part of a wider data investigation procedure.

C 2.3 Classification system development

C 2.3.1 Data acquisition and preparation

Data was obtained from the International Stormwater BMP Database, v.07.07.11, available on www.bmpdatabase.org. Data preparation included data categorisation, treatment of non-detects through transformation with the Regression on Order Statistics method, investigations into data quality, testing for normality in data and descriptive statistics analysis.

C 2.3.2 Statistical Significance Testing

Data set normality test results indicated that normality could not be assumed in many data sets, and that difference values between inflow and outflow data were generally non-symmetrical. The state of the data therefore necessitated the use of the non-parametric, but less powerful Sign test.

The software program STATISTICA v.10 (Copyright© StatSoft, Inc. 1984-2011) was used for all calculations. Statistical significance between inflow and outflow data was accepted at $p < 0.05$. A table published by Dixon (1952:468) was used to estimate power.

C 2.3.3 Normal Probability Plots (NPPs):

Normal Probability Plots (NPPs) were generated for untransformed as well as for log-transformed (natural logarithm) data sets with software program STATISTICA v.10 (Copyright© StatSoft, Inc. 1984-2011). Interpretations of plot results were found to be more suited to testing for normality in data than to interpretations of pond efficiencies. Cumulative Frequency Plots were found to be more suited to this.

C 2.3.4 Cumulative Frequency Plots (CFPs):

Graphical observations were limited to a visual categorisation of graphical behaviour according to plot point and regression line proximity. STATISTICA v.10 (Copyright© StatSoft, Inc. 1984-2011) was used to generate CFPs for all data sets. The Lowess smoothing method was used for the generation of regression lines.

C 2.4 Classification of Pond Efficiencies

Relationships between in/out CFPs resulted in the categorisation of general pond efficiencies into 2 basic observational types. Additional consideration of statistical significance results led to the establishment of 5 different behavioural types (BTs), which are further discussed.

Table C-1 Pond efficiency behavioural types observed in data

Graphical Observation	Indication	Statistically Significant Difference Between Inflow/Outflow Data?	Pond Efficiency Behavioural Types (BT)
A In/ out CFPs coincidental, closely adjacent and intersecting	Pond efficiencies are unresponsive and varied across the data range.	No	BT1 Pond efficiency behaviour is accepted to be generally unresponsive and varied across the data range.
		Yes	
B CFPs non-coincidental and distant in many areas	Possibly significant general efficiency.	Yes	BT2 Pond efficiency behaviour is generally positive and statistically significant.
			BT3 Pond efficiency behaviour is generally negative and statistically significant.
		No	BT4 Pond efficiency behaviour is generally positive but not statistically significant.
			BT5 Pond efficiency behaviour is generally negative but not statistically significant.

The behavioural types of pond efficiencies were classified as follows:

BT1 - Generally unresponsive efficiency: Pond efficiencies were classified as generally unresponsive in cases where in/out data points and regression lines in the CFPs were coincidental, closely adjacent and/or intersected along the majority of the data range. A statistically significant result for the data set was not held to negate this classification. This is because the Sign test results indicated significant differences (below a certain arbitrarily chosen p-value) between medians and could not prove or disprove an accepted level of efficiency on its own. Therefore, visual interpretation of graphical displays of data trumped the results of the Sign test in this case.

BT2 - Significantly positive efficiency: Pond efficiencies were classified as significantly positive when: (1) in/out data points and regression lines on the CFPs were generally positive, non-coincidental and distant in the majority of the data range, and; (2) the Sign test gave a statistically significant result between inflow and outflow data sets.

BT3 - Significantly negative efficiency: Pond efficiencies were classified as significantly negative when: (1) in/out data points and regression lines on the CFPs were generally negative, non-coincidental and distant in the majority of the data range, and; (2) the Sign test gave a statistically significant result between inflow and outflow data sets.

BT4 - Not significantly positive efficiency: Pond efficiencies were classified as not significantly positive when: (1) in/out data points and regression lines on the CFPs were generally positive, non-coincidental and distant in the majority of the data range, and; (2) the Sign test did not give a statistically significant result between inflow and outflow data sets.

<u>BT5 - Not significantly negative efficiency:</u> Pond efficiencies were classified as not significantly negative when: (1) in/out data points and regression lines on the CFPs were generally negative, non-coincidental and distant in the majority of the data range, and; (2) the Sign test did not give a statistically significant result between inflow and outflow data sets.

C 2.5 Examples

The results of four case studies are presented below to provide examples of pond efficiency classifications. Examples were chosen to illustrate the different classification types.

C 2.5.1 Sign test results

Sign test p-value results for the selected case studies are given in Table C2 below. Results were deemed to be statistically significant at $p < 0.05$.

Table C-2 Sign test p-value results for selected case studies

Case Study	**Sign test p-value**					
	Total		**Dissolved**		**Particulate**	
	Conc.	**Mass**	**Conc.**	**Mass**	**Conc.**	**Mass**
I5/I605 EDB - zinc	*0.15*	*0.15*	0.009	0.009	0.77	0.77
Lake Ellyn - zinc	**0.00006**	**0.00006**	**0.00006**	**0.002**	**0.0004**	**0.0004**
I605 SR91 EDB - copper	*0.22*	**0.04**	0.68	**0.04**	**0.04**	**0.04**
Central Park - cadmium	**0.03**	**0.01**	no data	no data	no data	no data

<u>Note:</u> (1) Values in bold denote statistically significant results at $p<0.05$. (2) Values in italics denote results with low statistical power (<0.4).

The power of the sign test was low for the I5/I605 EDB zinc (concentration and mass), the I605 SR91 EDB copper (concentration) total data sets. It is therefore possible that these case studies may have produced statistically significant results if larger sample sizes had been available.

C 2.5.2 Graphical displays of data

CFPs for the selected case studies were provided below. The following terms were used in the graphs:

Tot_In: Total substance in inflow

Tot_Out: Total substance in Outflow

Diss_In: Dissolved substance in Inflow

Diss_Out: Dissolved substance in Outflow

Part_In: Particulate substance in Inflow

Part_Out: Particulate substance in Outflow

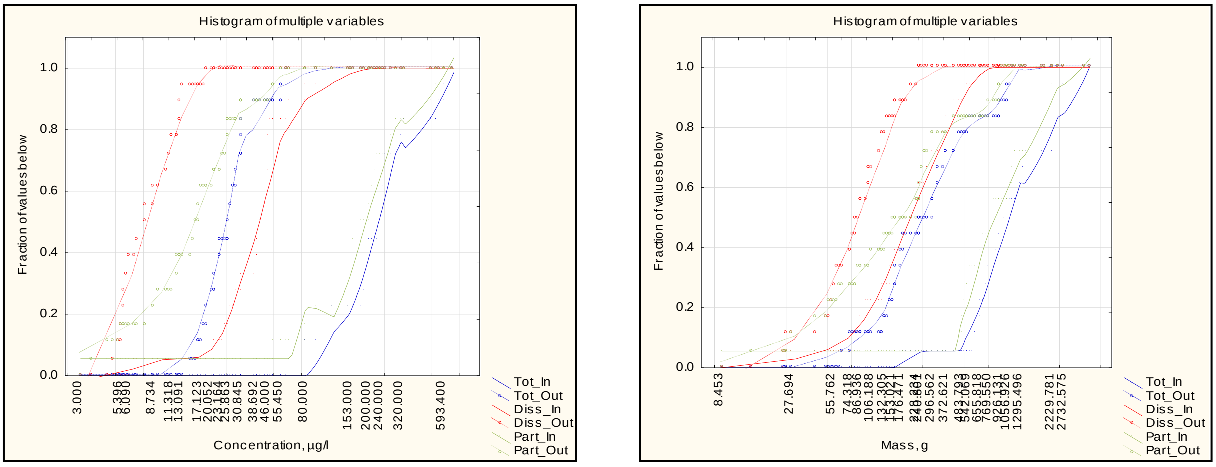


Figure C-46 I5 I605 EDB CFPs for zinc concentration and mass inflow/outflow values

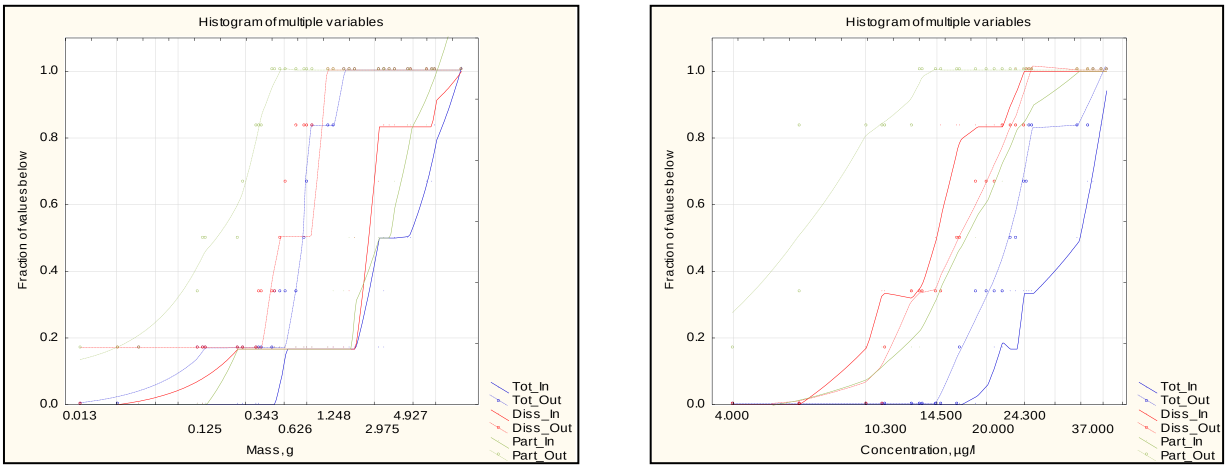


Figure C-47 Lake Ellyn CFPs for zinc concentration and mass inflow/outflow values

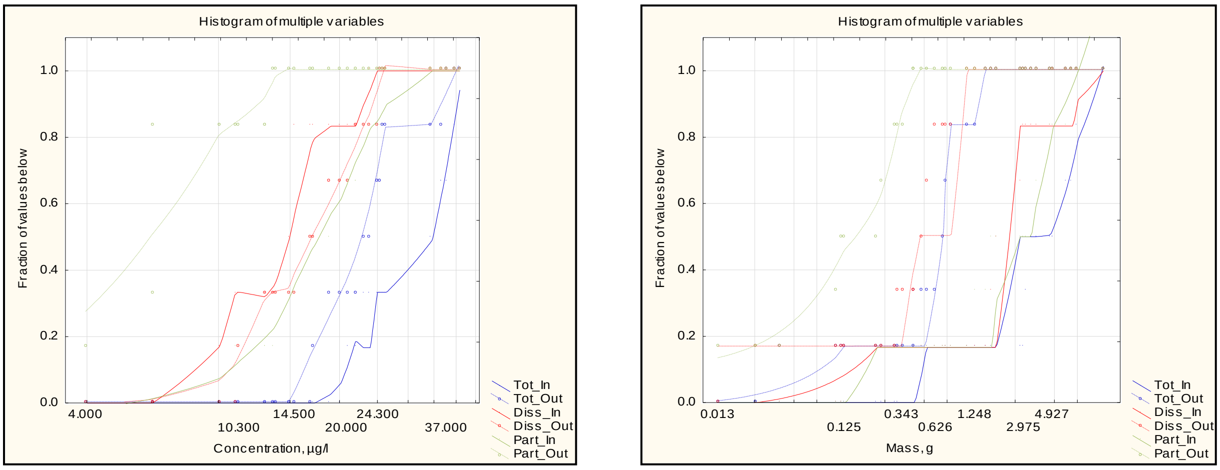


Figure C-48 I605 SR91 EDB CFPs for copper concentration and mass inflow/outflow values

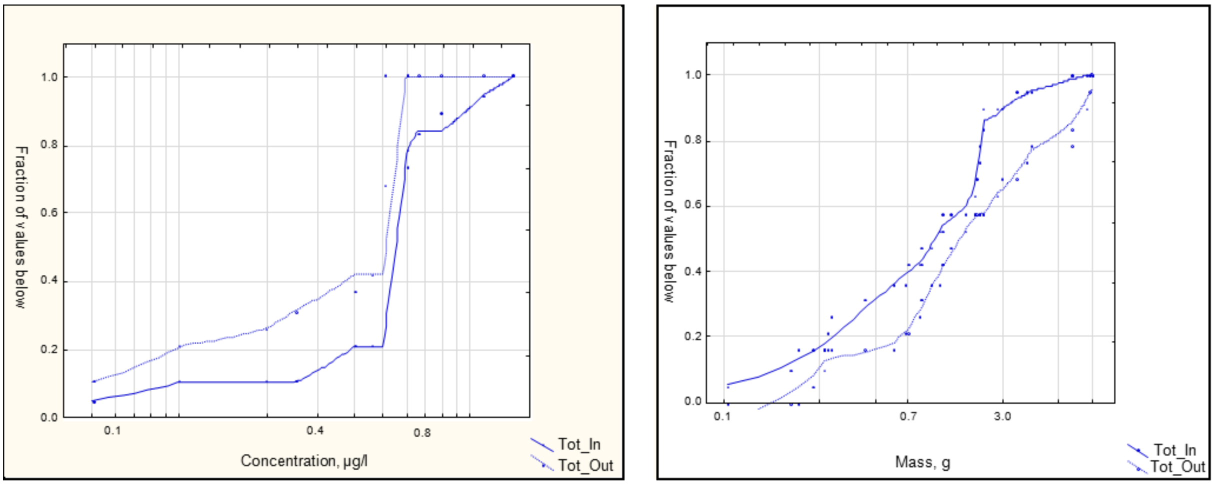


Figure C-49 Central Park retention pond CFPs for cadmium concentration mass inflow/outflow values: totals only

C 2.5.3 Observations and efficiency classifications

Behavioural observations coupled with the Sign test results and the resultant efficiency classifications are summarised in Table C 3. From the results it can be seen that complex cases may arise in which classification is unclear. For example, the I5 I605 EDB total zinc removal efficiencies for concentration and mass were classified as "generally unresponsive". Closer inspection of the efficiency results show that the power of the Sign test results was low (< 0.4) and that the removals alternated between positive in negative between low and high concentration and mass values. This singularity of the classification can therefore result in an oversimplification that fails to show underlying complicated, and variable, results.

Moreover, the graphical interpretations of efficiency are subjective. Cases can arise in which the interpretation of the graphs may be debated by other researchers. For example, the I5 I605 EDB dissolved zinc removal efficiencies were classified as "generally unresponsive", even though the results of the statistical significance tests were $p < 0.05$ in both cases. The interpretation of the graphs as "CFPs coincidental and closely adjacent in many areas" had a purely subjective basis. Therefore, in cases where CFPs show unclear indications of overall efficiencies, the results of the classification procedure with the EPM may differ from researcher to researcher.

C 2.6 Advantages of the classification system

The system provides a standardised methodology as well as terminology for pond efficiency classification.

The system is a supplement to the EPM, which is a highly recommended method (see GeoSyntec Consultants , Wright Water Engineers, Inc. (2009)) for pond efficiency determinations. The basis of the method is therefore already well-established amongst stormwater quality researchers.

Table C-3 Observations and efficiency classifications of selected cases

Data Type	Graphical Observation	Indication of Graphical Observations	Classification of Behavioural Type
I5 I605 EDB – Zinc			
Total and Particulate Concentration and Mass Data	In/out CFPs coincidental and closely adjacent in many areas	Pond efficiencies are unresponsive and varied across the data range	Sign test results: not statistically significant Suggested behavioural type: BT1 Pond efficiency classification: Generally unresponsive
Dissolved Concentration and Mass Data	In/out CFPs coincidental and closely adjacent in many areas	Pond efficiencies are unresponsive and varied across the data range	Sign test results: statistically significant Suggested behavioural type: BT1 Pond efficiency classification: Generally unresponsive
Lake Ellyn – Zinc			
Total, Dissolved and Particulate Concentration and Mass	In/out CFPs non-coincidental and distant in many areas	Possible significant general efficiency	Sign test results: statistically significant Suggested behavioural type: BT2 Pond efficiency classification: Significantly positive
I605 SR91 EDB – Copper			
Total Concentration	In/out CFPs non-coincidental and distant in many areas	Possible significant general efficiency	Sign test results: not statistically significant Suggested behavioural type: BT4 Pond efficiency classification: Not significantly positive
Total Mass	In/out CFPs non-coincidental and distant in many areas	Possible significant general efficiency.	Sign test results: statistically significant Suggested behavioural type: BT2 Pond efficiency classification: Significantly positive
Dissolved Concentration	In/out CFPs non-coincidental and distant in many areas	Possible significant general efficiency Note: removals were negative.	Sign test results: not statistically significant Suggested behavioural type: BT5 Pond efficiency classification: Not significantly negative
Dissolved Mass	In/out CFPs non-coincidental and distant in many areas	Possible significant general efficiency	Sign test results: statistically significant Suggested behavioural type: BT2 Pond efficiency classification: Significantly positive
Particulate Concentration and Mass	In/out CFPs non-coincidental and distant in many areas	Possible significant general efficiency	Sign test results: statistically significant Suggested behavioural type: BT2 Pond efficiency classification: Significantly positive
Central Park retention pond - Cadmium			
Total Concentration	In/out CFPs non-coincidental and distant in many areas	Possible significant general efficiency	Sign test results: statistically significant Suggested behavioural type: BT2 Pond efficiency classification: Significantly positive
Total Mass	In/out CFPs non-coincidental and distant in many areas	Possible significant general efficiency Note: removals were negative.	Sign test results: statistically significant Suggested behavioural type: BT3 Pond efficiency classification: Significantly negative

The classification system can be used to generate a singular descriptor of pond efficiencies, which can be used as a quick reference for the comparison of pond efficiencies across case studies.

The system is applicable to different substances (zinc, copper etc.) as well as fractions (total, dissolved, particulate) and therefore makes cross case study comparisons possible.

The system is supplemental to the EPM and follows on statistical as well as graphical interpretations of pond efficiencies. It is therefore based on a more comprehensive overview of pond efficiencies than can be provided by other methods such as those used for the determination of singular numerical descriptors of pond efficiencies, e.g. Efficiency Ratio, Summation of Loads etc. (see URS Greiner Woodward Clyde, Urban Drainage and Flood Control District, Urban Water Resources Research Council (UWRRC) of ASCE (1999) for further information on alternative methodologies for determination of pond efficiencies).

C 2.7 Shortcomings of the classification system

The main advantage of the system, which is the provision of a singular descriptor of pond efficiency, is also its main disadvantage. The singular descriptor impairs the methodological ability to deal with complicated and variable results. Complex cases can arise in which classification is unclear (as was seen in the I5 I605 EDB case).

The efficiency classifications are qualitative rather than quantitative. In this system there are only 5 classifications and therefore only 5 levels of comparison, whereas numerical descriptors may result in infinite levels of comparison.

Shortcomings of the Effluent Probability Method are inherited by the classification system, e.g.:

a) The graphical interpretations of efficiency are subjective. Cases can arise in which the interpretation of the graphs may be debated by other researchers (as was seen in the I5 I605 EDB case).

b) The system includes consideration of statistical significance, the use of which is a controversial topic among scientists.

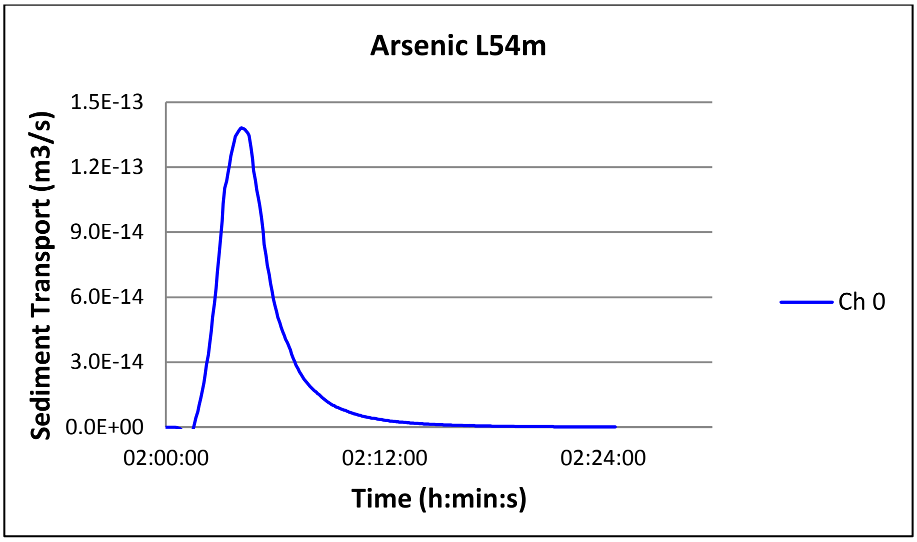
C 2.8 Conclusion

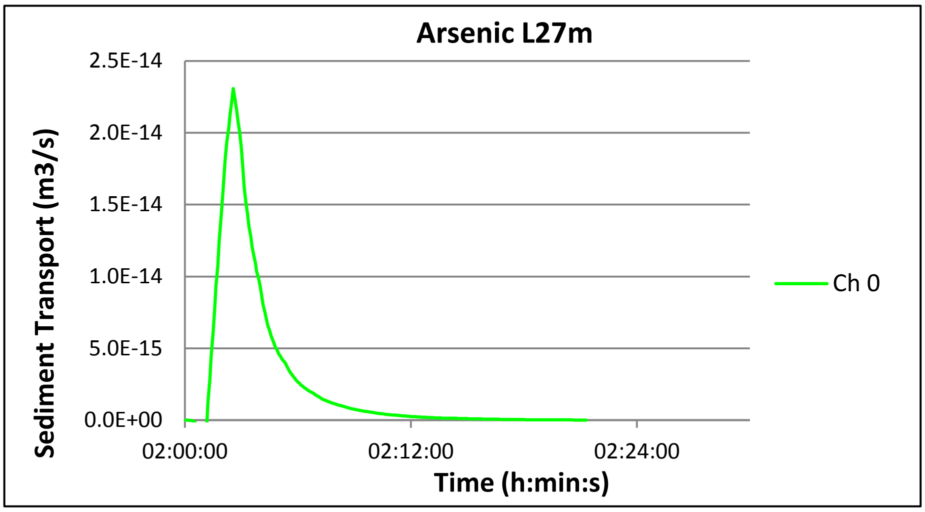
The Effluent Probability Method is a preferential method for evaluation of stormwater pond efficiencies, but does not lend itself to comparisons across case studies. The development of the classification system presented here was necessitated by a need to create a standard and singular basis on which pond efficiencies could be compared across case studies as part of a larger research project into the relationships between pond efficiencies and design.

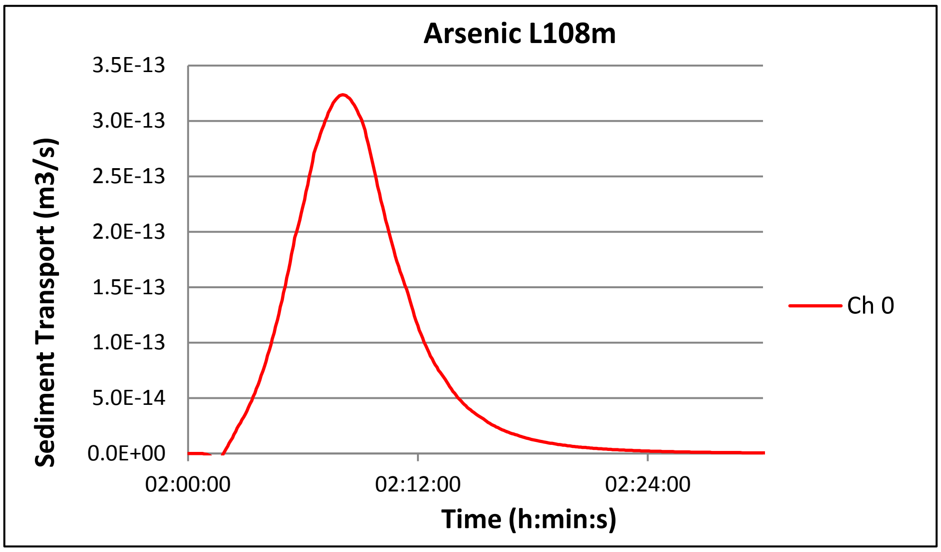
The main advantage as well as disadvantage of the system is the singular descriptor of efficiency for a pond, which allows comparison between case studies, but at the same time limits the ability to deal with complicated efficiencies over different data ranges. In addition, the system has inherited the advantages as well as the limitations of the Effluent Probability Method.

D. MIKE 11 software modelling sedimentation transport results for detention ponds

D 1 Arsenic







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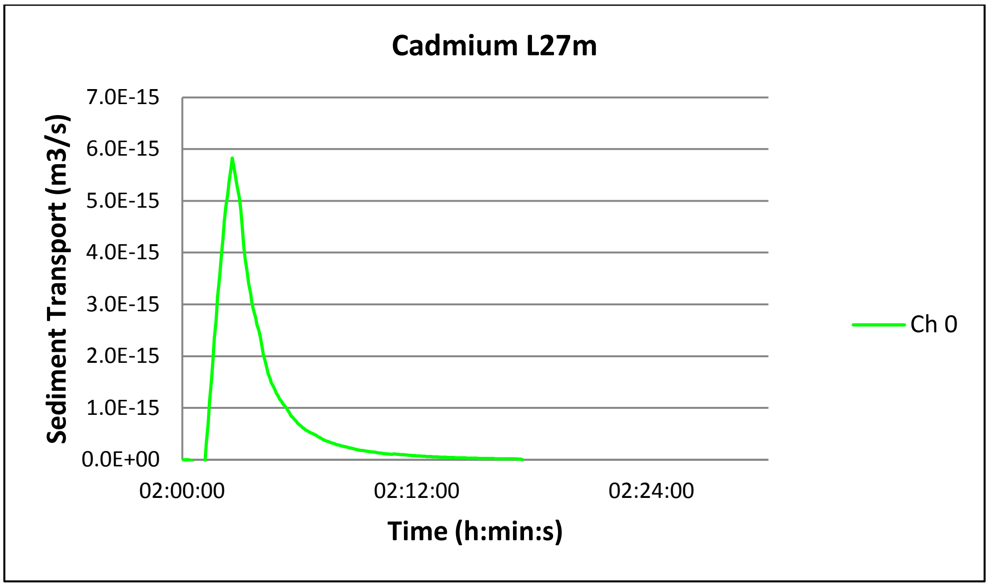
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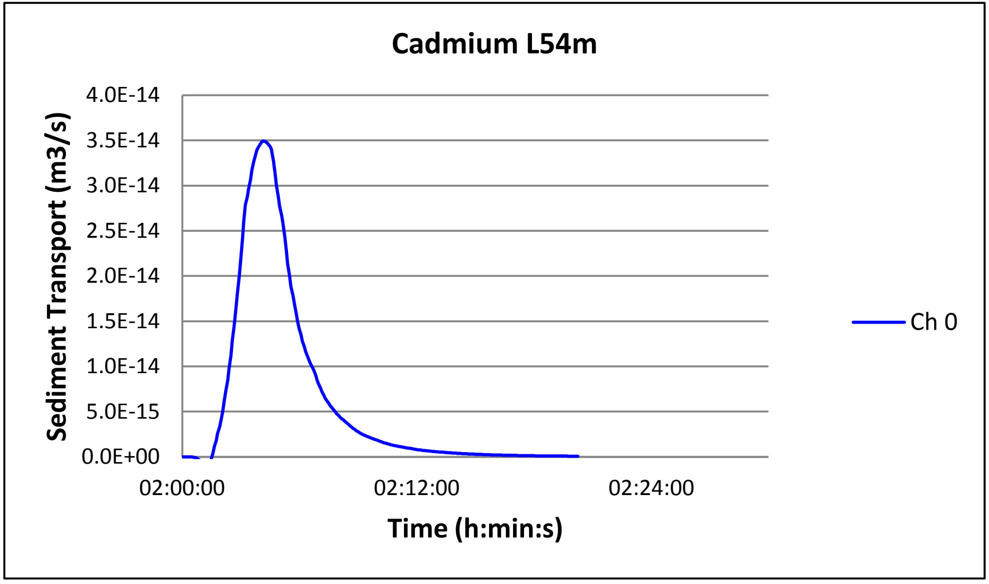
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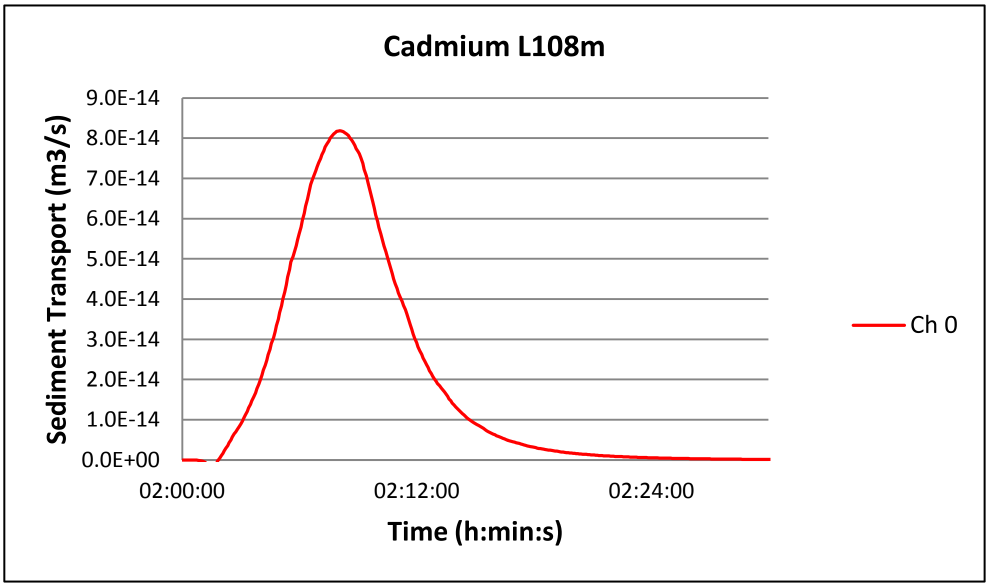
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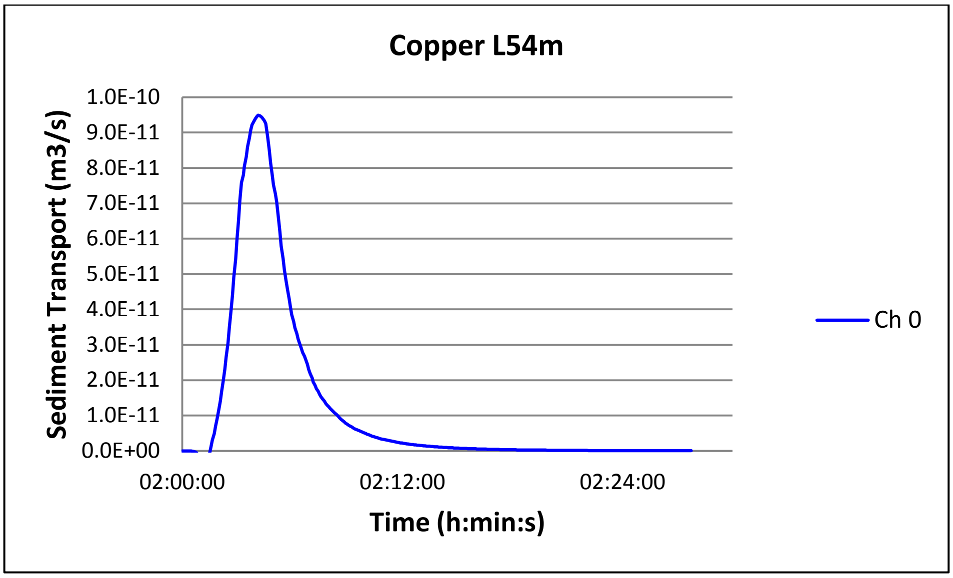
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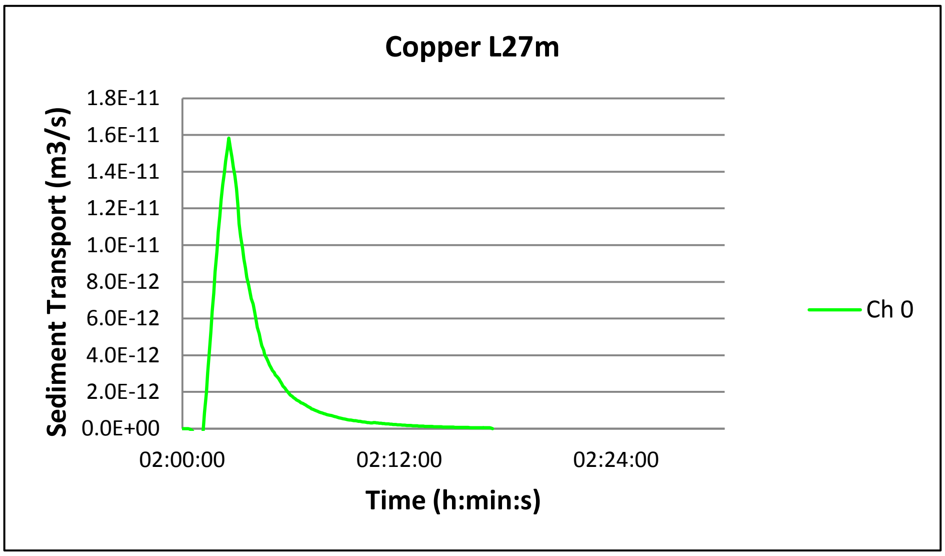
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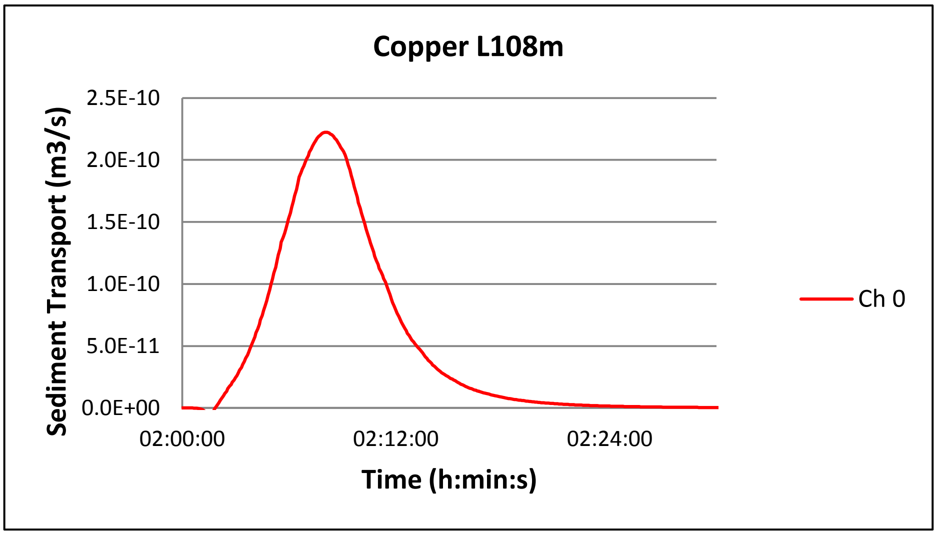
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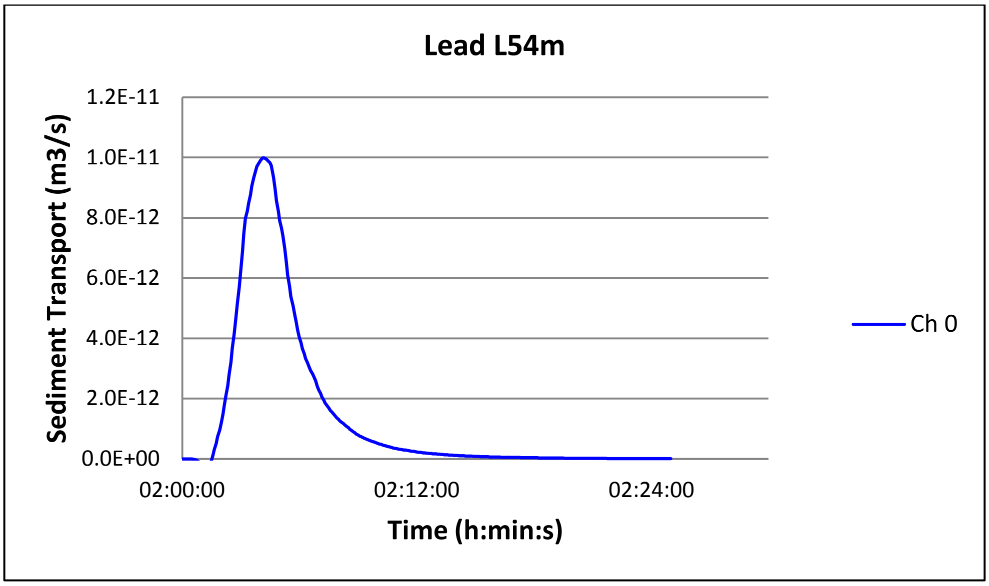
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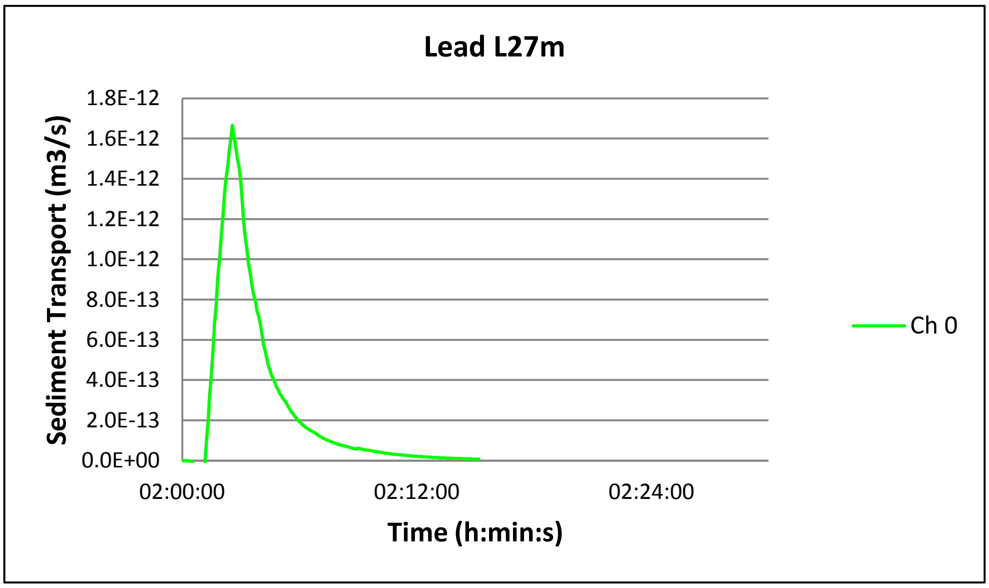
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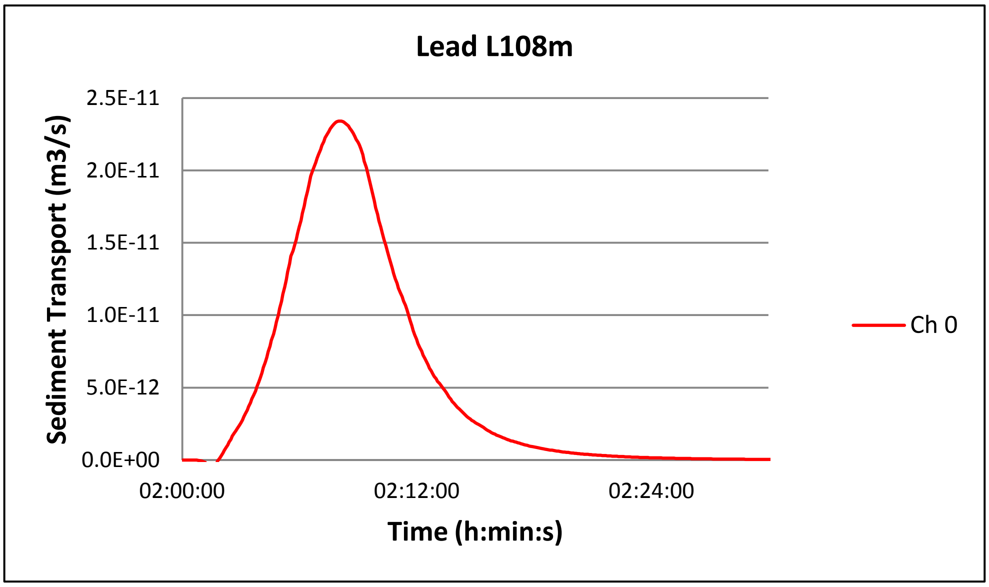
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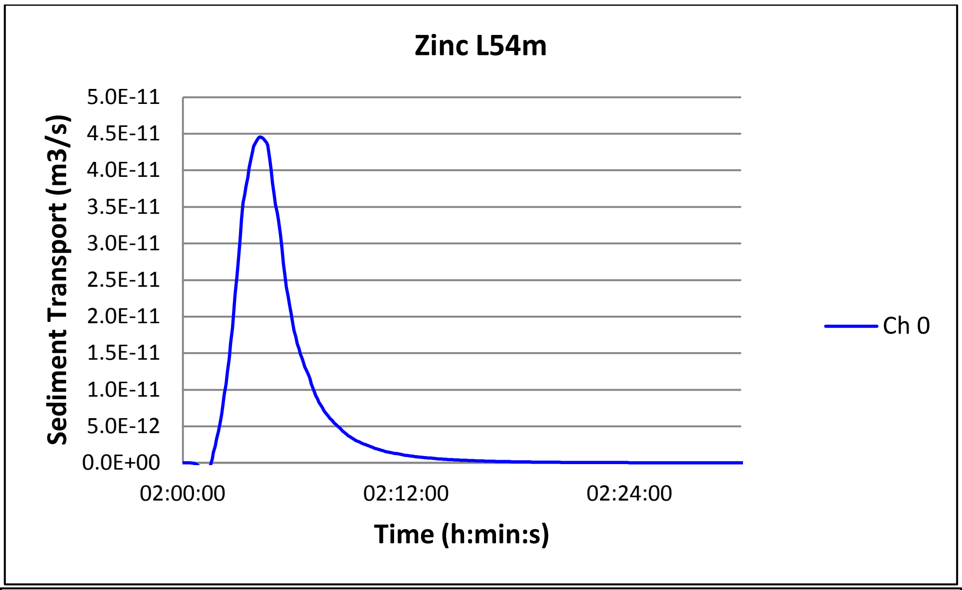
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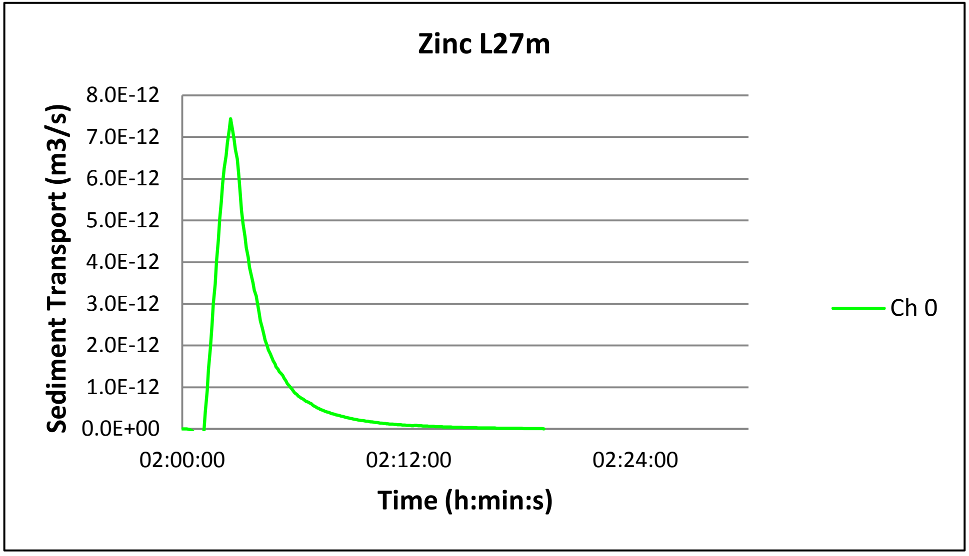
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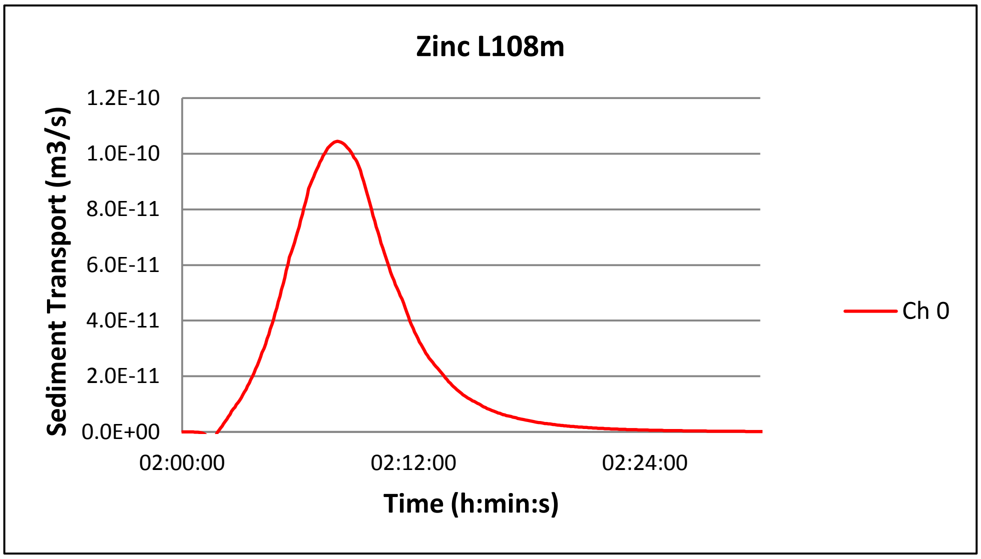
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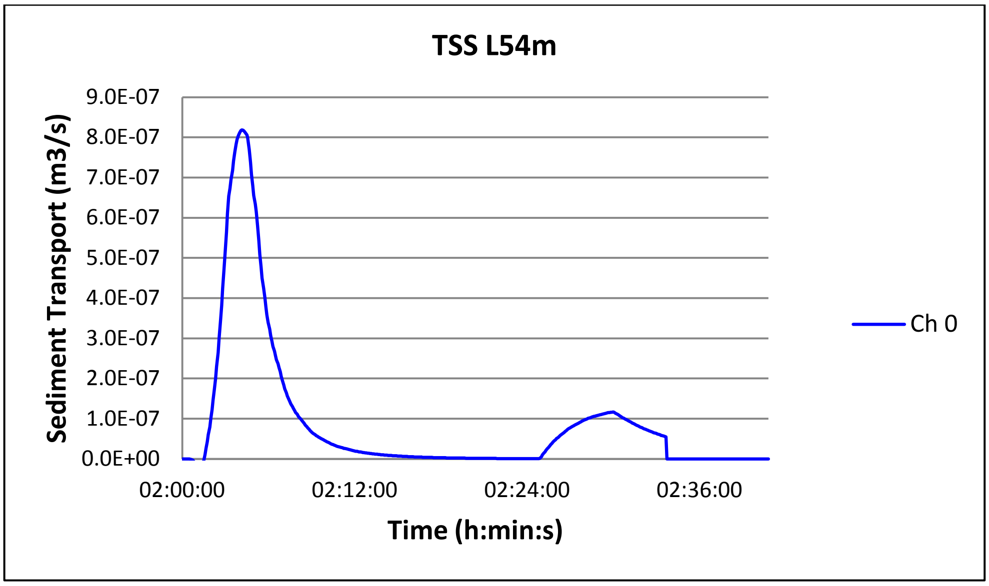
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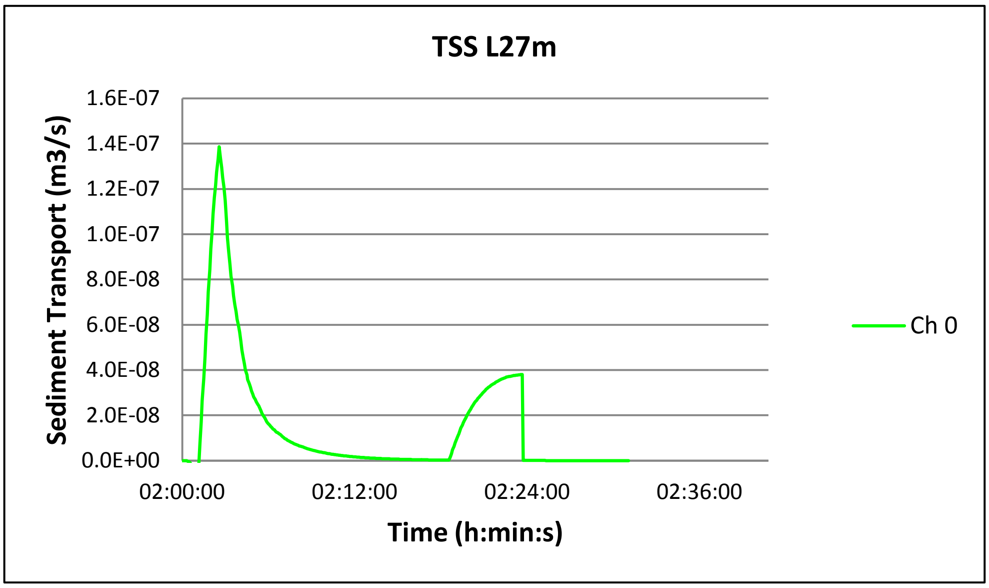
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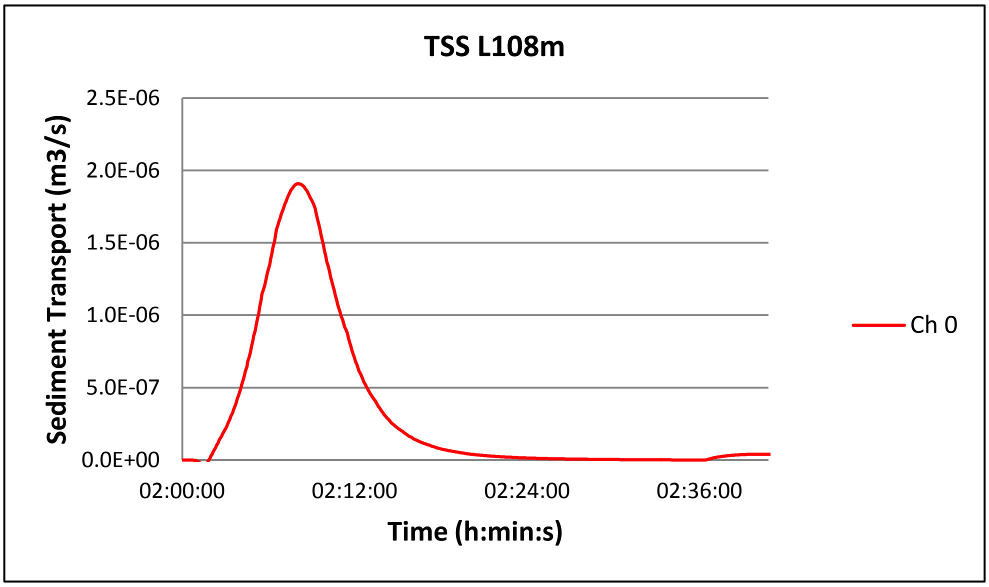
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E. Plate settler design example

Pond design example

A water quality design for at least 75% TSS and 70% copper removal for a detention pond is required for an urban watershed area (size 25 ha). The peak outflow must match the pre-development peak outflow rate of 0.14 m³/s. The length of pipe laid to the outflow point is 50 m, no bends are envisioned, average slope is 1:150. Water samples were taken during storms at the site storm outlet, which will be routed to the pond. Settling velocities of the captured material was determined in a laboratory setup. Samples were taken during the investigation of settling velocities to determine the fraction of TSS that is particulate copper for particle groups with different settling speeds. A runoff hydrograph was calculated.

The design approach includes a two basin system. The first basin, a high rate settler, will act as a clarifier. The second basin will function as a flood control element. This design was chosen because it allows high control of the two major processes required, viz. sedimentation and flood control.

A. HIGH RATE SETTLER:

Requirements:

Maximum system outflow: 0.2 m3/s (peak flow)
Required mass removals: 75 % TSS
70 % Particulate Copper

Space to be provided between plates for cleaning access: 0.6 m

Input:

Settling test results:

Settling time, T (min) (Reference 1)	3	5	10	20	40	60
TSS concentration (mg/l) (Reference 1)	114	96	72	38	8	2
Particulate copper concentration (µg/l)	32	25	20	14	6	4

Total depth (z): 1.83 m

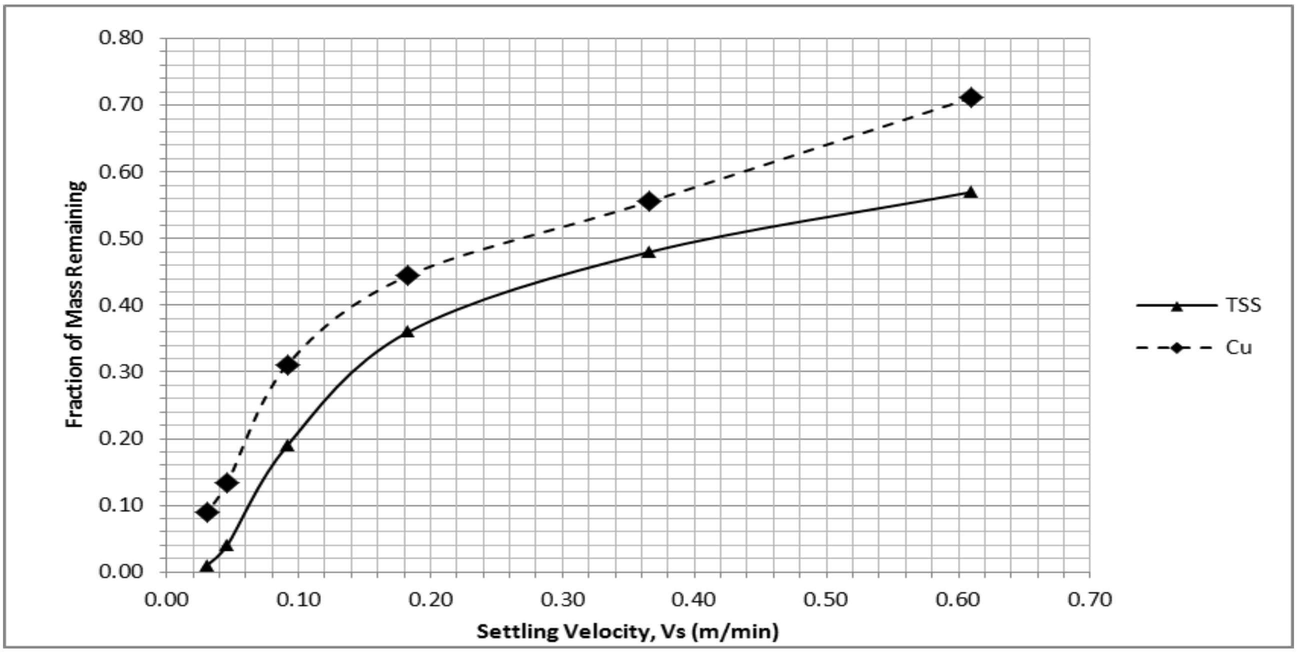
Sample original concentrations : 200 mg / lTSS, 45 µg/l Cu

Step 1. Estimate required settling velocities - graphical or analytical curve fitting procedures may be used

Graphical Procedure:

settling velocity Vs = depth (z) / time elapsed (min) (E.1)
Fraction mass remaining = measured concentration / sample original concentration (E.2)
Fraction mass removed = 1 - fraction mass remaining (E.3)

		Measured Concentrations (mg/l)		Fraction of Mass removed		Fraction of Mass remaining	
T (min)	Vs (m/min)	TSS	Cu part.	TSS (mg)	Cu part. (µg)	TSS (mg)	Cu part. (µg)
3	0.61	114	32	0.43	0.29	0.57	0.71
5	0.37	96	25	0.52	0.44	0.48	0.56
10	0.18	72	20	0.64	0.56	0.36	0.44
20	0.09	38	14	0.81	0.69	0.19	0.31
40	0.05	8	6	0.96	0.87	0.04	0.13
60	0.03	2	4	0.99	0.91	0.01	0.09



Estimated settling velocities:				
	75	% TSS removal =	25	% remaining requires Vs =	0.118
	70	% Cu removal =	30	% remaining requires Vs =	0.085

This is a conservative approach, iteration may be used to further refine for the amount of solids removed with slower velocities.

Step 2. High rate plate sedimentation tank design

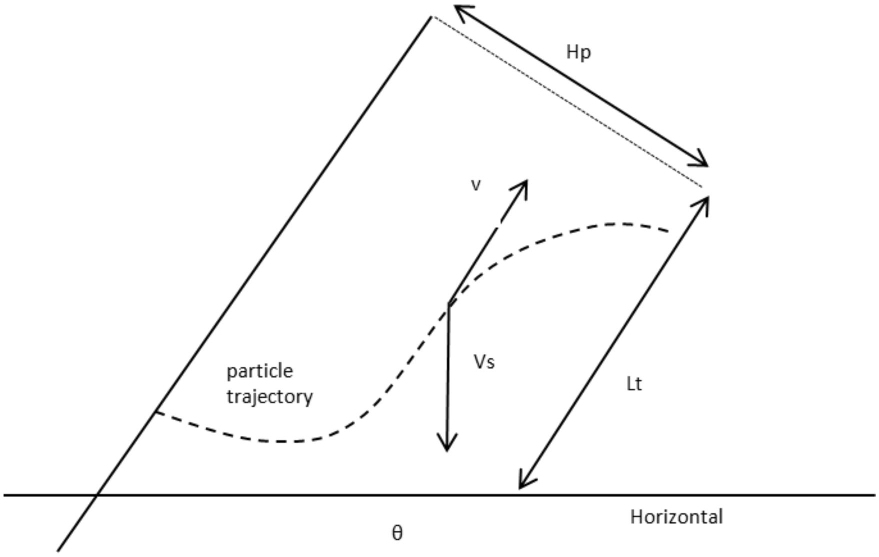


Figure adapted from (Binnie & Kimber 2011)(Chen & Liew 2003)

Governing Equations:

1. Flow approach: $V_s = Q / [(1 + (Lt/hp)\tan\theta) \times W \times (L - Lt\cos\theta) \times (Lt/hp) \times \sin\theta \times \cos\theta]$ (Chen & Liew 2003:9-60) (E.4)

Where Q = the flow through the settling zone, W = the width of the settling zone, L = the length of the settling zone

2. Velocity approach: $V_s = v\, Hp / (Hp\sin\theta + Lt\cos\theta)$ (Binnie & Kimber 2011:282) (E.5)

Input:

θ = 45 degrees = 0.785 rad
W = 10 m
L = 10 m
Vs required = 0.085 m/min = 0.00142 m/s

Calculations:

1. Hp = maintenance width * (sin θ) = 0.424 m (E.6)
Lt = **0.72 m** (Change value till Vs matches required Vs)
Vs from iteration: 0.00145 m/s (Chen & Liew 2003:9-60) 0.00063 (Binnie & Kimber 2011)
Nr of plates required = 38.2 say 39.0

<u>Check for laminar flow</u>

Re = ρ V L / η ρ = 1000 where L = Hp (E.7)
η = 0.00179

v = Q/A = 0.0012 m/s U = 0.00085 m/s 0.051 m/min < 0.085 m/min (E.8)

Re = 286

Checks:

Re < 800 (for laminar flow assumption)
U < chosen settling velocity

<u>B. FLOOD ROUTING</u>

Input:

<u>Inflow Hydrograph:</u>

time (h)	0	2	4	6	8	10	12	14	16	18
inflow, Qin (m3/s)	0.005	0.008	0.015	0.03	0.085	0.16	0.14	0.095	0.045	0.015

<u>Pipe details:</u>

Diameter (D), m: 0.25
Slope (S), m/m: 0.0067 or 1: 150
Length (L), m: 50
Material: smooth concrete
Mannings n: 0.012
Friction factor, f (λ) = 124.58 n^2/(D^1/3) *(Ref.3)* 0.0285 (E.9)
kL Entrance losses: 1.5

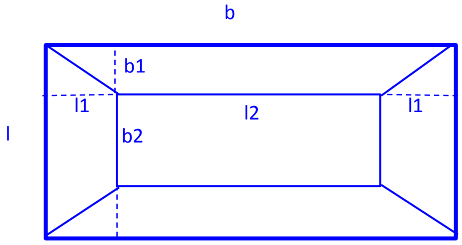
Step1. Determine the equation for structure outflow (O) as a function of head (hpond)

Governing equation:
H = hf + hL = fLQ^2/(12.1D^5) + kQ^2/(12.1D^4) (E.10)
H = hf + hL = hpond + 0.33 (E.11)
(pond depth) (Due to slope and pipe length to outflow)

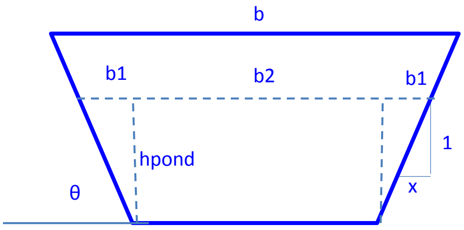
H = 120 Q^2 + 32 Q^2 = 152 Q^2
<u>Q =</u> 0.081 H^0.5 = <u>0.081</u> <u>(hpond +</u> <u>0.33</u> <u>)^0.5</u>

Step2. Determine the equation for structure volume as a function of head (hpond)

Pond schematic:



Plan



Section

Pond details:

Side slopes, m/m: 0.33 x = 3
θ = 0.3 radians 18.4 degrees

b2, m= 10.0
l2, m = 20.0

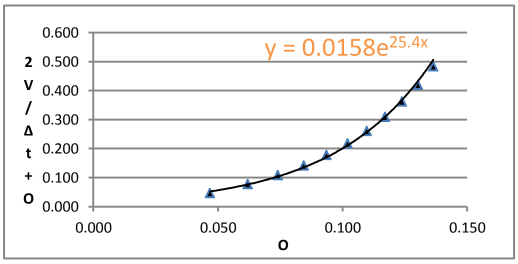
Equations:

Pond volume = (b2)(l2)hpond + (hpond^2)(x)b2 + (hpond^2)(x)l2 + 4/3(hpondx)^2(hpond) (E.12)

Step3. Relationships between stage, volume and outflow

hpond (m)	V (m3)	O(m3/s)	2V/Δt + O(m3/s)
0	0	0.047	0.047
0.25	56	0.062	0.077
0.5	124	0.074	0.108
0.75	206	0.084	0.141
1	302	0.094	0.177
1.25	414	0.102	0.217
1.5	543	0.110	0.261
1.75	690	0.117	0.309
2	856	0.124	0.362
2.25	1042	0.130	0.420
2.5	1250	0.136	0.484

where Δt = 7200 s

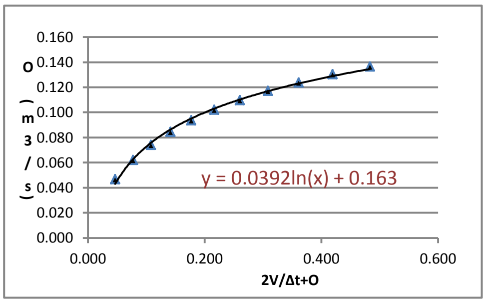


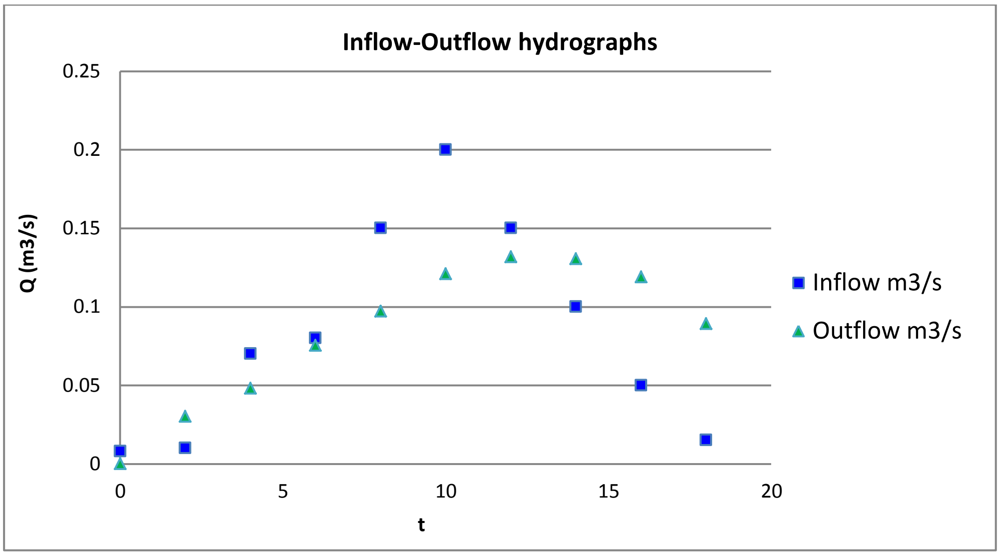
Step2. Tabular solution for reservoir routing

*Discharge preceding occurrence

Time (h)	Inflow m3/s	It + It+Δt m3/s	2V/Δt + O m3/s	(2V/Δt + O) - 2O m3/s	Outflow m3/s	Stage m	V m3
0	0.008		0.02	0.02	0.00	0.00	0.0
2	0.01	0.018	0.03	-0.03	0.030	0.00	0.0
4	0.07	0.08	0.05	-0.04	0.048	0.02	3.9
6	0.08	0.15	0.11	-0.04	0.075	0.53	134.0
8	0.15	0.23	0.19	-0.01	0.097	1.10	346.0
10	0.2	0.35	0.34	0.10	0.121	1.89	782.8
12	0.15	0.35	0.5	0.19	0.132	2.31	1088.2
14	0.1	0.25	0.4	0.18	0.131	2.26	1050.3
16	0.05	0.15	0.3	0.09	0.119	1.82	736.6

18	0.015	0.065	0.2	-0.03	0.089	0.88	254.3





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