Performance Evaluation of a Low Impact Development Retrofit for Urban Stormwater Treatment

Paul D. Le Bel

Thesis submitted to the faculty of the Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of

Master of Science
In
Environmental Engineering

Thomas J. Grizzard, Chair
Adil N. Godrej
David J. Sample

March 29, 2013
Manassas, VA

Keywords: Bioretention, Low Impact Development, Summation of Loads Method, Effluent Probability Method, Censored Datasets

Performance Evaluation of a Low Impact Development Retrofit for Urban Stormwater Treatment

Paul D. Le Bel

Abstract

The goal of Low Impact Development (LID) is to mimic the pre-development hydrologic regime of a catchment through infiltration, filtration, storage, evaporation, and detention of post-development runoff using small-scale hydrologic controls close to the source. A LID facility located in Northern Virginia was examined for pollutant removal and hydrologic performance. The treatment train included four in-line grass swales followed by a bioretention cell with a gravel base. The facility retained 85% of the rainfall. Influent and effluent pollutant loads were calculated using three common substitution methods for datasets censored by values below the analytical detection limit. The Summation of Loads (SOL) method was used to facilitate understanding of how data censoring affected performance results when substitution methods were used. The SOL analysis showed positive removal performance for most nutrient species, sediment, oxygen demanding substances, selected trace metals and total petroleum hydrocarbons. Negative performance was observed for oxidized nitrogen, total dissolved solids and oil & grease. LID facility influent and effluent loads were also compared using the Effluent Probability Method (EPM). The EPM analysis showed statistically significant ($p \leq 0.05$) pollutant load removal performance over the entire range of sampled events for total suspended solids, total phosphorus, total nitrogen, total Kjeldahl nitrogen, ammonia nitrogen, chemical oxygen demand, copper, zinc and alkalinity. EPM analysis did not show significant removals of oxidized nitrogen, total dissolved solids, orthophosphate phosphorus and hardness.

Acknowledgements
I would like to express my sincere gratitude to my advisor Dr. Thomas J. Grizzard for his guidance throughout this research and for his continued encouragement, advice and support while I have pursued my graduate studies. I would also like to thank my committee members Dr. Adil Godrej and Dr. David Sample who have also supported my professional and academic development throughout my time with Virginia Tech.

Additional thanks go to Dr. Randy Dymond and Kevin Young for their support, advice and expertise throughout this research.

Funding for this research was partially provided by the Fairfax County Department of Public Works and Environmental Services (DPWES). I would like to especially thank Russ Smith and Ron Tuttle of Fairfax County DPWES for their support and guidance throughout this research. Additional information and support was provided by Versar, Inc. and I would like to especially thank Tom Jones and Nancy Roth for the extensive use of their time and energy throughout this project. I would also like to thank Lynne Mowery of AMEC, Inc. for her help and support.

I would like to thank Justin Bartlett, Dr. Francisco Cubas, Dr. Saurav Kumar, Jia Liu and especially Chih-Yu (Yo) Wang for their enthusiastic support and constant willingness to help me during my graduate studies and research. You have all been instrumental in my development as a water resource engineer and I am truly appreciative for all the time, energy and assistance you have provided me.

Finally, I would like to thank my family and friends for their endless support and encouragement while I have pursued my degree.

Table of Contents

List of Figures

List of Tables

List of Abbreviations

Alk	Alkalinity
API	Antecedent Precipitation Index
ASCE	American Society of Civil Engineers
BACI	Before-After/Control-Impact Reference Watershed Approach
BDL	Below Detection Limit
BMP	Best Management Practice
Ca^{2+}	Calcium Ion
$CaCO_3$	Calcium Carbonate
Cd	Cadmium
CN	Curve Number
CO_3^{2-}	Carbonate Ion
COD	Chemical Oxygen Demand
CRRC	Cub Run Recreation Center
Cu	Copper
CUGKY	Total Inlet EMC or Load from GKY Sampler
CUIN	Total Inlet EMC or Load at the Cub Run LID Facility
CULYS	Total Inlet EMC or Load from Lysimeter Sampler
CUOUT	Total Inlet EMC or Load from Automated Sampler at the LID Facility Outfall
CUOUT-MZF	Modified CUOUT-ZF Dataset
CUOUT-ZF	CUOUT Loads Including Events with No Discharge at the Outfall and therefore No Effluent Loads
CUPVC	Total Inlet EMC or Load from PVC Sampler
DL	Detection Limit
DPWES	Fairfax County Department of Public Works and Environmental Services
DSAR	Detailed Statistical Analysis Report
EDF	Empirical Distribution Function
EMC	Event Mean Concentration
EPM	Effluent Probability Method
ER Method	Efficiency Ratio Method
f_{v24}	The Fraction of Input Water Measured Leaving Each System After 24 Hours
Hard	Hardness
HCO_3^-	Bicarbonate Ion
HFR	Hydrologic Footprint Residence
HSG	Hydrologic Soil Group
I_a	Initial Abstraction in SCS Runoff Curve Number Method
IHA	Indicators of Hydrologic Alteration
IHA-SMH Approaches	Indicators of Hydrologic Alteration – Sum of Mishits Approaches
KM Method	Kaplan-Meier Method
K-S test	*Kolmogorov-Smirnov* (K-S) Test
LID	Low Impact Development
Mg^{2+}	Magnesium Ion
MLE Method	Maximum Likelihood Estimation Method
N_2	Gaseous Nitrogen
NAI	No Adverse Impact
NH_3	Ammonia Nitrogen

NH_4^+-N	Ammonium Nitrogen
NO_2^--N	Nitrite Nitrogen
NO_3^--N	Nitrate Nitrogen
NOAA	National Oceanic and Atmospheric Administration
O&G	Oil and Grease
OP	Orthophosphate Phosphorus
Org-N	Organic Nitrogen
OxN	Oxidized Nitrogen
P	Rainfall in SCS Runoff Curve Number Method
Partial Exfiltration Reactor	PER
Pb	Lead
PPCC	Probability Plot Correlation Coefficient Test
Q	Runoff in SCS Runoff Curve Number Method
QA/QC Procedures	Quality Assurance and Quality Control Procedures
R_{delay}	Peak Delay Ratio
REDOX Environment	Oxidation-Reduction Environment
Robust ROS	Robust Regression on Ordered Statistics
ROS	Regression on Ordered Statistics
R_{peak}	Maximum Outflow to Inflow Peak Ratio
RVA	Range of Variability Approach
S	Potential Maximum Retention After Runoff Begins in SCS Runoff Curve Number Method
SCS	Soil Conservation Service
SOL Method	Summation of Loads Method
TDS	Total Dissolved Solids
TKN	Total Kjeldahl Nitrogen
TN	Total Nitrogen
TP	Total Phosphorus
TPH	Total Petroleum Hydrocarbons
TR-55	Technical Release 55
TSS	Total Suspended Solids
UKWIR	United Kingdom Water Industry Research
UNHSC	University of New Hampshire Stormwater Center
UOP	Unit Operation or Process
US EPA	U.S. Environmental Protection Agency
USDA	United States Department of Agriculture
USGS	United States Geological Survey
UWRRC	Urban Water Resources Research Council
VCF	Volumetric Clarifying Filter
WERF	Water Environment Research Foundation
WLC	Whole Life Cost
Zn	Zinc
α	Statistical Confidence Level
χ^2	*Chi-Square* Test

1 INTRODUCTION

1.1 Urbanization

Undeveloped lands typically generate relatively little stormwater runoff because most of the precipitation during storm events infiltrates into the soil where it will be available for evapotranspiration, groundwater recharge, shallow interflow, or any number of other natural processes in the hydrologic cycle. As a watershed is developed, or urbanized, land areas which were formerly forested or pastoral in nature are increasingly covered by impervious surfaces such as roads, parking lots, roofs, driveways and sidewalks. This increase in imperviousness fundamentally changes the hydrologic response of the urbanized site when compared to its pre-development condition. For a given rainfall event, the urbanized site will exhibit increased frequency of runoff, runoff volume, peak flows, temperatures and pollutant loads compared to its pre-development condition. The increased magnitude and frequency of stormwater runoff and consequent pollutant loads generated by urbanized watersheds can cause severe environmental degradation including channel erosion, increased flooding, decreased water quality and degraded or destroyed aquatic habitats in water bodies such as streams, rivers, lakes, estuaries and wetlands. Stormwater runoff due to urbanization is one of the leading sources of pollution for all water body types in the United States (Roesner et al., 2001; Barber et al., 2003; Hsieh and Davis, 2003; McCuen, 2003; Sansalone and Teng, 2004; Meyer, 2005; Davis, 2007; EPA, 2007; Guo, 2008; Guo and Cheng, 2008; Li and Davis, 2008; Sansalone et al., 2008; Li and Davis, 2009; Palhegyi, 2010b; Palhegyi, 2010a; Reichold et al., 2010; Carpenter and Kaluvakolanu, 2011; DeBusk et al., 2011; Giacomoni et al., 2012; McGarity, 2012). Stormwater controls and devices are often used to address and mitigate the effects of urbanization on the downstream aquatic environment.

1.2 CRRC Low Impact Development Facility Monitoring Project

The Cub Run Recreation Center (CRRC) Low Impact Development (LID) study site is an urban stormwater management retrofit located within the Cub Run watershed in the community of Chantilly, in western Fairfax County, Virginia. The facility is adjacent to a parking lot serving the CRRC and Westfield High School, and serves a total drainage area of 1.6 acres including 0.63 acres of asphalt parking lot, 0.86 acres of grassy-wooded area, and 0.11 acres of the LID facility itself (Versar, 2011; VT-OWML, 2012). The treatment train is gravity flow, and includes four in-line grass swales followed by a bioretention cell with a gravel base. Stormwater runoff enters the grass swales from the parking lot to the north and the grassy and wooded area to the south, as shown in Figure 1-1. The grass swales were designed to allow water ponding deeper than six inches in any swale to overflow into the next cell. The bioretention cell was designed to allow water ponding deeper than six inches to discharge by means of an overflow in to an adjacent 15 inch PVC pipe from which samples were taken. The pipe discharged into a curb inlet that received additional parking lot drainage. Outflows from the curb inlet were routed to a conventional detention pond (Versar, 2011).

Versar, Inc. working with AMEC, PLC under contract with the Fairfax County Department of Public Works and Environmental Services (DPWES) monitored the CRRC LID facility during two periods from September 2008 – June 2010 and March 2011 – May 2012. Installation of the monitoring equipment took place during August 2008. Continuous flow monitoring (at the LID facility outfall only), meteorological data, soil moisture and storm monitoring was performed by ATR Associates, Inc. under subcontract to Versar, Inc. from September 2008 to July 2009 and solely by Versar, Inc. from July 2009 to June 2010 and again from March 2011 to May 2012 (Versar, 2011). In July, 2011, Virginia Tech entered into an agreement with DPWES to conduct a performance analysis of the LID stormwater retrofit. Faculty, staff, and students of the Departments of Biological Systems Engineering and Civil and Environmental Engineering were involved in the project, and contributed to the performance analysis.

The collected datasets, provided by Versar (2011), consisted of continuous monitoring for meteorology and hydrology, along with discrete sampling, and subsequent analysis for selected water quality parameters during targeted storm events. The LID facility was monitored for water quality during 25 storm events over the course of the two monitoring periods. Passive and automated devices were used to collect samples that facilitated comparisons of water quality and flows at inflow and outflow locations, respectively. The water quality monitoring included post-storm analyses for the event mean concentrations of nutrients such as phosphorus and nitrogen, trace metals such as copper and zinc, and other important water quality parameters such as total suspended solids and total dissolved solids. The water quality data were then used along with the meteorological and hydrologic data to calculate inflow and outflow loadings for constituents of interest. Flow estimates were made using different techniques at the inflow and outflow points.

Water quality benefits from LID practices and other infiltration-based stormwater BMPs are a function of physical, chemical, and biological processes as well as reductions in stormwater runoff volumes (Davis et al., 2006; Davis, 2007; Geosyntec and WWE, 2009). For this reason, metrics based on changes in the total pollutant load over the monitoring period were chosen to assess the pollutant removal performance of the facility (Davis, 2007; Geosyntec and WWE, 2009). The Summation of Loads method (Minton, 2005; Hunt et al., 2006; Cates et al., 2009; Chi-Feng et al., 2009; Geosyntec and WWE, 2009; Williams et al., 2009; McNett et al., 2011) and the Effluent Probability Method (Strecker et al., 2001; Geosyntec and WWE, 2009; Williams et al., 2009) were chosen for constituent load reduction analyses.

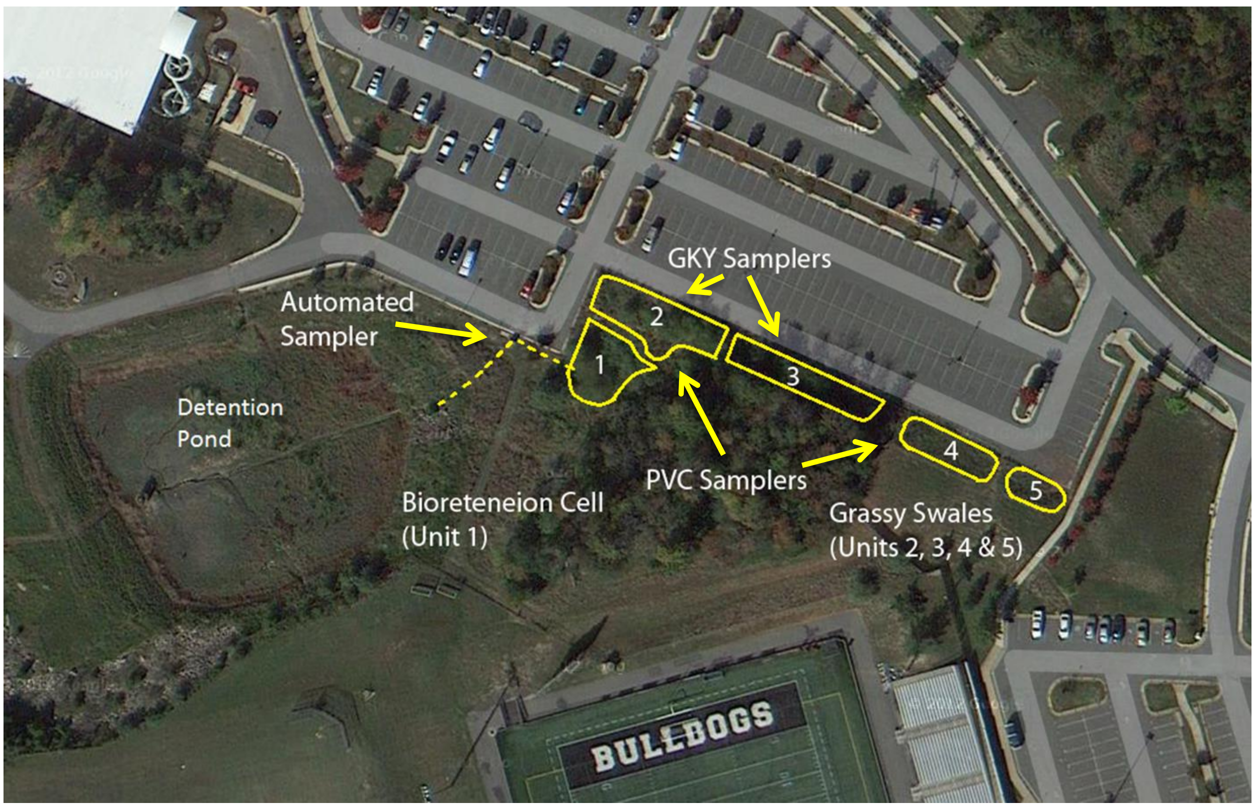


Figure 1-1. Aerial view of the Cub Run Recreation Center LID facility with approximate outlines for the bioretention cell, grass swales and sampler locations (VT-OWML, 2012; Google Maps, 2013) Used under fair use, 2013.

1.3 References

Barber, M. E., King, S. G., Yonge, D. R. and Hathhorn, W. E. (2003). “Ecology Ditch: A Best Management Practice for Storm Water Runoff Mitigation.” Journal of Hydrologic Engineering **8**(3): 111-122.

Carpenter, D. D. and Kaluvakolanu, P. (2011). “Effect of Roof Surface Type on Storm-Water Runoff from Full-Scale Roofs in a Temperate Climate.” Journal of Irrigation and Drainage Engineering **137**(3): 161-169.

Cates, E. L., Westphal, M. J., Cox, J. H., Calabria, J. and Patch, S. C. (2009). “Field Evaluation of a Proprietary Storm-Water Treatment System: Removal Efficiency and Relationships to Peak Flow, Season, and Dry Time.” Journal of Environmental Engineering **135**(7): 511-517.

Chi-Feng, C., Jen-Yang, L., Chih-Hong, H., Way-Ling, C. and Nai-Ling, C. (2009). “Performance evaluation of a full-scale natural treatment system for nonpoint source and point source pollution removal.” Environmental Monitoring & Assessment **157**(1-4): 391-406.

Davis, A. P. (2007). “Field Performance of Bioretention: Water Quality.” Environmental Engineering Science **24**(8): 1048-1064.

Davis, A. P., Shokouhian, M., Sharma, H. and Minami, C. (2006). “Water Quality Improvement through Bioretention Media: Nitrogen and Phosphorus Removal.” Water Environment Research **78**(3): 284-293.

DeBusk, K. M., Hunt, W. F. and Line, D. E. (2011). “Bioretention Outflow: Does It Mimic Nonurban Watershed Shallow Interflow?” Journal of Hydrologic Engineering **16**(3): 274-279.

EPA, U. S. (2007). “Reducing Stormwater Costs through Low Impact Development (LID) Strategies and Practices.” Nonpoint Source Control Branch.

Geosyntec and WWE, Geosyntec Consultants, Wright Water Engineers, Inc. (2009) “Urban Stormwater BMP Performance Monitoring” U.S. Environmental Protection Agency Prepared with support from the U.S. EPA, Water Environmental Research Foundation, Federal Highway Administration, and the Environmental and Water Resources Institute of the American Society of Civil Engineers, http://www.bmpdatabase.org

Giacomoni, M. H., Zechman, E. M. and Brumbelow, K. (2012). “Hydrologic Footprint Residence: Environmentally Friendly Criteria for Best Management Practices.” Journal of Hydrologic Engineering **17**(1): 99-108.

Google Maps (2013). “Cub Run Rec Center Satellite Image Google Maps, Used under fair use, 2013.”. Retrieved 2/15/2013, from http://goo.gl/maps/LzirW, Fair use determination attached.

Guo, J. C. Y. (2008). “Volume-Based Imperviousness for Storm Water Designs.” Journal of Irrigation and Drainage Engineering **134**(2): 193-196.

Guo, J. C. Y. and Cheng, J. Y. C. (2008). “Retrofit Storm Water Retention Volume for Low Impact Development.” Journal of Irrigation and Drainage Engineering **134**(6): 872-876.

Hsieh, C.-h. and Davis, A. P. (2003). Evaluation of Bioretention for Treatment of Urban Storm Water Runoff, ASCE.

Hunt, W. F., Jarrett, A. R., Smith, J. T. and Sharkey, L. J. (2006). "Evaluating Bioretention Hydrology and Nutrient Removal at Three Field Sites in North Carolina." Journal of Irrigation and Drainage Engineering **132**(6): 600-608.

Li, H. and Davis, A. (2009). "Water Quality Improvement through Reductions of Pollutant Loads Using Bioretention." Journal of Environmental Engineering **135**(8): 567-576.

Li, H. and Davis, A. P. (2008). "Heavy Metal Capture and Accumulation in Bioretention Media." Environmental Science & Technology **42**(14): 5247-5253.

McCuen, R. H. (2003). "Smart Growth: Hydrologic Perspective." Journal of Professional Issues in Engineering Education and Practice **129**(3): 151-154.

McGarity, A. E. (2012). "Storm-Water Investment Strategy Evaluation Model for Impaired Urban Watersheds." Journal of Water Resources Planning and Management **138**(2): 111-124.

McNett, J. K., Hunt, W. F. and Davis, A. P. (2011). "Influent Pollutant Concentrations as Predictors of Effluent Pollutant Concentrations for Mid-Atlantic Bioretention." Journal of Environmental Engineering **137**(9): 790-799.

Meyer, S. C. (2005). "Analysis of base flow trends in urban streams, northeastern Illinois, USA." Hydrogeology journal **13**(5-6): 871-885.

Minton, G. (2005). Stormwater Treatment - Biological, Chemical, and Engineering Principles, Resource Planning Associates.

Palhegyi, G. E. (2010a). "Designing Storm-Water Controls to Promote Sustainable Ecosystems: Science and Application." Journal of Hydrologic Engineering **15**(6): 504-511.

Palhegyi, G. E. (2010b). "Modeling and Sizing Bioretention Using Flow Duration Control." Journal of Hydrologic Engineering **15**(6): 417-425.

Reichold, L., Zechman, E. M., Brill, E. D. and Holmes, H. (2010). "Simulation-Optimization Framework to Support Sustainable Watershed Development by Mimicking the Predevelopment Flow Regime." Journal of Water Resources Planning and Management **136**(3): 366-375.

Roesner, L. A., Bledsoe, B. P. and Brashear, R. W. (2001). "Are Best-Management-Practice Criteria Really Environmentally Friendly?" Journal of Water Resources Planning and Management **127**(3): 150-154.

Sansalone, J., Kuang, X. and Ranieri, V. (2008). "Permeable Pavement as a Hydraulic and Filtration Interface for Urban Drainage." Journal of Irrigation and Drainage Engineering **134**(5): 666-674.

Sansalone, J. and Teng, Z. (2004). "In Situ Partial Exfiltration of Rainfall Runoff. I: Quality and Quantity Attenuation." Journal of Environmental Engineering **130**(9): 990-1007.

Strecker, E., Quigley, M., Urbonas, B., Jones, J. and Clary, J. (2001). "Determining Urban Storm Water BMP Effectiveness." Journal of Water Resources Planning and Management **127**(3): 144-149.

Versar, I. (2011). "Performance Monitoring [Volume Reduction and Water Quality] At Cub Run Recenter Stormwater Improvements, Fairfax County, Virginia."

VT-OWML, Virginia Tech Occoquan Watershed Monitoring Laboratory (2012). Fairfax County-Performance Assessment of LID Practices Data Repository. Scholar, Virginia Tech, Versar, Inc.; Fairfax County Government; Virginia Tech Faculty and Students.

Williams, G., Roseen, R. M., Lenhart, J. H. and Kayhanian, M. (2009). Potential Data Analysis Methodology to Evaluate the Performance of Manufactured BMPs. World Environmental and Water Resources Congress 2009**:** 1-10.

2 LITERATURE REVIEW

2.1 Urbanization

The increased magnitude and frequency of stormwater runoff and consequent pollutant loads generated by urbanized watersheds can cause severe environmental degradation including channel erosion, increased flooding, decreased water quality and degraded or destroyed aquatic habitats in water bodies such as streams, rivers, lakes, estuaries and wetlands. Stormwater runoff due to urbanization is one of the leading sources of pollution for all water body types in the United States (Roesner et al., 2001; Barber et al., 2003; Davis, 2007; EPA, 2007; Giacomoni et al., 2012). Stormwater controls and devices are often used to address and mitigate the effects of urbanization on the downstream aquatic environment.

2.2 Best Management Practices

In the context of urban stormwater management, best management practices (BMPs) include a range of structural, non-structural and site design practices intended to remove, reduce, retard or prevent stormwater runoff and its associated pollutants from reaching receiving waters in an urbanized or otherwise developed environment. Structural BMPs rely on a wide range of hydrological, physical, biological and chemical processes. Non-Structural BMPs typically involve community education and outreach programs. Overall site designs such as Low Impact Development (LID), Cluster Development, No Adverse Impact (NAI) and smart growth strategies combine a variety of structural and non-structural BMPs in order to reduce the environmental impacts associated with urbanization and development (Hsieh and Davis, 2003; McCuen, 2003; Quigley et al., 2005; Traver et al., 2008; Geosyntec and WWE, 2009; Williams and Wise, 2009; Clary et al., 2011).

2.2.1 Low Impact Development

Low Impact Development (LID) is a comprehensive land planning and engineering design approach to managing stormwater runoff. The goal of LID is to mimic the pre-development hydrologic regime of a watershed through infiltration, filtration, storage, evaporation and detention of post-development runoff using small-scale hydrologic controls close to the source. Urban developments which employ LID practices are expected to produce outflow hydrographs similar to those that would be found at the site during its predevelopment condition. LID practices may also be retrofitted into existing, traditional stormwater conveyance systems. LID

BMPs include practices such as bioretention cells and rain gardens, bioswales, infiltration basins and trenches, stormwater wetlands, vegetated rooftops or green roofs, rain barrels or cisterns, permeable pavers, porous pavement, tree planters and site design practices such as narrow streets, reduced imperviousness, minimal curb and gutter use and preservation of natural areas (Hsieh and Davis, 2003; Davis, 2007; EPA, 2007; Beyerlein, 2008; Davis, 2008; Guo and Cheng, 2008; Traver et al., 2008; Geosyntec and WWE, 2009; Carpenter and Hallam, 2010; Guo, 2010; O'Neill and Davis, 2010; Palhegyi, 2010b; Palhegyi, 2010a; Brown and Hunt III, 2011b; Clary et al., 2011; DeBusk et al., 2011). In contrast to the small-scale approach of LID, conventional stormwater management approaches typically concentrate runoff and convey it through impervious curb and gutter systems to an end-of-pipe facility at the bottom of the drainage area designed to store and slowly release flows (EPA, 2007; Geosyntec and WWE, 2009; Guo, 2010; LeFevre et al., 2010).

If LID practices are to be adopted on a given site, consideration of the overall design philosophy and practice is paramount during all phases of development. Proper site planning should include measures to preserve natural infiltration characteristics of the landscape by minimizing disturbance and avoiding soil compaction wherever possible throughout the project phasing and construction. Impervious areas should be minimized, including rooftop and building footprints, and widths of travelway coverage including streets, driveways, sidewalks and parking lots aisles. Design and construction goals should include maintaining natural drainage patterns and designing drainage paths that will increase the time of concentration and promote infiltration into soils whenever runoff is generated. Source controls should include minimizing and isolating pollutants from contact with rainfall or runoff by segregating, covering and containing pollutant generating materials, wastes and activities (Davis, 2008; Geosyntec and WWE, 2009).

BMPs may be categorized in numerous ways, including, but not limited to, the hydrological, physical, chemical and biological processes they employ. While individual sites will generally have a unique combination of BMPs and design approaches, there are some features and processes which are consistently incorporated into many designs. Geosyntec and WWE (2009) breaks these typical features into four categories: infiltration practices which mimic natural drainage, green roofs and facades, rainwater harvesting infrastructure and permeable pavements, pavers and overlays.

Infiltration Practices

Infiltration practices are used to route surface runoff into subsurface soils or media where it is temporarily held in pore spaces before evaporating, transpiring from vegetation, exfiltrating into surrounding subsoils and groundwater, discharging as interflow or exiting through underdrains. Infiltration BMPs include bioretention cells or rain gardens, bioswales and vegetated filter strips, infiltration basins and trenches, tree planters, among others. In addition to infiltration, some practices include specialized media and/or internal water storage zones which promote the removal of some important dissolved pollutants such as orthophosphate phosphorus or nitrate and nitrite nitrogen. Pollutant removal is achieved through processes such as filtration, sorption and other biogeochemical interactions (Hsieh and Davis, 2003; Kim et al., 2003; Sansalone and Teng, 2004; Davis et al., 2006; Hunt et al., 2006; EPA, 2007; Davis, 2008; Li and Davis, 2008; Davis et al., 2009; Geosyntec and WWE, 2009; He and Davis, 2009; Clark and Pitt, 2010; Lucas, 2010; Sansalone et al., 2010; Brown and Hunt III, 2011b). Evidence suggests that infiltration BMP performance for dissolved constituents (e.g. nitrate/nitrite, orthophosphate and dissolved metals) capture may be highly dependent on the hydraulic residence time within the practice, along with media depth and other characteristics including media organic matter content, cation exchange capacity, pH, and initial chemical composition (Hsieh and Davis, 2003; Hunt et al., 2006; Davis et al., 2009; Li and Davis, 2009; Clark and Pitt, 2010; O'Neill and Davis, 2010; Pitt et al., 2010; Sansalone et al., 2010; Brown and Hunt III, 2011b). A variety of vegetation types, including grasses, shrubs and small trees may be used to promote evapotranspiration, maintain soil porosity and encourage biological uptake and or degradation of some pollutants. It should be noted that nutrient and micronutrient uptake by vegetation will reduce pollutant loads only if new growth is regularly harvested (usually annually) to remove excess biomass before decay and decomposition can result in re-release to the watershed (Kim et al., 2003; Davis et al., 2006; EPA, 2007; Davis, 2008; Li and Davis, 2008; Davis et al., 2009; Geosyntec and WWE, 2009; He and Davis, 2009; Lucas, 2010). Pollutant build-up and removal may be of concern for infiltration BMPs, however particulate-bound pollutants are typically captured in the upper soil horizon and may be removed by replacing the topsoil (Davis et al., 2006; EPA, 2007; Li and Davis, 2008; Davis et al., 2009).

Green Roofs

Green roofs and green facades are typically vegetated bioretention cells/rain gardens contained within an impervious membrane with some type of underdrain located on a rooftop, parking garage or similar structure. The hydrological, physical, chemical and biological processes employed and consequent benefits realized by green roofs and facades are the same as those in other infiltration practices with underdrains. The green roof media and vegetation have the potential to store, evaporate, and evapotranspire precipitation and reduce peak flows when conditions produce flows in the underdrain. Green roofs and facades have additional non-water quality related benefits such as reducing the urban heat island effect and improving the aesthetic environment (EPA, 2007; Beyerlein, 2008; Davis, 2008; Geosyntec and WWE, 2009; She and Pang, 2010; Voyde et al., 2010; Carpenter and Kaluvakolanu, 2011). Green roofs may be categorized by their media depth/weight and assemblage of plant materials. Extensive green roofs have shallower, lower weight media layers and are typically populated with low profile drought-tolerant plants such as sedums. Intensive green roofs have thicker, and consequently heavier, media layers and are capable of supporting larger plantings such as small trees. Intensive green roofs typically require additional structural support for the roof and are generally more expensive compared to extensive green roofs (She and Pang, 2010; Carpenter and Kaluvakolanu, 2011; Houdeshel et al., 2011).

Rainwater Harvesting

Cisterns, rain barrels and other forms of rainwater harvesting may be used to collect and store runoff from impervious surfaces, typically traditional rooftops, to be used at a later time for non-potable uses such as irrigation. Rainwater harvesting can effectively alter runoff timing, reduce peak flows and decrease runoff volumes, however it is important to note that in some parts of the country water rights issues constrain or limit this practice (Geosyntec and WWE, 2009).

Permeable Pavements

Permeable or porous pavements, pavers and overlays are designed to function as load bearing structures that allow stormwater to infiltrate though the hard surface into the underlying soils or media, thereby reducing runoff volumes, peaks flows and improving water quality through filtration processes (Beyerlein, 2008; Sansalone et al., 2008; Geosyntec and WWE, 2009; Roseen et al., 2012; WEF and ASCE, 2012).

Because of storage and infiltration limitations, LID designs and BMPs are more effective at reproducing pre-development hydrologic conditions for small storm events than for large storm events (Barber et al., 2003; EPA, 2007; Davis, 2008; Cates et al., 2009; Davis et al., 2009; Carpenter and Kaluvakolanu, 2011; Giacomoni et al., 2012). For large and extreme rainfall events, LID conveyance practices may be employed to control and mitigate flood conditions while conveying bypassed water to a more conventional end-of-pipe stormwater management practice such as a detention basin at the outlet of the watershed (EPA, 2007; Guo, 2010; Giacomoni et al., 2012). The antecedent moisture conditions also have a pronounced effect on the performance of infiltration-based BMPs for small storm events (Barber et al., 2003; Davis, 2008; Davis et al., 2009; Carpenter and Kaluvakolanu, 2011).

Quigley et al. (2005) categorized urban stormwater management processes by their fundamental process category, unit operation or process (UOP), and the treatment system components (i.e. BMPs) which may be employed to achieve desired stormwater volume and pollutant reduction performance. It should be noted that many BMPs exhibit multiple UOPs and can therefore be included in multiple categories (Minton, 2005; Quigley et al., 2005; Davis et al., 2009; Sansalone et al., 2010). This categorization was adapted from Quigley et al. (2005) and expanded from other literature sources and is shown in Table 2-1.

Table 2-1. BMPs categorized by Fundamental Process Category and Unit Operation and Process.

Fundamental Process Category	**Unit Operation or Process**	**Examples of BMPs capable of providing UOP**
Hydrological Operations	Flow Attenuation	Extended detention basins Retention/detention ponds Wetlands Tanks/Vaults Rain Barrels/Cisterns
	Volume Reduction	Infiltration/exfiltration trenches and basins Porous pavement Permeable Pavers Bioretention systems Dry well Extended detention basins Partial Exfiltration Reactor (PER) Volumetric Clarifying Filter (VCF) Bioswales Hydrodynamic Separator Green Roofs Tree Planters
Physical Treatment Operations	Density Separation	Extended detention basins Retention/detention ponds Wetlands Settling basins Tanks/Vaults Rain Barrels/Cisterns Swales with check dams Oil-water separators Vortex separators
	Size Separation and Exclusion	Screens/bars/trash racks Biofilters Bioretention systems Porous pavement Permeable Pavers Infiltration/exfiltration trenches and basins Manufactured bioretention systems Media/sand/compost filters Hydrodynamic separators Catch basin inserts

Table 2-1. BMPs categorized by Fundamental Process Category and Unit Operation and Process (Continued).

Fundamental Process Category	**Unit Operation or Process**	**Examples of BMPs capable of providing UOP**
		Partial Exfiltration Reactor (PER) Volumetric Clarifying Filter (VCF) Bioswales Hydrodynamic Separator Tree Planters
	Absorption	Biofilters Bioretention systems Media/sand/compost filters Catch basin inserts Infiltration/exfiltration trenches and basins Partial Exfiltration Reactor (PER) Volumetric Clarifying Filter (VCF) Bioswales Hydrodynamic Separator Green Roofs
Biological Processes	Nutrient Assimilation	Wetlands/Wetland channels Bioretention systems Biofilters Retention ponds Bioswales Green Roofs Tree Planters
	Uptake and Storage	Wetlands/wetland channels Bioretention systems Biofilters Retention ponds Bioswales
	Microbially Mediated Transformation	Wetlands/Wetland channels Bioretention systems Biofilters Retention ponds Bioswales Green Roofs Tree Planters

Table 2-1. BMPs categorized by Fundamental Process Category and Unit Operation and Process (Continued).

Fundamental Process Category	**Unit Operation or Process**	**Examples of BMPs capable of providing UOP**
Chemical Processes	Flocculation/Precipitation	Detention/Retention ponds
	Adsorption and Ion Exchange	Subsurface wetlands Media/Sand/Compost filters Infiltration/exfiltration trenches and basins Bioretention with an internal water storage layer or zone. Partial Exfiltration Reactor (PER) Volumetric Clarifying Filter (VCF) Bioswales Hydrodynamic Separator
	Ultra-Violet Disinfection	Shallow retention ponds Advanced treatment systems
	Chemical Disinfection	Custom devices for mixing chlorine or aerating with ozone Advanced treatment systems

Adapted from (Quigley et al., 2005) and expanded from other literature sources including (Barber et al., 2003; Sansalone and Teng, 2004; Minton, 2005; Quigley et al., 2005; Davis, 2007; Pitt et al., 2007; Traver et al., 2008; Cates et al., 2009; Geosyntec and WWE, 2009; Roseen et al., 2009; Palhegyi, 2010b; Sansalone et al., 2010; She and Pang, 2010; Brown and Hunt III, 2011b).

2.3 Importance of Monitoring and Modeling

2.3.1 Hydrologic and Meteorological Monitoring and Modeling

The accurate collection and analysis of meteorological, hydrologic and hydraulic data is one of the most important components of a BMP monitoring study, and is essential for LID site analysis. Meteorological, hydrological and hydraulic data are key components of the watershed water balances needed to evaluate LID sites. Accurate flow measurements are needed to complete water balance calculations and are critical for estimating BMP capture and bypass volumes along with volume losses (Geosyntec and WWE, 2009; Denich and Bradford, 2010). These flow rate measurements also directly affect the estimates of event mean concentrations (EMCs) and pollutant loads (Davis, 2007; Geosyntec and WWE, 2009). According to Geosyntec and WWE (2009), "LID studies without well designed and implemented hydrologic and hydraulic monitoring components are of little value to the technical community.".

Due to the nature of LID design, measuring inflows for BMPs can be quite challenging. When actual inflow monitoring is not feasible it may be possible to calculate or model the inflow given other measurable parameters (Geosyntec and WWE, 2009). One simple approach to estimating flows when actual monitoring is not feasible is to use the volumetric runoff coefficient approach. This approach uses an empirical relationship that provides an estimate of total volume of runoff based on the total volume of rainfall during a storm event and using pre-calibrated estimates of the volumetric runoff coefficient and depression storage. The volumetric runoff coefficient approach uses the following equation (Geosyntec and WWE, 2009; Guo, 2010; Carpenter and Kaluvakolanu, 2011):

$$\text{Volume}_{\text{Runoff}} = \text{Volume}_{\text{Rainfall}} \text{ x Volumetric Runoff Coefficient} - \text{Depression Storage}$$

This method is usually applied to small catchment areas such as parking lots where monitoring data have been collected long enough to provide an accurate estimate of the volumetric runoff coefficient and depression storage but more precise methods of calculating flow have been deemed prohibitive.

Surface water runoff volumes have also been estimated using the Soil Conservation Service (SCS) runoff curve number method as outlined by Technical Release 55 (TR-55) by the United States Department of Agriculture Natural Resources Conservation Service (NRCS, 1986). TR-55 presents a simplified procedure for estimating storm runoff volumes, peak discharge rates, hydrographs and storage volumes required for floodwater reservoirs. The so-called SCS runoff curve number method has been widely used to estimate inflows when actual monitoring data are unavailable (LeFevre et al., 2010; Giacomoni et al., 2012).

The SCS runoff equation (NRCS, 1986) is given as:

$$Q = \frac{(P - I_a)^2}{(P - I_a) + S}$$

Where:

Q = runoff (in), P = rainfall (in), S = potential maximum retention after runoff begins (in), I_a = initial abstraction (in) = all losses before runoff begins (in)

Initial abstraction (I_a) may be approximated by the following empirical equation based on SCS watershed studies (NRCS, 1986; Bedient, 2002):

$$I_a = 0.2S$$

Where: $S = \frac{1000}{CN} - 10$

Substituting 0.2S for I_a in the original runoff equation gives:

$$Q = \frac{(P - 0.2S)^2}{(P + 0.8S)}$$

The curve number (CN) has a range from 0 to 100 and depends on the soil and cover conditions of the watershed, which include the hydrologic soil group, cover type, treatment, hydrologic condition and antecedent runoff condition (NRCS, 1986). In essence, the CN may be viewed as a surrogate for watershed imperviousness, and therefore, hydrologic response. In TR-55, curve numbers representing average antecedent runoff conditions are provided for some typical watershed environments (i.e. urban, cultivated agricultural, other agricultural, arid and semiarid rangelands) (NRCS, 1986). As presented in TR-55, CNs assume directly connected impervious areas, however the manual provides methods to determine and/or modify the CN for particular characteristics of a watershed, such as non-directly connected impervious areas and percent imperviousness values outside of the assumed range (NRCS, 1986).

While the simple nature of the curve number method allows its application with minimal data requirements (storm depth and curve numbers), the approach also creates some challenges and limitations with regards to its ability to predict event-scale hydrologic response in real world applications (Ponce and Hawkins, 1996). While the method provides prediction for average conditions that are useful for design purposes, the modeling accuracy has been observed to decrease for actual rain events, because of the inability to account for effects of rainfall duration or intensity (NRCS, 1986; Ponce and Hawkins, 1996; Lamont et al., 2008; Chung et al., 2010). The method has also been observed to be less accurate when runoff depth is less than 0.5 inches (NRCS, 1986). Several investigators have also found the often assumed initial abstraction ratio of 0.2S may not accurately reflect specific watershed conditions present at every site of interest

(Ponce and Hawkins, 1996; Lamont et al., 2008; Chung et al., 2010). The absence of clear guidance on how to account for variability in antecedent moisture conditions (Ponce and Hawkins, 1996; Chung et al., 2010), spatial scale effects (Ponce and Hawkins, 1996) and land use changes (Ogden et al., 2011), have all been cited as potential barriers to application of the method. Consideration of the effects of simplifications and consequent limitations should be taken into account when applying the curve number method.

In BMP performance assessments, the flow balance is always important. However, in practices where infiltration may be responsible for a significant fraction of the constituent removal efficiency, direct measurements of surface inflows and infiltration become critical. Consequently, studies where accurate flow data are necessary for the evaluation of performance of a BMP, flow estimation techniques like the volumetric runoff coefficient approach or the SCS curve number method are not considered acceptable alternatives where actual flow monitoring is feasible (Geosyntec and WWE, 2009).

The effective monitoring of meteorological conditions, especially precipitation, is another essential component of any LID site analysis, and provides important storm event information such as precipitation depth, duration and intensities (Geosyntec and WWE, 2009). Precipitation depths may be used to both quantify rainfall retention for a LID site (EPA, 2000; Geosyntec and WWE, 2009; Clary et al., 2011) and as a check against questionable flow volumes recorded at a LID site outfall (Geosyntec and WWE, 2009; Clary et al., 2011). There are several types of rain gauges available for monitoring precipitation including standard rain gauges, tipping bucket rain gauges (Burton and Pitt, 2001; Geosyntec and WWE, 2009), weighing rain gauges and optical rain gauges (Geosyntec and WWE, 2009). While the choice of rain gauge type for any particular LID site study will depend on the monitoring needs and available funds, the benefits of having accurate high resolution precipitation data cannot be overstated. It is important to position meteorological instrumentation within or as close as possible to the drainage area tributary to the BMP of interest. Real-time data available over the internet from rain gages operated by the U.S. Geological Survey (USGS), the National Weather Service and any nearby municipalities may also be considered if the station(s) are in close proximity to the monitoring site (typically less than 1 mile away if at the same elevation) (Geosyntec and WWE, 2009). Because precipitation can vary significantly within a small geographic area, the usability of precipitation data from nearby stations will depend heavily on the local climate, weather patterns and surrounding topographical characteristics of the LID site (Burton and Pitt, 2001; Geosyntec and WWE, 2009). The use of off-site data sources for meteorological conditions should be validated to ensure they accurately represent conditions at the study site.

2.3.2 Water Quality Monitoring

Accurate collection and analysis of water quality data is an important component of the characterization and analysis of LID practices.

2.3.2.1 Water Quality Sample Collection Techniques

Water quality samples may be collected either manually or with automated sampling devices. Samples may range from representing the water quality of stormwater runoff at a single point in time (grab sample) to the entire storm event (composite sample).

Grab & First Flush Samples

Grab samples are individual samples collected within a short period of time and essentially make possible an instantaneous description of stormwater quality at a particular location. A grab sample collected during the beginning of a storm event may be used to characterize pollutants associated with the first flush (Minton, 2005; Geosyntec and WWE, 2009; Ma et al., 2009; Williams et al., 2009). A first flush sample often has the highest pollutant concentrations or mass loads in storm event runoff because it contains many of the pollutants that have accumulated on the surface of the drainage area during the antecedent dry period before the storm (Sansalone and Cristina, 2004; Minton, 2005; Geosyntec and WWE, 2009).

Composite & Event Mean Concentration Samples

A composite sample is a mixture of individual sample aliquots which were collected at specific intervals of time or flow during a storm event (Minton, 2005; Geosyntec and WWE, 2009). Due to the variability in constituent concentrations through a given storm event, a single composite sample concentration known as the event mean concentration (EMC) is often used as an event-based representation of concentration (Sansalone and Teng, 2004; Sansalone and Cristina, 2004; Davis, 2007; Cates et al., 2009; Li and Davis, 2009; Sansalone et al., 2010). An EMC may be used as a surrogate for the water quality constituent concentration that would result if the entire storm event runoff was collected and analyzed (Davis, 2007). A flow-weighted EMC may be mathematically represented as (Sansalone and Teng, 2004; Sansalone and Cristina, 2004; Davis, 2007):

$$EMC = \frac{Total\ Pollutant\ Mass}{Total\ Runoff\ Volume} = \frac{M}{V} = \bar{C} = \frac{\int_0^{t_r} c(t)q(t)dt}{\int_0^{t_r} q(t)\,dt}$$

Where M = total mass of a constituent over entire event duration (M); V = total volume of runoff over entire event duration (L^3); $\bar{C}$ = flow weighted average concentration for entire event ($M\ L^{-3}$); c(t) = pollutant concentration as a function of time ($M\ L^{-3}$); q(t) = runoff flow rate as a function of time ($L^3\ T^{-1}$); and the limits of integration refer to the initiation and cessation of runoff (t=0 and $t=t_r$, respectively) in units of time (T).

Time Proportional Composite Samples

Time proportional composite samples are prepared by collecting individual sample aliquots of equal volume at equal increments of time during a storm event and then mixing the aliquots to form a single sample for analysis. Time proportional composite samples do not account for variations in flow and thus generally do not provide reliable estimates of the EMCs or pollutant loads unless the time interval is very short and the flow rate remains relatively constant throughout the storm event.

Flow-Weighted Composite Samples

Flow-weighted composite samples are more suitable for estimating EMCs and pollutant loads and can be collected in several ways including volume proportional to flow rate (constant time), volume proportional to flow volume increment (constant time) and time proportional to flow volume increment (constant volume) (EPA, 1992; Minton, 2005; Geosyntec and WWE, 2009; Williams et al., 2009). If automated sampling equipment is being employed, the third flow-weighted composite sample method, time proportional to flow volume increment (constant volume), is generally preferred because it minimizes the need for measuring and splitting samples which are activities which can contribute to increased sampling errors (Geosyntec and WWE, 2009; Williams et al., 2009).

Consideration of Sampling Location, Criteria & Frequency

The locations of samplers at a study site, the criteria for commencing sampling, and the subsequent sampling frequency are important factors determining the representativeness of the water quality samples collected. Sampler placement should be limited to locations where the flow is well-mixed across the conduit cross-sectional area so that samples are fully representative of the discharge entering or leaving the study site. Sampling frequency, or the criteria by which sampling occurs, and the total number of storms monitored should be defined based on site-specific conditions, study objectives and available resources. Thoughtful planning and consideration should be given during the development of a monitoring strategy to ensure study objectives such as the statistical analysis of influent and effluent conditions can be accomplished with appropriate levels of confidence (Geosyntec and WWE, 2009).

2.3.2.2 Water Quality Parameters of Interest

Geosyntec and WWE (2009) details of-interest parameters and water quality constituents typically found in urban stormwater runoff and the recommended detection limits to be employed for analysis. Typical parameters monitored include pH, conductivity, temperature, reduction potential (redox), turbidity, total suspended solids (TSS), suspended sediment concentration (SSC), total hardness, chloride, Fecal Coliform, E.coli, Enterococci, orthophosphate phosphorus (OP or SRP), total phosphorus (TP), total Kjeldahl nitrogen (TKN), nitrate + nitrate nitrogen (Ox-N), ammonia nitrogen (NH_3-N), total and dissolved cadmium, total and dissolved copper, total and dissolved lead, total and dissolved zinc, organophosphate phosphorus, total petroleum hydrocarbons (TPH) and oil and grease (O&G) (Hsieh and Davis, 2003; Minton, 2005; Pitt et al., 2007; Traver et al., 2008; Cates et al., 2009; Davis et al., 2009; Geosyntec and WWE, 2009; Roseen et al., 2009; Sansalone et al., 2010; Lenhart, 2011). Because stormwater runoff has the potential to contain a variety of substances that can adversely affect water quality, the choice of constituents to monitor is dependent upon many factors including the site-specific conditions, study objectives and available resources (Geosyntec and WWE, 2009). Each constituent monitored should be selected to provide useful information regarding the physical and biogeochemical conditions present, and the associated processes, within a stormwater BMP. The importance of some common water quality parameters and their associated pollutant removal mechanisms is discussed in section 2.11 which addresses BMP pollutant removal performance reported in the literature.

2.4 Water Quality Benefits

Water quality benefits and load reductions from LID sites and BMPs are a function of both water quality treatment processes (such as filtration of particle bound pollutants, removal of dissolved pollutants through amended media and nutrient uptake by vegetation) and reductions in stormwater runoff volumes (Davis et al., 2006; Davis, 2007; Geosyntec and WWE, 2009). With this in mind, the description and analysis of water quality benefits and load reductions achieved at a LID site should include an account of the pollutant loads removed through treatment as well as the reductions achieved through volume reduction (Davis, 2007; Geosyntec and WWE, 2009). However, because stormwater runoff generally remains dispersed where entering LID practices, it may not always be possible to directly measure inflow volumes and concentrations. For this reason, quantifying load reductions may be more difficult because of the difficulty in having the same level of confidence in both inflow (often estimated) and observed outflow loads. Because of this limitation, the use of reference watersheds in assessing water quality benefits and load reductions is commonly used in LID performance analysis (Geosyntec and WWE, 2009).

Typically, LID sites achieve water quality benefits by reducing the frequency and magnitude of discharge, thereby reducing the average concentrations of pollutants and, by extension, loads, in the outflow (Davis, 2007; Geosyntec and WWE, 2009). Reducing the frequency of discharge necessarily reduces the potential for water quality impacts associated with urban stormwater runoff. While reducing the frequency of discharge is an important mechanism through which LID practices achieve water quality benefits, it should be noted that pollutants which build up between discharge events have the potential to exit BMPs during larger rainfall events which do produce discharge. This is one reason long-term monitoring is an important aspect of LID and BMP performance analysis (Geosyntec and WWE, 2009). Reductions in the concentrations of pollutants in the discharge are typically interpreted through the average event mean concentration (EMC) or as a distribution of EMCs. It is important to note that concentration reductions may be less than expected, and may even increase, for sites that achieve significant volume reductions or where the influent concentrations are initially low or are considered irreducible (Strecker et al., 2001; Davis et al., 2006; Geosyntec and WWE, 2009; Brown and Hunt III, 2011a). Performance metrics based on EMC reductions alone may, therefore, be misleading because they do not consider the size of the storm event or the amount of runoff volume retained by the stormwater BMP (Davis et al., 2006; Davis, 2007; Cates et al., 2009; Li and Davis, 2009). As noted earlier, pollutant load reductions may be a function of both water quality treatment processes and volume reductions in LID practices (Davis, 2007; Geosyntec and WWE, 2009; Li and Davis, 2009; Clary et al., 2011). To accurately assess performance, estimates of pollutant load reductions should include long term monitoring to predict BMP uptake and release of pollutants on a seasonal, annual and ultimately complete life-cycle basis (Brown and Hunt III, 2011a). The non-linear runoff response typical of LID watersheds should be taken into consideration because a few large storms may often be found to dominate the overall discharge volume at a site and pollutant concentrations also tend to be greater during more intense rainfall events. Considering the above, performance metrics based on the total pollutant load removal over a representative period of the meteorological and hydrologic record are more representative measures of the overall system efficiency and are consequently more appropriate for assessing the pollutant reduction performance of a LID site (Davis, 2007; Cates et al., 2009; Geosyntec and WWE, 2009). Pollutant loads are generally calculated using a flow-weighted average concentration (EMC) and multiplying it by the total volume of flow over the averaging period. Depending on the objective of the analysis, the averaging period can include only the time it takes to obtain an individual grab sample, an entire storm event, a season, a year, or some other interval (Geosyntec and WWE, 2009). Determining the load of a pollutant during any particular storm event typically requires the use of an event mean concentration (EMC) of the pollutant of interest and the total volume of the storm event (Davis, 2007; Lenhart, 2007; Geosyntec and WWE, 2009; Li and Davis, 2009). For storm events where discharge volumes are known, but water quality sampling was not conducted, the load may be estimated using an average EMC for the pollutant of interest during events of similar hydrologic response and multiplying it by the total discharge volume of the unsampled event. Caution should be exercised when interpreting performance results based on estimated pollutant loads calculated from average EMC values (Geosyntec and WWE, 2009). It should be recognized that pollutant loading may occur during dry weather events if there is a baseflow condition sufficient to produce flow in the BMP (Geosyntec and WWE, 2009; Carpenter and Kaluvakolanu, 2011).

2.5 Reference Watersheds

Reference watersheds are often used to evaluate the effectiveness of a particular BMP or suite of BMPs at a study site when a detailed comparison between inlet and outlet water quality parameters is not possible. To effectively assess performance of a BMP using the reference watershed approach, an accurate accounting of the variations between the watersheds is critical (Strecker et al., 2001; Geosyntec and WWE, 2009; Clary et al., 2011). In ‘Urban Stormwater BMP Performance Monitoring,’ (Geosyntec and WWE, 2009), it is noted that, “As the characteristics of the two watersheds diverge, the effect of the BMP is masked by the large number of variables in the system; the noise in the data becomes greater than the signal.".

2.5.1 Before-After/Control-Impact (BACI) Reference Watershed Approach

The before-after reference watershed approach requires monitoring of a proposed development site during both the pre-development and post-development states. The comparison of hydrologic and water quality parameters between pre- and post-development may then serve as the basis for characterizing the effectiveness of the LID design and BMPs employed at the site. One drawback to the before-after approach is the need for an extended monitoring period to monitor and accurately characterize both the pre-LID-retrofit and post-LID-retrofit hydrologic regimes. The control-impact reference watershed approach uses a nearby control watershed which has similar physical and hydrologic characteristics to the LID watershed site. Using this approach, the control and impact watersheds are monitored simultaneously and monitoring will require less time than the before-after reference watershed approach. It is essential that the control and impact watersheds be located near each other because of the spatial variations of meteorological conditions that can be expected. Variations between the two watersheds, while necessarily minimal to begin with, must be taken into account appropriately if a valid comparison and performance assessment is to be made. It should also be noted that the Before-After/Control-Impact (BACI) reference watershed approaches may be used together (Strecker et al., 2001; Geosyntec and WWE, 2009).

2.5.2 Traditional Development-LID Reference Watershed Approach

Comparison of a traditional development and a LID implementation is another reference watershed approach. In this monitoring strategy, two watersheds with comparable pre-development characteristics are developed with comparable land use. However, one site is developed using traditional development designs and techniques while the other site is developed using LID designs and BMPs. As with the control-impact approach, the physical and hydrological characteristics of the paired watersheds must be similar and they must be located near each other to eliminate meteorological variables to the maximum extent possible. The hydrologic and water quality parameters of the two sites may then be compared and a performance assessment of the LID site can be made (Strecker et al., 2001; Geosyntec and WWE, 2009).

While sites developed with LID designs and BMPs may be compared to control sites or traditionally designed watersheds, directly comparing the pre-LID-retrofit condition of a site to the post-LID-retrofit hydrological and water quality parameters may be the most direct and informative method to evaluate LID retrofit performance (Strecker et al., 2001; Geosyntec and WWE, 2009). A combination of reference watershed approaches may also be applied towards the determination of LID performance analysis and evaluation. Ultimately, the reference watershed approach best suited for any LID/BMP performance analysis combination will be based on the study objectives and project constraints (Geosyntec and WWE, 2009).

2.6 BMP Performance Analysis

2.6.1 Hydrologic Performance Metrics

Hydrologic performance metrics may be used to compare and assess how well LID design and BMPs are performing with regards to water quantity. Potential hydrologic performance metrics include (Barber et al., 2003; McCuen, 2003; Davis, 2008; Geosyntec and WWE, 2009; Carpenter and Hallam, 2010; Guo, 2010; LeFevre et al., 2010; Palhegyi, 2010a; Reichold et al., 2010; Brown and Hunt III, 2011a; Carpenter and Kaluvakolanu, 2011; Clary et al., 2011; DeBusk et al., 2011; Giacomoni et al., 2012):

- Largest rainfall event (depth and duration) producing no discharge;
- Smallest rainfall event (depth and duration) to produce discharge;
- Long-term cumulative discharge volume per unit rainfall (long-term volumetric runoff coefficient);
- Largest rainfall quantity producing no discharge taking antecedent conditions (wet or dry) into account using the Antecedent Precipitation Index (API);
- Average of storm-by-storm volumetric runoff coefficient under wet and dry API;
- Largest rainfall quantity producing no discharge with a varying 7-day antecedent rainfall;
- Peak flow rates for specific average rainfall intensities over the time of concentration;
- Hydrograph lag time;

- Time of concentration under varied rainfall intensities and APIs;
- Maximum outflow peak to inflow peak ratio (R_{peak});
- Peak delay ratio (R_{delay});
- The fraction of input water measured leaving each system after 24 hours (f_{v24});
- Net Instantaneous Volume metric;
    - Compares the total volume of rainfall on a catchment during a hypothetical instantaneous event to the storage volume available in the LID practices to which the catchment drains.
- Storage Recovery Rate;
    - Rate at which hydrologically available temporary storage is recovered.
- Discharge Volume per Drainage Area;
- Discharge Volume per Impervious Area;
- Runoff Volume Reduction;
- Discharge Comparison to Non-urban Watershed Shallow Interflow;
- Flow Rates per Drainage Area;
- Flow Rates per Drainage Area per Depth of Precipitation;
- Simulation-Optimization Techniques using metrics such as the Indicators of Hydrologic Alteration (IHA), the Range of Variability Approach (RVA) and changes in flow duration curves;
    - Can be used to assess differences in pre- and post-development flow regimes (e.g. magnitude, duration, timing, frequency, rate of change, etc.). The use of flow regime characterization metrics such as the Indicators of Hydrologic Alteration (IHA), the Range of Variability Approach (RVA) and changes in flow duration

curves are often the basis for simulation-optimization approaches and may be used concurrently as exampled by the IHA/RVA and the IHA-sum of mishits (IHA-SMH) approaches (Reichold et al., 2010).

- Hydrologic Footprint Residence (HFR);
    - Quantifies the impact of urbanization on downstream water bodies on the basis of the inundation dynamics of the flow regime using the time series of the inundated area, called the inundated land curve. The HFR associated with a particular storm event is the area of land that is inundated and the duration over which it is inundated as a storm wave passes through a specified reach of a receiving water body. It is expressed in units of area-time, such as acre-hours and is calculated by evaluating the definite integral of the inundated land curve (i.e. the area under the curve) (Giacomoni et al., 2012).
- Comparison of pre- and post-development runoff frequency curves;
- Comparison of pre- and post-development flow duration curves.

2.6.2 Water Quality Performance Metrics

The efficiency of stormwater BMPs at providing water quality benefits may be evaluated in numerous ways. Quantifying the efficiency of BMPs has often centered on percent removal evaluations, however percent removal metrics alone, even when results are statistically significant, often fail to provide useful valuations of the performance of a BMP. This is because percent removals are typically based on the difference between influent and effluent concentrations. This computation fails to take into account that low concentration influent flows are more difficult to treat, and will result in lower percent removals compared to higher strength influents even if the resulting effluent concentrations are identical (Strecker et al., 2001; Davis, 2007; Lenhart, 2007; Pitt et al., 2007; Davis et al., 2009; Geosyntec and WWE, 2009; Clary et al., 2011; Lenhart, 2011; McNett et al., 2011). Percent removal metrics also fail to take background, or irreducible concentrations, into account (Strecker et al., 2001; Lenhart, 2011; McNett et al., 2011). The use of the Effluent Probability Method is a recommended alternative to evaluate BMP performance (Strecker et al., 2001; Davis, 2007; Chi-Feng et al., 2009; Geosyntec and WWE, 2009; Li and Davis, 2009; Williams et al., 2009).

2.6.2.1 Effluent Probability Method

Application of the Effluent Probability Method consists of three principal steps (Strecker et al., 2001; Geosyntec and WWE, 2009; Williams et al., 2009):

- A distributional adherence test to determine if the data follow a particular distribution (environmental data most often follow the lognormal distribution);
- Statistical tests to determine if any perceived differences between the influent and effluent EMCs or loads are statistically significant;
- Plotting the log-transformed data of influent and effluent EMCs or loads for all storm events on a normal probability plot.

The assumptions of the Effluent Probability Method include:

- The rank of the pollution concentration or load in influent is consistent with that in the effluent (Chi-Feng et al., 2009);
- The lognormal distribution is an appropriate approximation for the sample data (Strecker et al., 2001; Chi-Feng et al., 2009; Geosyntec and WWE, 2009).

Other methods/metrics commonly used to calculate BMP efficiency and performance include the following and are further described below (Hsieh and Davis, 2003; Sansalone and Teng, 2004; Hunt et al., 2006; Cates et al., 2009; Geosyntec and WWE, 2009; Roseen et al., 2009; Carpenter and Hallam, 2010; Brown and Hunt III, 2011a; Brown and Hunt III, 2011b; Lenhart, 2011; McNett et al., 2011):

- Efficiency Ratio method;
- Summation of Loads method;
- Percent removal relative to irreducible concentrations, ambient water quality or receiving water quality standards method;
- Reference watersheds and before/after studies.

2.6.2.2 Efficiency Ratio Method

The Efficiency Ratio (ER) method defines the efficiency of any given stormwater BMP to remove pollutants as the ratio of the average inlet event mean concentration (EMC) to the average outlet EMC. The overall change in average EMC over the monitoring period is presented as a percent decrease between the average inlet and outlet EMCs (Minton, 2005; Yu and Stanford, 2007; Chi-Feng et al., 2009; Geosyntec and WWE, 2009; Roseen et al., 2009; Brown and Hunt III, 2011a; McNett et al., 2011), or:

$$ER = 1 - \frac{average\ outlet\ EMC}{average\ inlet\ EMC}$$

The assumptions of the efficiency ratio method include (Minton, 2005; Geosyntec and WWE, 2009):

- All storm events are weighted equally, regardless of relative magnitude of storm;
- If all storms had been monitored, the average inlet and outlet EMCs would be similar to those that were monitored.

It should be noted that performance metrics based on concentration reductions may be misleading since they do not consider the size of the storm event or the amount of runoff volume retained by the stormwater BMP (Davis et al., 2006; Davis, 2007; Cates et al., 2009; Li and Davis, 2009). Because of this, concentration based metrics may not be appropriate for performance analysis of stormwater BMPs which utilize mechanisms such as infiltration. Consequently, performance metrics based on the total pollutant load removal over a representative period of the meteorological and hydrologic record have been found to be more representative measures of overall system efficiency, and more appropriate for assessing pollutant reduction performance of a LID site (Minton, 2005; Davis, 2007; Cates et al., 2009; Geosyntec and WWE, 2009).

2.6.2.3 Summation of Loads Method

The Summation of Loads (SOL) method defines the efficiency of a given BMP to remove pollutants as the ratio of the summation of all incoming (inlet) loads to the summation of all outgoing (outlet) loads. The overall change in load for each pollutant over the monitoring period is presented as a percent decrease between the summation of inlet and outlet loads (Minton, 2005; Hunt et al., 2006; Cates et al., 2009; Chi-Feng et al., 2009; Geosyntec and WWE, 2009; Williams et al., 2009; McNett et al., 2011), or:

$$SOL = 1 - \frac{\sum Outlet\ Loads}{\sum Inlet\ Loads}$$

The assumptions on which the Summation of Loads method is based include (Minton, 2005; Geosyntec and WWE, 2009):

- The removal of material is most relevant over the entire period of analysis;
- Monitoring data accurately represent the entire total loads in and out of the BMP for a period long enough to overshadow temporary internal storage of pollutants;
- Any significant unmonitored storms had inlet to outlet load ratios similar to the storms that were monitored;
- No materials were exported during dry periods, or if they were, the ratio of inlet to outlet loads during these periods was similar to the ratio of the loads during the monitored storm events.

It has also been reported that a small number of large storms will generally dominate the computed SOL efficiency (Geosyntec and WWE, 2009).

2.6.2.4 Percent Removal Relative to Irreducible Concentrations, Ambient Water Quality or Water Quality Standards

The concept of an irreducible concentration suggests that it may sometimes be more useful to report pollutant removal performance of a BMP relative to some achievable level of treatment, natural background condition, or specific water quality standard rather than directly comparing influent and effluent concentrations. Efficiencies computed in this way would therefore be based on the ability of a BMP to achieve a certain level of effluent water quality instead of a certain level of pollutant reduction percentage (Geosyntec and WWE, 2009; Brown and Hunt III, 2011b; Lenhart, 2011). The relative efficiency comparing pollutant reductions between influent and effluent conditions to the possible reduction between the influent and an irreducible condition may be calculated as follows (Geosyntec and WWE, 2009; Williams et al., 2009):

$$Relative\ \ Efficiency\ = \frac{Efficiency\ \ Ratio}{Achievable\ Efficency} = \frac{\dfrac{C_{Influent} - C_{Effluent}}{C_{Influent}}}{\dfrac{C_{Influent} - C_{Irreducible}}{C_{Influent}}} = \frac{C_{Influent} - C_{Effluent}}{C_{Influent} - C_{Irreducible}}$$

Similarly, the percent removal relative to ambient water quality or a specific water quality standard can be calculated as follows (Geosyntec and WWE, 2009; Williams et al., 2009):

$$Percent\ \ Removal\ \ Relative\ \ to\ \ Receiving\ \ Water\ \ Quality = \frac{C_{Influent} - C_{Effluent}}{C_{Influent} - C_{Background/Standard}}$$

2.6.2.5 Reference Watersheds

Reference watersheds may be used with the above water quality metrics to compare effluent conditions from a BMP study site to the influent conditions from a control site. Use of such reference watersheds assumes that the quality of the untreated stormwater at the control site accurately represents the quality of the inflow stormwater at the BMP study site (Minton, 2005).

Whatever method is used to analyze BMP performance, an understanding of the constraints, assumptions and implications of each method is required for accurate interpretations and conclusions. All methods should be complemented by applicable descriptive statistics and statistical analyses (parametric or non-parametric) demonstrating the level of significance.

2.7 Descriptive Statistics and Methods of Statistical Analysis

Descriptive statistics include measures of distribution location or central tendency such as the mean and median, measures of spread or variability such as the standard deviation and interquartile range and measures of skewness or symmetry such as the coefficient of skewness and the quartile skew coefficient (Minton, 2005; Geosyntec and WWE, 2009). Comparative data analysis allows the determination of statistically significant differences between two datasets. Such an analysis is directly applicable to assessing BMP performance because it enables the comparison of inflow to outflow characteristics for a particular BMP or the comparison of BMP performance to results reported in the literature. Independent or non-paired datasets may be compared using the Rank-Sum Test or the t-Test depending on the underlying dataset distributions. Dependent or paired datasets may be compared using the Sign Test, Rank-Sign Test or the Paired t-Test, again depending on the underlying dataset distributions (Cates et al., 2009; Geosyntec and WWE, 2009; Pitt et al., 2010; Brown and Hunt III, 2011a; Brown and Hunt III, 2011b). Additional methods of statistical comparison include the Wilcoxon Rank Sum test, the Mann-Whitney test and ANOVA tests (Sansalone and Teng, 2004; Davis, 2007; Brown and Hunt III, 2010; Brown and Hunt III, 2011a; Brown and Hunt III, 2011b; Carpenter and Kaluvakolanu, 2011; DeBusk et al., 2011; Lenhart, 2011). It is important to recognize that some descriptive statistics and methods of statistical analysis are more appropriate than others given the characteristics of a particular dataset such as its underlying distribution. Methods are generally divided into two categories: parametric and non-parametric statistics (Gallagher, 2011).

2.7.1 Testing for Distributional Adherence

Testing for distributional adherence is an important step in statistical analysis and in some pollutant removal performance metrics because it reveals if the data follow a particular distribution (such as the normal or lognormal). For example, the effluent probably method requires the determination of the distribution of the dataset to enable the proper type of transform to take place to best represent the influent and effluent concentrations or loads on a normal probability plot. Additionally, the use of parametric or nonparametric statistics is based largely on the assumed distribution of the datasets (Strecker et al., 2001; Geosyntec and WWE, 2009; Williams et al., 2009).

2.7.2 Relevance of the Lognormal Distribution

A lognormal probability distribution is often used to represent environmental data, including water quality data, because such datasets are often positively skewed. The assumption that a population is lognormally distributed implies that the standard deviation is proportional to the mean and the data are left-bounded by zero (Helsel, 2002; Geosyntec and WWE, 2009; Helsel, 2012). The lognormal distribution has been shown to be a good fit for urban stormwater runoff EMC data for many water quality constituents (EPA, 1983; Van Buren et al., 1997; Strecker et al., 2001; Davis, 2007; Geosyntec and WWE, 2009; Williams et al., 2009; Sansalone et al., 2010; Brown and Hunt III, 2011a; Brown and Hunt III, 2011b). There are also some water quality parameters in urban stormwater runoff which are not generally found to fit a lognormal distribution. These typically include pH, dissolved oxygen, bacterial counts, turbidity, total dissolved solids, chlorides, sulfate and COD (Van Buren et al., 1997; Geosyntec and WWE, 2009). For this reason, while many stormwater runoff water quality parameters exhibit lognormal characteristics, the distribution should still be confirmed for each parameter independently (Strecker et al., 2001; Geosyntec and WWE, 2009).

2.7.3 Parametric Statistics

Parametric statistics assume the data arise from a single statistical distribution such as a normal distribution. The distribution under which the data are modeled under should be determined using a combination of scientific judgment, graphical measures and goodness-of-fit tests. Some common goodness-of-fit tests include the *Kolmogorov-Smirnov* (K-S) test, the modified Lilliefors test, the *chi-square* (χ^2) test, the Shapiro-Wilk test, the probability plot correlation coefficient (PPCC) test, the Creamer-von Mises test and the Anderson Darling test (Helsel, 2002; Geosyntec and WWE, 2009; Brown and Hunt III, 2011b; Helsel, 2012).Once a statistical distribution has been determined and selected for a particular dataset, the parameters of the distribution such as the central tendency, variability and skew may be estimated using approaches such as the method of moments, the method of maximum likelihood and the method of L-moments (Cates et al., 2009; Geosyntec and WWE, 2009; Brown and Hunt III, 2011b).

2.7.4 Nonparametric Statistics

Nonparametric statistics are based on the rank or position of the data after being sorted by magnitude and do not assume an underlying distribution (Montgomery, 1999; Geosyntec and WWE, 2009; Helsel, 2012; WEF and ASCE, 2012). Compared to parametric statistics, nonparametric statistics are less affected by the presence of outliers because only the order and not the magnitudes of the individual data points are taken into consideration (Montgomery, 1999; Geosyntec and WWE, 2009). When using comparative statistics between two datasets, if the data appear to follow different or unknown distributions (Montgomery, 1999; Geosyntec and WWE, 2009; Helsel, 2012), or if either dataset contains a high proportion of non-detects, nonparametric analysis may be more appropriate than parametric analysis (Geosyntec and WWE, 2009; Helsel, 2012).

2.8 Graphical Analysis

Graphical analysis of data from BMP studies can provide key insights about the general characteristics of the dataset and enable researchers to identify unexpected trends. Common plots often used to describe and visually display environmental data include histograms, quantile plots, probability plots, box plots, scatter plots, within-storm time series plots, flow duration curves, inundated land curves, storm hydrographs and pollutographs (Strecker et al., 2001; Geosyntec and WWE, 2009; Palhegyi, 2010b; Palhegyi, 2010a; Clary et al., 2011; McNett et al., 2011; Giacomoni et al., 2012). Some common plots frequently used in water resource engineering are discussed further below.

Histograms may be used to visualize the empirical distribution of a dataset by categorizing the data into bins and plotting the number of data points within each bin as the dependent variable while the bins themselves are plotted as the independent variable. Histograms may thereby provide a rough estimate of the shape or symmetry of the probability density function of the underlying distribution from which the sample data arise (Helsel, 2002; Geosyntec and WWE, 2009).

Quantile plots are plots of the empirical distribution function and may be used to display the cumulative frequency, or frequency of non-exceedance, of each observation within a dataset. Quantile plots are constructed by ranking the observations within a dataset, and then for each observation calculating an estimated percentile, or the probability of being less than or equal to that observation, as the plotting position (Helsel, 2002; Geosyntec and WWE, 2009; Helsel, 2012) Quantile plots can also be created to display or compare water quality, volume and flow metrics for a study site or between watersheds (Strecker et al., 2001; Geosyntec and WWE, 2009; Palhegyi, 2010a; Giacomoni et al., 2012).

Probability plots, also called quantile-quantile plots or Q-Q plots, may be used to test the similarity of a sample dataset distribution to that of a theoretical distribution such as the normal or lognormal distribution. Such probability plots may be created by altering the percentile scale of an empirical distribution function to match the percentiles (or normal scores) of an assumed distribution. If the sample data follow the assumed distribution, the plotted points will fall along a straight line in the probability plot (Helsel, 2012). If the plotted points do not fall along a straight line, the sample data may then be transformed to test for alternative distributions in a similar manner (Geosyntec and WWE, 2009; Williams et al., 2009). Probability plots may also be used to graphically compare influent and effluent concentrations or loads, such as in the Effluent Probability Method (Strecker et al., 2001; Geosyntec and WWE, 2009).

Box plots, or box and whisker plots, display the center, spread and skewness of a dataset along with any outliers. Typically, the upper and lower boundaries of the box are the 25^{th} and 75^{th} percentiles, and a horizontal line within the box represents the 50^{th} percentile. Observations which fall outside of the central box are often represented using whiskers extending vertically from the bottom and top of the box if those observations are within a certain range (typically 1.5 times the interquartile range) or with asterisks or other point symbols if the distance between the particular observation and the lower or upper horizontal boundary (1^{st} or 3^{rd} quartile) is greater than the user-defined whisker range (again, typically 1.5 times the interquartile range) (Montgomery, 1999; Helsel, 2002; Geosyntec and WWE, 2009; Helsel, 2012). Box plots are often used to graphically compare water quality data between influent and effluent concentrations and loads (Strecker et al., 2001; Geosyntec and WWE, 2009; Helsel, 2012).

Scatter plots compare the values of two continuous variables, typically labeled as the x- and y-variables, and may be used to discern potential relationships between paired datasets or any temporal trend within a single dataset. Scatter plots are constructed by plotting a single x-y point for each coordinate pair corresponding to their respective values in reference to the x- and y-axes of a two-dimensional graph (Geosyntec and WWE, 2009; Helsel, 2012). Plots of constituent concentrations as a function of time, during a monitoring period or within a storm event, for example, may be a useful display of water quality at a study site or watershed (Strecker et al., 2001; Geosyntec and WWE, 2009; Clary et al., 2011; Helsel, 2012). Scatter plots comparing influent and effluent pollutant concentrations, loads or runoff volumes may also be used to display BMP performance (Clary et al., 2011; McNett et al., 2011).

Storm hydrographs, flow duration curves, and inundated land curves, which all display volumes of runoff or flooded area per unit of time, are examples of scatter plots being used for the graphical analysis of water volume at a study site or watershed. Storm hydrographs represent the flow vs. time of stormwater runoff during an event and are often used to help characterize the effect of a BMP, or suite of BMPs, on the hydraulic regime of a site (including the magnitude, duration and timing of stormwater runoff) (Geosyntec and WWE, 2009; Palhegyi, 2010b; Palhegyi, 2010a; Clary et al., 2011; Giacomoni et al., 2012). Flow duration curves may be used to compare stormwater runoff discharges between two or more study sites or watersheds. Comparison of flow duration curves between a LID-retrofitted and control site may be useful in determining the effect of the BMPs on the hydraulic regime of a site (Palhegyi, 2010b; Palhegyi, 2010a). An inundated land curve is a time series representing the area of land that is inundated as a storm wave passes through a specified reach of a receiving water body. The inundated land curve may be used to calculate hydrologic performance metrics such as the hydrologic footprint residence (HFR) (Giacomoni et al., 2012).

2.9 Analysis of Censored Data

Nondetects in environmental datasets are values reported to be only below an analytical reporting limit, and typically result in censored datasets. Nondetects in water quality data are typically low-level concentrations of chemicals with values known only to be somewhere between zero and the analytical detection/reporting limits (Helsel, 2002; Geosyntec and WWE, 2009; Helsel, 2012). Substitution methods such as replacing censored data with values equal to one-half the detection limit are common in the environmental engineering literature. However, substitution methods have been shown by Helsel (2012) to introduce "invasive" patterns and signals not present in the original dataset. Substitution methods arbitrarily change the distribution of datasets and may cause artificial relationships to be inferred between variables. Helsel (2012) demonstrated that substitution methods are not neutral, but instead "invasive," because such methods may introduce a pattern or signal to the data which is different than the native pattern of the original dataset, and thereby not reflective of reality. Helsel (2012) recommends the use of three data analysis approaches when censored data are present: (1) using nonparametric methods after censoring at the highest reporting limit; (2) using the maximum likelihood estimation (MLE) method which is a survival analysis procedure assuming a specific distribution; (3) and using a nonparametric survival analysis procedure such as the Kaplan-Meier (KM) and Turnbull methods. Helsel (2012) has also recommended imputation methods such as robust regression on ordered statistics (ROS) and robust MLE when the level of censoring within a dataset is greater than 50% but less than 80%. When used correctly, these approaches avoid the introduction of invasive patterns and signals associated with other (and often more commonly used) substitution methods (Helsel, 2012). Additionally, Helsel (2012) provided a set of guidelines which takes the sample size and level of censoring present into account when deciding upon the best course of action to statistically evaluate datasets with censored data. The use of such approaches and guidelines is recommended when the analysis of data including nondetects is required (Helsel, 2012), as is common in environmental science and engineering, especially in the analysis of water quality data.

2.10 Consideration of Measurement Error

Measurement error, particularly in the precision and accuracy of system inflow and outflow volume measurements, should be considered while interpreting volumetric data (Geosyntec and WWE, 2009; LeFevre et al., 2010; Clary et al., 2011). Random measurement error caused by the resolution of monitoring equipment can be magnified in the evaluation of volume reductions. This is particularly true for practices that achieve relatively small volume reductions, or for which only a limited number of data points have been collected. The impacts of measurement precision on study conclusions can be reduced by using approaches that aggregate long-term inflow and outflow volumes such as the comparison of total inflow to total outflow volumes or total rain to total discharge volumes. Also, increased sample size will help reduce the impacts on the dataset associated with random measurement errors. It should be noted the metric "relative volume reduction" or "percent volume reduction" on a storm-by-storm basis is particularly sensitive to the effects of measurement precision (Geosyntec and WWE, 2009; Clary et al., 2011).

The accuracy of volumetric measurements may also be affected by non-random errors such as the improper installation or calibration of monitoring equipment and flow control devices such as flumes and weirs. Proper inspection and maintenance practices must be followed to avoid non-random errors related to malfunctioning equipment (e.g. sediment plugging or building up in or on the flow measuring equipment), or inappropriate operating conditions (e.g. debris or sediment build up affecting the empirical relationship between flow depth and discharge rate at a weir notch) (Geosyntec and WWE, 2009; Clary et al., 2011). In addition to measurement inaccuracy, failure to account for all system inflows and outflows is an additional source of systematic error. Some examples of commonly unmeasured volumes include: volume of direct precipitation on the BMP, volume of groundwater seepage into the practice, volume of water removed by evapotranspiration, and any other volume that is not directly measured by equipment at the discrete monitoring locations. If measuring these volumes is not possible, the unmeasured volumes should be estimated wherever possible and taken into account as appropriate to reduce inaccuracies during volumetric analysis (Geosyntec and WWE, 2009; Denich and Bradford, 2010; Clary et al., 2011).

The use of appropriate sampling methods, field procedures and laboratory procedures, along with the proper quality assurance and quality control (QA/QC) procedures are critical to ensuring accurate water quality monitoring data. Methods and techniques which maintain and confirm the integrity of samples include the use of pollutant-specific sample containers; QA/QC field measures such as field blank samples to test for sample contamination; and QA/QC laboratory measures such as method blanks to determine the level of contamination associated with laboratory reagents and glassware, and laboratory duplicates to assess the reproducibility of analysis methods (Geosyntec and WWE, 2009).

For monitoring data to be properly interpreted, thorough documentation of the BMP as constructed in the field (i.e. as-builts) is required, along with any maintenance records and service logs to provide a proper description of the condition of the BMP throughout the study. If the as-built conditions deviate from the design plans, the performance of a BMP may be incorrectly attributed to design characteristics which do not actually exist in the field (Brown and Hunt III, 2011a; Clary et al., 2011). For example, if field conditions required a bioretention cell to be constructed with a smaller internal water storage zone than in the design, it might be expected that the practice would remove less oxidized nitrogen than originally expected. If the change in the internal water storage zone was not documented in as-built records, however, it may have been falsely concluded that the bioretention cell, as designed, performed poorly with regard to oxidized nitrogen removal. On the other hand, if the internal water storage zone was greater than the design value, data interpretation might indicate better performance than would be warranted for a given size. Such mischaracterizations of the performance of an internal water storage zone could have future implications on sizing of the practice, dissuade other researchers from further investigating what appears to be a poorly performing BMP, or misrepresent what should realistically be expected from the BMP of interest.

2.11 BMP Literature Review: Hydrologic and Pollutant Removal Performance

2.11.1 BMP Literature Review: Hydrologic Performance

Infiltration-based BMPs route surface runoff into the subsurface soils/media where it is temporarily held in pore spaces before evaporating, transpiring from vegetation, exfiltrating into surrounding subsoils and groundwater, discharging as interflow or exiting through underdrains. Infiltration BMPs have been shown to effectively reduce and delay effluent stormwater runoff volumes and peak flows, thereby mimicking the pre-development hydrologic regime of a watershed (EPA, 2007; Davis, 2008; Davis et al., 2009; Brown and Hunt III, 2011a; DeBusk et al., 2011; Lenhart, 2011). Greater volume and peak flow reductions and delays are typically observed for smaller storm events (EPA, 2007; Davis, 2008; Davis et al., 2009; Brown and Hunt III, 2011a), when favorable antecedent moisture conditions prevail (i.e. the subsurface soils/media is unsaturated) (Davis et al., 2009; Brown and Hunt III, 2011a), and during warmer months (Emerson and Traver, 2008; Davis et al., 2009). Infiltration BMPs include bioretention cells or rain gardens, bioswales and vegetated filter strips, infiltration basins and trenches, among others (Strecker et al., 2001; Quigley et al., 2005; Davis, 2008; Davis et al., 2009; Brown and Hunt III, 2011a; Lenhart, 2011).

Green roofs and green facades are typically vegetated bioretention cells/rain gardens contained within an impervious membrane with some type of underdrain located on a rooftop, parking garage or similar structure. The hydrological, physical, chemical and biological processes employed and benefits realized from green roofs are the same as those in other infiltration practices with underdrains (She and Pang, 2010; Carpenter and Kaluvakolanu, 2011). The green roof media and vegetation have the potential to store, evaporate, and evapotranspire precipitation and have been shown to effectively reduce and delay effluent stormwater runoff volumes and peak flows, thereby mimicking the pre-development hydrologic regime of the watershed (Beyerlein, 2008; She and Pang, 2010; Voyde et al., 2010; Carpenter and Kaluvakolanu, 2011; Welker and Wadzuk, 2011). Because stormwater runoff volume reduction is mainly a function of evapotranspiration from the green roof media and vegetation it is necessary to find a balance between maintaining the health of the vegetation through irrigation and providing advantageous media conditions which promote water storage within the media instead of flow through and ultimately drainage from the green roof. If a green roof is not sufficiently irrigated, the vegetation will become stressed and diverge from its maximum water use capacity. If the green roof is excessively irrigated, while the vegetation will be unstressed and thereby able to achieve maximum water use, there will be reduced storage available within the media substrate and the effectiveness of the green roof at reducing stormwater runoff volume will decrease (Voyde et al., 2010).

Permeable or porous pavements, pavers and overlays are designed to function as load bearing structures that allow stormwater to infiltrate though the hard surface into the underlying soils or media, thereby reducing runoff volumes, peaks flows and improving water quality through filtration processes (Beyerlein, 2008; Sansalone et al., 2008; Geosyntec and WWE, 2009; Roseen et al., 2012; WEF and ASCE, 2012). Similar to other filtration based BMPs, the effectiveness of permeable pavements at reducing and delaying stormwater runoff volumes and peak flows has been shown to be highly variable and depends on storm event characteristics such as rainfall intensity and the subsurface antecedent moisture conditions. Typically, stormwater volume retention decreases and peak flows increase as rainfall intensities increase and as subsurface conditions become saturated (LeFevre et al., 2010; Roseen et al., 2012). Many permeable pavement BMPs are installed along with other stormwater BMPs such as bioretention cells or vegetated swales to achieve LID goals of mimicking the pre-development hydrologic regime of a watershed (LeFevre et al., 2010).

2.11.2 BMP Literature Review: Water Quality Performance

2.11.2.1 Pollutant Removal Mechanisms for Some Common Water Quality Constituents

Phosphorus and Nitrogen Removal

Reports in the literature on the removal of phosphorus and nitrogen in bioretention facilities exhibit great variability due to the complex physical, chemical and biological interactions present in stormwater BMP environments. Additionally, differences in site design and other management practices may also be expected to affect nutrient removal performance (Davis et al., 2006; Davis et al., 2009; Li and Davis, 2009; Lucas, W. and Greenway, M., 2011; Lucas, W. C. and Greenway, M., 2011).

In general, the effectiveness of phosphorus removal is closely related to the phosphorus content of the soil media used in the bioretention cell. If a bioretention cell media has a relatively high initial phosphorus content, then the ability of the facility to remove dissolved phosphorus is reduced. If the media has a relatively low initial phosphorus content, the dissolved phosphorus in the influent may sorb to iron and aluminum oxides in the soil media. Particle-bound phosphorus is removed through settling and filtration processes along with suspended solids and is generally more related to the total suspended solids removal (Davis et al., 2006; Hunt et al., 2006; Davis, 2007; Davis et al., 2009; Li and Davis, 2009; Lucas, W. and Greenway, M., 2011).

Nitrogen interactions in the aquatic environment are complex, and removal or conversion in stormwater BMPs may be expected to be highly dependent on the forms present, and the oxidation-reduction (REDOX) environment of the system. It is important to note that nitrogen removals are best calculated on a total nitrogen (TN) basis because of the many pathways for conversion of species that exist in the nitrogen cycle. TN is expressed as the sum of total Kjeldahl nitrogen (TKN) and oxidized nitrogen (OxN), TKN is the sum of ammonia, ammonium, and organic nitrogen (TKN=NH_3-N+NH_4^+-N+organic-N) and oxidized nitrogen is the sum of nitrite and nitrate (OxN=NO_2^--N+NO_3^--N) (Li and Davis, 2009; Rice, 2012). To illustrate some of the conversion pathways, a simplified version of the nitrogen cycle (Grady, 2011) is depicted in Figure 2-1:

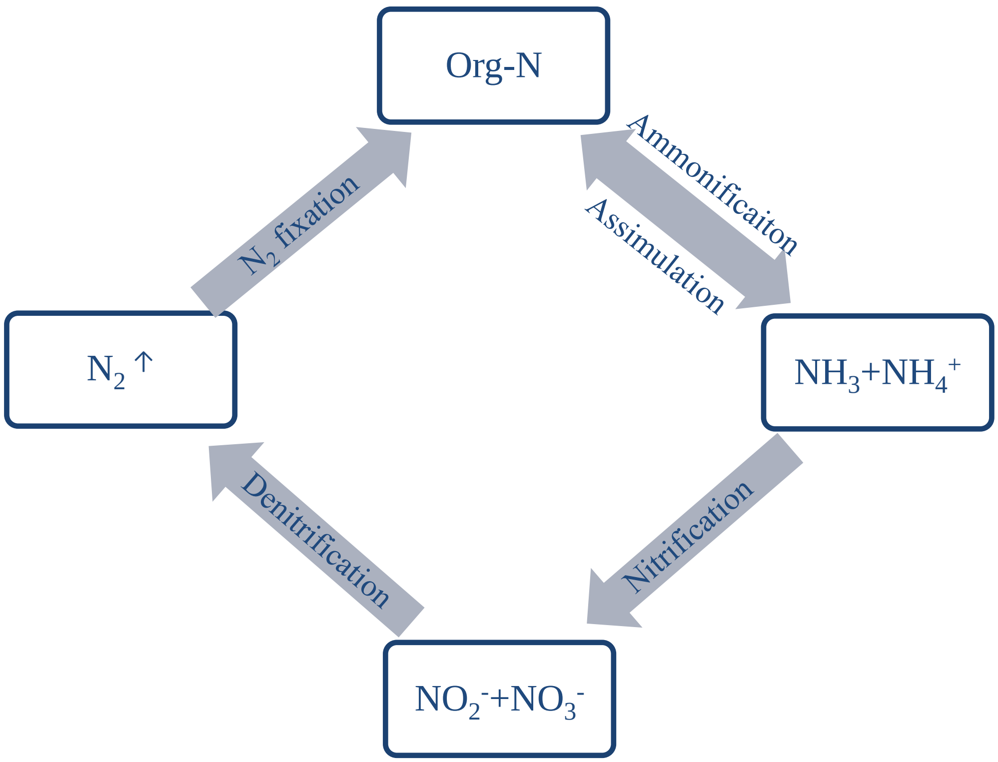


Figure 2-1. Simplified Nitrogen Cycle, Based on: Grady (2011).

Organic nitrogen is microbially converted into ammonia/ammonium and then nitrite/nitrate through the processes of ammonification and nitrification, respectively. These are the dominant microbial processes which occur under aerobic conditions in most stormwater BMPs.

Denitrification, or the conversion of oxidized nitrogen to gaseous nitrogen, which may be lost to the atmosphere, can only occur when anoxic, or oxygen deprived, conditions are established (Davis et al., 2006; Hunt et al., 2006; Davis, 2007; Lucas, W. C. and Greenway, M., 2011). Such anoxic conditions may occur naturally in small pockets within a conventionally drained stormwater BMP or may be engineered into the BMP as an internal water storage zone which promotes the conditions necessary for denitrification to occur (Davis et al., 2006; Hunt et al., 2006; Davis, 2007). Without the periodic presence of anoxic zones, microbes within stormwater BMPs may be expected to continuously oxidize available organic nitrogen and ammonia to nitrite and nitrate. In addition, because oxidized nitrogen forms are present as anions and are highly soluble, they do not readily sorb to the negatively charged soil media, and are usually lost from the BMP in a subsequent discharge (Benjamin, 2002; Burton, 2002; Davis et al., 2006; Davis et al., 2009). The exception, of course, occurs when anoxic conditions (in the presence of sufficient organic matter) are subsequently established in the BMP. It should be noted however, that even with the continuous conversion of organic nitrogen and ammonia nitrogen to oxidized nitrogen, total Kjeldahl nitrogen still typically dominates the total nitrogen balance within many stormwater BMPs (Davis et al., 2006).

In general, stormwater BMPs have been found to reduce total nitrogen loads mainly through the sorption of organic nitrogen to organic matter in the media. However, increases in oxidized nitrogen are frequently noted in the literature. When managed properly, the uptake of nutrients by vegetation within a BMP may also play a significant role in the removal of nutrients from incoming stormwater runoff (Davis et al., 2006; Davis et al., 2009; Lucas, W. C. and Greenway, M., 2011).

Total Suspended Solids Removal

Total suspended solids (TSS) removal is typically very high in stormwater BMPs which are designed to utilize sedimentation and infiltration processes (Davis, 2007; Davis et al., 2009). It should be noted that during an initial stabilization period in bioretention BMPs, TSS and other particulate-bound pollutants tend to be produced, instead of reduced, as fine soil media are washed out during the first few events (Davis, 2007).

Trace Metals Removal

Trace metals such as copper, cadmium, zinc and lead may be present in both dissolved and particulate forms in urban stormwater, and tend to be efficiently removed in bioretention BMPs. Particulate-bound metals may be removed through filtration and sedimentation processes. Depending on the physical and chemical composition of the media, dissolved metals such as copper, zinc and lead will also typically sorb to organic matter and soils present in the upper surface layers of the BMP media (Davis, 2007; Li and Davis, 2008; Davis et al., 2009).

Oil & Grease and Total Petroleum Hydrocarbons Removal

Oil and Grease components, including total petroleum hydrocarbons, typically exhibit high removals from stormwater runoff in bioretention BMPs. Oil and Grease components are initially removed through filtration and sorption to organic matter present in the media, followed by microbial degradation (Hsieh and Davis, 2005; Hsieh and Davis, 2005; Hong et al., 2006; Davis et al., 2009).

Chemical Oxygen Demand Removal

Chemical oxygen demand (COD) is often used as a surrogate measure for the removal efficiency of organic matter from stormwater runoff (Benjamin, 2002; Rice, 2012). The COD test provides a relatively quick, consistent estimate of the maximum oxygen (O_2) consumption that could be expected from the degradation of (mostly) organic constituents within a stormwater BMP (Benjamin, 2002). COD may be taken as indicative of the removal of organic matter through the processes of filtration and biological degradation. Conversely, if the stormwater BMP is leaching oxidizable materials such as organic matter, then increases in COD may be observed in the effluent (Ergas et al., 2010). Removal of biochemically oxidizable compounds from stormwater runoff is important to ensure that the potential oxygen demand is not exerted in downstream aquatic environments (Burton, 2002; Miller, 2002).

Total Dissolved Solids, Alkalinity and Hardness Removal

Total dissolved solids (TDS) is a measure of the nonvolatile dissolved species, principally comprised of the ions of inorganic salts such as calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+), potassium (K^+), bicarbonate (HCO_3^-), chloride (Cl^-), nitrate (NO_3^-) and sulfate (SO_4^{2-}) in stormwater runoff (Benjamin, 2002; Burton, 2002; Davis et al., 2009). High concentrations of some inorganic salts, such as sodium chloride (NaCl), may be expected in the runoff generated from roads, parking lots and sidewalks in regions that experience snow and ice during the winter season (Burton, 2002; Davis et al., 2009). The removal of such dissolved solids from stormwater is difficult due to their highly soluble nature (Benjamin, 2002; Burton, 2002). Some dissolved solids, however, may be more readily be removed from solution through processes such as precipitation, ion-exchange, absorption and biological transformation, depending on the physical and biogeochemical conditions within the BMP (Burton, 2002). Generally, little removal is expected, except for transformations due to pH change and REDOX reactions.

Alkalinity is a measure of the capacity of a water to resist changes in pH resulting from the introduction of acidic species. While most natural systems contain a variety of species capable of neutralizing acids, the dominant forms present in most natural systems are the carbonate (CO_3^{2-}) and bicarbonate (HCO_3^-) species. For computational simplicity, alkalinity is reported as mg/L as $CaCO_3$ (Benjamin, 2002; Rice, 2012). Increases or decreases in alkalinity within a stormwater BMP may be indicative of other processes occurring. For example, because the process of nitrification ($NH_4^+ \rightarrow NO_2^- \rightarrow NO_3^-$) consumes alkalinity and the process of denitrification ($NO_3^- \rightarrow N_2$) produces alkalinity (Grady, 2011), the analysis of alkalinity changes within a practice may give some insights into whether either process is occurring. If increases in oxidized nitrogen are occurring concurrently with decreases in alkalinity, the hypothesis of nitrification is strengthened. If alkalinity is not decreasing, then nitrification is not likely the dominant process by which oxidized nitrogen is being produced within the BMP. Conversely, if oxidized nitrogen is decreasing within the BMP, the hypothesis that denitrification is the dominate mechanism removing oxidized nitrogen from the BMP would be strengthened if increases in alkalinity were also observed. It should be noted that if both nitrification and denitrification are occurring within a BMP, the net change in alkalinity will likely be smaller than if either process was occurring alone.

Hardness is defined as the sum (expressed as mg/L of $CaCO_3$) of polyvalent cations present in a water sample. As a practical matter, this is most often taken to be the sum of the calcium (Ca^{2+}) and magnesium (Mg^{2+}) ions, because these are the most abundant. Depending on the alkalinity, the total hardness may be distributed between carbonate and non-carbonate) forms (Rice, 2012). Hardness may be removed or produced within a stormwater BMP through processes such as ion-exchange, sorption and biological transformation of calcium and magnesium ions, and is largely dependent on the biogeochemical soil conditions present in the media of a BMP (Clark et al., 2009).

Pollutant Removal Performance Reported in the Literature

Tables 2-2, 2-3 and 2-4 provide summaries of removal performances as found in the literature for studies employing bioretention cells, green roofs and porous asphalt, respectively, for stormwater management. A wide range of pollutant removal performances was reported for most water quality constituents from the LID stormwater management studies found in the literature.

Bioretention Performance

Table 2-2 presents summaries of reported bioretention performance from some recent studies reported in the literature using concentration-based and mass-based performance metrics. As may be seen from the individual studies in the table, wide ranges of pollutant removal performance are not uncommon for the constituents listed. In examining the mass-based results from the literature in Table 2-2, it may be seen that the median percent removals for TP, TN, TSS, Cu and Zn were 51%, 40%, 84%, 72% and 95%, respectively.

Virginia Department of Conservation and Recreation (2011) provides the EMC and load reduction credits, as a percent reductions, given to bioretention cells in Virginia for stormwater management. The credit given depends on design factors such as the surface area ratio between the bioretention cell and contributing drainage area, filter media depth, infiltration properties of surrounding subsoils and the amount of development within the watershed. Generally, bioretention cell designs are divided into two categories: level 1 and 2 design. While both level 1 and level 2 design bioretention cells are considered to provide stormwater treatment, level 2 designs are considered to provide greater treatment and are given greater reduction credits (Virginia Department of Conservation and Recreation, 2011). For total phosphorus (TP), level 1 design bioretention cells are given reduction credits of 25% and 55% for EMC and load reductions, respectively. For TP, level 2 design bioretention cells are given reduction credits of 50% and 90% for EMC and load reductions, respectively (Virginia Department of Conservation and Recreation, 2011). For total nitrogen (TN), level 1 design bioretention cells are given reduction credits of 40% and 64% for EMC and load reductions, respectively. For TN, level 2 design bioretention cells are given reduction credits of 60% and 90% for EMC and load reductions, respectively (Virginia Department of Conservation and Recreation, 2011).

As previously noted, wide ranges of pollutant removal performance are not uncommon for the constituents listed in Table 2-2. Median values for TP removal reported in the studies cited were 29% and 51% for EMC and load reductions, respectively. While these values compare well with the removal credits given by Virginia Department of Conservation and Recreation (2011) for level 1 design bioretention cells, they are substantially below the removal credits given for level 2 design bioretention cells.

Median values for TN removal reported in the studies cited in Table 2-2 were 41% and 40% for EMC and load reductions, respectively. While the median EMC reduction percentage value compared well with the removal credit given by Virginia Department of Conservation and Recreation (2011) for level 1 design bioretention cells, the median load reduction value was 20% lower than the level 1 design credit. Similar to TP, both EMC and load median removals in the studies cited were substantially below the removal credits given for level 2 design bioretention cells.

The wide ranges of pollutant removal performance reported within the literature and the divergence of the EMC and load removals from the credits provided to bioretention cells by the Virginia Department of Conservation and Recreation (2011) suggests monitoring and evaluation of individual bioretention cells may be warranted to ensure stormwater treatment goals are being achieved as designed.

Green Roof Performance

Table 2-3 presents summaries of reported green roof performance from some recent studies reported in the literature using concentration-based and mass-based performance metrics. Pollutant removal performances found in the literature typically compare discharge water quality from a green roof to either that of a comparable control roof or to the water quality of the rainfall without exposure to any type of roof surface. While some studies do address the effect of green roofs on the reduction or production of pollutant loads over the respective monitoring period, many only consider the effect of green roofs on the concentrations of pollutants within stormwater discharge. As may be seen from the individual studies cited, wide ranges of pollutant removal performance were reported for most water quality constituents from green roof studies reported in the literature. Mass-based percent removals for TP reported in the literature were between -1160% and 28%. Mass-based percent removals for nitrogen reported in the literature were between -123% and 91% for NO_3^--N, 76% for NO_2^--N, 15% for TKN, and 98% for NH_3-N + NH_4^+-N. Mass-based percent removals for solids reported in the literature were between -829% and -88% for total solids and 89% for TSS. Mass-based percent removals for Cu and Zn reported in the literature were 86% and 70%, respectively.

Porous Asphalt Performance

Table 2-4 presents summaries of reported porous asphalt performance from a recent study reported in the literature using the efficiency ratio performance metric. Roseen et al. (2009) reported reductions of 24%, -35%, 96% and 79% for TP, dissolved inorganic nitrogen (DIN), TSS and Zn, respectively, from a porous asphalt study site.

Table 2-2. Performance Removals for Bioretention Studies as found in the Literature.

Site Name	Type of Performance Analysis	Percent Removal (Conc.)	Percent Removal (Mass)	Reference
Summary of TP Removal from Bioretention Studies				
Greenbelt, Maryland	Change in Mean Conc.	65%		Davis et al. (2006)
Largo, Maryland	Change in Mean Conc.	87%		Davis et al. (2006)
Durham, New Hampshire	Efficiency Ratio (ER)	27%		Roseen et al. (2009)
Durham, New Hampshire	Efficiency Ratio (ER)	-38%		Roseen et al. (2009)
College Park, Maryland	Efficiency Ratio (ER)	74%		Davis (2007)
College Park, Maryland	Efficiency Ratio (ER)	68%		Davis (2007)
Charlotte, North Carolina	Efficiency Ratio (ER)	31%		Hunt et al. (2008)
Rocky Mount, North Carolina	Efficiency Ratio (ER)	-10%		Brown and Hunt III (2011b)
College Park, Maryland	Median Removal	-200%		Li and Davis (2009)
Silver Spring, Maryland	Median Removal	0%		Li and Davis (2009)
Greensboro, North Carolina	Summation of Loads (SOL)		-240%	Hunt et al. (2006)
Chapel Hill, North Carolina	Summation of Loads (SOL)		65%	Hunt et al. (2006)
Nashville, North Carolina	Summation of Loads (SOL)		5%	Brown and Hunt III (2011a)
Nashville, North Carolina	Summation of Loads (SOL)		44%	Brown and Hunt III (2011a)
College Park, Maryland	Summation of Loads (SOL)		80%	Li and Davis (2009)
Silver Spring, Maryland	Summation of Loads (SOL)		58%	Li and Davis (2009)
Summary of Orthophosphate Phosphorus (OP) Removal from Bioretention Studies				
Rocky Mount, North Carolina	Efficiency Ratio (ER)	64%		Brown and Hunt III (2011b)
Greensboro, North Carolina	Summation of Loads (SOL)		-9%	Hunt et al. (2006)
Chapel Hill, North Carolina	Summation of Loads (SOL)		69%	Hunt et al. (2006)
Nashville, North Carolina	Summation of Loads (SOL)		-37%	Brown and Hunt III (2011a)
Nashville, North Carolina	Summation of Loads (SOL)		-5%	Brown and Hunt III (2011a)
Summary of TN Removal from Bioretention Studies				
Greenbelt, Maryland	Change in Mean Conc.	49%		Davis et al. (2006)
Largo, Maryland	Change in Mean Conc.	59%		Davis et al. (2006)
Charlotte, North Carolina	Efficiency Ratio (ER)	32%		Hunt et al. (2008)

Table 2-2. Performance Removals for Bioretention Studies as found in the Literature (Continued).

Site Name	Type of Performance Analysis	Percent Removal (Conc.)	Percent Removal (Mass)	Reference
Rocky Mount, North Carolina	Efficiency Ratio (ER)	58%		Brown and Hunt III (2011b)
College Park, Maryland	Median Removal	-53%		Li and Davis (2009)
Silver Spring, Maryland	Median Removal	-10%		Li and Davis (2009)
Greensboro, North Carolina	Summation of Loads (SOL)		40%	Hunt et al. (2006)
Chapel Hill, North Carolina	Summation of Loads (SOL)		40%	Hunt et al. (2006)
Nashville, North Carolina	Summation of Loads (SOL)		12%	Brown and Hunt III (2011a)
Nashville, North Carolina	Summation of Loads (SOL)		13%	Brown and Hunt III (2011a)
College Park, Maryland	Summation of Loads (SOL)		73%	Li and Davis (2009)
Silver Spring, Maryland	Summation of Loads (SOL)		63%	Li and Davis (2009)
Summary of OxN Removal from Bioretention Studies				
Charlotte, North Carolina	Efficiency Ratio (ER)	-5%		Hunt et al. (2008)
Rocky Mount, North Carolina	Efficiency Ratio (ER)	58%		Brown and Hunt III (2011b)
Nashville, North Carolina	Summation of Loads (SOL)		-81%	Brown and Hunt III (2011a)
Nashville, North Carolina	Summation of Loads (SOL)		-142%	Brown and Hunt III (2011a)
Summary of Nitrate Nitrogen (NO_3^--N) Removal from Bioretention Studies				
Greenbelt, Maryland	Change in Mean Conc.	16%		Davis et al. (2006)
Largo, Maryland	Change in Mean Conc.	15%		Davis et al. (2006)
College Park, Maryland	Efficiency Ratio (ER)	79%		Davis (2007)
College Park, Maryland	Efficiency Ratio (ER)	86%		Davis (2007)
College Park, Maryland	Median Removal	-170%		Li and Davis (2009)
Silver Spring, Maryland	Median Removal	86%		Li and Davis (2009)
Greensboro, North Carolina	Summation of Loads (SOL)		75%	Hunt et al. (2006)
Chapel Hill, North Carolina	Summation of Loads (SOL)		13%	Hunt et al. (2006)
College Park, Maryland	Summation of Loads (SOL)		79%	Li and Davis (2009)
Silver Spring, Maryland	Summation of Loads (SOL)		95%	Li and Davis (2009)
Summary of Nitrite Nitrogen (NO_2^--N) Removal from Bioretention Studies				
College Park, Maryland	Median Removal	0%		Li and Davis (2009)

Table 2-2. Performance Removals for Bioretention Studies as found in the Literature (Continued).

Site Name	Type of Performance Analysis	Percent Removal (Conc.)	Percent Removal (Mass)	Reference
Silver Spring, Maryland	Median Removal	0%		Li and Davis (2009)
College Park, Maryland	Summation of Loads (SOL)		85%	Li and Davis (2009)
Silver Spring, Maryland	Summation of Loads (SOL)		70%	Li and Davis (2009)
Summary of Total Kjeldahl Nitrogen (TKN) Removal from Bioretention Studies				
Greenbelt, Maryland	Change in Mean Conc.	52%		Davis et al. (2006)
Largo, Maryland	Change in Mean Conc.	67%		Davis et al. (2006)
Charlotte, North Carolina	Efficiency Ratio (ER)	44%		Hunt et al. (2008)
Rocky Mount, North Carolina	Efficiency Ratio (ER)	58%		Brown and Hunt III (2011b)
College Park, Maryland	Median Removal	-11%		Li and Davis (2009)
Silver Spring, Maryland	Median Removal	-30%		Li and Davis (2009)
Greensboro, North Carolina	Summation of Loads (SOL)		-5%	Hunt et al. (2006)
Chapel Hill, North Carolina	Summation of Loads (SOL)		45%	Hunt et al. (2006)
Nashville, North Carolina	Summation of Loads (SOL)		39%	Brown and Hunt III (2011a)
Nashville, North Carolina	Summation of Loads (SOL)		58%	Brown and Hunt III (2011a)
College Park, Maryland	Summation of Loads (SOL)		73%	Li and Davis (2009)
Silver Spring, Maryland	Summation of Loads (SOL)		40%	Li and Davis (2009)
Summary of Ammonia Nitrogen (NH_3 -N) Removal from Bioretention Studies				
Greensboro, North Carolina	Summation of Loads (SOL)		-1%	Hunt et al. (2006)
Chapel Hill, North Carolina	Summation of Loads (SOL)		86%	Hunt et al. (2006)
Nashville, North Carolina	Summation of Loads (SOL)		78%	Brown and Hunt III (2011a)
Nashville, North Carolina	Summation of Loads (SOL)		79%	Brown and Hunt III (2011a)
Summary of Ammonium Nitrogen (NH_4^+ -N) Removal from Bioretention Studies				
Charlotte, North Carolina	Efficiency Ratio (ER)	73%		Hunt et al. (2008)
Summary of Organic Nitrogen (org-N) Removal from Bioretention Studies				
Rocky Mount, North Carolina	Efficiency Ratio (ER)	50%		Brown and Hunt III (2011b)
Nashville, North Carolina	Summation of Loads (SOL)		13%	Brown and Hunt III (2011a)
Nashville, North Carolina	Summation of Loads (SOL)		43%	Brown and Hunt III (2011a)

Table 2-2. Performance Removals for Bioretention Studies as found in the Literature (Continued).

Site Name	Type of Performance Analysis	Percent Removal (Conc.)	Percent Removal (Mass)	Reference
Summary of Dissolved Inorganic Nitrogen (DIN) Removal from Bioretention Studies				
Durham, New Hampshire	Efficiency Ratio (ER)	75%		Roseen et al. (2009)
Durham, New Hampshire	Efficiency Ratio (ER)	41%		Roseen et al. (2009)
Durham, New Hampshire	Efficiency Ratio (ER)	65%		Roseen et al. (2009)
Summary of Total Suspended Solids (TSS) Removal from Bioretention Studies				
Durham, New Hampshire	Efficiency Ratio (ER)	86%		Roseen et al. (2009)
Durham, New Hampshire	Efficiency Ratio (ER)	86%		Roseen et al. (2009)
Durham, New Hampshire	Efficiency Ratio (ER)	52%		Roseen et al. (2009)
College Park, Maryland	Efficiency Ratio (ER)	22%		Davis (2007)
College Park, Maryland	Efficiency Ratio (ER)	41%		Davis (2007)
Charlotte, North Carolina	Efficiency Ratio (ER)	60%		Hunt et al. (2008)
Rocky Mount, North Carolina	Efficiency Ratio (ER)	58%		Brown and Hunt III (2011b)
College Park, Maryland	Median Removal	88%		Li and Davis (2009)
Silver Spring, Maryland	Median Removal	88%		Li and Davis (2009)
Greensboro, North Carolina	Summation of Loads (SOL)		-170%	Hunt et al. (2006)
Nashville, North Carolina	Summation of Loads (SOL)		71%	Brown and Hunt III (2011a)
Nashville, North Carolina	Summation of Loads (SOL)		84%	Brown and Hunt III (2011a)
College Park, Maryland	Summation of Loads (SOL)		97%	Li and Davis (2009)
Silver Spring, Maryland	Summation of Loads (SOL)		93%	Li and Davis (2009)
Summary of Copper (Cu) Removal from Bioretention Studies				
Largo, Maryland	Change in Mean Conc.	43%		Davis et al. (2006)
Greenbelt, Maryland	Change in Mean Conc.	97%		Davis et al. (2006)
College Park, Maryland	Efficiency Ratio (ER)	51%		Davis (2007)
College Park, Maryland	Efficiency Ratio (ER)	57%		Davis (2007)
Charlotte, North Carolina	Efficiency Ratio (ER)	54%		Hunt et al. (2008)
College Park, Maryland	Median Removal	31%		Li and Davis (2009)
Silver Spring, Maryland	Median Removal	0%		Li and Davis (2009)

Table 2-2. Performance Removals for Bioretention Studies as found in the Literature (Continued).

Site Name	Type of Performance Analysis	Percent Removal (Conc.)	Percent Removal (Mass)	Reference
Greensboro, North Carolina	Summation of Loads (SOL)		99%	Hunt et al. (2006)
College Park, Maryland	Summation of Loads (SOL)		72%	Li and Davis (2009)
Silver Spring, Maryland	Summation of Loads (SOL)		63%	Li and Davis (2009)
Summary of Iron (Fe) Removal from Bioretention Studies				
Charlotte, North Carolina	Efficiency Ratio (ER)	-330%		Hunt et al. (2008)
Greensboro, North Carolina	Summation of Loads (SOL)		-13000%	Hunt et al. (2006)
Summary of Zinc (Zn) Removal from Bioretention Studies				
Largo, Maryland	Change in Mean Conc.	64%		Davis et al. (2003)
Greenbelt, Maryland	Change in Mean Conc.	>95%		Davis et al. (2003)
Durham, New Hampshire	Efficiency Ratio (ER)	95%		Roseen et al. (2009)
Durham, New Hampshire	Efficiency Ratio (ER)	80%		Roseen et al. (2009)
Durham, New Hampshire	Efficiency Ratio (ER)	72%		Roseen et al. (2009)
College Park, Maryland	Efficiency Ratio (ER)	57%		Davis (2007)
College Park, Maryland	Efficiency Ratio (ER)	63%		Davis (2007)
Charlotte, North Carolina	Efficiency Ratio (ER)	77%		Hunt et al. (2008)
College Park, Maryland	Median Removal	78%		Li and Davis (2009)
Silver Spring, Maryland	Median Removal	80%		Li and Davis (2009)
Greensboro, North Carolina	Summation of Loads (SOL)		98%	Hunt et al. (2006)
College Park, Maryland	Summation of Loads (SOL)		94%	Li and Davis (2009)
Silver Spring, Maryland	Summation of Loads (SOL)		95%	Li and Davis (2009)
Summary of Lead (Pb) Removal from Bioretention Studies				
Largo, Maryland	Change in Mean Conc.	70%		Davis et al. (2003)
Greenbelt, Maryland	Change in Mean Conc.	>95%		Davis et al. (2003)
College Park, Maryland	Efficiency Ratio (ER)	79%		Davis (2007)
College Park, Maryland	Efficiency Ratio (ER)	86%		Davis (2007)
Charlotte, North Carolina	Efficiency Ratio (ER)	31%		Hunt et al. (2008)
College Park, Maryland	Median Removal	55%		Li and Davis (2009)

Table 2-2. Performance Removals for Bioretention Studies as found in the Literature (Continued).

Site Name	**Type of Performance Analysis**	**Percent Removal (Conc.)**	**Percent Removal (Mass)**	**Reference**
Silver Spring, Maryland	Median Removal	0%		Li and Davis (2009)
Greensboro, North Carolina	Summation of Loads (SOL)		81%	Hunt et al. (2006)
College Park, Maryland	Summation of Loads (SOL)		86%	Li and Davis (2009)
Silver Spring, Maryland	Summation of Loads (SOL)		83%	Li and Davis (2009)
Summary of Total Petroleum Hydrocarbons-Diesel (TPH-D) Removal from Bioretention Studies				
Durham, New Hampshire	Efficiency Ratio (ER)	99%		Roseen et al. (2009)
Durham, New Hampshire	Efficiency Ratio (ER)	84%		Roseen et al. (2009)
Durham, New Hampshire	Efficiency Ratio (ER)	53%		Roseen et al. (2009)

Table 2-3. Performance Removals for Green Roof Studies as found in the Literature.

Site Name	Type of Performance Analysis	% (Conc)	% (Mass)	Reference
Summary of TP Removal from Green Roof Studies				
Southfield, MI	Mean Mass Removal[1]		28%	Carpenter and Kaluvakolanu (2011)
Southfield, MI	Mean Mass Removal[2]		-1160%	Carpenter and Kaluvakolanu (2011)
Toronto, Ontario	Unit Area Load Removal[3]		-248%	Van Seters et al. (2009)
Waterloo, Ontario	Mean Conc. Removal [4]	-548%		Linden and Stone (2009)
Waterloo, Ontario	Mean Conc. Removal [5]	-491%		Linden and Stone (2009)
Estonia	Mean Conc. Removal [6]	-2630%		Teemusk and Mander (2011)
Estonia	Mean Conc. Removal [7]	-1200%		Teemusk and Mander (2011)
Summary of TN Removal from Green Roof Studies				
Estonia	Mean Conc. Removal [6]	-55%		Teemusk and Mander (2011)
Estonia	Mean Conc. Removal [7]	-183%		Teemusk and Mander (2011)
Summary of $NO3^-$-N Removal from Green Roof Studies				
Southfield, MI	Mean Mass Removal[1]		21%	Carpenter and Kaluvakolanu (2011)
Southfield, MI	Mean Mass Removal[2]		-123%	Carpenter and Kaluvakolanu (2011)
Toronto, Ontario	Percent Difference Unit Area Load [3]		91%	Van Seters et al. (2009)
Estonia	Mean Conc. Removal [6]	30%		Teemusk and Mander (2011)
Estonia	Mean Conc. Removal [7]	5%		Teemusk and Mander (2011)
Summary of $NO2^-$-N Removal from Green Roof Studies				
Toronto, Ontario	Percent Difference Unit Area Load [3]		76%	Van Seters et al. (2009)
Summary of TKN Removal from Green Roof Studies				
Toronto, Ontario	Percent Difference Unit Area Load [3]		15%	Van Seters et al. (2009)
Summary of NH_3 -N + NH_4^+ -N Removal from Green Roof Studies				
Toronto, Ontario	Percent Difference Unit Area Load [3]		98%	Van Seters et al. (2009)
Summary of NH_4^+ -N Removal from Green Roof Studies				
Estonia	Mean Conc. Removal [6]	69%		Teemusk and Mander (2011)
Estonia	Mean Conc. Removal [7]	33%		Teemusk and Mander (2011)
Summary of Total Solids Removal from Green Roof Studies				
Southfield, MI	Mean Mass Removal[1]		-88%	Carpenter and Kaluvakolanu (2011)
Southfield, MI	Mean Mass Removal[2]		-829%	Carpenter and Kaluvakolanu (2011)

Table 2-3. Performance Removals for Green Roof Studies as found in the Literature (Continued).

Site Name	Type of Performance Analysis	% (Conc)	% (Mass)	Reference
Summary of Total Suspended Solids Removal from Green Roof Studies				
Toronto, Ontario	Percent Difference Unit Area Load [3]		89%	Van Seters et al. (2009)
Waterloo, Ontario	Mean Conc. Removal [4]	33%		Linden and Stone (2009)
Waterloo, Ontario	Mean Conc. Removal [5]	-143%		Linden and Stone (2009)
Summary of Total Dissolved Solids Removal from Green Roof Studies				
Waterloo, Ontario	Mean Conc. Removal [4]	-274%		Linden and Stone (2009)
Waterloo, Ontario	Mean Conc. Removal [5]	-908%		Linden and Stone (2009)
Summary of Chemical Oxygen Demand Solids Removal from Green Roof Studies				
Estonia	Mean Conc. Removal [6]	-140%		Teemusk and Mander (2011)
Estonia	Mean Conc. Removal [7]	-380%		Teemusk and Mander (2011)
Summary of Copper Removal from Green Roof Studies				
Toronto, Ontario	Percent Difference Unit Area Load [3]		86%	Van Seters et al. (2009)
Summary of Cadmium Removal from Green Roof Studies				
Toronto, Ontario	Percent Difference Unit Area Load [3]		52%	Van Seters et al. (2009)
Summary of Lead Removal from Green Roof Studies				
Toronto, Ontario	Percent Difference Unit Area Load [3]		53%	Van Seters et al. (2009)
Summary of Zinc Removal from Green Roof Studies				
Toronto, Ontario	Percent Difference Unit Area Load [3]		70%	Van Seters et al. (2009)
Summary of Hardness (as $CaCO_3$) Removal from Green Roof Studies				
Toronto, Ontario	Percent Difference Unit Area Load [3]		-121%	Van Seters et al. (2009)
Estonia	Mean Conc. Removal [6]	-2738%		Teemusk and Mander (2011)
Estonia	Mean Conc. Removal [7]	-2927%		Teemusk and Mander (2011)

[1] Green Roof vs. Asphalt Roof: The percent reduction between the green roof and asphalt roof was calculated using the mean value from each of the respective load datasets which were comprised of five storm events each (Carpenter and Kaluvakolanu, 2011).
[2] Green Roof vs. Stone-Ballasted Roof: The percent reduction between the green roof and stone-ballasted roof was calculated using the mean value from each of the respective load datasets which were comprised of five storm events each (Carpenter and Kaluvakolanu, 2011).
[3] Green Roof vs. Modified Bitumen Roof: Unit area loads from both roofs included sampled and unsampled events over the two year monitoring period. Sampled event loads were calculated by multiplying the sample concentration by the storm discharge volume. Unsampled events were estimated by multiplying the average concentration from the sampled events by the unsampled storm discharge volume. The overall unit area load was then calculated by summing the loads from the sampled and unsampled events for each roof. This method assumes that the mean concentration for the sampled and unsampled events is similar (Van Seters et al., 2009).
[4] Green Roof vs. Bitumen Roof: The percent reduction between the green and control roofs was calculated using the mean value from each of the respective

concentration datasets which were comprised of 18 storm events each (Linden and Stone, 2009).
[5] Green Roof vs. Rainfall: The percent reduction between the green roof and rainfall was calculated using the mean value from each of the respective concentration datasets which were comprised of 18 storm events each (Linden and Stone, 2009).
[6] Average of 8 Green Roofs vs. 1 Steel Roof: Discharge water quality was monitored from eight green roofs located across Estonia.
Each green roof was monitored during a single storm event which occurred between 2007 and 2009. The water quality results from all eight green roofs/events were averaged to arrive at an average value for the concentration of each water quality constituent (Teemusk and Mander, 2011). The average green roof concentrations were then compared to the discharge water quality results from a steel roof also monitored during a single event. A percent reduction value was assigned by comparing the average green roof concentration to the steel roof concentration for each water quality constituent.
[7] Average of 8 Green Roofs vs. 1 Rainfall Event: Discharge water quality was monitored from eight green roofs located across Estonia. Each green roof was monitored during a single storm event which occurred between 2007 and 2009. The water quality results from all eight green roofs/events were averaged to arrive at an average value for the concentration of each water quality constituent (Teemusk and Mander, 2011). The average green roof concentrations were then compared to rainfall concentrations also monitored during a single event. A percent reduction value was assigned by comparing the average green roof concentration to the rainfall concentration for each water quality constituent.

Table 2-4. Performance Removals for Porous Asphalt Studies as found in the Literature.

Summary of TP Removal from Porous Asphalt Study				
Site Name	Type of Performance Analysis	% (Conc)	% (Mass)	Reference
Durham, New Hampshire	Efficiency Ratio (ER)	24%		Roseen et al. (2009)
Summary of Dissolved Inorganic Nitrogen (DIN) Removal from Porous Asphalt Study				
Durham, New Hampshire	Efficiency Ratio (ER)	-35%		Roseen et al. (2009)
Summary of Total Suspended Solids (TSS) Removal from Porous Asphalt Study				
Durham, New Hampshire	Efficiency Ratio (ER)	96%		Roseen et al. (2009)
Summary of Zinc (Zn) Removal from Porous Asphalt Study				
Durham, New Hampshire	Efficiency Ratio (ER)	79%		Roseen et al. (2009)
Summary of Total Petroleum Hydrocarbons-Diesel (TPH-D) Removal from Porous Asphalt Study				
Durham, New Hampshire	Efficiency Ratio (ER)	100%		Roseen et al. (2009)

2.12 Consideration of BMP Seasonal Performance

Seasonal performance of stormwater management practices must be considered during the design phase of a development. If located where cold climate conditions occur during the winter months, special considerations, including the hydrology and pollutant loads of snowmelt and the temperature dependency of aquatic chemistry, water density and ion exchange capacity must be taken into account to ensure proper water resource protection (Roseen et al., 2009). Seasonal variation in the performance of infiltration based BMPs can be attributed to changes in evapotranspiration, root uptake, mechanical root activity, activity of burrowing insects such as earthworms and the temperature dependence of hydraulic conductivity (Emerson and Traver, 2008).

Emerson and Traver (2008) proposed that decreased winter performance can be mainly attributed to the temperature dependency of hydraulic conductivity (due to temperature induced changes in the viscosity of water) and all other mechanisms of decreased infiltration performance are insignificant in comparison. Emerson and Traver (2008) continuously monitored a bioinfiltration traffic island and a pervious concrete infiltration basin located on the campus of Villanova University over a two year period to assess the long-term and seasonal changes in the infiltration process at both BMPs. Both infiltration based BMPs showed considerable seasonal variation, with decreased performance achieved during the colder winter months, however neither exhibited evidence of a systematic decrease in performance during the monitoring period. It should be noted the monitoring period did not include the first 1.5 years of BMP operation and likely missed any decreased infiltration performance associated with the startup period expected for some BMPs as the soil surface develops (Emerson and Traver, 2008).

Roseen et al. (2009) monitored 15 stormwater management practices located at the University of New Hampshire Stormwater Center (UNHSC) field facility between August 2004 and August 2006 and examined seasonal variations in contaminant removal and hydraulic performance. The practices included three conventional BMPs (a stone-lined swale, a vegetated swale and a retention pond), six LID BMPs (a surface sand filter, two bioretention systems, a subsurface gravel wetland, a street tree and porous asphalt), and seven proprietary manufactured systems (two treatment trains including a hydrodynamic separator followed by a filter system, a multi-chambered pretreatment system followed by a large subsurface infiltration device, and three hydrodynamic separators). Seasons were assigned as 6-month intervals with summer occurring May-October and winter occurring November-April. Roseen et al. (2009) assessed seasonal hydraulic performance by monitoring storm events and evaluating the runoff hydrograph using coefficients of the lag time and peak flow reduction, thereby considering the overall hydraulic efficiency of the BMP for a given storm event. The stone-lined swale was the only BMP for which a pronounced decline in winter performance was observed for both peak flow and lag time. Impacts from the cold climate conditions were observed for the remaining 14 BMPs however they were not substantial with regard to changes in the hydraulic efficiencies. Roseen et al. (2009) noted that the observed impacts from the cold climate conditions may be attributable to seasonal differences in rainfall pattern which were not accounted for or due to changes in water viscosity. Seasonal and annual EMCs from rainfall events were calculated and compared using removal efficiencies and efficiency ratios for water quality parameters including total suspended solids, total petroleum hydrocarbons-diesel range, dissolved inorganic nitrogen (nitrate, nitrite and ammonia), total phosphorus and total zinc. With the exception of nitrate, seasonal pollutant removal performance varied little for the filtration systems, infiltration systems and retention pond. In contrast, the hydrodynamic separators and the stone-line swale had noticeable seasonal performance declines during the winter months. Overall, the performance evaluations indicate that the LID BMPs maintain a high level of hydraulic and contaminant removal performance during the winter months (with the exception of poor nitrate removal) and that frozen filter media did not appear to reduce performance. It should be noted that stone-lined swales and hydrodynamic separators both showed decreased performance during the winter months and alternative stormwater management practices should be considered when cold climate conditions are expected at the site (Roseen et al., 2009).

Roseen et al. (2012) examined the hydraulic and water quality performance of a porous pavement stormwater management system in coastal New Hampshire from 2004 to 2008. Although significant frost penetration was observed, there was no consistent statistical difference between seasonal performances for the porous pavement system. In addition, adverse freeze-thaw effects such as heaving, typical of conventional parking lot pavements, were not observed during the monitoring period indicating a longer life cycle for the porous pavement than is expected from conventional pavements in cold climate conditions.

Hunt et al. (2006) found mass removal rates to be greater during warmer seasons (spring, summer and fall) compared to colder seasons (winter) for three bioretention sites in North Carolina. The difference between warm- and cold-season pollutant load removals was determined to be caused by decreases in stormwater volume reduction during the winter due to decreased exfiltration and evapotranspiration within the bioretention cells.

2.13 Consideration of Construction Practices

Construction processes may be optimized to promote better BMP performance through relatively simple techniques. Certain excavation techniques and soil-moisture conditions can cause higher levels of soil compaction which will decrease the infiltration rates of the soils surrounding an infiltration BMP and negatively affect the exfiltration rate of infiltrated stormwater out of the BMP. Brown and Hunt III (2010) demonstrated the effect of excavating a bioretention cell pit using a “rake” vs. “scoop” method during dry and wet soil moisture conditions in both sandy and clayey soils. The rake excavation technique used the teeth of the backhoe bucket to scarify and till the final 30 cm (12 in.) of the pit surface. The more conventional scoop excavation technique is consistent with sewer and utility line placement where the surface is smoothed and compacted to minimize shifting and settling. Each excavation technique was used during dry and wet soil-moisture conditions for a sandy and a clayey soil site. Compared to the scoop method, the rake method created more pore spaces which promoted exfiltration of water into the underlying soils. The difference was most evident in wet conditions, where the hydraulic conductivity and infiltration rate of the rake method were significantly greater than that of the scoop method with p-values of 0.005 and 0.034, respectively. During dry conditions, there was no statistically significant difference between excavation techniques. Based on the study results, and because no additional cost is associated with the rake method, Brown and Hunt III (2010) recommended the use of the rake method over the scoop method and suggests excavation activities take place during dry soil-moisture conditions in all but pure sand soil environments.

2.14 Cost Considerations and Estimates

Cost considerations and estimates are an important aspect of increasing the use and deployment of low impact development (LID) designs and BMPs by public- and private-sector developers (EPA, 2007; Houdeshel et al., 2011). Life-cycle costs which include capital, maintenance and operating costs should be estimated during site design. The Water Environment Research Foundation (WERF), in collaboration with the United Kingdom Water Industry Research

(UKWIR) and the U.S. Environmental Protection Agency (EPA), developed a whole-life-cost (WLC) estimation spreadsheet tool designed to assist in planning-level cost estimations for LID designs and BMPs (Water Environment Research Foundation, 2009; Houdeshel et al., 2011). The WLC tool includes cost estimating models for stormwater BMPs including retention ponds, planted swales, extended detention basins, permeable pavers, green roofs, residential rain gardens, parking-lot-scale curb-contained bioretention, in-curb planter vaults and cisterns collecting runoff from commercial buildings. The WLC spreadsheet tool is currently available at no cost at www.werf.org/bmpcost (Water Environment Research Foundation, 2009; Houdeshel et al., 2011).

In an analysis of 17 case studies using LID design practices and BMP installations, EPA (2007) concluded that applying LID techniques can reduce development costs while improving environmental performance compared to traditional stormwater management approaches. Construction cost savings are typically achieved from reductions in infrastructure requirements associated with conventional stormwater management, such as curb and gutter conveyance systems and large retention ponds. Some LID practices, such as bioretention cells and roof gardens, were reported to increase construction costs due to increased design, material and labor costs (EPA, 2007). However, it was reported that the WLC analysis, which included the downstream environmental benefits, found that the increased initial capital costs were offset through longer-term cost savings. The cost savings identified included reduced downstream flooding and property damage, reduced cleanups and need for stream bank restorations associated with increased erosion and sediment loads from urbanized watersheds and the potential of increased real estate value and property tax revenue generated from more aesthetically pleasing properties which utilize LID design and BMPs (EPA, 2007; Guo et al., 2010; Houdeshel et al., 2011). Maintenance requirements and costs should also be considered when determining the BMPs to implement (EPA, 1999; Sansalone and Teng, 2004; EPA, 2007; Houdeshel et al., 2011). Maintenance can be broken down into two primary categories: functional maintenance and aesthetic maintenance (EPA, 1999; Davis et al., 2009). Functional maintenance is important for BMP performance and safety reasons, while aesthetic maintenance is important primarily for public acceptance of the BMP. It should be noted that some BMPs require infrequent but costly maintenance while others need more frequent but less costly maintenance to ensure long-term performance (EPA, 1999). EPA (1999) provides recommended maintenance schedules and estimates of annual maintenance costs for some common BMPs including bioretention cells, grass swales and retention ponds, and may be helpful in the planning-level determination of BMP operation and maintenance requirements and costs. For example, EPA (1999) reported maintenance activities for bioretention practices should include the repair of eroded areas, mulching of void areas, removal and replacement of all dead and diseased vegetation, watering of plant material and replacement of mulch layers. While some maintenance activities should be completed on an as needed basis, others are expected to be required on a bi-annual or annual basis. The annual maintenance cost for bioretention practices are estimated to less than 1% of the cost to construct the practice (EPA, 1999).

Williams and Wise (2009) evaluated four alternative development scenarios for the Gainesville, Florida residential market from November 1999 to October 2001 using a hedonic price analysis technique to estimate the ratio of construction cost to buyer valuation:

- *Traditional Development* - Development with a conventional curb and gutter stormwater conveyance system with larger lot sizes, and no deliberate attempt to apply site planning concepts for increased water resource protection;

- *Cluster Development* **-** Development with a conventional curb and gutter stormwater conveyance system (similar to Traditional Development), however smaller lot sizes and reductions in impervious surfaces are prioritized at the site planning level to increase preservation of natural open spaces and thereby decrease impacts of development on water resources;

- *Partial LID* **-** Traditional Development with a decentralized infiltration based stormwater conveyance system with retention storage in swales and raingardens;

- *Full LID* **-** Cluster development with a decentralized infiltration based stormwater conveyance system with retention storage in swales and raingardens.

The hedonic price analysis showed that, while all four development alternatives were economically viable, some provided greater returns on investment. For example, while the LID stormwater conveyance system variable reduced construction costs, it also reduced buyer valuations. Consequently, it did not perform well when coupled with the traditional development design because the decrease in construction costs was outweighed by the decrease in buyer valuation when compared to the traditional development with a conventional stormwater conveyance system alternative. The authors suggested that higher buyer valuation of conventional curb and gutter conveyance systems may be attributable to a perceived higher standard of engineering compared to the grass swales and rain gardens present with LID practices. While the buyer valuations of Traditional vs. Cluster development design with and without LID stormwater conveyance were specific to the particular study area and time frame, some general conclusions may be made. Developers using LID, clustering or any other alternative development practice must consider buyer valuation along with capital, maintenance and operational costs when determining the site planning method to be implemented in order to meet water resource protection goals while achieving a satisfactory return on investment (Williams and Wise, 2009; Houdeshel et al., 2011). Additionally, it has been noted that local government officials may not look favorably on development alternatives which decrease property values and consequent tax revenues (Williams and Wise, 2009). Others, however, note that lost tax revenues may be recouped by decreased costs associated with the avoidance of aquatic habitat restorations and flood damage mitigated by LID designs and BMPs (EPA, 2007; Williams and Wise, 2009; Houdeshel et al., 2011). Simulation-Optimization approaches for watershed development design can be used to give developers, policy makers and the public additional choices during the design phase of development in a watershed. Having several alternative development solutions which perform similarly well with respect to water resource protection and financially but are maximally different in design choices enables a wide variety of options to be available (Reichold et al., 2010; Lee et al., 2012; McGarity, 2012).

2.15 The International Stormwater Best Management Practices (*BMP*) *Database*

In 1996, the U.S. Environmental Protection Agency (EPA) entered into a cooperative agreement with the American Society of Civil Engineers (ASCE) and the Urban Water Resources Research Council (UWRRC) to initiate the International Stormwater Best Management Practice (BMP) Database project (Geosyntec and WWE, 2009; Clary et al., 2011). The goals of the database project included the development of a standardized set of monitoring and reporting protocols for urban stormwater BMP performance studies and assembling and summarizing previously conducted and on-going BMP study data into a standardized format to support performance analysis (Geosyntec and WWE, 2009; Clary et al., 2011).

When submitting a LID study to the International Stormwater BMP Database, data must be entered in accordance with reporting protocols specified in an Excel spreadsheet package downloadable from http://www.bmpdatabase.org/DataEntry.htm. General test site information is used to identify the study, its location, climate characteristics and involved parties. Watershed information such as soil type, land use, imperviousness, hydraulically connected imperviousness and other factors related to storm drainage system efficiency are used to identify the conditions in the area tributary to the BMP. General information and cost data for BMPs include parameters such as the date of installation; various basic design parameters; maintenance and rehabilitation types and frequencies; and capital, installation and maintenance costs. Monitoring data requested includes precipitation, flow and water quality data (Clary et al., 2011).

In addition, each BMP study in the database contains a Detailed Statistical Analysis Report (DSAR) for each monitored parameter which provides guidance about the efficiency of the treatment practice. The DSAR includes the following assessments (Geosyntec and WWE, 2009):

1) Arithmetic estimate of the mean inflow and outflow EMC;

2) Bootstrap estimate of the mean inflow and outflow EMC;

3) Data plots such as time series plots, box plots and probability plots;

4) Summary of distributional characteristics;

5) Hypothetical test results from non-parametric analysis;

6) Hypothetical test results for parametric analysis;

7) Test of Equal Variance.

For more detailed information on database requirements, procedures and guidelines are outlined on the International Stormwater BMP Database website http://www.bmpdatabase.org/ or in the relevant literature including Geosyntec and WWE (2009) and Clary et al. (2011). Consideration of the various requirements for inclusion of a LID site research data to the International Stormwater BMP Database should be taken into account during the stages of planning, implementation and evaluation.

2.16 References

Barber, M. E., King, S. G., Yonge, D. R. and Hathhorn, W. E. (2003). "Ecology Ditch: A Best Management Practice for Storm Water Runoff Mitigation." Journal of Hydrologic Engineering **8**(3): 111-122.

Bedient, P. B. H., Wayne C. (2002). Hydrology and Floodplain Analysis, Third Edition. Upper Saddle River, NJ, Prentice Hall.

Benjamin, M. M. (2002). Water Chemistry, McGraw-Hill.

Beyerlein, D. (2008). LID Analysis Considerations in Western Washington. Low Impact Development for Urban Ecosystem and Habitat Protection**:** 1-9.

Brown, R. and Hunt III, W. (2010). "Impacts of Construction Activity on Bioretention Performance." Journal of Hydrologic Engineering **15**(6): 386-394.

Brown, R. and Hunt III, W. (2011a). "Impacts of Media Depth on Effluent Water Quality and Hydrologic Performance of Undersized Bioretention Cells." Journal of Irrigation and Drainage Engineering **137**(3): 132-143.

Brown, R. and Hunt III, W. (2011b). "Underdrain Configuration to Enhance Bioretention Exfiltration to Reduce Pollutant Loads." Journal of Environmental Engineering **137**(11): 1082-1091.

Burton, G. A., Jr.; and Pitt, R. E. (2001). Stormwater Effects Handbook: A Toolbox for Watershed Managers, Scientists, and Engineers. Lewis Publishers.

Burton, G. A., Jr.; Pitt, Robert E. (2002). Stormwater Effects Handbook, Lewis Publishers.

Carpenter, D. D. and Hallam, L. (2010). "Influence of Planting Soil Mix Characteristics on Bioretention Cell Design and Performance." Journal of Hydrologic Engineering **15**(6): 404-416.

Carpenter, D. D. and Kaluvakolanu, P. (2011). "Effect of Roof Surface Type on Storm-Water Runoff from Full-Scale Roofs in a Temperate Climate." Journal of Irrigation and Drainage Engineering **137**(3): 161-169.

Cates, E. L., Westphal, M. J., Cox, J. H., Calabria, J. and Patch, S. C. (2009). "Field Evaluation of a Proprietary Storm-Water Treatment System: Removal Efficiency and Relationships to Peak Flow, Season, and Dry Time." Journal of Environmental Engineering **135**(7): 511-517.

Chi-Feng, C., Jen-Yang, L., Chih-Hong, H., Way-Ling, C. and Nai-Ling, C. (2009). "Performance evaluation of a full-scale natural treatment system for nonpoint source and point source pollution removal." Environmental Monitoring & Assessment **157**(1-4): 391-406.

Chung, W., Wang, I. and Wang, R. (2010). "Theory-Based SCS-CN Method and Its Applications." Journal of Hydrologic Engineering **15**(12): 1045-1058.

Clark, S. E., Mikula, J. B., Baker, K. H. and Treese, D. P. (2009). Pollutant Transport within the Vadose Zone: Interactions of Soil Horizon Chemistry on Water Quality. World Environmental and Water Resources Congress 2009**:** 1-9.

Clark, S. E. and Pitt, R. (2010). Considerations in Selecting a (Bio)Filtration Media to Optimize Lifespan and Pollutant Removal, ASCE.

Clary, J., Quigley, M., Poresky, A., Earles, A., Strecker, E., Leisenring, M. and Jones, J. (2011). "Integration of Low-Impact Development into the International Stormwater BMP Database." Journal of Irrigation and Drainage Engineering **137**(3): 190-198.

Davis, A. P. (2007). "Field Performance of Bioretention: Water Quality." Environmental Engineering Science **24**(8): 1048-1064.

Davis, A. P. (2008). "Field Performance of Bioretention: Hydrology Impacts." Journal of Hydrologic Engineering **13**(2): 90-95.

Davis, A. P., Hunt, W. F., Traver, R. G. and Clar, M. (2009). "Bioretention Technology: Overview of Current Practice and Future Needs." Journal of Environmental Engineering **135**(3): 109-117.

Davis, A. P., Shokouhian, M., Sharma, H. and Minami, C. (2006). "Water Quality Improvement through Bioretention Media: Nitrogen and Phosphorus Removal." Water Environment Research **78**(3): 284-293.

Davis, A. P., Shokouhian, M., Sharma, H., Minami, C. and Winogradoff, D. (2003). "Water Quality Improvement through Bioretention: Lead, Copper, and Zinc Removal." Water Environment Research **75**(1): 73-82.

DeBusk, K. M., Hunt, W. F. and Line, D. E. (2011). "Bioretention Outflow: Does It Mimic Nonurban Watershed Shallow Interflow?" Journal of Hydrologic Engineering **16**(3): 274-279.

Denich, C. and Bradford, A. (2010). "Estimation of Evapotranspiration from Bioretention Areas Using Weighing Lysimeters." Journal of Hydrologic Engineering **15**(6): 522-530.

Emerson, C. H. and Traver, R. G. (2008). "Multiyear and Seasonal Variation of Infiltration from Storm-Water Best Management Practices." Journal of Irrigation and Drainage Engineering **134**(5): 598-605.

EPA, U. S. (1999) "Preliminary Data Summary of Urban Stormwater Best Management Practices"

EPA, U. S. (2000). "Low Impact Development (LID) - A Literature Review."

EPA, U. S. (2007). “Reducing Stormwater Costs through Low Impact Development (LID) Strategies and Practices.” Nonpoint Source Control Branch.

EPA, U. S. E. P. A. (1983). “Results of the Nationwide Urban Runoff Program: Volume 1 - Final Report.”

EPA, U. S. E. P. A. (1992). “National Pollutant Discharge Elimination System Stormwater Sampling Guidance Document.”

Ergas, S., Sengupta, S., Siegel, R., Pandit, A., Yao, Y. and Yuan, X. (2010). “Performance of Nitrogen-Removing Bioretention Systems for Control of Agricultural Runoff.” Journal of Environmental Engineering **136**(10): 1105-1112.

Gallagher, D. (2011). “VT CEE 5724 Environmental Monitoring and Sampling Lecture Spring 2011.”

Geosyntec and WWE, Geosyntec Consultants, Wright Water Engineers, Inc. (2009) “Urban Stormwater BMP Performance Monitoring” U.S. Environmental Protection Agency Prepared with support from the U.S. EPA, Water Environmental Research Foundation, Federal Highway Administration, and the Environmental and Water Resources Institute of the American Society of Civil Engineers, http://www.bmpdatabase.org

Giacomoni, M. H., Zechman, E. M. and Brumbelow, K. (2012). “Hydrologic Footprint Residence: Environmentally Friendly Criteria for Best Management Practices.” Journal of Hydrologic Engineering **17**(1): 99-108.

Grady, C. P. L., Jr; Daigger, Glen T.; Love, Nancy G.; Filipe, Carlos D.M. (2011). Biological Wastewater Treatment, IWA Publishing.

Guo, J. C. Y. (2010). “Preservation of Watershed Regime for Low-Impact Development through Detention.” Journal of Hydrologic Engineering **15**(1): 15-19.

Guo, J. C. Y., Blackler, G. E., Earles, T. A. and MacKenzie, K. (2010). “Incentive Index Developed to Evaluate Storm-Water Low-Impact Designs.” Journal of Environmental Engineering **136**(12): 1341-1346.

Guo, J. C. Y. and Cheng, J. Y. C. (2008). “Retrofit Storm Water Retention Volume for Low Impact Development.” Journal of Irrigation and Drainage Engineering **134**(6): 872-876.

He, Z. and Davis, A. P. (2009). Unit Process Modeling of Stormwater Flow and Pollutant Sorption in a Bioretention Cell, ASCE.

Helsel, D. R. (2012). “Statistics for Censored Environmental Data Using Minitab and R.”

Helsel, D. R. and Hirsch, R. M. (2002). “Statistical Methods in Water Resources Techniques of Water Resources Investigations.” U.S. Geological Survey **Book 4**(chapter A3).

Hong, E., Seagren, E. A. and Davis, A. P. (2006). "Sustainable Oil and Grease Removal from Synthetic Stormwater Runoff Using Bench-Scale Bioretention Studies." Water Environment Research **78**(2): 141-155.

Houdeshel, C. D., Pomeroy, C. A., Hair, L. and Moeller, J. (2011). "Cost-Estimating Tools for Low-Impact Development Best Management Practices: Challenges, Limitations, and Implications." Journal of Irrigation and Drainage Engineering **137**(3): 183-189.

Hsieh, C.-h. and Davis, A. P. (2003). Evaluation of Bioretention for Treatment of Urban Storm Water Runoff, ASCE.

Hsieh, C.-h. and Davis, A. P. (2005). "Evaluation and Optimization of Bioretention Media for Treatment of Urban Storm Water Runoff." Journal of Environmental Engineering **131**(11): 1521-1531.

Hsieh, C. H. and Davis, A. P. (2005). "Multiple-event study of bioretention for treatment of urban storm water runoff." Water Science & Technology **51**(3/4): 177-181.

Hunt, W. F., Jarrett, A. R., Smith, J. T. and Sharkey, L. J. (2006). "Evaluating Bioretention Hydrology and Nutrient Removal at Three Field Sites in North Carolina." Journal of Irrigation and Drainage Engineering **132**(6): 600-608.

Hunt, W. F., Smith, J. T., Jadlocki, S. J., Hathaway, J. M. and Eubanks, P. R. (2008). "Pollutant Removal and Peak Flow Mitigation by a Bioretention Cell in Urban Charlotte, N.C." Journal of Environmental Engineering **134**(5): 403-408.

Kim, H., Seagren, E. A. and Davis, A. P. (2003). "Engineered Bioretention for Removal of Nitrate from Stormwater Runoff." Water Environment Research **75**(4): 355-367.

Lamont, S., Eli, R. and Fletcher, J. (2008). "Continuous Hydrologic Models and Curve Numbers: A Path Forward." Journal of Hydrologic Engineering **13**(7): 621-635.

Lee, J. G., Selvakumar, A., Alvi, K., Riverson, J., Zhen, J. X., Shoemaker, L. and Lai, F.-h. (2012). "A watershed-scale design optimization model for stormwater best management practices." Environmental Modelling & Software **37**(0): 6-18.

LeFevre, N.-J. B., David W. Watkins, J., Gierke, J. S. and Brophy-Price, J. (2010). "Hydrologic Performance Monitoring of an Underdrained Low-Impact Development Storm-Water Management System." Journal of Irrigation and Drainage Engineering **136**(5): 333-339.

Lenhart, H. A. and Hunt, W. F. (2011). "Evaluating Four Storm-Water Performance Metrics with a North Carolina Coastal Plain Storm-Water Wetland." Journal of Environmental Engineering **137**(2): 155-162.

Lenhart, J. H. (2007). BMP Performance Expectation Functions – A Simple Method for Evaluating Stormwater Treatment BMP Performance Data. 9th Biennial Conference on Stormwater Research & Watershed Management.

Li, H. and Davis, A. (2009). "Water Quality Improvement through Reductions of Pollutant Loads Using Bioretention." Journal of Environmental Engineering **135**(8): 567-576.

Li, H. and Davis, A. P. (2008). "Heavy Metal Capture and Accumulation in Bioretention Media." Environmental Science & Technology **42**(14): 5247-5253.

Linden, K. V. and Stone, M. (2009). "Treatment Performance of an Extensive Vegetated Roof in Waterloo, Ontario." Water Quality Research Journal of Canada **44**(1): 26-32.

Lucas, W. and Greenway, M. (2011). "Phosphorus Retention by Bioretention Mesocosms Using Media Formulated for Phosphorus Sorption: Response to Accelerated Loads." Journal of Irrigation and Drainage Engineering **137**(3): 144-153.

Lucas, W. C. (2010). "Design of Integrated Bioinfiltration-Detention Urban Retrofits with Design Storm and Continuous Simulation Methods." Journal of Hydrologic Engineering **15**(6): 486-498.

Lucas, W. C. and Greenway, M. (2011). "Hydraulic Response and Nitrogen Retention in Bioretention Mesocosms with Regulated Outlets: Part IINitrogen Retention." Water Environment Research **83**(8): 703-713.

Ma, J., Kang, J., Kayhanian, M. and Stenstrom, M. (2009). "Sampling Issues in Urban Runoff Monitoring Programs: Composite versus Grab." Journal of Environmental Engineering **135**(3): 118-127.

McCuen, R. H. (2003). "Smart Growth: Hydrologic Perspective." Journal of Professional Issues in Engineering Education and Practice **129**(3): 151-154.

McGarity, A. E. (2012). "Storm-Water Investment Strategy Evaluation Model for Impaired Urban Watersheds." Journal of Water Resources Planning and Management **138**(2): 111-124.

McNett, J. K., Hunt, W. F. and Davis, A. P. (2011). "Influent Pollutant Concentrations as Predictors of Effluent Pollutant Concentrations for Mid-Atlantic Bioretention." Journal of Environmental Engineering **137**(9): 790-799.

Miller, G. T., Jr. (2002). Living in the Environment, Brooks/Cole Thomas Learning.

Minton, G. (2005). Stormwater Treatment - Biological, Chemical, and Engineering Principles, Resource Planning Associates.

Montgomery, D. C. and Runger, G. C. (1999). Applied Statistics and Probability for Engineers, John Wiley & Sons, Inc.

NRCS, USDA Natural Resources Conservation Service (1986). "Urban Hydrology for Small Watersheds TR-55."

O'Neill, S. W. and Davis, A. P. (2010). Analysis of Bioretention Media Specifications and Relationships to Overall Performance, ASCE.

Ogden, F. L., Downer, C. W., Pradhan, N. R. and Nelson, E. J. (2011). Predicting Hydrologic Effects of Land-Use Change: Problems with the Curve Number Approach. World Environmental and Water Resources Congress 2011**:** 4801-4810.

Palhegyi, G. E. (2010a). "Designing Storm-Water Controls to Promote Sustainable Ecosystems: Science and Application." Journal of Hydrologic Engineering **15**(6): 504-511.

Palhegyi, G. E. (2010b). "Modeling and Sizing Bioretention Using Flow Duration Control." Journal of Hydrologic Engineering **15**(6): 417-425.

Pitt, R., Clark, S. and Steets, B. (2010). Evaluation of the Contaminant Removal Potential of Biofiltration Media, ASCE.

Pitt, R., Nara, Y., Kirby, J. and Durrans, S. R. (2007). Particulate Transport in Grass Swales, ASCE.

Ponce, V. and Hawkins, R. (1996). "Runoff Curve Number: Has It Reached Maturity?" Journal of Hydrologic Engineering **1**(1): 11-19.

Quigley, M. M., Strecker, E. W., Leisenring, M., Huber, W. C., Heaney, J., Weinstein, N., Sansalone, J. and Bodine, D. (2005). The Integrated Unit Process Design Approach for Urban Water Quality Design, ASCE.

Reichold, L., Zechman, E. M., Brill, E. D. and Holmes, H. (2010). "Simulation-Optimization Framework to Support Sustainable Watershed Development by Mimicking the Predevelopment Flow Regime." Journal of Water Resources Planning and Management **136**(3): 366-375.

Rice, E. B., Rodger; Eaton, Andrew; Clesceri, Lenore (2012). Standard Methods For the Examination of Water and Wastewater, American Public Health Association; American Water Works Association; Water Environment Federation.

Roesner, L. A., Bledsoe, B. P. and Brashear, R. W. (2001). "Are Best-Management-Practice Criteria Really Environmentally Friendly?" Journal of Water Resources Planning and Management **127**(3): 150-154.

Roseen, R. M., Ballestero, T. P., Houle, J. J., Avellaneda, P., Briggs, J., Fowler, G. and Wildey, R. (2009). "Seasonal Performance Variations for Storm-Water Management Systems in Cold Climate Conditions." Journal of Environmental Engineering **135**(3): 128-137.

Roseen, R. M., Ballestero, T. P., Houle, J. J., Briggs, J. F. and Houle, K. M. (2012). "Water Quality and Hydrologic Performance of a Porous Asphalt Pavement as a Storm-Water Treatment Strategy in a Cold Climate." Journal of Environmental Engineering **138**(1): 81-89.

Sansalone, J., Kuang, X. and Ranieri, V. (2008). "Permeable Pavement as a Hydraulic and Filtration Interface for Urban Drainage." Journal of Irrigation and Drainage Engineering **134**(5): 666-674.

Sansalone, J., Liu, B. and Ying, G. (2010). "Volumetric Filtration of Rainfall Runoff. II: Event-Based and Interevent Nutrient Fate." Journal of Environmental Engineering **136**(12): 1331-1340.

Sansalone, J. and Teng, Z. (2004). "In Situ Partial Exfiltration of Rainfall Runoff. I: Quality and Quantity Attenuation." Journal of Environmental Engineering **130**(9): 990-1007.

Sansalone, J. J. and Cristina, C. M. (2004). "First Flush Concepts for Suspended and Dissolved Solids in Small Impervious Watersheds." Journal of Environmental Engineering **130**(11): 1301-1314.

She, N. and Pang, J. (2010). "Physically Based Green Roof Model." Journal of Hydrologic Engineering **15**(6): 458-464.

Strecker, E., Quigley, M., Urbonas, B., Jones, J. and Clary, J. (2001). "Determining Urban Storm Water BMP Effectiveness." Journal of Water Resources Planning and Management **127**(3): 144-149.

Teemusk, A. and Mander, Ü. (2011). "The Influence of Green Roofs on Runoff Water Quality: A Case Study from Estonia." Water Resources Management **25**(14): 3699-3713.

Traver, R. G., Davis, A. P., Hunt, W. F. and Cheng, M.-S. (2008). Stormwater Concepts --- No Adverse Impact, ASCE.

Van Buren, M. A., Watt, W. E. and Marsalek, J. (1997). "Application of the log-normal and normal distributions to stormwater quality parameters." Water Research **31**(1): 95-104.

Van Seters, T., Rocha, L., Smith, D. and MacMillan, G. (2009). "Evaluation of Green Roofs for Runoff Retention, Runoff Quality, and Leachability." Water Quality Research Journal of Canada **44**(1): 33-47.

Virginia Department of Conservation and Recreation (2011) "Virginia DCR Stormwater Design Spec. No. 9, Bioretention, Version 1.9" Recreation, V. D. o. C. a.

Voyde, E., Fassman, E., Simcock, R. and Wells, J. (2010). "Quantifying Evapotranspiration Rates for New Zealand Green Roofs." Journal of Hydrologic Engineering **15**(6): 395-403.

Water Environment Research Foundation (2009). User's Guide to the BMP and LID Whole Life Cost Models. Water Environment Research Foundation. **Version 2.0**.

WEF and ASCE, Water Environment Federation, American Society of Civil Engineers, Environmental & Water Resource Institute, (2012). Design of Urban Stormwater Controls, McGraw Hill.

Welker, A. L. and Wadzuk, B. M. (2011). Development of a Stormwater Control Measure Microcosm to Measure Evapotranspiration. Geo-Frontiers 2011**:** 3068-3076.

Williams, E. S. and Wise, W. R. (2009). "Economic Impacts of Alternative Approaches to Storm-Water Management and Land Development." Journal of Water Resources Planning and Management **135**(6): 537-546.

Williams, G., Roseen, R. M., Lenhart, J. H. and Kayhanian, M. (2009). Potential Data Analysis Methodology to Evaluate the Performance of Manufactured BMPs. World Environmental and Water Resources Congress 2009**:** 1-10.

Yu, S. L. and Stanford, R. L. (2007). Field Evaluation of a Stormwater Bioretention Filtration System. World Environmental and Water Resources Congress 2007**:** 1-10.

3 METHODOLOGY

3.1 CRRC Low Impact Development Facility

The Cub Run Recreation Center (CRRC) low impact development (LID) study site is an urban stormwater management retrofit located within the Cub Run watershed in the community of Chantilly, in western Fairfax County, Virginia. The facility is adjacent to a parking lot serving the CRRC and Westfield High School, and serves a total drainage area of 1.6 acres including 0.63 acres of asphalt parking lot, 0.86 acres of grassy-wooded area, and 0.11 acres of the LID facility itself. The treatment train is gravity flow, and includes four in-line grass swales followed by a bioretention cell with a gravel base. Stormwater runoff enters the grass swales from the parking lot to the north and the grassy and wooded area to the south, as shown in Figure 3-1. The grass swales were designed to allow water ponding deeper than six inches in any swale to overflow into the next cell. The bioretention cell was designed to allow water ponding deeper than six inches to discharge by means of an overflow in to an adjacent 15 inch PVC pipe from which samples were taken. The pipe discharged into a curb inlet that received additional parking lot drainage. Outflows from the curb inlet were routed to a conventional detention pond (Versar, 2011).

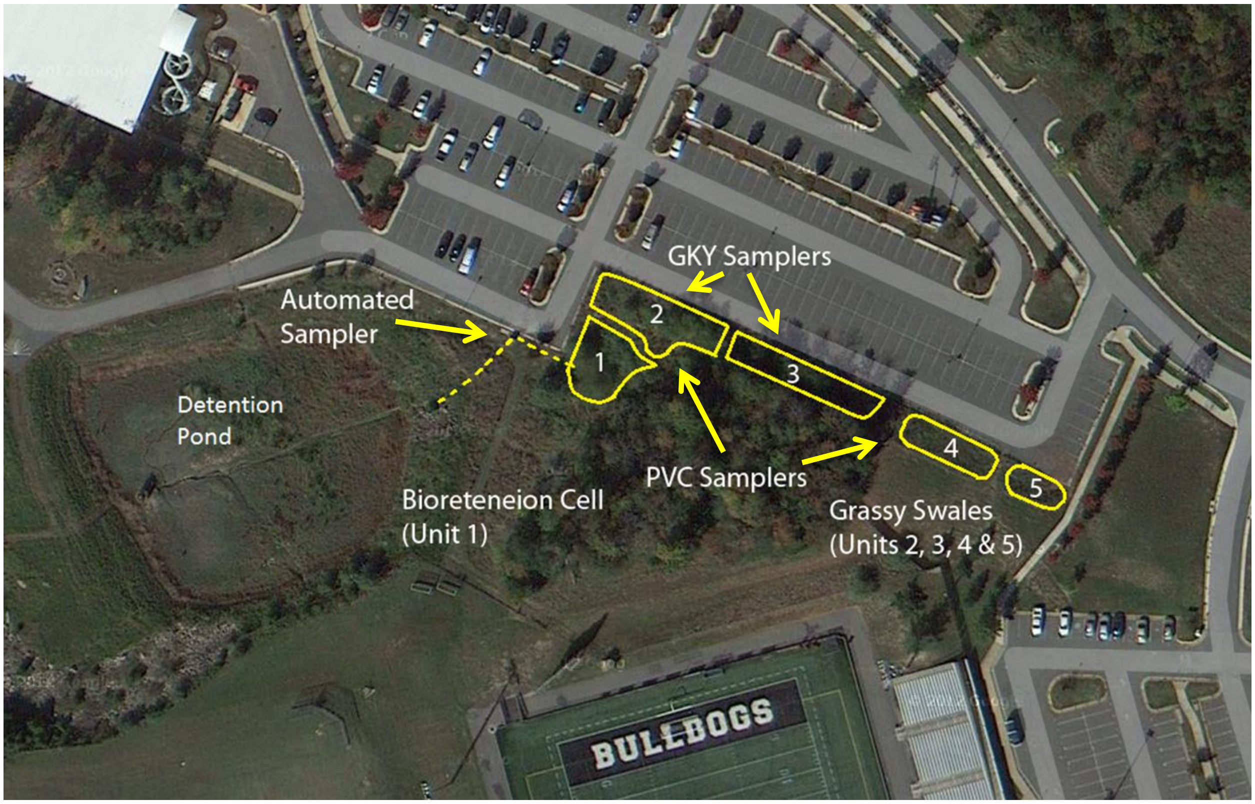


Figure 3-1. Aerial view of the Cub Run Recreation Center LID facility with approximate outlines for the bioretention cell, grass swales and sampler locations (VT-OWML, 2012; Google Maps, 2013) Used under fair use, 2013.

3.2 LID Facility Monitoring

Versar, Inc. under contract with the Fairfax County Department of Public Works and Environmental Services (DPWES) conducted monitoring of the CRRC LID facility during two periods from September 2008 – June 2010 and March 2011 – May 2012. Installation of the monitoring equipment took place during August 2008. Continuous flow monitoring (at the LID facility outfall only), meteorological data, soil moisture and storm monitoring was performed by ATR Associates, Inc. under subcontract to Versar, Inc. from September 2008 to July 2009 and solely by Versar, Inc. from July 2009 to June 2010 and again from March 2011 to May 2012 (Versar, 2011). In July, 2011, Virginia Tech entered into an agreement with DPWES to conduct a performance analysis of the LID stormwater retrofit. Faculty, staff, and students of the Departments of Biological Systems Engineering and Civil and Environmental Engineering were involved in the project, and contributed to the performance analysis.

The collected datasets, provided by Versar (2011), consisted of continuous monitoring for meteorology and hydrology, along with discrete sampling, and subsequent analysis for selected water quality parameters during targeted storm events. The LID facility was monitored for water quality during 25 storm events over the course of the two monitoring periods. Passive and automated devices were used to collect samples that facilitated comparisons of water quality and flows at inflow and outflow locations, respectively. The water quality monitoring included post-storm analyses for the event mean concentrations of nutrients such as phosphorus and nitrogen, trace metals such as copper and zinc, and other important water quality parameters such as total suspended solids and total dissolved solids. The water quality data were then used along with the meteorological and hydrologic data to calculate inflow and outflow loadings for constituents of interest. Flow estimates were made using different techniques at the inflow and outflow points.

3.3 Flow Rate Monitoring and Flow Volume Estimates

LID facility outflows were continuously monitored using a depth sensor and a 60^0 V-notch weir located within the outfall pipe from the bioretention cell (Versar, 2011). Continuous flow data were logged electronically and integrated using the trapezoidal method over the duration of a storm event to arrive at outflow discharge volume estimates (Versar, 2011). Inflow discharge volumes were estimated using the Soil Conservation Service (SCS) runoff curve number method as outlined by Technical Release 55 (TR-55) by the United States Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS, 1986).

3.3.1 Inflow Volume Estimates

3.3.1.1 SCS Runoff Curve Number Method

TR-55 presents a simplified procedure for estimating storm runoff volumes, peak discharge rates, hydrographs and storage volumes required for floodwater reservoirs. The so-called SCS runoff curve number method has been widely used to estimate inflows when actual monitoring data are unavailable (LeFevre et al., 2010; Giacomoni et al., 2012).

Versar (2011) conducted a previous performance analysis of the LID facility and reported the curve numbers of 98 and 69.5, respectively, for the adjacent parking lot and grassy and wooded areas. While the curve number of 98 remained a valid estimate for the parking lot, the grassy and wooded area curve number was updated to reflect a more recent soil survey map provided by Fairfax County (2011). The updated soil survey map designated the grassy and wooded area soils adjacent to the LID facility as hydrologic soil group (HSG) D. Taking the new HSG D designation into account, the grassy and wooded area weighted curve number was determined to be 79, which is an area-weighted composite of the curve numbers for a fully developed urban area consisting of open space in good condition (CN 80) and an agricultural land comprised of woods in good condition (CN 77) (NRCS, 1986).

3.3.1.2 Limitations of the SCS Runoff Curve Number Method

Because the initial abstraction term includes all losses before runoff begins, the curve number method assumes that runoff does not occur until the precipitation depth exceeds the initial abstraction depth. Because the initial abstraction may be calculated as a function of the curve number, it may be assumed that, for any given curve number, there is a precipitation depth that must be exceeded before which the SCS runoff curve number calculation would produce realistic runoff values. By setting runoff (Q) in the curve number method equation to zero and applying the curve number of interest, the precipitation depth threshold required to satisfy the $P \geq 0.2S$ constraint may be found (McCuen, 2004). For the CRRC parking lot (CN=98), the threshold precipitation depth was found to be approximately 0.04 inches, while for the grassy and wooded area (CN=79), the threshold precipitation depth was found to be approximately 0.53 inches.

The minimum precipitation threshold may be assumed to have no appreciable effect on parking lot runoff volume estimates, because samples were not collected until at least 0.2 inches of rain was expected (Versar, 2011). However, it may be seen to have a pronounced effect on runoff estimates for the grassy and wooded areas. The curve number method restricts the production of surface runoff to storms with rainfall depths of 0.53 inches and greater. Six of the sixteen (37.5%) events with samples taken from the grassy and wooded areas were found to have had rainfall depths less than 0.53 inches. A clear, but not easily quantified, bias in the dataset appears to have resulted from setting the total runoff volume from these events to zero for the grassy and wooded area. The zero-flow value is not reflective of reality because inflow water quality samples were retrieved following each of the events. Nevertheless, the observation that flows did occur when none were predicted may argue for a re-assessment of the appropriateness of using the SCS runoff curve number method for flow estimation in this case. Absent a flow to associate with samples collected in events with rainfall less than 0.53 inches, the inflow loads from the grassy and wooded areas were assumed to be zero, and those inputs removed from the dataset provided by Versar (2011). It should be noted, however, that because of the often dispersed nature of inflows to LID practices, it is not always feasible to physically monitor all the BMP inflows, and estimating such ungaged flows is not an uncommon practice.

While the simple nature of the curve number method allows its application with minimal data requirements (storm depth and curve numbers), the approach also creates some challenges and limitations with regards to its ability to predict event-scale hydrologic response in real world applications (Ponce and Hawkins, 1996). While the method provides prediction for average conditions that are useful for design purposes, the modeling accuracy has been observed to decrease for actual rain events, because of the inability to account for effects of rainfall duration or intensity (NRCS, 1986; Ponce and Hawkins, 1996; Lamont et al., 2008; Chung et al., 2010). The method has also been observed to be less accurate when runoff depth is less than 0.5 inches (NRCS, 1986). Several investigators have also found the often assumed initial abstraction ratio of 0.2S may not accurately reflect specific watershed conditions present at every site of interest (Ponce and Hawkins, 1996; Lamont et al., 2008; Chung et al., 2010). The absence of clear guidance on how to account for variability in antecedent moisture conditions (Ponce and Hawkins, 1996; Chung et al., 2010), spatial scale effects (Ponce and Hawkins, 1996) and land use changes (Ogden et al., 2011), have all been cited as potential barriers to application of the method.

Given the potential problems with down-scaling the curve number method for use in runoff predictions for individual events on small catchments, it is not surprising that the accuracy of the BMP inflow load predictions at the CRRC LID facility is subject to some uncertainty. In BMP performance assessments, the flow balance is always important. However, in practices where infiltration may be responsible for a significant fraction of the constituent removal efficiency, direct measurements of surface inflows and infiltration become critical. Because of this, performance assessments developed from the analysis of the CRRC monitoring program data must take into account the uncertainty introduced by (as yet) unvalidated estimation methods.

3.3.2 Outflow Volume Calculations

Flows exiting the LID facility were measured with a 60^0 V-notch plywood weir installed at the end of the 15-inch PVC outlet pipe where it entered a catch basin. An ISCO Model 720 integrated flow module with integrated pressure transducer was used to measure flows. The pressure transducer sensor was installed upstream of the weir to record the head on the weir notch, and the flow module logged static head data at 10-minute intervals. Using the appropriate weir equation, static head was converted to flow rate with proprietary ISCO Flowlink Software. The flow module provided an activation signal to an attached automated sampler during runoff events (Versar, 2011; ISCO, 2012). Storm event flow volumes were calculated by integrating the 10-minute flow data during events using the trapezoidal rule (Hass, 2007).

3.4 Sampling

3.4.1 LID Facility Inflow Samplers

The LID facility received sheet flow from the adjacent parking area, grassy area and wooded area. Sheet flow samples from the parking area were collected using two GKY 'First-Flush' samplers (Versar, 2011; GKY, 2012). The GKY samplers received sheet flow from the adjacent parking lot area as it flowed into the LID facility at Swale 2 and Swale 3 as shown in Figure 3-1. A schematic of the GKY samplers is provided in Figure 3-2.

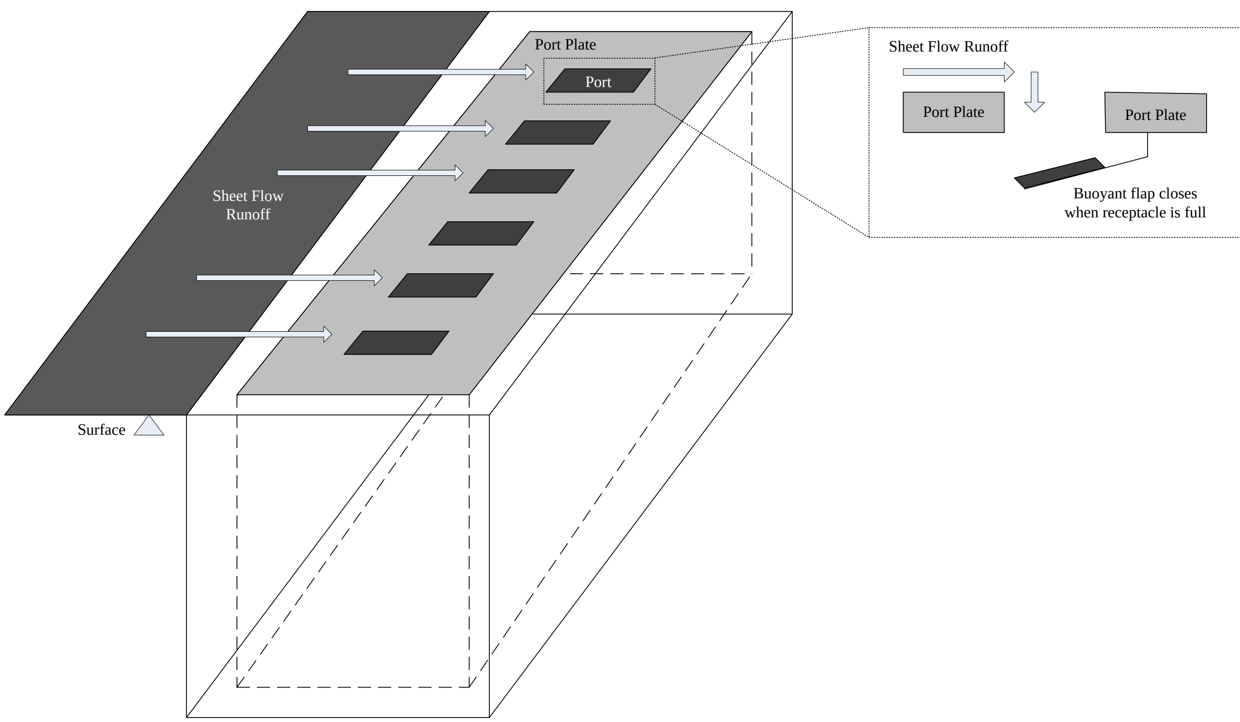


Figure 3-2. Schematic of a GKY First Flush Sampler.

Sheet flow samples from the grassy and wooded areas were taken with samplers constructed by Versar (2011) with two 5-foot sections of 4-inch PVC pipe capped at the ends and installed normal to the fall line. The runoff entered the samplers through a ½ inch slot and a Plexiglas lip attached to the lower edge of the opening to direct runoff into the pipes. The samplers were placed into shallow trenches with cement aprons to mold the Plexiglas lip against the surrounding turf. The PVC samplers receiving drainage from the grassy area and wooded areas were located at the edge of the BMP at Swale 2 and Swale 3, respectively, as shown in Figure 3-1. A schematic of the PVC Samplers is provided in Figure 3-3.

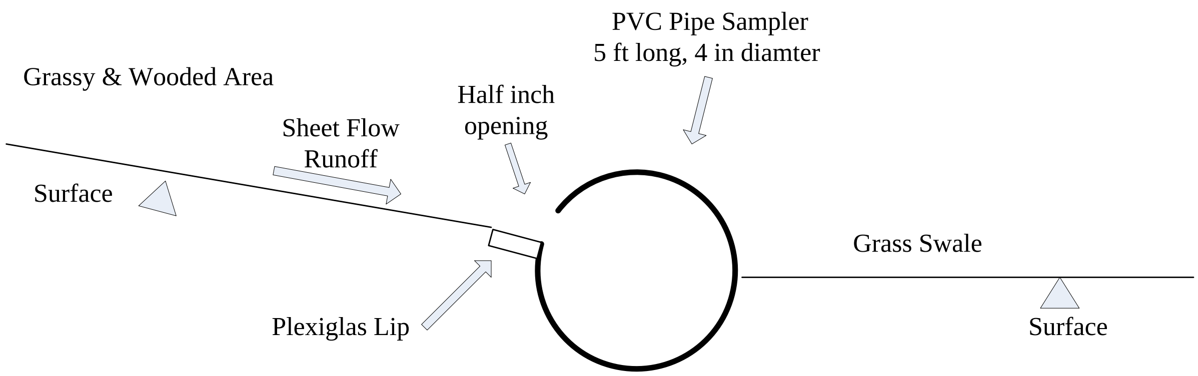


Figure 3-3. Side view schematic of a PVC Sampler.

The sheet flow samples were assumed to be composites representative of the runoff from the contributing drainage areas (Versar, 2011). The available data did not make it possible to estimate the lost flow (if any) for events where the sheet flow samplers were filled and had no additional void capacity to store water. In spite of this, it may be concluded that the performance data are conservative, and the actual removals are likely to be somewhat higher.

3.4.2 LID Facility Infiltration Sampler

A lysimeter sampler was buried under Swale 4 to collect infiltrated stormwater using a receptacle bucket (Versar, 2011; VT-OWML, 2012). Samples were taken from the lysimeter each day following a targeted storm event until no additional leachate was observed. Due to the expectation that flow into the lysimeter sampler would be relatively small, the sample volumes collected each day after a storm event were simply added together to make an overall composite sample (VT-OWML, 2012). The lysimeter sampler was installed on June 15, 2011 (Versar, 2011). Consequently, no samples were taken during the first monitoring period.

3.4.3 LID Facility Outfall Sampler

Samples of the outflow discharge were taken from the LID facility outlet pipe using an ISCO model 6712 portable automated sampler (Versar, 2011; ISCO, 2012). The automated sampler had a collection capacity of 24 1-L water samples in polypropylene bottles and was housed in a nearby equipment shelter constructed of plywood and secured with a padlock (Versar, 2011). A polypropylene sample strainer was placed behind the 60^0 V-notch weir in the PVC outlet pipe and was connected to the sampler through flexible vinyl tubing (Versar, 2011). During targeted storm events, the sampler was activated when the water level in the PVC outlet pipe exceeded 0.54 inches. The sampler was programmed to take discrete samples at time intervals, usually between 45 minutes to 2 hours, to maximize the number of samples obtained while the outfall discharged runoff and account for the extended time the bioretention area dewatered (Versar, 2011; Jones, 2013).The sampler retrieved aliquots that could be combined into a flow-weighted composite at a later time (Versar, 2011; ISCO, 2012). The resulting storm sample composites were taken to be representative of the event mean concentration (EMC) values for any constituents subsequently analyzed. The automated sampler was located above the catch basin receiving outflow from the bioretention cell, as shown in Figure 3-1. A schematic of the sampling apparatus at the LID facility outfall is provided in Figure 3-4.

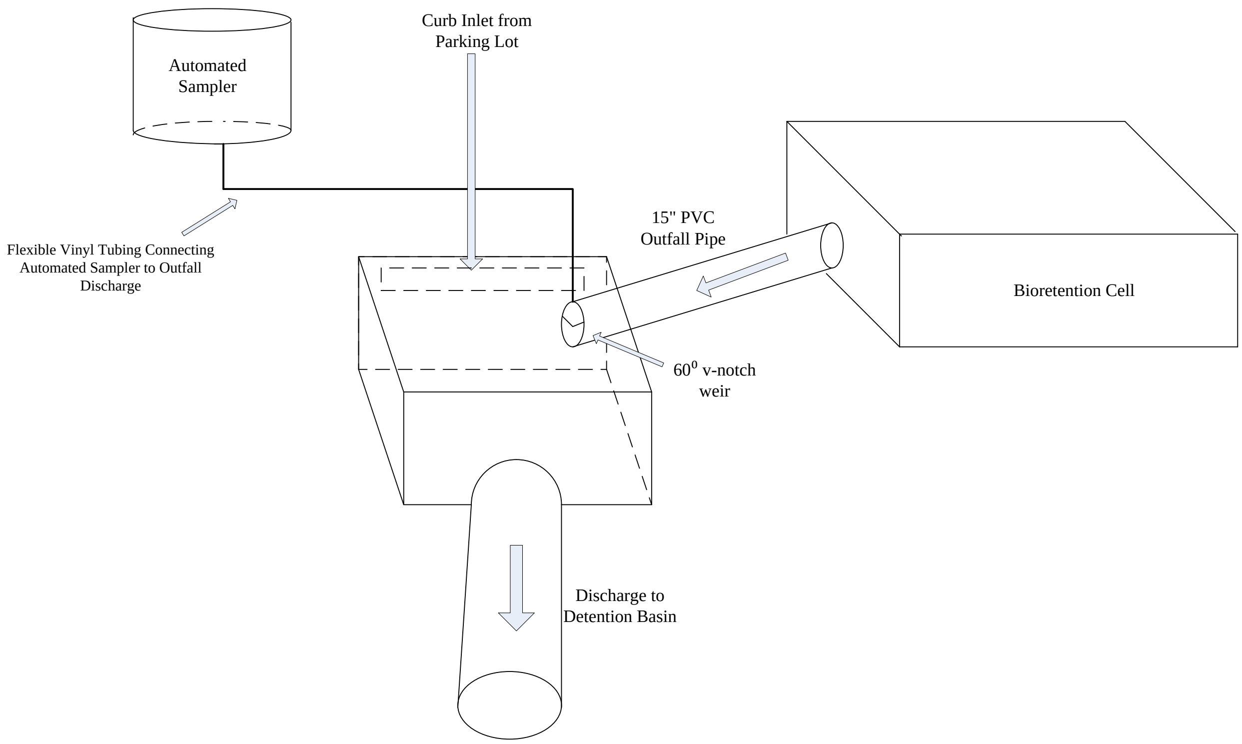


Figure 3-4. Schematic of the sampling apparatus at the LID facility outfall.

3.4.4 Water Quality Constituents Monitored

During targeted storm events, sample analyses included total phosphorus (TP), oxidized nitrogen (OxN), total Kjeldahl nitrogen (TKN), ammonia nitrogen (NH_3), total suspended solids (TSS), chemical oxygen demand (COD), total dissolved solids (TDS), copper (Cu), cadmium (Cd), zinc (Zn), lead (Pb), oil and grease (O&G), total petroleum hydrocarbons (TPH), alkalinity (Alk), hardness (Hard) and orthophosphate phosphorus (OP) (Versar, 2011; VT-OWML, 2012).

Table 3-1 lists the water quality parameters monitored on a discrete basis for targeted storm events for the two monitoring periods. The table also shows the analytical methods reported and the applicable reporting limits (Versar, 2011; VT-OWML, 2012).

Table 3-1. Discrete water quality parameters monitored for targeted storm events.

Monitoring Period	September 2008 – June 2010		March 2011- May 2012	
Parameter	**Reportable Detection Limit (mg/L)**	**Method**	**Reportable Detection Limit (mg/L)**	**Method**
Total Phosphorus	0.01	SM 4500P-E	0.01	SM 4500P-E
Oxidized Nitrogen	0.02	SM 4500NO3-H	0.02	SM 4500NO3-H
Total Kjeldahl Nitrogen	0.5	SM 4500NH3-C	0.5	SM 4500NH3-C
Ammonia Nitrogen	0.2	SM 4500NH3-C	0.2	SM 4500NH3-C
Total Suspended Solids	1	SM 2540 D	1	SM 2540 D
Chemical Oxygen Demand[1]			10	EPA 410.4 & SM 5220-D
Total Dissolved Solids[1]			10	SM 2540C
Copper[3]	0.01	EPA 200.8	0.002	EPA 200.8
Cadmium	0.0005	EPA 200.8	0.0005	EPA 200.8
Zinc	0.01	EPA 200.8	0.01	EPA 200.8
Lead[3]	0.01 & 0.002	EPA 200.8	0.002	EPA 200.8
Oil and Grease	5	EPA 1664	5	EPA 1664
Total Petroleum Hydrocarbons[1]			5	EPA 1664
Alkalinity[2]	1	SM 2320 B		
Hardness[2]	1	SM 2340 B		
Orthophosphate Phosphorus[2]	0.01	SM 4500P-E		

[1] Chemical Oxygen Demand (COD), Total Dissolved Solids (TDS) and Total Petroleum Hydrocarbons (TPH) were not tested for during the first monitoring period September 2008 – June 2010. [2] Alkalinity, Hardness and Orthophosphate Phosphorus were not tested for during the most recent monitoring period March 2011- May 2012. [3] Copper and Lead had different reporting limits for the two monitoring periods.

3.4.5 Continuous Meteorological and Water Quality Parameters

An Onset Model H21-001 (Onset, 2012) weather station was installed to record continuous meteorological and water temperature data for the entire project period. The station was tripod-mounted and secured with guy wires adjacent to the downstream section of the bioretention cell. As with flow, meteorological and water temperature data were recorded at 10-minute intervals by an associated data logger. The weather station was configured to record precipitation, air temperature, relative humidity, wind speed, wind gust speed, solar radiation, soil moisture at three different depths, temperature of LID facility discharge water, and temperature of water discharging from non-LID areas at the western end of the parking lot (Versar, 2011).

3.5 Storm Monitoring

Decisions on storm selection for water quality monitoring were taken after closely monitoring rainfall predictions on available weather services, including NOAA (Versar, 2011). Field staff acted on high-probability weather predictions by traveling to the site with appropriate equipment for targeted storms that were predicted to deliver at least 0.2 inches of rainfall. Of the 25 storm events monitored in the two monitoring periods, nine were reported to produce no flow at the LID facility outfall (Versar, 2011). To prepare for storm sampling, field technicians programmed the automated sampler to obtain time-paced water samples at intervals corresponding to the predicted duration of rainfall. Staff also installed pre-cleaned sample receipt tubs into the GKY samplers, and checked the PVC pipe samplers for cleanliness and proper alignment with the concrete apron (Versar, 2011).

Once storm sampling was underway, field staff checked online weather resources (e.g. http://www.wunderground.com/wundermap) to ensure the minimum required rainfall had taken place. If so, staff visited the site with previously prepared bottles to collect and transport the water samples. At the site, level data were downloaded from the ISCO equipment to facilitate constructing tables of discharge volume per discrete sample to be used to construct volume-weighted composite samples. Samples were also retrieved from the GKY samplers, and the vessels were examined to compare collected volumes. Sub-samples from the GKY samplers were proportionally combined into one-liter, parameter-specific collection and transport bottles. The PVC pipe samplers were removed from the trenches and emptied into a pre-cleaned bucket, mixed, and subsequently poured into one-liter, parameter-specific bottles (Versar, 2011).

Following a sampled storm event, staff removed the discrete sample carrier from the automated sampler, and the individual one-liter bottles were capped and transported to Versar, Inc. facilities to prepare for analysis (Versar, 2011). Flows were computed from the recorded 10-minute level data using the appropriate weir equation with ISCO Flowlink software. Versar (2011) described the compositing procedure where “The flow rate data were then integrated over the sampling interval time to obtain total discharge volume per discrete bottle. The discharge volume-proportional subsample amount from each bottle was poured off and combined to form one composite sample.” As with the sheet flow samples, the composite sample was also split between one-liter parameter specific bottles (Versar, 2011).

Lysimeter samples were reported to be collected each day following a storm event until no further leachate was observed. The daily sample volumes were combined to construct an overall lysimeter composite sample, which could then be analyzed for total phosphorus, oxidized nitrogen and total Kjeldahl nitrogen (Versar, 2011). Because influent flows were estimated using the SCS runoff curve number method, an accurate description of the water balance, including infiltration and evapotranspiration, at the LID facility was not possible. While lysimeter samples were analyzed and reported for TP, OxN and TKN concentrations, further evaluation of the lysimeter samples was limited due to uncertainties in the water balance at the LID facility.

3.6 Site Maintenance

Staff visited the CRRC site on a biweekly basis between storm events to ensure the monitoring equipment was working properly. Site maintenance was also reported as taking place on an as-needed basis while staff were on site to prepare for a storm event, or to collect samples from a storm event (Versar, 2011).

Regular maintenance of the site was reported to include checking the overall condition of the equipment; checking power-up status of equipment; exchanging batteries if needed; downloading accumulated meteorological, water temperature, and water level data to a field laptop computer; repairing or securing equipment as needed; and filling out equipment status field data reports (Versar, 2011). Weather station and water temperature data were downloaded by staff using Hoboware Pro software from Onset (2012). Water level and flow data were downloaded using Flowlink version 4.15 software from ISCO (2012). A log of site visits between July 2009 – June

2010 and March 2011 – May 2012 was provided by Versar and is available in the performance analysis reports prepared by Versar (2011) and Grizzard and Le Bel (2013).

3.7 Accounting for Censored Observations

3.7.1 Robust Regression on Ordered Statistics

Regression on ordered statistics (ROS) methods calculate summary statistics using a least-squares regression on a probability plot. For robust ROS, summary statistics are calculated by imputing values for censored observations based on a parametric model and combining those imputed estimates with the uncensored data (Helsel, 2012). A probability plot is used to fit a regression equation using the uncensored observations within a dataset. The normal scores for censored observations are then used with the previously defined regression equation to assign values for the censored observations. The assigned values may then be imputed and combined with the uncensored observations enabling the computation of summary statistics as though no censoring was present within the dataset. The process avoids transformation bias because it does not require transforming summary statistics (such as the mean and standard deviation) across scales (Helsel, 2012). Robust ROS was used in the analysis of the CRRC LID facility data to produce probability plots, also called quantile-quantile or Q-Q plots, which account for any censored observations.

3.7.2 Kaplan-Meier Method

The nonparametric Kaplan-Meier method is the standard method for estimating summary statistics of censored survival data (right-censored) and may also be applied to left-censored environmental data (Helsel, 2012). The Kaplan-Meier method produces estimates of the survival probability function 'S' for right-censored data but may be applied to environmental data (typically left-censored and bounded by 0) by 'flipping' the data by subtracting every observation by a value that is greater than the maximum value within the dataset. The survival probability function applied to left-censored data essentially produces an empirical distribution function (EDF) of the data and is able to incorporate censored (or below detection limit) observations in environmental data (Helsel, 2012). Using the Kaplan-Meier method to estimate summary statistics for censored environmental data, including the EDF, makes it possible to utilize the Effluent Probability Method (Strecker et al., 2001; Geosyntec and WWE, 2009;

Williams et al., 2009) to compare influent and effluent loads at the CRRC LID facility while still incorporating the effects of below detection limit observations (Helsel, 2012).

3.7.3 Limitations of the Kaplan-Meier Method and Robust ROS

It should be noted that the Kaplan-Meier method is not recommended for datasets which have greater than 50% censoring (Helsel, 2012). For data sets with 50-80% censoring, Helsel (2012) recommends methods such as robust regression on ordered statistics, robust maximum likelihood estimation or multiple imputation may be used to estimate summary statistics. For data sets with greater than 80% censoring, summary statistics cannot be accurately estimated and the analysis is found to be more limited. In such cases, analysis may be limited to reporting the percentage of observations above or below the maximum reporting limit (Helsel, 2012).

3.8 Methods of Calculating BMP Efficiency

3.8.1 Mass-Based Methods for Assessing Stormwater BMPs

Pollutant load reductions are a function of both water quality treatment processes and volume reductions in LID practices (Davis, 2007; Geosyntec and WWE, 2009; Clary et al., 2011). To accurately assess performance, estimates of pollutant load reductions should include long term monitoring to predict BMP uptake and release of pollutants on a complete life-cycle basis (Brown and Hunt III, 2011). The non-linear runoff response typical of LID watersheds should be taken into consideration because a few large storms may often be found to dominate the overall discharge volume at a site and pollutant concentrations also tend to be greater during more intense rainfall events. Performance metrics based on the total pollutant load removal over a representative period of the meteorological and hydrologic record are more representative measures of the overall system efficiency and are consequently more appropriate for assessing pollutant reduction performance of a LID site (Davis, 2007; Geosyntec and WWE, 2009). The Summation of Loads Method (Minton, 2005; Hunt et al., 2006; Cates et al., 2009; Chi-Feng et al., 2009; Geosyntec and WWE, 2009; Williams et al., 2009; McNett et al., 2011) and the Effluent Probability Method (Strecker et al., 2001; Geosyntec and WWE, 2009; Williams et al., 2009) were chosen for constituent load reduction analyses.

3.8.2 Summation of Loads

The Summation of Loads (SOL) method was used to compare influent and effluent loads at the LID facility using three common substitution methods for censored observations: (1) setting below detection limit (BDL) observations to zero, (2) setting BDL observations to one-half the detection limit, and (3) setting BDL observations to the detection limit. The SOL method defines the efficiency of a given BMP to remove pollutants as the ratio of the summation of all incoming (inlet) loads to the summation of all outgoing (outlet) loads. The overall change in load for each pollutant over the monitoring period is presented as a percent decrease between the summation of inlet and outlet loads (Minton, 2005; Hunt et al., 2006; Cates et al., 2009; Chi-Feng et al., 2009; Geosyntec and WWE, 2009; Williams et al., 2009; McNett et al., 2011).

3.8.2.1 LID Facility Inlet Load Calculations

To facilitate the use of the Summation of Loads method as a performance analysis metric for the CRRC LID facility, volume-weighted event mean concentration (EMC) and load were calculated to represent the total inlet load for any combination of storm event and water quality parameter. The total inlet EMC or load at the Cub Run LID facility was designated as 'CUIN' to maintain consistency with previous performance evaluations. CUIN for each storm event and discrete water quality parameter was calculated by determining the total loads flowing into the LID facility as measured by the GKY and PVC samplers, identified as CUGKY and CUPVC, respectively. The load from each sampler was calculated by multiplying the EMC by the total inflow volume from the respective drainage areas for the GKY and PVC samplers as estimated by the SCS runoff curve number method. The loads from the GKY and PVC samplers were then summed to give the total load delivered to the LID facility. A volume-weighted EMC for CUIN was then obtained by dividing the total load by the total inflow volume calculated by summing the inflows from the parking lot and grassy and wooded areas. The equations describing the CUIN EMC and loads are as follows:

$$CUIN_{Load} = \left(\left(EMC_{GKY} x Inflow_{Parking\ Lot}\right) + \left(EMC_{PVC} x Inflow_{Grassy\ \&\ Wooded\ Area}\right)\right) x \frac{1\ g}{1000mg}$$

$$CUIN_{EMC} = \frac{\left(EMC_{GKY} x Inflow_{Parking\ Lot}\right) + \left(EMC_{PVC} x Inflow_{Grassy\ \&\ Wooded\ Area}\right)}{\left(Inflow_{Parking\ Lot} + Inflow_{Grassy\ \&\ Wooded\ Area}\right)}$$

Where:

- $CUIN_{Load}$ = Total load delivered to the LID facility (grams) from sheet flow runoff from both the parking lot and the grassy and wooded areas;

- $CUIN_{EMC}$ = Volume-weighted EMC for CUIN (mg/L);
- EMC_{GKY} = EMC reported from GKY sampler (mg/L);
- EMC_{PVC} = EMC reported from PVC sampler (mg/L);
- $Inflow_{Parking\ Lot}$ = Volume of runoff entering LID facility from the parking lot (L);
- $Inflow_{Grassy\ \&\ Wooded\ Area}$ = Volume of runoff entering LID facility from the grassy and wooded areas (L).

Limitations and Special Considerations for Calculating $CUIN_{EMC}$ and $CUIN_{Load}$

For nine of the 25 storm events with CUIN samples, the grassy and wooded area (CUPVC) runoff calculated using the SCS runoff curve number method was set to zero because the rain depth was less than 0.53 inches. Because of this, the volume weighted EMC and load for each of these events originated only from the parking lot (CUGKY). For these events, censored or uncensored values for the volume weighted EMC and load were set to the values computed for the CUGKY samples.

EMC values and loads from CUPVC were set to zero for the following storm events:

- 9/25/2008 (Storm No. 2008268.1) – Storm Event Rain Depth = 0.47 inches
- 9/11/2009 (Storm No. 2009253.1) – Storm Event Rain Depth = 0.15 inches
- 9/26/2009 (Storm No. 2009268.1) – Storm Event Rain Depth = 0.48 inches
- 12/2/2009 (Storm No. 2009335.1) – Storm Event Rain Depth = 0.44 inches
- 3/11/2010 (Storm No. 2010069.1) – Storm Event Rain Depth = 0.44 inches
- 8/13/2011 (Storm No. 2011224.1) – Storm Event Rain Depth = 0.34 inches
- 9/23/2011 (Storm No. 2011265.1) – Storm Event Rain Depth = 0.31 inches
- 1/26/2012 (Storm No. 2012025.1) – Storm Event Rain Depth = 0.14 inches
- 3/24/2012 (Storm No. 2012083.1) – Storm Event Rain Depth = 0.40 inches

For the remaining 16 storm events making up the CUIN dataset, the volume weighted EMC was a value between the CUGKY EMC and CUPVC EMC. In determining whether the volume weighted EMC value is censored (below the detection limit) or uncensored (above the detection limit), four possibilities must be considered:

- CUGKY and CUPVC EMCs are both uncensored and therefore the volume weighted CUIN EMC is also uncensored;
- CUGKY and CUPVC EMCs are both censored and therefore the volume weighted CUIN EMC is also censored;
- CUGKY EMC is censored while CUPVC is uncensored;
- CUGKY EMC is uncensored while CUPVC EMC is censored.

The first two cases are straightforward and did not require any additional steps in analyzing the data. The volume weighted EMC values and constituent mass load for each event were calculated as previously described.

The cases where either the PVC or GKY sample had a censored value for a constituent measurement required the development of an alternate procedure for the computation of a volume-weighted EMC for CUIN. For events where one of the two EMC values was a censored observation, a value of one-half the reporting limit was substituted for the censored value. This value was used to calculate a volume weighted CUIN EMC which was then used to compute an event load for the constituent of interest. As has been previously discussed, substituting values for censored observations is generally held to weaken the power of an analysis (Helsel, 2012), but there is value gained in this case because it makes possible the inclusion of an additional 5 events for the inflow analysis. This procedure was required for the following five events and water quality constituents: Storm No. 2009153.1 (6/3/2009) for OxN; Storm No. 2011247.1 (9/5/2011) for NH_3; Storm No. 2011247.1 (9/5/2011) for TDS; Storm No. 2011339.1 (12/6/2011) for Cd and Storm No. 2011247.1 (9/5/2011) for Pb.

3.8.2.2 LID Facility Outlet Loads Calculations

LID facility outlet loads for any combination of water quality parameter and storm event were calculated as the product of the water quality parameter EMC reported at the outfall, designated

CUOUT for Cub Run outfall, and the storm event total discharge at the outlet (Davis et al., 2006; Davis, 2007; Li and Davis, 2009), or:

$$CUOUT_{Load} = EMC_{OUT} x Outflow_{LID\ Facility} x \frac{1g}{1000mg}$$

Where:

- $CUOUT_{Load}$ = Total load discharging from the LID facility outfall (grams);
- EMC_{OUT} = EMC reported from outfall sampler (mg/L);
- $Outflow_{LID\ Facility}$ = Volume of runoff discharging from the LID facility outfall (L).

3.8.3 Effluent Probability Method

The Effluent Probability Method (EPM) was also used to compare influent and effluent loads at the LID facility. The EPM analysis was not performed on Cd, Pb, O&G, and TPH due to the high level of censoring in their respective datasets. For data sets with greater than 80% censoring, summary statistics could not be accurately estimated and the analysis was limited to reporting the percentage of observations above or below the maximum reporting limit (Helsel, 2012). Developing performance assessments using the Effluent Probability Method requires three principal steps (Strecker et al., 2001; Geosyntec and WWE, 2009; Williams et al., 2009):

- Distributional adherence test to determine if the data follow a particular distribution;
- Statistical tests to determine if any perceived differences between the influent and effluent EMCs or loads are statistically significant;
- Plotting the log-transformed data of influent and effluent EMCs or loads for all storm events on a normal probability plot.

3.8.3.1Distributional Adherence Tests

Testing for distributional adherence is an important step in the Effluent Probability Method because it reveals if the data follow a particular distribution (such as the normal or lognormal). Determining the distribution of the dataset allows for the proper type of transform to take place to best represent the influent and effluent concentrations or loads on a normal probability plot. Additionally, the use of parametric or nonparametric statistics is based largely on the assumed distribution of the datasets (Strecker et al., 2001; Geosyntec and WWE, 2009; Williams et al., 2009). Probability plots, also called quantile-quantile plots or Q-Q plots, may be used to test the similarity of a sample dataset distribution to that of a theoretical distribution such as the normal or lognormal distribution. Robust regression on ordered statistics (ROS) were used in the CRRC LID facility data analysis to produce probability plots which account for any censored (below detection limit) observations in the LID facility inflow/outflow water quality data.

3.8.3.2 Statistical Tests to Determine Significant Differences

The use of statistical tests to determine if there is statistical significance to any perceived differences between influent and effluent EMCs or loads is another important step in the Effluent Probability Method (Strecker et al., 2001; Geosyntec and WWE, 2009; Williams et al., 2009). It has been suggested that a 95 percent confidence level ($\alpha = 0.05$) be used when performing appropriate statistical analysis tests comparing the influent and effluent conditions (Geosyntec and WWE, 2009).

Generalized Wilcoxon Test

The generalized Wilcoxon test, also called the Peto–Prentice or Peto–Peto test, is a nonparametric statistical test which determines if there is a significant difference in the cumulative distributions between two or more datasets (Helsel, 2012). The generalized Wilcoxon test is an expansion of the Wilcoxon rank-sum test. The generalized Wilcoxon test takes censored observations into account by using the Kaplan-Meier method to estimate the percentiles of the empirical distribution function for the sample data. Using the Kaplan-Meier method effectively incorporates information contained in the censored (below detection limit) observations and adjusts the dataset ranks appropriately (Helsel, 2012).

The generalized Wilcoxon test was used to test for significant differences in the cumulative distributions between influent and effluent load datasets at the LID facility. This nonparametric statistical test was chosen because of its ability to incorporate censored observations. In addition, while the $CUIN_{Load}$ datasets tend to approximate the lognormal distribution, the $CUOUT_{Load}$ datasets do not when storm events which produced zero loads (no flow), are included. For this reason, a nonparametric statistical test, such as the generalized Wilcoxon test, is more appropriate for use than some more common parametric statistical tests.

3.8.3.3 Effluent Probability Method Plots

The Effluent Probability Method shows the log-transformed data of all influent and effluent EMCs or loads for all storm events on a normal probability plot, and allows for the graphical analysis of stormwater BMP performance over the entire range of influent and effluent conditions (Strecker et al., 2001; Chi-Feng et al., 2009; Geosyntec and WWE, 2009; Williams et al., 2009). The plotting position of each datum (an observed concentration or load within the influent or effluent dataset for a particular water quality parameter) is based on the cumulative frequency of that datum as calculated by an empirical distribution function for the individual dataset (Chi-Feng et al., 2009; Geosyntec and WWE, 2009; Helsel, 2012). By comparing the influent and effluent water quality in this manner, the plot promotes a greater and more thorough understanding of how a BMP performs over the sampled range of influent concentrations and loadings (Strecker et al., 2001; Geosyntec and WWE, 2009; Williams et al., 2009).

Accounting for Censored Observations and Storm Events with no Discharge

For the CRRC LID facility, the Effluent Probability Method plots were produced using the empirical distribution function percentile data calculated with the Kaplan-Meier method, which makes it possible to incorporate any censored (below detection limit) observations (Helsel, 2012).

It should be noted that an analysis dataset was created to include all observations in the CUOUT load dataset in addition to all storm events which produced no discharge at the outfall and, consequently, no effluent load. This dataset was named CUOUT-ZF to represent the CUOUT load dataset with the zero flow events included. CUOUT-ZF is important because without the inclusion of all storm events where no discharge occurred at the outfall and therefore an effluent load of zero may be assumed, the stormwater BMP performance would be unduly affected in a negative manner. Omitting storm events with no discharge (and no loads) at the outfall would bias the water quality data toward only large events that produce flow (Davis et al., 2006; Davis, 2007).

For left-bounded environmental data, the probability of any observed data point being lower than zero is 0%. Due to the limitation of using a probability plot for the y-axis of the Effluent Probability Method, the 0% and 100% probabilities cannot be included on the graph as they mathematically extend to negative and positive infinity, respectively, as seen on the standard normal distribution (Montgomery, 1999). However, the effect of the storm events with no effluent flows and zero loads is still accounted for through the increased percentiles for all observations greater than the lowest data value.

When using the Kaplan-Meier method to calculate the empirical distribution function for the Effluent Probability Method plots, it should be noted the smallest observed value in a dataset will have a cumulative frequency, or frequency of non-exceedance, of 0%. If the smallest datum is a censored observation, the smallest detected observation will consequently have a non-zero cumulative frequency. Additionally, all censored observations less than the lowest non-censored (above the detection limit) observation have indeterminate probabilities since they are only known to be below the reporting limit and cannot be assigned precise values (Helsel, 2012). Because the Effluent Probability Method uses a probability plot for the y-axis, the smallest observed value with a cumulative frequency of 0%, while still accounted for through the increased percentiles for all observations greater than it, will not appear on the plot.

3.8.4 Differences between Summation of Loads Method and Effluent Probability Method

Generally, measuring pollutant removal performance of a BMP using either the Summation of Loads method or the Effluent Probability Method comparing influent and effluent loads will produce similar performance analysis results. While the Summation of Loads method provides a single value representative of the overall pollutant removal performance of the BMP during the monitoring period, the Effluent Probability Method provides a graphical representation depicting the entire range of performance for all monitored storm events.

The availability of a single percent reduction value allows for a simple performance comparison between practices or watersheds. The graphical representation of performance in the Effluent Probability Method, however, facilitates a greater understanding of how the BMP is performing under various storm event conditions (e.g., performance at the minimum, 25^{th}, 50^{th} and 75^{th} percentiles, and maximum storm events observed).

One major advantage of the Effluent Probability Method is the ability to include all sampled storm events in both the influent and effluent datasets. Because the Summation of Loads method defines the efficiency of any given stormwater BMP to remove pollutants as the ratio of the summation of all incoming (inlet) loads to the summation of all outgoing (outlet) loads (Minton, 2005; Hunt et al., 2006; Cates et al., 2009; Chi-Feng et al., 2009; Geosyntec and WWE, 2009; Williams et al., 2009; McNett et al., 2011) it requires the use of paired events only. For this reason, event data that enhance the understanding of either inflow or outflow loads, but are not paired, cannot be used in the Summation of Loads performance analysis. While the Effluent Probability Method does assume that the rank order of the concentrations or loads within the influent dataset are associated with those in the effluent dataset (Burton and Pitt, 2001; Chi-Feng et al., 2009), it does not require the strict use of paired events only (Geosyntec and WWE, 2009), and all sampled storm event data may be used in the analysis, even if unpaired.

3.9 References

Brown, R. and Hunt III, W. (2011). "Impacts of Media Depth on Effluent Water Quality and Hydrologic Performance of Undersized Bioretention Cells." Journal of Irrigation and Drainage Engineering **137**(3): 132-143.

Burton, G. A., Jr.; and Pitt, R. E. (2001). Stormwater Effects Handbook: A Toolbox for Watershed Managers, Scientists, and Engineers. Lewis Publishers.

Cates, E. L., Westphal, M. J., Cox, J. H., Calabria, J. and Patch, S. C. (2009). "Field Evaluation of a Proprietary Storm-Water Treatment System: Removal Efficiency and Relationships to Peak Flow, Season, and Dry Time." Journal of Environmental Engineering **135**(7): 511-517.

Chi-Feng, C., Jen-Yang, L., Chih-Hong, H., Way-Ling, C. and Nai-Ling, C. (2009). "Performance evaluation of a full-scale natural treatment system for nonpoint source and point source pollution removal." Environmental Monitoring & Assessment **157**(1-4): 391-406.

Chung, W., Wang, I. and Wang, R. (2010). "Theory-Based SCS-CN Method and Its Applications." Journal of Hydrologic Engineering **15**(12): 1045-1058.

Clary, J., Quigley, M., Poresky, A., Earles, A., Strecker, E., Leisenring, M. and Jones, J. (2011). "Integration of Low-Impact Development into the International Stormwater BMP Database." Journal of Irrigation and Drainage Engineering **137**(3): 190-198.

Davis, A. P. (2007). "Field Performance of Bioretention: Water Quality." Environmental Engineering Science **24**(8): 1048-1064.

Davis, A. P., Shokouhian, M., Sharma, H. and Minami, C. (2006). "Water Quality Improvement through Bioretention Media: Nitrogen and Phosphorus Removal." Water Environment Research **78**(3): 284-293.

Geosyntec and WWE, Geosyntec Consultants, Wright Water Engineers, Inc. (2009) "Urban Stormwater BMP Performance Monitoring" U.S. Environmental Protection Agency Prepared with support from the U.S. EPA, Water Environmental Research Foundation, Federal Highway

Administration, and the Environmental and Water Resources Institute of the American Society of Civil Engineers, http://www.bmpdatabase.org

Giacomoni, M. H., Zechman, E. M. and Brumbelow, K. (2012). "Hydrologic Footprint Residence: Environmentally Friendly Criteria for Best Management Practices." Journal of Hydrologic Engineering **17**(1): 99-108.

GIS and Mapping Services (2011) "Soils Map 33-4" Fairfax County, D. o. I. T., Enterprise Services Division, GIS and Mapping Services

GKY, GKY & Associates (2012). Retrieved 10/25/2012, from http://www.gky.com/products/.

Google Maps (2013). "Cub Run Rec Center Satellite Image Google Maps, Used under fair use, 2013.". Retrieved 2/15/2013, from http://goo.gl/maps/LzirW, Fair use determination attached.

Grizzard, T. and Le Bel, P. (2013). Analysis of Monitoring Data at Cub Run Recreation Center Stormwater Improvements Fairfax County, Virginia, Virginia Tech.

Hass, J. W., Maurice D.; Thomas, George B, Jr. (2007). University Calculus, Pearson Addison Wesley.

Helsel, D. R. (2012). "Statistics for Censored Environmental Data Using Minitab and R."

Hunt, W. F., Jarrett, A. R., Smith, J. T. and Sharkey, L. J. (2006). "Evaluating Bioretention Hydrology and Nutrient Removal at Three Field Sites in North Carolina." Journal of Irrigation and Drainage Engineering **132**(6): 600-608.

ISCO, T. I.-. (2012). Retrieved 10/25/2012, from http://www.isco.com/products/products1.asp?PL=201.

Jones, T. (2013). Personal Communications with Tom Jones of Versar, Inc.

Lamont, S., Eli, R. and Fletcher, J. (2008). "Continuous Hydrologic Models and Curve Numbers: A Path Forward." Journal of Hydrologic Engineering **13**(7): 621-635.

LeFevre, N.-J. B., David W. Watkins, J., Gierke, J. S. and Brophy-Price, J. (2010). "Hydrologic Performance Monitoring of an Underdrained Low-Impact Development Storm-Water Management System." Journal of Irrigation and Drainage Engineering **136**(5): 333-339.

Li, H. and Davis, A. (2009). "Water Quality Improvement through Reductions of Pollutant Loads Using Bioretention." Journal of Environmental Engineering **135**(8): 567-576.

McCuen, R. H. (2004). Hydrologic Analysis and Design, Pearson Prentice Hall.

McNett, J. K., Hunt, W. F. and Davis, A. P. (2011). "Influent Pollutant Concentrations as Predictors of Effluent Pollutant Concentrations for Mid-Atlantic Bioretention." Journal of Environmental Engineering **137**(9): 790-799.

Minton, G. (2005). Stormwater Treatment - Biological, Chemical, and Engineering Principles, Resource Planning Associates.

Montgomery, D. C. and Runger, G. C. (1999). Applied Statistics and Probability for Engineers, John Wiley & Sons, Inc.

NRCS, USDA Natural Resources Conservation Service (1986). "Urban Hydrology for Small Watersheds TR-55."

Ogden, F. L., Downer, C. W., Pradhan, N. R. and Nelson, E. J. (2011). Predicting Hydrologic Effects of Land-Use Change: Problems with the Curve Number Approach. World Environmental and Water Resources Congress 2011**:** 4801-4810.

Onset, Onset Computer Corporation (2012). Retrieved 10/25/2012, from http://www.onsetcomp.com/.

Ponce, V. and Hawkins, R. (1996). "Runoff Curve Number: Has It Reached Maturity?" Journal of Hydrologic Engineering **1**(1): 11-19.

Strecker, E., Quigley, M., Urbonas, B., Jones, J. and Clary, J. (2001). "Determining Urban Storm Water BMP Effectiveness." Journal of Water Resources Planning and Management **127**(3): 144-149.

Versar, I. (2011). "Performance Monitoring [Volume Reduction and Water Quality] At Cub Run Recenter Stormwater Improvements, Fairfax County, Virginia."

VT-OWML, Virginia Tech Occoquan Watershed Monitoring Laboratory (2012). Fairfax County-Performance Assessment of LID Practices Data Repository. Scholar, Virginia Tech, Versar, Inc.; Fairfax County Government; Virginia Tech Faculty and Students.

Williams, G., Roseen, R. M., Lenhart, J. H. and Kayhanian, M. (2009). Potential Data Analysis Methodology to Evaluate the Performance of Manufactured BMPs. World Environmental and Water Resources Congress 2009**:** 1-10.

4 MANUSCRIPT I: "PERFORMANCE EVALUATION OF A LOW IMPACT DEVELOPMENT RETROFIT EMPLOYING A SUM OF LOADS ANALYSIS"

4.1 Abstract

The goal of Low Impact Development (LID) is to mimic the pre-development hydrologic regime of a catchment through infiltration, filtration, storage, evaporation, and detention of post-development runoff using small-scale hydrologic controls close to the source. A LID facility was examined for pollutant removal and hydrologic performance. The facility treatment train included four in-line grass swales followed by a bioretention cell with a gravel base. The LID facility retained 85% of the rainfall. LID facility influent and effluent pollutant loads were calculated using three common substitution methods for analytical datasets censored by values below detection limit. The Summation of Loads (SOL) method was used to compare each set of influent and effluent load datasets to facilitate understanding how the level of data censoring affected the performance results. The SOL analysis showed positive removal performance for total phosphorus, orthophosphate phosphorus, total nitrogen, total Kjeldahl nitrogen, ammonia nitrogen, total suspended solids, chemical oxygen demand, copper, cadmium, zinc, lead, total petroleum hydrocarbons, alkalinity and hardness. Negative performance was observed for oxidized nitrogen, total dissolved solids and oil & grease.

4.2 Introduction

4.2.1 Urbanization

Undeveloped lands typically generate relatively little stormwater runoff because most of the precipitation during storm events infiltrates into the soil where it will be available for evapotranspiration, groundwater recharge, shallow interflow, or any number of other natural processes in the hydrologic cycle. As a watershed is developed, or urbanized, land areas which were formerly forested or pastoral in nature are increasingly covered by impervious surfaces such as roads, parking lots, roofs, driveways and sidewalks. This increase in imperviousness fundamentally changes the hydrologic response of the urbanized site when compared to its pre-development condition. For a given rainfall event, the urbanized site will exhibit increased frequency of runoff, runoff volume, peak flows, temperatures and pollutant loads compared to its pre-development condition. The increased magnitude and frequency of stormwater runoff and consequent pollutant loads generated by urbanized watersheds can cause severe environmental degradation including channel erosion, increased flooding, decreased water quality and degraded or destroyed aquatic habitats in water bodies such as streams, rivers, lakes, estuaries and wetlands. Stormwater runoff due to urbanization is one of the leading sources of pollution for all water body types in the United States (Roesner et al., 2001; Barber et al., 2003; Hsieh and Davis, 2003; McCuen, 2003; Sansalone and Teng, 2004; Meyer, 2005; Davis, 2007; EPA, 2007; Guo, 2008; Guo and Cheng, 2008; Li and Davis, 2008; Sansalone et al., 2008; Li and Davis, 2009; Palhegyi, 2010b; Palhegyi, 2010a; Reichold et al., 2010; Carpenter and Kaluvakolanu, 2011; DeBusk et al., 2011; Giacomoni et al., 2012; McGarity, 2012).

4.2.2 Best Management Practices

In the context of urban stormwater management, best management practices (BMPs) include a range of structural, non-structural and site design practices intended to remove, reduce, retard or prevent stormwater runoff and its associated pollutants from reaching receiving waters in an urbanized or otherwise developed environment. Structural BMPs rely on a wide range of hydrological, physical, biological and chemical processes. Non-Structural BMPs typically involve community education and outreach programs. Overall site designs such as Low Impact Development (LID), Cluster Development, No Adverse Impact (NAI) and smart growth strategies combine a variety of structural and non-structural BMPs in order to reduce the environmental impacts associated with urbanization and development (Hsieh and Davis, 2003; McCuen, 2003; Quigley et al., 2005; Traver et al., 2008; Geosyntec and WWE, 2009; Williams and Wise, 2009; Clary et al., 2011).

4.2.3 Low Impact Development

Low Impact Development (LID) is a comprehensive land planning and engineering design approach to managing stormwater runoff. The goal of LID is to mimic the pre-development hydrologic regime of a watershed through infiltration, filtration, storage, evaporation and detention of post-development runoff using small-scale hydrologic controls close to the source. Urban developments which employ LID practices are expected to produce outflow hydrographs similar to those that would be found at the site during its predevelopment condition. LID practices may also be retrofitted into existing, traditional stormwater conveyance systems. LID BMPs include practices such as bioretention cells and rain gardens, bioswales, infiltration basins and trenches, stormwater wetlands, vegetated rooftops or green roofs, rain barrels or cisterns, permeable pavers, porous pavement, tree planters and site design practices such as narrow streets, reduced imperviousness, minimal curb and gutter use and preservation of natural areas (Hsieh and Davis, 2003; Davis, 2007; EPA, 2007; Beyerlein, 2008; Davis, 2008; Guo and Cheng, 2008; Traver et al., 2008; Geosyntec and WWE, 2009; Carpenter and Hallam, 2010; Guo, 2010; O'Neill and Davis, 2010; Palhegyi, 2010b; Palhegyi, 2010a; Brown and Hunt III, 2011b; Clary et al., 2011; DeBusk et al., 2011).

Infiltration practices are used to route surface runoff into subsurface soils or media where it is temporarily held in pore spaces before evaporating, transpiring from vegetation, exfiltrating into surrounding subsoils and groundwater, discharging as interflow or exiting through underdrains. Infiltration BMPs include bioretention cells or rain gardens, bioswales and vegetated filter strips, infiltration basins and trenches, and tree planters, among others. In addition to infiltration, some practices include specialized media and/or internal water storage zones which promote the removal of some important dissolved pollutants such as orthophosphate phosphorus or nitrate and nitrite nitrogen. Pollutant removal is achieved through processes such as settling, filtration, sorption and other biogeochemical interactions (Hsieh and Davis, 2003; Kim et al., 2003; Sansalone and Teng, 2004; Davis et al., 2006; Hunt et al., 2006; EPA, 2007; Davis, 2008; Li and Davis, 2008; Davis et al., 2009; Geosyntec and WWE, 2009; He and Davis, 2009; Clark and Pitt, 2010; Lucas, 2010; Sansalone et al., 2010; Brown and Hunt III, 2011b). Evidence suggests that infiltration BMP performance for dissolved constituents (e.g. nitrate/nitrite, orthophosphate and dissolved metals) capture may be highly dependent on the hydraulic residence time within the practice, along with media depth and other characteristics including media organic matter content, cation exchange capacity, pH, and initial chemical composition (Hsieh and Davis, 2003; Hunt et al., 2006; Davis et al., 2009; Li and Davis, 2009; Clark and Pitt, 2010; O'Neill and Davis, 2010; Pitt et al., 2010; Sansalone et al., 2010; Brown and Hunt III, 2011b). A variety of vegetation types, including grasses, shrubs and small trees may be used to promote evapotranspiration, maintain soil porosity and encourage biological uptake and or degradation of some pollutants. It should be noted that nutrient and micronutrient uptake by vegetation will reduce pollutant loads only if new growth is regularly harvested (usually annually) to remove excess biomass before decay and decomposition can result in re-release to the watershed (Kim et al., 2003; Davis et al., 2006; EPA, 2007; Davis, 2008; Li and Davis, 2008; Davis et al., 2009; Geosyntec and WWE, 2009; He and Davis, 2009; Lucas, 2010). Pollutant build-up and removal may be of concern for infiltration BMPs, however particulate-bound pollutants are typically captured in the upper soil horizon and may be removed by replacing the topsoil (Davis et al., 2006; EPA, 2007; Li and Davis, 2008; Davis et al., 2009).

4.2.4 CRRC Low Impact Development Facility Monitoring Project

The Cub Run Recreation Center (CRRC) LID study site is an urban stormwater management retrofit located within the Cub Run watershed in the community of Chantilly, in western Fairfax County, Virginia. The facility is adjacent to a parking lot serving the CRRC and Westfield High School, and serves a total drainage area of 1.6 acres including 0.63 acres of asphalt parking lot, 0.86 acres of grassy-wooded area, and 0.11 acres of the LID facility itself (Versar, 2011; VT-OWML, 2012). The treatment train is gravity flow, and includes four in-line grass swales followed by a bioretention cell with a gravel base. Stormwater runoff enters the grass swales from the parking lot to the north and the grassy and wooded area to the south, as shown in Figure 4-1. The grass swales were designed to allow water ponding deeper than six inches in any swale to overflow into the next cell. The bioretention cell was designed to allow water ponding deeper than six inches to discharge by means of an overflow in to an adjacent 15 inch PVC pipe from which samples were taken. The pipe discharged into a curb inlet that received additional parking lot drainage. Outflows from the curb inlet were routed to a conventional detention pond (Versar, 2011).

Versar, Inc. under contract with the Fairfax County Department of Public Works and Environmental Services (DPWES) monitored the CRRC LID facility during two periods from September 2008 – June 2010 and March 2011 – May 2012. Installation of the monitoring equipment took place during August 2008. Continuous flow monitoring (at the LID facility outfall only), meteorological data, soil moisture and storm monitoring was performed by ATR Associates, Inc. under subcontract to Versar, Inc. from September 2008 to July 2009 and solely by Versar, Inc. from July 2009 to June 2010 and again from March 2011 to May 2012 (Versar, 2011). In July, 2011, Virginia Tech entered into an agreement with DPWES to conduct a performance analysis of the LID stormwater retrofit. Faculty, staff, and students of the Departments of Biological Systems Engineering and Civil and Environmental Engineering were involved in the project, and contributed to the performance analysis.

The collected datasets, provided by Versar (2011), consisted of continuous monitoring for meteorology and hydrology, along with discrete sampling, and subsequent analysis for selected water quality parameters during targeted storm events. The LID facility was monitored for water quality during 25 storm events over the course of the two monitoring periods. Passive and automated devices were used to collect samples that facilitated comparisons of water quality and flows at inflow and outflow locations, respectively. The water quality monitoring included post-storm analyses for the event mean concentrations of nutrients such as phosphorus and nitrogen, trace metals such as copper and zinc, and other important water quality parameters such as total suspended solids and total dissolved solids. The water quality data were then used along with the meteorological and hydrologic data to calculate inflow and outflow loadings for constituents of interest. Flow estimates were made using different techniques at the inflow and outflow points.

Water quality benefits from LID practices and other infiltration-based stormwater BMPs are a function of physical, chemical, and biological processes as well as reductions in stormwater runoff volumes (Davis et al., 2006; Davis, 2007; Geosyntec and WWE, 2009). For this reason, metrics based on changes in the total pollutant load over the monitoring period were chosen to assess the pollutant removal performance of the facility (Davis, 2007; Geosyntec and WWE, 2009). The Summation of Loads method (Minton, 2005; Hunt et al., 2006; Cates et al., 2009;

Chi-Feng et al., 2009; Geosyntec and WWE, 2009; Williams et al., 2009; McNett et al., 2011) was chosen for constituent load reduction analyses.

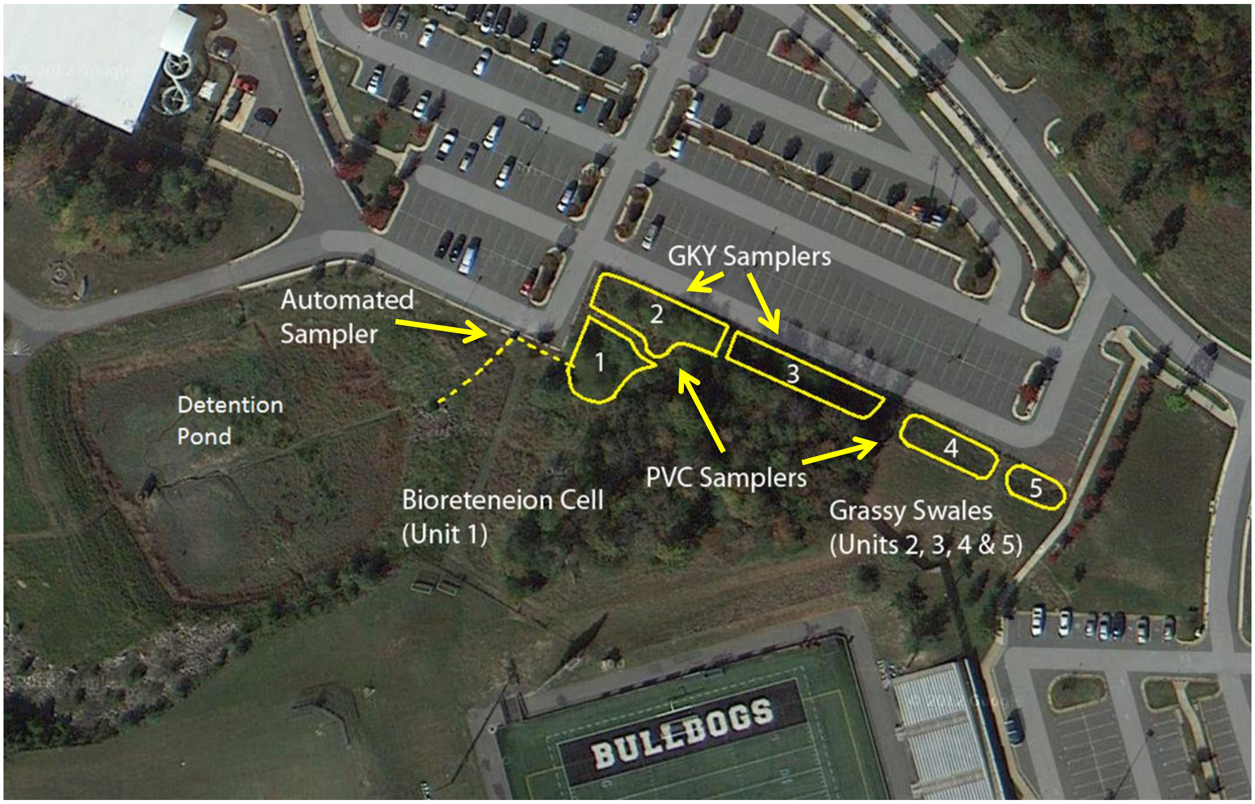


Figure 4-1. Aerial view of the Cub Run Recreation Center LID facility with approximate outlines for the bioretention cell, grass swales and sampler locations (VT-OWML, 2012; Google Maps, 2013) Used under fair use, 2013.

4.3 CRRC LID Facility Methodology

4.3.1 Flow Rate Monitoring and Flow Volume Estimates

LID facility outflows were continuously monitored using a depth sensor and a 60^0 V-notch weir located within the outfall pipe from the bioretention cell (Versar, 2011). Continuous flow data were logged electronically and integrated using the trapezoidal method over the duration of a storm event to arrive at outflow discharge volume estimates (Versar, 2011). Inflow discharge volumes were estimated using the Soil Conservation Service (SCS) runoff curve number method as outlined by Technical Release 55 (TR-55) by the United States Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS, 1986).

4.3.1.1 Inflow Volume Estimates

SCS Runoff Curve Number Method

TR-55 presents a simplified procedure for estimating storm runoff volumes, peak discharge rates, hydrographs and storage volumes required for floodwater reservoirs. The so-called SCS runoff curve number method has been widely used to estimate inflows when actual monitoring data are unavailable (LeFevre et al., 2010; Giacomoni et al., 2012).

The SCS runoff equation (NRCS, 1986) is given as:

$$Q = \frac{(P - I_a)^2}{(P - I_a) + S}$$

Where: Q = runoff (in), P = rainfall (in), S = potential maximum retention after runoff begins (in), I_a = initial abstraction (in) = all losses before runoff begins (in)

Initial abstraction (I_a) may be approximated by the following empirical equation based on SCS watershed studies (NRCS, 1986; Bedient, 2002):

$$I_a = 0.2S$$

Where: $S = \frac{1000}{CN} - 10$

Substituting 0.2S for I_a in the original runoff equation gives:

$$Q = \frac{(P - 0.2S)^2}{(P + 0.8S)}$$

The curve number (CN) has a range from 0 to 100 and depends on the soil and cover conditions of the watershed, which include the hydrologic soil group, cover type, treatment, hydrologic condition and antecedent runoff condition (NRCS, 1986). In essence, the CN may be viewed as a surrogate for watershed imperviousness, and therefore, hydrologic response.

Versar (2011) conducted a performance analysis of the LID facility and reported the curve numbers of 98 and 69.5, respectively, for the adjacent parking lot and grassy and wooded areas. While the curve number of 98 remained a valid estimate for the parking lot, the grassy and wooded area curve number was updated to reflect a more recent soil survey map provided by Fairfax County (2011). The updated soil survey map designated the grassy and wooded area soils adjacent to the LID facility as hydrologic soil group (HSG) D. Taking the new HSG D designation into account, the grassy and wooded area weighted curve number was determined to be 79, which is an area-weighted composite of the curve numbers for a fully developed urban area consisting of open space in good condition (CN 80) and an agricultural land comprised of woods in good condition (CN 77) (NRCS, 1986).

Limitations of the SCS Runoff Curve Number Method

Because the initial abstraction term includes all losses before runoff begins, the curve number method assumes that runoff does not occur until the precipitation depth exceeds the initial abstraction depth. Because the initial abstraction may be calculated as a function of the curve number, it may be assumed that, for any given curve number, there is a precipitation depth that must be exceeded before which the SCS runoff curve number calculation would produce realistic runoff values. By setting runoff (Q) in the curve number method equation to zero and applying the curve number of interest, the precipitation depth threshold required to satisfy the $P \geq 0.2S$ constraint may be found (McCuen, 2004). For the CRRC parking lot (CN=98), the threshold precipitation depth was found to be approximately 0.04 inches, while for the grassy and wooded area (CN=79), the threshold precipitation depth was found to be approximately 0.53 inches.

The minimum precipitation threshold may be assumed to have no appreciable effect on parking lot runoff volume estimates, because samples were not collected until at least 0.2 inches of rain was expected (Versar, 2011). However, it may be seen to have a pronounced effect on runoff estimates for the grassy and wooded areas. The curve number method restricts the production of surface runoff to storms with rainfall depths of 0.53 inches and greater. Six of the sixteen (37.5%) events with samples taken from the grassy and wooded areas were found to have had rainfall depths less than 0.53 inches. A clear, but not easily quantified, bias in the dataset appears to have resulted from setting the total runoff volume from these events to zero for the grassy and wooded area. The zero-flow value is not reflective of reality because inflow water quality samples were retrieved following each of the events. Nevertheless, the observation that flows did occur when none were predicted may argue for a re-assessment of the appropriateness of using the SCS runoff curve number method for flow estimation in this case. Absent a flow to associate with samples collected in events with rainfall less than 0.53 inches, the inflow loads from the grassy and wooded areas were assumed to be zero, and those inputs removed from the dataset provided by Versar (2011). It should be noted, however, that because of the often dispersed nature of inflows to LID practices, it is not always feasible to physically monitor all the BMP inflows, and estimating such ungaged flows is not an uncommon practice.

While the simple nature of the curve number method allows its application with minimal data requirements (storm depth and curve numbers), the approach also creates some challenges and limitations with regards to its ability to predict event-scale hydrologic response in real world applications (Ponce and Hawkins, 1996). While the method provides prediction for average conditions that are useful for design purposes, the modeling accuracy has been observed to decrease for actual rain events, because of the inability to account for effects of rainfall duration or intensity (NRCS, 1986; Ponce and Hawkins, 1996; Lamont et al., 2008; Chung et al., 2010). The method has also been observed to be less accurate when runoff depth is less than 0.5 inches (NRCS, 1986). Several investigators have also found the often assumed initial abstraction ratio of 0.2S may not accurately reflect specific watershed conditions present at every site of interest (Ponce and Hawkins, 1996; Lamont et al., 2008; Chung et al., 2010). The absence of clear guidance on how to account for variability in antecedent moisture conditions (Ponce and Hawkins, 1996; Chung et al., 2010), spatial scale effects (Ponce and Hawkins, 1996) and land use changes (Ogden et al., 2011), have all been cited as potential barriers to application of the method.

Given the potential problems with down-scaling the curve number method for use in runoff predictions for individual events on small catchments, it is not surprising that the accuracy of the BMP inflow load predictions at the CRRC LID facility is subject to some uncertainty. In BMP performance assessments, the flow balance is always important. However, in practices where infiltration may be responsible for a significant fraction of the constituent removal efficiency, direct measurements of surface inflows and infiltration become critical. Because of this, performance assessments developed from the analysis of the CRRC monitoring program data must take into account the uncertainty introduced by (as yet) unvalidated estimation methods.

4.3.1.2 Outflow Volume Calculations

Flows exiting the LID facility were measured with a 60^0 V-notch plywood weir installed at the end of the 15-inch PVC outlet pipe where it entered a catch basin. An ISCO Model 720 integrated flow module with integrated pressure transducer was used to measure flows. The pressure transducer sensor was installed upstream of the weir to record the head on the weir notch, and the flow module logged static head data at 10-minute intervals. Using the appropriate weir equation, static head was converted to flow rate with proprietary ISCO Flowlink Software. The flow module provided an activation signal to an attached automated sampler during runoff events (Versar, 2011; ISCO, 2012). Storm event flow volumes were calculated by integrating the 10-minute flow data during events using the trapezoidal rule (Hass, 2007).

4.3.2 Sampling

4.3.2.1 LID Facility Inflow Samplers

The LID facility received sheet flow from the adjacent parking area, grassy area and wooded area. Sheet flow samples from the parking area were collected using two GKY 'First-Flush' samplers (Versar, 2011; GKY, 2012). The GKY samplers received sheet flow from the adjacent parking lot area as it flowed into the LID facility at Swale 2 and Swale 3 as shown in Figure 4-1. A schematic of the GKY samplers is provided in Figure 4-2.

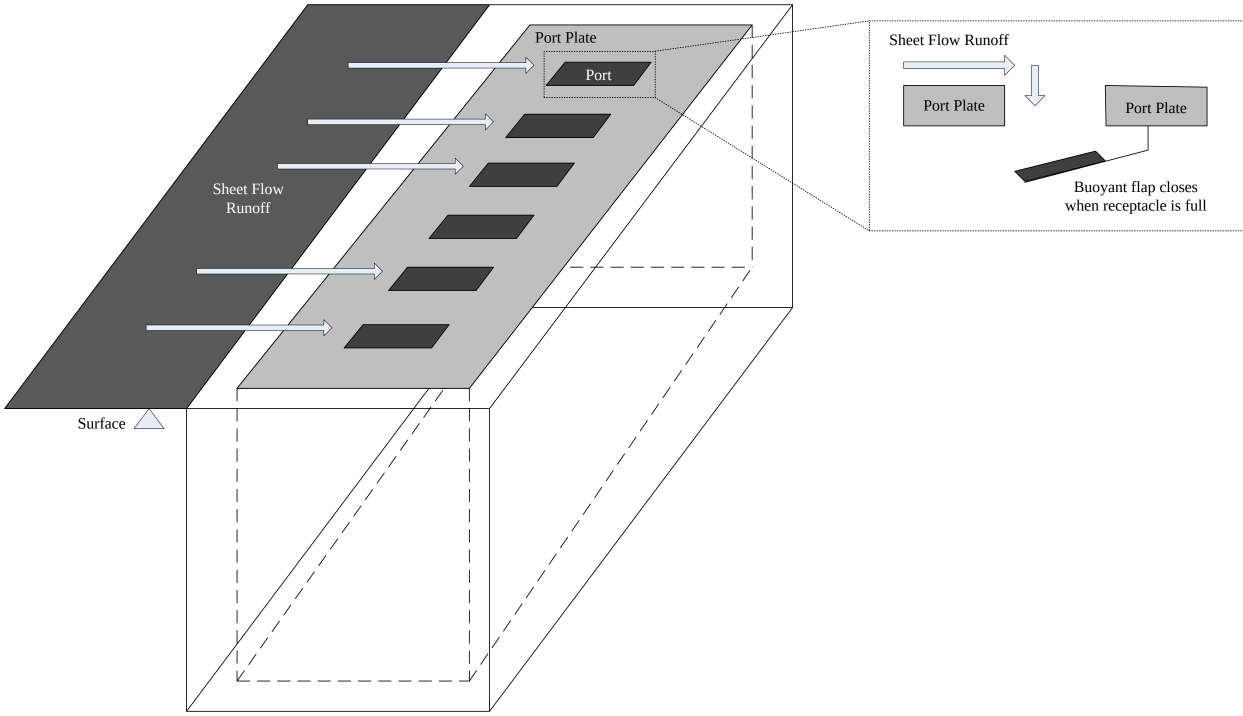


Figure 4-2. Schematic of a GKY First Flush Sampler.

Sheet flow samples from the grassy and wooded areas were taken with samplers constructed by Versar (2011) with two 5-foot sections of 4-inch PVC pipe capped at the ends and installed normal to the fall line. The runoff entered the samplers through a ½ inch slot and a Plexiglas lip attached to the lower edge of the opening to direct runoff into the pipes. The samplers were placed into shallow trenches with cement aprons to mold the Plexiglas lip against the surrounding turf. The PVC samplers receiving drainage from the grassy area and wooded areas were located at the edge of the BMP at Swale 2 and Swale 3, respectively, as shown in Figure 4-1. A schematic of the PVC Samplers is provided in Figure 4-3.

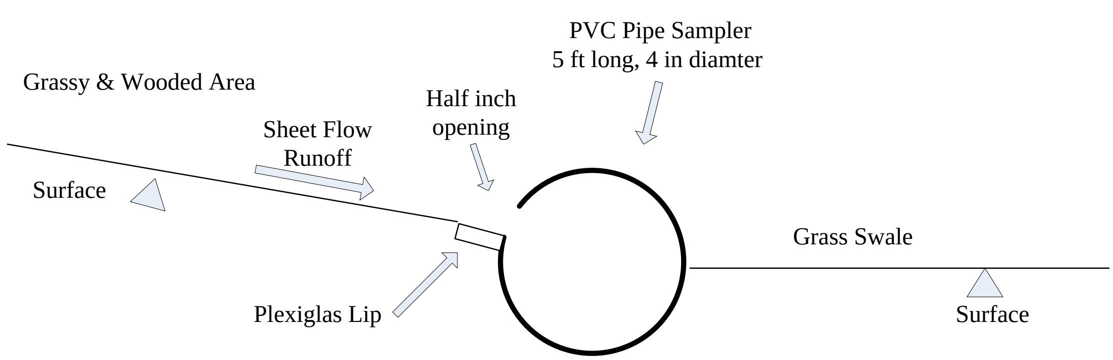


Figure 4-3. Side view schematic of a PVC Sampler.

The sheet flow samples were assumed to be composites representative of the runoff from the contributing drainage areas (Versar, 2011). The available data did not make it possible to estimate the lost flow (if any) for events where the sheet flow samplers were filled and had no additional void capacity to store water. In spite of this, it may be concluded that the performance data are conservative, and the actual removals are likely to be somewhat higher.

4.3.2.2 LID Facility Infiltration Sampler

A lysimeter sampler was buried under Swale 4 to collect infiltrated stormwater using a receptacle bucket (Versar, 2011; VT-OWML, 2012). Samples were taken from the lysimeter each day following a targeted storm event until no additional leachate was observed. Due to the expectation that flow into the lysimeter sampler would be relatively small, the sample volumes collected each day after a storm event were simply added together to make an overall composite sample (VT-OWML, 2012). The lysimeter sampler was installed on June 15, 2011 (Versar, 2011). Consequently, no samples were taken during the first monitoring period.

4.3.2.3 LID Facility Outfall Sampler

Samples of the outflow discharge were taken from the LID facility outlet pipe using an ISCO model 6712 portable automated sampler (Versar, 2011; ISCO, 2012). The automated sampler had a collection capacity of 24 1 L water samples in polypropylene bottles and was housed in a nearby equipment shelter constructed of plywood and secured with a padlock (Versar, 2011). A polypropylene sample strainer was placed behind the 60^0 V-notch weir in the PVC outlet pipe and was connected to the sampler through flexible vinyl tubing (Versar, 2011). During targeted storm events, the sampler was activated when the water level in the PVC outlet pipe exceeded 0.54 inches The sampler was programmed to take discrete samples at time intervals, usually between 45 minutes to 2 hours, to maximize the number of samples obtained while the outfall discharged runoff and account for the extended time the bioretention area dewatered (Versar, 2011; Jones, 2013).The sampler retrieved aliquots that could be combined into a flow-weighted composite at a later time (Versar, 2011; ISCO, 2012). The resulting storm sample composites were taken to be representative of the event mean concentration (EMC) values for any constituents subsequently analyzed. The automated sampler was located above the catch basin receiving outflow from the bioretention cell, as shown in Figure 4-1. A schematic of the sampling apparatus at the LID facility outfall is provided in Figure 4-4.

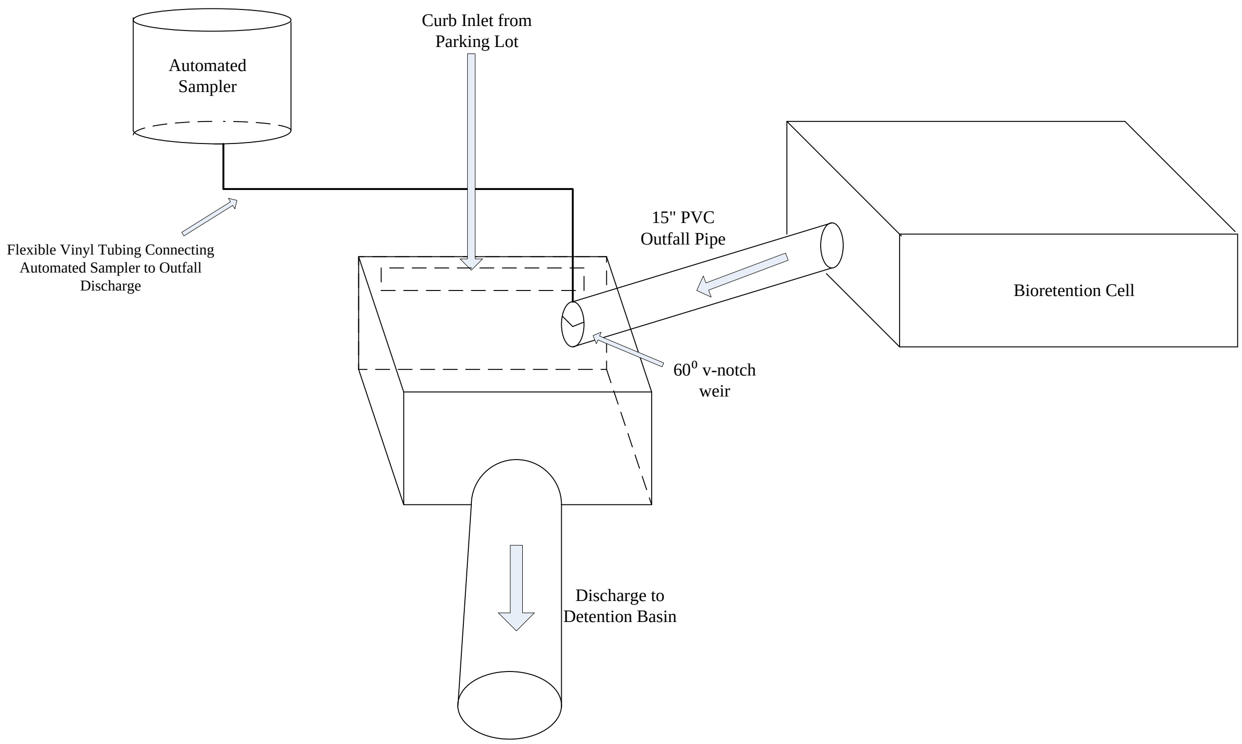


Figure 4-4. Schematic of the sampling apparatus at the LID facility outfall.

4.3.2.4 Water Quality Constituents Monitored

During targeted storm events, sample analyses included total phosphorus (TP), oxidized nitrogen (OxN), total Kjeldahl nitrogen (TKN), ammonia nitrogen (NH_3), total suspended solids (TSS), chemical oxygen demand (COD), total dissolved solids (TDS), copper (Cu), cadmium (Cd), zinc (Zn), lead (Pb), oil and grease (O&G), total petroleum hydrocarbons (TPH), alkalinity (Alk), hardness (Hard) and orthophosphate phosphorus (OP) (Versar, 2011; VT-OWML, 2012).

Table 4-1 lists the water quality parameters monitored on a discrete basis for targeted storm events for the two monitoring periods. The table also shows the analytical methods reported and the applicable reporting limits (Versar, 2011; VT-OWML, 2012).

Table 4-1. Discrete water quality parameters monitored for targeted storm events.

Monitoring Period	September 2008 – June 2010		March 2011- May 2012	
Parameter	**Reportable Detection Limit (mg/L)**	**Method**	**Reportable Detection Limit (mg/L)**	**Method**
Total Phosphorus	0.01	SM 4500P-E	0.01	SM 4500P-E
Oxidized Nitrogen	0.02	SM 4500NO3-H	0.02	SM 4500NO3-H
Total Kjeldahl Nitrogen	0.5	SM 4500NH3-C	0.5	SM 4500NH3-C
Ammonia Nitrogen	0.2	SM 4500NH3-C	0.2	SM 4500NH3-C
Total Suspended Solids	1	SM 2540 D	1	SM 2540 D
Chemical Oxygen Demand[1]			10	EPA 410.4 & SM 5220-D
Total Dissolved Solids[1]			10	SM 2540C
Copper[3]	0.01	EPA 200.8	0.002	EPA 200.8
Cadmium	0.0005	EPA 200.8	0.0005	EPA 200.8
Zinc	0.01	EPA 200.8	0.01	EPA 200.8
Lead[3]	0.01 & 0.002	EPA 200.8	0.002	EPA 200.8
Oil and Grease	5	EPA 1664	5	EPA 1664
Total Petroleum Hydrocarbons[1]			5	EPA 1664
Alkalinity[2]	1	SM 2320 B		
Hardness[2]	1	SM 2340 B		
Orthophosphate Phosphorus[2]	0.01	SM 4500P-E		

[1] Chemical Oxygen Demand (COD), Total Dissolved Solids (TDS) and Total Petroleum Hydrocarbons (TPH) were not tested for during the first monitoring period September 2008 – June 2010. [2] Alkalinity, Hardness and Orthophosphate Phosphorus were not tested for during the most recent monitoring period March 2011- May 2012. [3] Copper and Lead had different reporting limits for the two monitoring periods.

4.3.2.5 Continuous Meteorological and Water Quality Parameters

An Onset Model H21-001 (Onset, 2012) weather station was installed to record continuous meteorological and water temperature data for the entire project period. The station was tripod-mounted and secured with guy wires adjacent to the downstream section of the bioretention cell. As with flow, meteorological and water temperature data were recorded at 10-minute intervals by an associated data logger. The weather station was configured to record precipitation, air temperature, relative humidity, wind speed, wind gust speed, solar radiation, soil moisture at three different depths, temperature of LID facility discharge water, and temperature of water discharging from non-LID areas at the western end of the parking lot (Versar, 2011).

4.3.3 Storm Monitoring

Decisions on storm selection for water quality monitoring were taken after closely monitoring rainfall predictions on available weather services, including NOAA (Versar, 2011). Field staff acted on high-probability weather predictions by traveling to the site with appropriate equipment for targeted storms that were predicted to deliver at least 0.2 inches of rainfall. Of the 25 storm events monitored in the two monitoring periods, nine were reported to produce no flow at the LID facility outfall (Versar, 2011). To prepare for storm sampling, field technicians programmed the automated sampler to obtain time-paced water samples at intervals corresponding to the predicted duration of rainfall. Staff also installed pre-cleaned sample receipt tubs into the GKY samplers, and checked the PVC pipe samplers for cleanliness and proper alignment with the concrete apron (Versar, 2011).

Once storm sampling was underway, field staff checked online weather resources (e.g. http://www.wunderground.com/wundermap) to ensure the minimum required rainfall had taken place. If so, staff visited the site with previously prepared bottles to collect and transport the water samples. At the site, level data were downloaded from the ISCO equipment to facilitate constructing tables of discharge volume per discrete sample to be used to construct volume-weighted composite samples. Samples were also retrieved from the GKY samplers, and the vessels were examined to compare collected volumes. Sub-samples from the GKY samplers were proportionally combined into one-liter, parameter-specific collection and transport bottles. The PVC pipe samplers were removed from the trenches and emptied into a pre-cleaned bucket, mixed, and subsequently poured into one-liter, parameter-specific bottles (Versar, 2011).

Following a sampled storm event, staff removed the discrete sample carrier from the automated sampler, and the individual one-liter bottles were capped and transported to Versar, Inc. facilities to prepare for analysis (Versar, 2011). Flows were computed from the recorded 10-minute level data using the appropriate weir equation with ISCO Flowlink software. Versar (2011) described the compositing procedure where "The flow rate data were then integrated over the sampling interval time to obtain total discharge volume per discrete bottle. The discharge volume-proportional subsample amount from each bottle was poured off and combined to form one composite sample." As with the sheet flow samples, the composite sample was also split between one-liter parameter specific bottles (Versar, 2011).

Lysimeter samples were reported to be collected each day following a storm event until no further leachate was observed. The daily sample volumes were combined to construct an overall lysimeter composite sample, which could then be analyzed for total phosphorus, oxidized nitrogen and total Kjeldahl nitrogen (Versar, 2011). Because influent flows were estimated using the SCS runoff curve number method, an accurate description of the water balance, including infiltration and evapotranspiration, at the LID facility was not possible. While lysimeter samples were analyzed and reported for TP, OxN and TKN concentrations, further evaluation of the lysimeter samples was limited due to uncertainties in the water balance at the LID facility.

4.3.4 Site Maintenance

Staff visited the CRRC site on a biweekly basis between storm events to ensure the monitoring equipment was working properly. Site maintenance was also reported as taking place on an as-needed basis while staff were on site to prepare for a storm event, or to collect samples from a storm event (Versar, 2011).

Regular maintenance of the site was reported to include checking the overall condition of the equipment; checking power-up status of equipment; exchanging batteries if needed; downloading accumulated meteorological, water temperature, and water level data to a field laptop computer; repairing or securing equipment as needed; and filling out equipment status field data reports (Versar, 2011). Weather station and water temperature data were downloaded by staff using Hoboware Pro software from Onset (2012). Water level and flow data were downloaded using Flowlink version 4.15 software from ISCO (2012). A log of site visits between July 2009 – June

2010 and March 2011 – May 2012 was provided by Versar and is available in the performance analysis reports prepared by Versar (2011) and Grizzard and Le Bel (2013).

4.3.5 Accounting for Censored Observations

Analysis of Censored Data

Nondetects in environmental datasets are values reported to be only below an analytical reporting limit, and typically result in censored datasets. Nondetects in water quality data are typically low-level concentrations of chemicals with values known only to be somewhere between zero and the analytical detection/reporting limits (Helsel, 2002; Geosyntec and WWE, 2009; Helsel, 2012). Substitution methods such as replacing censored data with values equal to one-half the detection limit are common in the environmental engineering literature. However, substitution methods have been shown by Helsel (2012) to introduce "invasive" patterns and signals not present in the original dataset. Substitution methods arbitrarily change the distribution of datasets and may cause artificial relationships to be inferred between variables. Helsel (2012) demonstrated that substitution methods are not neutral, but instead "invasive," because such methods may introduce a pattern or signal to the data which is different than the native pattern of the original dataset, and thereby not reflective of reality. Helsel (2012) recommends the use of three data analysis approaches when censored data are present: (1) using nonparametric methods after censoring at the highest reporting limit; (2) using the maximum likelihood estimation (MLE) method which is a survival analysis procedure assuming a specific distribution; (3) and using a nonparametric survival analysis procedure such as the Kaplan-Meier (KM) and Turnbull methods. Helsel (2012) has also recommended imputation methods such as robust regression on ordered statistics (ROS) and robust MLE when the level of censoring within a dataset is greater than 50% but less than 80%. When used correctly, these approaches avoid the introduction of invasive patterns and signals associated with other (and often more commonly used) substitution methods (Helsel, 2012).

4.3.6 Methods of Calculating BMP Efficiency

4.3.6.1 Mass-Based Methods for Assessing Stormwater BMPs

Water quality benefits and load reductions from LID practices and other BMPs are a function of both water quality treatment processes (such as filtration of particle-bound pollutants, removal of dissolved pollutants through amended media, and nutrient uptake by vegetation) and stormwater runoff volume reductions (Davis et al., 2006; Davis, 2007; Geosyntec and WWE, 2009). Because of this, performance metrics based on the total pollutant load removal over a representative period of the meteorological and hydrologic record are more representative measures of the overall system efficiency and are consequently more appropriate for assessing pollutant reduction performance of a LID site (Davis, 2007; Geosyntec and WWE, 2009). The Summation of Loads method (Minton, 2005; Hunt et al., 2006; Cates et al., 2009; Chi-Feng et al., 2009; Geosyntec and WWE, 2009; Williams et al., 2009; McNett et al., 2011) was chosen for constituent load reduction analyses.

4.3.6.2 Summation of Loads

The Summation of Loads (SOL) method was used to compare influent and effluent loads at the LID facility using three common substitution methods for censored observations: (1) setting below detection limit (BDL) observations to zero, (2) setting BDL observations to one-half the detection limit, and (3) setting BDL observations to the detection limit. The SOL method defines the efficiency of a given BMP to remove pollutants as the ratio of the summation of all incoming (inlet) loads to the summation of all outgoing (outlet) loads. The overall change in load for each pollutant over the monitoring period is presented as a percent decrease between the summation of inlet and outlet loads (Minton, 2005; Hunt et al., 2006; Cates et al., 2009; Chi-Feng et al., 2009; Geosyntec and WWE, 2009; Williams et al., 2009; McNett et al., 2011), or:

$$SOL = 1 - \frac{\sum Outlet\ Loads}{\sum Inlet\ Loads}$$

The assumptions on which the Summation of Loads method is based include (Minton, 2005; Geosyntec and WWE, 2009):

- The removal of material is most relevant over the entire period of analysis;
- Monitoring data accurately represent the entire total loads in and out of the BMP for a period long enough to overshadow temporary internal storage of pollutants;
- Any significant unmonitored storms had inlet to outlet load ratios similar to the storms that were monitored;

- No materials were exported during dry periods, or if they were, the ratio of inlet to outlet loads during these periods was similar to the ratio of the loads during the monitored storm events.

It has also been reported that a small number of large storms will generally dominate the computed SOL efficiency (Geosyntec and WWE, 2009).

4.3.6.3 LID Facility Load Calculations

LID Facility Inlet Load Calculations

To facilitate the use of the Summation of Loads method as a performance analysis metric for the CRRC LID facility, volume-weighted event mean concentration (EMC) and load were calculated to represent the total inlet load for any combination of storm event and water quality parameter. The total inlet EMC or load at the Cub Run LID facility was designated as 'CUIN' to maintain consistency with previous performance evaluations. CUIN for each storm event and discrete water quality parameter was calculated by determining the total loads flowing into the LID facility as measured by the GKY and PVC samplers, identified as CUGKY and CUPVC, respectively. The load from each sampler was calculated by multiplying the EMC by the total inflow volume from the respective drainage areas for the GKY and PVC samplers as estimated by the SCS runoff curve number method. The loads from the GKY and PVC samplers were then summed to give the total load delivered to the LID facility. A volume-weighted EMC for CUIN was then obtained by dividing the total load by the total inflow volume calculated by summing the inflows from the parking lot and grassy and wooded areas. The equations describing the CUIN EMC and loads are as follows:

$$CUIN_{Load} = \left(\left(EMC_{GKY} x Inflow_{Parking\ Lot}\right) + \left(EMC_{PVC} x Inflow_{Grassy\ \&\ Wooded\ Area}\right)\right) x \frac{1\,g}{1000mg}$$

$$CUIN_{EMC} = \frac{\left(EMC_{GKY} x Inflow_{Parking\ Lot}\right) + \left(EMC_{PVC} x Inflow_{Grassy\ \&\ Wooded\ Area}\right)}{\left(Inflow_{Parking\ Lot} + Inflow_{Grassy\ \&\ Wooded\ Area}\right)}$$

Where:

- $CUIN_{Load}$ = Total load delivered to the LID facility (grams) from sheet flow runoff from both the parking lot and the grassy and wooded areas;

- $CUIN_{EMC}$ = Volume-weighted EMC for CUIN (mg/L);
- EMC_{GKY} = EMC reported from GKY sampler (mg/L);
- EMC_{PVC} = EMC reported from PVC sampler (mg/L);
- $Inflow_{Parking\ Lot}$ = Volume of runoff entering LID facility from the parking lot (L);
- $Inflow_{Grassy\ \&\ Wooded\ Area}$ = Volume of runoff entering LID facility from the grassy and wooded areas (L).

LID Facility Outlet Loads Calculations

LID facility outlet loads for any combination of water quality parameter and storm event were calculated as the product of the water quality parameter EMC reported at the outfall, designated CUOUT for the Cub Run outfall, and the storm event total discharge at the outlet (Davis et al., 2006; Davis, 2007; Li and Davis, 2009), or:

$$CUOUT_{Load} = EMC_{OUT} x Outflow_{LID\ Facility} x \frac{1g}{1000mg}$$

Where:

- $CUOUT_{Load}$ = Total load discharging from the LID facility outfall (grams);
- EMC_{OUT} = EMC reported from outfall sampler (mg/L);
- $Outflow_{LID\ Facility}$ = Volume of runoff discharging from the LID facility outfall (L).

4.4 Results

4.4.1 Representativeness of Dataset

4.4.1.1 Duration of Study

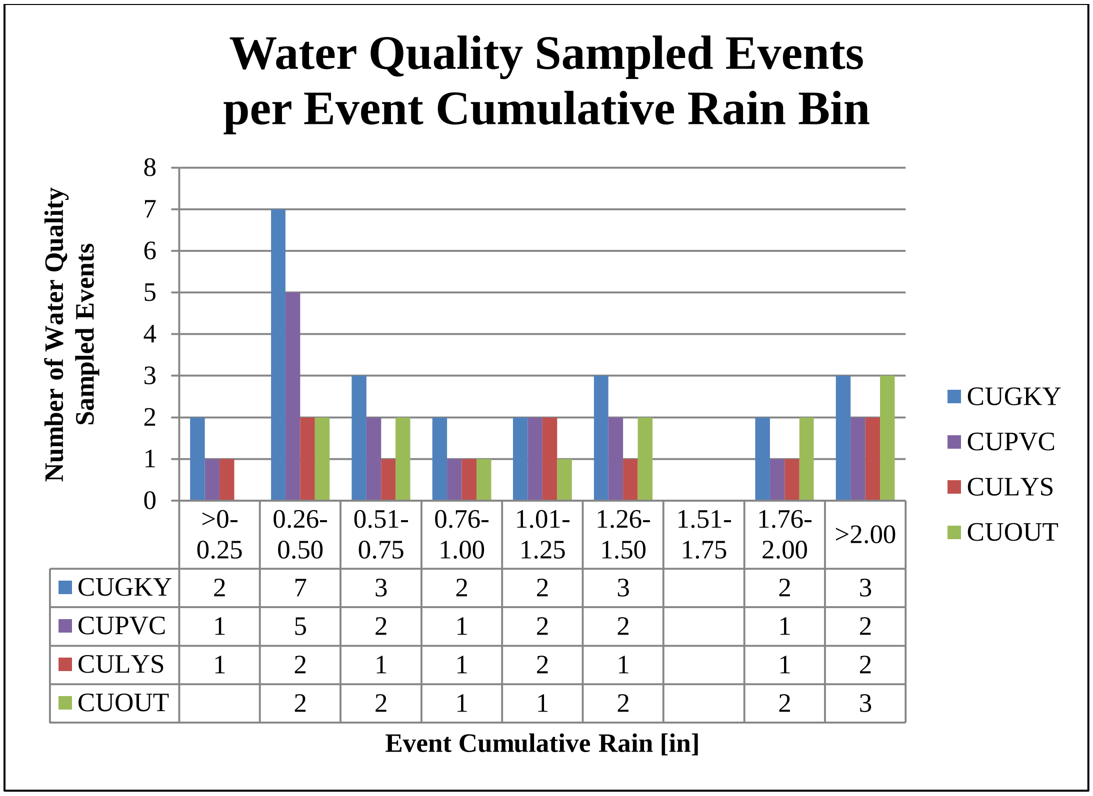
The Cub Run Recreation Center LID facility was monitored during two distinct monitoring periods. The first period ranged from September, 2008 to June, 2010 and the second monitoring period ranged from March, 2011 to May, 2012. During each period, continuous flow monitoring (at the LID facility outfall only), continuous meteorological data, and continuous soil moisture data were collected. Discrete water quality sampling for targeted storm events was also conducted (Versar, 2011).

4.4.1.2 Number of Storm Events and Water Quality Monitored Events

During the two monitoring periods, 183 events were reported where at least 0.01 inches of precipitation occurred (Versar, 2011; VT-OWML, 2012). Of these 183 events, 73 events had precipitation depths equal to or greater than 0.2 inches, which was the minimum pre-storm prediction required to mobilize field staff to sample an event (Versar, 2011). Two events, on 9/11/2009 and 1/26/2011, were monitored for water quality even though their precipitation depths were less than the threshold.

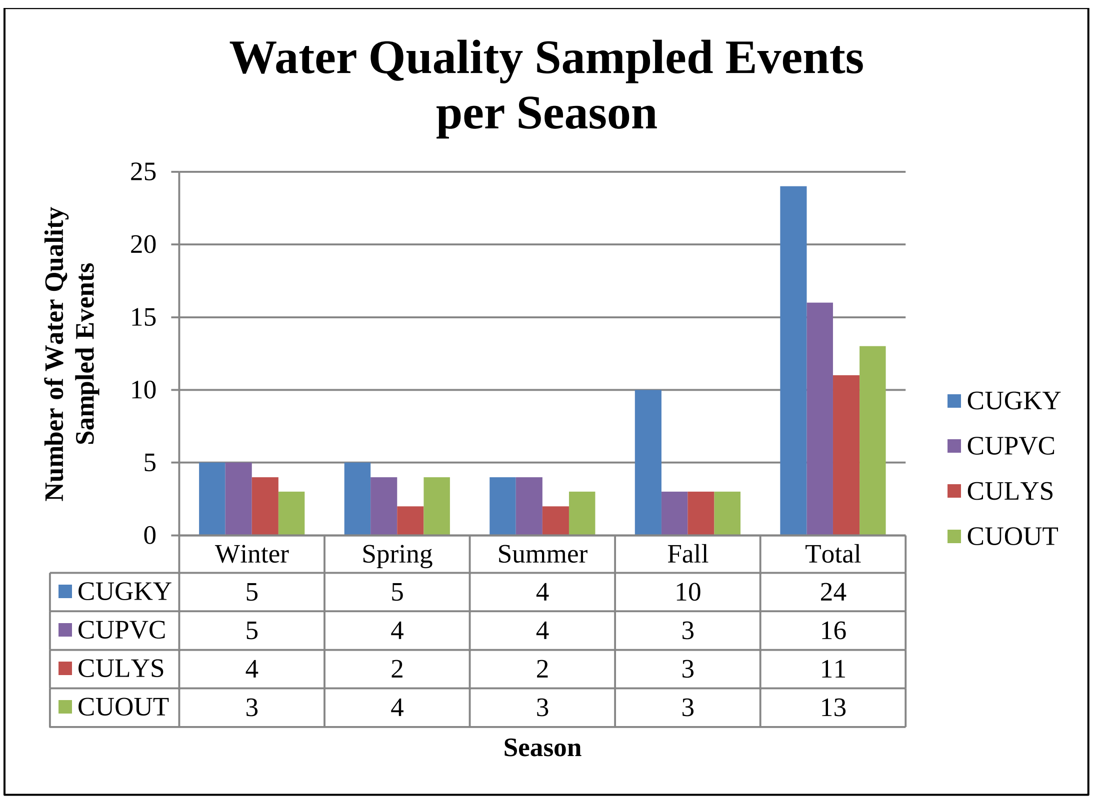
During the two monitoring periods, 25 storm events were monitored for water quality. When the 9/11/2009 and 1/26/2011 storm events were included, the number of events with qualifying precipitation depths increased to 75. From this, it may be seen that 1/3 of all eligible storm events, based on a precipitation depth of 0.2 inches or greater, were monitored for water quality.

Figures 4-5 and 4-6 show a summary of the rainfall event size and seasonal distribution of the events sampled for water quality. For the analysis, winter was defined as December – February; spring as March – May; summer as June – August; and fall as September – November. The water quality events sampled were rather evenly distributed across both rainfall depth and season, although there was a noticeable spike in events sampled with the GKY and PVC samplers at lesser rainfall depths. This is consistent with the previous observation that smaller events were less likely to produce outflow at the LID facility discharge (CUOUT).



	>0-0.25	0.26-0.50	0.51-0.75	0.76-1.00	1.01-1.25	1.26-1.50	1.51-1.75	1.76-2.00	>2.00
CUGKY	2	7	3	2	2	3		2	3
CUPVC	1	5	2	1	2	2		1	2
CULYS	1	2	1	1	2	1		1	2
CUOUT		2	2	1	1	2		2	3

Figure 4-5. Water quality sampled events per cumulative rain amount bar graph.



	Winter	Spring	Summer	Fall	Total
CUGKY	5	5	4	10	24
CUPVC	5	4	4	3	16
CULYS	4	2	2	3	11
CUOUT	3	4	3	3	13

Figure 4-6. Water quality sampled events per season bar graph.

4.4.2 Assessment of Monitoring System Equipment Performance

In the 2011 performance monitoring report produced by Versar (2011), the monitoring equipment design was found to have been adequate for capturing inflows and outflows and generally functioned as designed. Occasional equipment failures were found to have occurred.

Most of the difficulties with monitoring system integrity were due to a variety of problems associated with snow disposal on the Cub Run Recreation Center parking lot. Freezing of the GKY and PVC samplers in the winter of 2009-2010, and limited access due to snow accumulation were both reported to limit the number of sampling attempts (Versar, 2011). In examining the data provided in the much milder winter of 2011, it was apparent that the weather had a much decreased impact on sampling.

A comprehensive examination of equipment failures during the two monitoring periods may be found in Grizzard and Le Bel (2013).

4.4.3 Monitoring Data

4.4.3.1 Rainfall and Runoff Statistics for Storm Events Monitored for Water Quality

Rainfall and runoff statistics for the 25 monitored storm events for the Cub Run Recreation Center LID facility are provided in Table 4-2. The table includes data previously reported by Versar (2011) from the first monitoring period, and data reported to Virginia Tech for the second monitoring period (VT-OWML, 2012). As has been previously noted, the SCS runoff curve number method was used to estimate runoff volumes for the parking lot area and the grassy and wooded area.

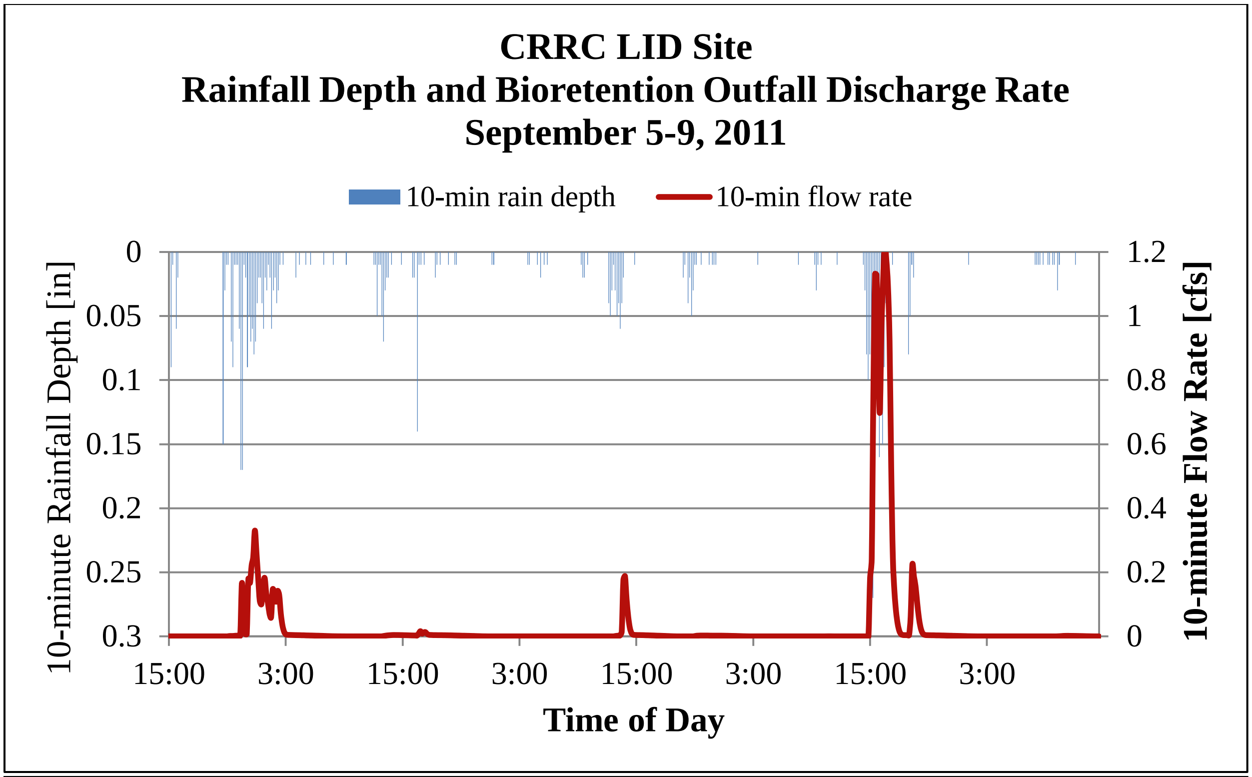
4.4.3.2 Storm Event Hydrographs and Total Flow Volume Time Series Plots

Ten-minute rainfall intensity, flow rate at the LID facility outfall, accumulated flow volume at the outfall and available precipitation volume is presented in Figure 4-7 for the water quality monitored storm event which occurred September 5 – 9, 2011. This event was chosen for display because of the relatively high rainfall total (5.13 inches) and duration (93.2 hours). Available precipitation volume was taken as the product of event rainfall and catchment area. Storm event hydrographs and hyetographs for all 25 water quality monitored events may be found in Figures A-8 – A-32 in Appendix A.

Table 4-2. Storm and runoff statistics for valid storms monitored at Cub Run Recreation Center LID facility.

	Measured Values		Calculated Values		Values Estimated by SCS Runoff CN Method				Measured and Calculated Values						
Event Date	**Total Rain (in.)**	**Outfall Volume (ft^3)**	**Outfall Equivalent Rain (in.)**	**Rain Retained (%)**	**Total Runoff Pavement (ft^3)**	**Runoff with CN Pavement (in.)**	**Total runoff Grassy/ Wooded (ft^3)**	**Runoff with CN Grassy/ Wooded (in.)**	**Dry Time (hr.)**	**Rainfall Duration (hr.)**	**Elevated Flow Duration (hr.)**	**Average Rainfall Rate (in./hr.)**	**Amount of Rain Before Flow (in.)**	**Time Before Flow (hr.)**	**Rainfall Rate Before Flow (in./hr.)**
9/25/08	0.47	0.00	0.00	100%	665	0.29	0	0.00	298.9[2]	18.42	N.R.	0.026	N.R.	N.R.	N.R.
4/20/09	1.80[1]	N.D.	N.D.	N.D.	3605	1.58	1279	0.00	98.8	25.67	N.D.	0.070	N.D.	N.D.	N.D.
6/3/09	1.28[1]	3394.73	0.58	54%	2433	1.06	513	0.00	85.9	1.50	4.00	0.853	0.43	0.33	1.303
8/21/09	2.36[1]	707.31	0.16	95%	4875	2.13	2326	0.22	368.5	15.50	6.17	0.152	1.62	7.67	0.211
9/11/09	0.15	0.00	0.00	100%	87	0.04	0	0.05	69.5	6.83	N.R.	0.022	N.R.	N.R.	N.R.
9/26/09	0.48	N.D.	N.D.	N.D.	686	0.30	0	0.10	30.1	31.17	N.R.	0.015	N.R.	N.R.	N.R.
10/15/09	0.62	0.00	0.00	100%	979	0.43	9	0.00	8.3	30.50	N.R.	0.020	N.R.	N.R.	N.R.
10/24/09	1.42	3178.18	0.73	61%	2747	1.20	695	0.00	151.7	5.83	3.00	0.243	0.21	2.67	0.079
10/27/09	0.92	602.35	0.14	89%	1632	0.71	155	0.00	10.7	13.00	3.00	0.071	0.55	7.83	0.070
11/11/09	1.09	0.00	0.00	100%	2009	0.88	303	0.09	230.1	35.50	N.R.	0.031	N.R.	N.R.	N.R.
12/2/09	0.44	4.20	0.001	100%	604	0.26	0	0.00	42.7	14.17	0.67	0.031	0.35	10.50	0.033
3/11/10	0.44	13.70	0.003	99%	604	0.26	0	0.15	217.3	9.33	4.83	0.047	0.43	6.83	0.063
3/28/10	0.62	141.49	0.03	96%	979	0.43	9	2.91	58.0	7.00	9.50	0.089	0.31	1.67	0.186
7/8/11	1.06	27.03	0.005	100%	1942	0.85	273	0.00	438.8	2.3	5.3	0.172	0.61	0.83	0.732
8/13/11	0.34	0.00	0.00	100%	407	0.18	0	0.80	140.5	33.5	N.R.	0.010	N.R.	N.R.	N.R.
8/27/11	1.23	67.79	0.01	99%	2321	1.01	454	0.39	44.0	19.7	15.8	0.056	0.46	6.00	0.077
9/5/11	5.13	10855.3	1.87	64%	11190	4.89	9097	0.01	51.2	93.2	89.5	0.054	0.37	6.00	0.062
9/23/11	0.32	0.00	0.00	100%	369	0.16	0	0.00	29.5	49.3	N.R.	0.006	N.R.	N.R.	N.R.
10/12/11	2.44	5395.19	0.93	62%	5057	2.21	2490	0.24	7.0	47.8	37.2	0.045	0.48	16.50	0.029
12/6/11	1.76	5195.13	0.89	49%	3514	1.54	1212	0.00	153.7	43.7	24.2	0.034	0.48	27.67	0.017
1/11/12	0.72	709.20	0.12	83%	1194	0.52	39	0.04	23.7	16.5	9.8	0.031	0.42	13.50	0.031
1/26/12	0.14	0.00	0.00	100%	74	0.03	0	0.00	58.8	29.7	N.R.	0.005	N.R.	N.R.	N.R.
2/29/12	1.47	2335.43	0.4	73%	2860	1.25	764	0.00	110.8	64.5	67.8	0.021	0.43	2.83	0.152
3/24/12	0.40	0.00	0.00	100%	524	0.23	0	0.00	508.3	15.5	N.R.	0.026	N.R.	N.R.	N.R.
4/21/12	0.86	59.28	0.01	99%	1500	0.66	113	0.22	65.8	44.8	7.7	0.019	0.51	24.50	0.021

N.R. = not applicable due to no runoff from the outfall pipe.
N.D. = data unavailable
[1] = Total rainfall determined from KVACHANT3 gauge located in Chantilly, VA.
[2] = Antecedent dry time determined from KIAD gauge located at Dulles International Airport.



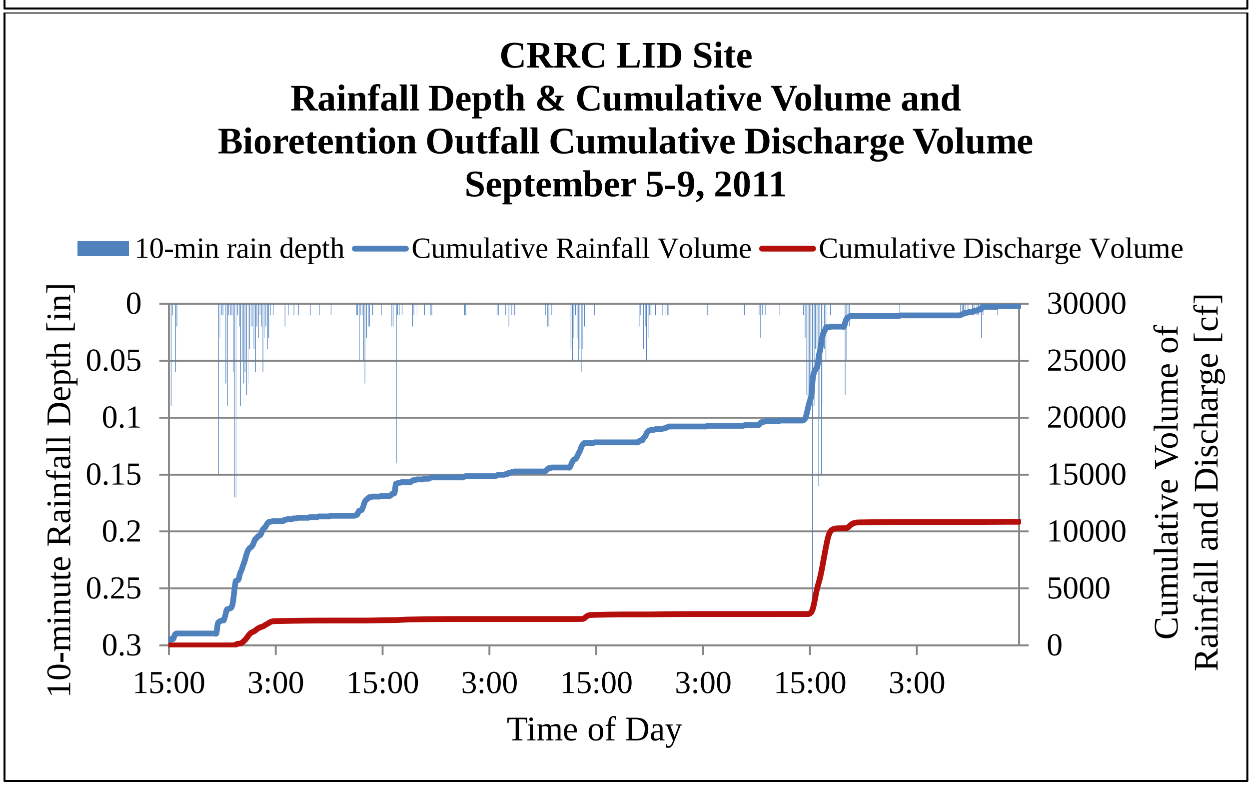


Figure 4-7. Hydrograph and hyetograph of Sept 5-9, 2011 storm event.
Dry time = 51.2 hrs.

4.4.3.3 Water Quality Results

Event Mean Concentration Results for Individual Storm Events

The computed event mean concentration (EMC) results for each sampled storm event in both monitoring periods are presented in Table 4-3.

Load Results for Individual Storm Events for CUIN & CUOUT

Table 4-4 presents the loads for CUIN and CUOUT for each sampled storm event after substituting zero for any censored, or below detection limit, observations. Loads calculated by substituting one-half the detection limit and the detection limit, respectively, for any censored observations are presented in Tables B-9 and B-10 in Appendix B. The Summation of Loads method will be performed on each set of data to demonstrate the effect of using each substitution method on the results for the Summation of Loads method.

Percent Censoring for Each Water Quality Parameter

Table 4-5 presents the percent censoring for each measured water quality parameter for the CUIN, CUOUT and CUOUT-ZF load datasets. The importance of using non-substitution methods to account for censored observations becomes apparent when viewing the Summation of Load analysis results for highly censored parameters. The higher the percent censoring for a particular water quality parameter, the more influence the value chosen to substitute for the below detection limit observations has on performance analysis results.

Table 4-3. Analytical results for monitored storm events.

Event Date	Pollutant Concentration (mg/L)																			
	Total Phosphorus					Total Nitrogen[2]					Oxidized Nitrogen					Total Kjeldahl Nitrogen				
	GKY	PVC	IN[1]	LYS[3]	OUT	GKY	PVC	IN[1]	LYS[3]	OUT	GKY	PVC	IN[1]	LYS[3]	OUT	GKY	PVC	IN[1]	LYS[3]	OUT
9/25/08	0.09		0.09			1.07		1.07			0.57		0.57			0.5		0.50		
4/20/09	1.3		0.96		0.28	3.72		2.75			0.22		0.16		0.25	3.5		2.58		2
6/3/09	0.04	0.12	0.05		0.24	2.18	3.02	2.32		2.06	0.38	<0.02	0.32		0.26	1.8	3	2.01		1.8
8/21/09	0.13		0.09		0.31	1.65		1.12		0.58	0.35		0.24		0.58	1.3		0.88		1.8
9/11/09	1.3		1.30			9.16		9.16			0.16		0.16			9		9.00		
9/26/09	0.06		0.06			1.00		1.00			0.1		0.10			0.9		0.90		
10/15/09	0.06		0.06			0.92		0.91			0.22		0.22			0.7		0.69		
10/24/09	0.18		0.14			2.12		1.69			0.42		0.34			1.7		1.36		
10/27/09	0.09		0.08			1.32		1.21			0.02		0.02			1.3		1.19		
11/11/09	0.12		0.10			5.10		4.43			2.6		2.26			2.5		2.17		
12/2/09	0.14	2.4	0.14			1.84		1.84			0.24	<0.02	0.24			1.6	11	1.60		
3/11/10	0.4	0.6	0.40		0.19	2.55		2.55		2.00	0.35	<0.02	0.35		1.1	2.2	3.7	2.20		0.9
3/28/10	0.77	0.63	0.77		0.28	3.80	4.11	3.80		2.09	0.1	0.11	0.10		0.49	3.7	4	3.70		1.6
7/8/11	0.04	1.2	0.18	0.74	0.35	1.16	5.30	1.67	28.40	4.40	0.26	2.40	0.52	20.00	1.80	0.90	2.90	1.15	8.40	2.60
8/13/11	0.15	4.7	0.15			2.15		2.15			0.45	5.70	0.45			1.70	17.00	1.70		
8/27/11		0.36	0.06	1.3			1.83	0.30	23.60			0.13	0.02	18.00			1.70	0.28	5.60	
9/5/11	0.23	0.45	0.33	0.32	0.23	0.85	1.49	1.14	1.92	2.10	0.05	0.09	0.07	0.52	0.70	0.80	1.40	1.07	1.40	1.40
9/23/11	0.06	0.72	0.06	0.72		1.59		1.59	5.10		0.89	6.90	0.89	1.70		0.70	3.50	0.70	3.40	
10/12/11	0.25	0.79	0.43	0.36	0.2	1.16	4.55	2.28	3.20	2.50	0.06	0.05	0.06	1.1	1.4	1.1	4.5	2.22	2.1	1.1
12/6/11	0.64	0.75	0.67	0.33	0.24	4.82	5.22	4.92	1.16	1.33	<0.02	<0.02	<0.02	0.16	0.13	4.8	5.2	4.90	1	1.2
1/11/12	0.48	0.91	0.49	0.35	0.17	3.60	5.66	3.66	2.90	1.51	0.1	0.16	0.10	1.3	0.61	3.5	5.5	3.56	1.6	0.9
1/26/12	0.27	1.4	0.27	0.64		1.20		1.20	2.60		0.1	0.06	0.10	0.6		1.1	4.4	1.10	2	
2/29/12	0.63	2.1	0.94	0.41	0.46	2.92	7.08	3.80	3.20	2.12	0.12	0.18	0.13	1.3	0.62	2.8	6.9	3.66	1.9	1.5
3/24/12	0.1	2	0.10	0.44		1.00		1.00	4.06		0.2	0.35	0.20	0.36		0.8	27	0.80	3.7	
4/21/12	0.21	0.51	0.23	0.37	0.35	1.58	3.42	1.71	3.50	1.33	0.08	0.52	0.11	1.3	0.53	1.5	2.9	1.60	2.2	0.8

[1]IN refers to the volume-weighted CUIN as discussed earlier in the report. [2]Total Nitrogen = (OxN_{Load} + TKN_{Load})/(Vol. of Runoff for Sampler's Drainage Area)
[3]Lysimeter samples were only taken for TP, OxN and TKN. Lysimeter samples were only taken during the 2nd monitoring period.
Blank cells are indicative of a storm event which was sampled for water quality but not for that particular water quality constituent.

Table 4-3. Analytical results for monitored storm events (Continued).

Event Date	Pollutant Concentration (mg/L)															
	Ammonia Nitrogen				Total Suspended Solids				Chemical Oxygen Demand[4]				Total Dissolved Solids[4]			
	GKY	PVC	IN[1]	OUT	GKY	PVC	IN[1]	OUT	GKY	PVC	IN[1]	OUT	GKY	PVC	IN[1]	OUT
9/25/08	0.3		0.30		32		32									
4/20/09					450		332	74								
6/3/09	1.1	0.6	1.01	0.4	4	56	13	10								
8/21/09	0.5		0.34	<0.2	25		17	2								
9/11/09	5.9		5.90		11		11									
9/26/09	0.2		0.20		4		4									
10/15/09	<0.2		<0.20		6		6									
10/24/09	<0.2		<0.16		28		22									
10/27/09	0.3		0.27		9		8									
11/11/09	0.9		0.78		9		8									
12/2/09	0.3	1	0.30		6	1600	6									
3/11/10	0.5	0.6	0.50	0.3	190	280	190	19								
3/28/10	0.4	0.7	0.40	0.3	480	290	478	14								
7/8/11	0.30	0.40	0.31	0.40	2	190	25	2	30	70	35	55	24	110	35	120
8/13/11	0.80	0.80	0.80		2		2		83		83		19		19	
8/27/11		<0.2	<0.03			28	5			41	7			<10	<1.7	
9/5/11	<0.2	13.00	5.88	<0.2	8	250	117	29	48	100	71	70	<10	65	32	72
9/23/11	<0.2	0.70	<0.2		9		9		35	50	35		<10		<10	
10/12/11	0.2	0.2	0.20	<0.2	150	490	262	10	110	200	140	37	28	88	48	77
12/6/11	0.3	0.6	0.38	<0.2	610	790	656	32	250	200	237	44	51	21	43	69
1/11/12	0.2	0.8	0.22	<0.2	290	680	302	28	150	180	151	22	39	78	40	54
1/26/12	0.3	0.4	0.30		170	580	170		120	170	120		<10	130	<10	
2/29/12	0.2	0.7	0.31	0.2	180	700	290	58	190	240	201	66	85	180	105	76
3/24/12	0.3	1.4	0.30		17	1300	17		40	310	40		<10	<10	<10	
4/21/12	0.3	0.8	0.33	<0.2	74	95	75	10	85	91	85	34	17	67	20	97

[1]IN refers to the volume-weighted EMC referred to as CUIN and discussed in previous sections.
[4]COD and TDS were not tested for during 1st monitoring period.
Blank cells are indicative of a storm event which was sampled for water quality but not for that particular water quality constituent.

Table 4-3. Analytical results for monitored storm events (Continued).

Event Date	Pollutant Concentration (mg/L)											
	Copper				Cadmium				Zinc			
	GKY	PVC	IN[1]	OUT	GKY	PVC	IN[1]	OUT	GKY	PVC	IN[1]	OUT
9/25/08	<0.01		<0.01		<0.0005		<0.0005		0.073		0.07	
4/20/09	0.058		0.0428	<0.01	<0.0005		<0.0004	<0.0005	1.8			0.064
6/3/09	0.0033	0.014	0.0052	0.0069	<0.0005	<0.0005	<0.0005	<0.0005	0.044	0.032	0.04	0.02
8/21/09	0.0056		0.0038	0.0098	<0.0005		<0.0003	<0.0005	0.055		0.04	0.093
9/11/09	0.0062		0.0062		<0.0005		<0.0005		0.024		0.02	
9/26/09	0.0028		0.0028		<0.0005		<0.0005		<0.01		<0.01	
10/15/09	0.0022		0.0022		<0.0005		<0.0005		0.019		0.019	
10/24/09	0.014		0.0112		<0.0005		<0.0004		0.05		0.040	
10/27/09	0.0035		0.0032		<0.0005		<0.0005		0.033		0.030	
11/11/09	0.0049		0.0043		<0.0005		<0.0004		0.032		0.028	
12/2/09	0.0054	0.125	0.0054		<0.0005	0.0015	<0.0005		0.017	0.17	0.017	
3/11/10	0.024	0.018	0.0240	0.0051	0.002	<0.0005	0.0020	<0.0005	0.094	0.041	0.094	0.04
3/28/10	0.041	0.024	0.0408	0.0093	0.0028	<0.0005	0.0028	0.00055	0.13	0.15	0.130	0.037
7/8/11	0.005		0.0044		<0.0005		<0.0004		0.074		0.065	
8/13/11	0.0071	0.104	0.0071		<0.0005	0.0019	<0.0005		0.04	0.15	0.040	
8/27/11		0.014	0.0023			0.001	0.0002			0.034	0.006	
9/5/11	0.00692	0.063	0.0321	0.0059	<0.0005	<0.0005	<0.0005	<0.0005	0.02	0.046	0.032	<0.01
9/23/11	0.013	0.035	0.0130		0.00065	0.00083	0.0007		0.073	0.089	0.073	
10/12/11	0.023	0.04	0.0286	0.0064	<0.0005	<0.0005	<0.0005	<0.0005	0.073	0.07	0.072	0.019
12/6/11	0.08	0.069	0.0772	0.0075	0.00065	<0.0005	0.0005	<0.0005	0.25	0.14	0.222	0.023
1/11/12	0.024	0.069	0.0254	0.0075	<0.0005	<0.0005	<0.0005	<0.0005	0.14	0.15	0.140	0.02
1/26/12	0.015	0.034	0.0150		<0.0005	<0.0005	<0.0005		0.1	0.07	0.100	
2/29/12	0.03	0.08	0.0405	0.01	<0.0005	<0.0005	<0.0005	<0.0005	0.12	0.13	0.122	0.02
3/24/12	<0.002		<0.002		0.001		0.0010		0.03	0	0.030	
4/21/12	0.011	0.015	0.0113	0.006	<0.0005	<0.0005	<0.0005	<0.0005	0.07	0.03	0.067	0.02

[1]IN refers to the volume-weighted EMC referred to as CUIN and discussed in previous sections.
Blank cells are indicative of a storm event which was sampled for water quality but not for that particular water quality constituent.

Table 4-3. Analytical results for monitored storm events (Continued).

Event Date	Pollutant Concentration (mg/L)											
	Lead				Oil and Grease				Total Petroleum Hydrocarbons			
	GKY	PVC	IN[1]	OUT	GKY	PVC	IN[1]	OUT	GKY	PVC	IN[1]	OUT
9/25/08	<0.01		<0.01									
4/20/09	0.032		0.024	<0.01	42		31.0					
6/3/09	<0.002	<0.002	<0.002	<0.002	5.7	10	6.4					
8/21/09	<0.002		<0.001	<0.002	<5		<3.38					
9/11/09	<0.002		<0.002		<5		<5					
9/26/09	<0.002		<0.002		<5		<5					
10/15/09	<0.002		<0.002		<5		<4.96					
10/24/09	0.0021		0.002		<5		<3.99					
10/27/09	<0.002		<0.002		<5		<4.57					
11/11/09	<0.002		<0.002		<5		<4.35					
12/2/09	<0.002	0.022	<0.002		<5		<5					
3/11/10	0.014	0.0057	0.014	<0.002	<5		<5					
3/28/10	0.02	0.009	0.0199	<0.002	<5		<4.96					
7/8/11	<0.002		<0.002		<5		<4.38					
8/13/11	<0.002	0.016	<0.002		<5		<5					
8/27/11		<0.002	<0.0003			<5	<0.82					
9/5/11	<0.002	0.0081	0.004184	<0.002	<5	<5	<5	5.8				
9/23/11	0.012	0.004	0.012		<5		<5					
10/12/11	0.0054	0.0077	0.006	<0.002	<5	<5	<5	14				
12/6/11	0.024	0.0084	0.020	<0.002					<5	<5	<5	<5
1/11/12	0.016	0.011	0.016	<0.002					<5	<5	<5	<5
1/26/12	0.021	0.013	0.021						<5	<5	<5	
2/29/12	0.016	0.014	0.016	<0.002					<5	<5	<5	<5
3/24/12	<0.002	0	<0.002						<5		<5	
4/21/12	0.007	0.002	0.007	<0.002					<5	<5	<5	<5

[1]IN refers to the volume-weighted EMC referred to as CUIN and discussed in previous sections.
Blank cells are indicative of a storm event which was sampled for water quality but not for that particular water quality constituent.

Table 4-3. Analytical results for monitored storm events (Continued).

Event Date	Pollutant Concentration (mg/L)											
	Alkalinity[5]				Hardness[5]				Orthophosphate[5]			
	GKY	PVC	IN[1]	OUT	GKY	PVC	IN[1]	OUT	GKY	PVC	IN[1]	OUT
9/25/08	22		22		36		36		0.05		0.05	
4/20/09												
6/3/09	2	70	14	25	16	220	52	110	0.02	0.07	0.03	0.18
8/21/09	2		1	52	2		1	2	0.10		0.07	0.17
9/11/09	12		12		40		40		0.87		0.87	
9/26/09	2		2		<1			68	0.04		0.04	
10/15/09	12		12		<1		<0.99		0.02		0.02	
10/24/09	8		6		12		10		0.08		0.06	
10/27/09	8		7		<1		<0.91		0.05		0.05	
11/11/09	<1		<0.87		30		26		0.05		0.04	
12/2/09	6	140	6		88	220	88		0.09	0.15	0.09	
3/11/10	170	16	170	76	30	60	30	14	<0.01	<0.01	<0.01	0.14
3/28/10	20	130	21	48	130	80	130	100	0.02	<0.01	0.02	0.20
7/8/11												
8/13/11												
8/27/11												
9/5/11												
9/23/11												
10/12/11												
12/6/11												
1/11/12												
1/26/12												
2/29/12												
3/24/12												
4/21/12												

[1]IN refers to the volume-weighted EMC referred to as CUIN and discussed in previous sections.
[5]Alkalinity, Hardness and Orthophosphate were not sampled for during the 2nd monitoring period.
Blank cells are indicative of a storm event which was sampled for water quality but not for that particular water quality constituent.

Table 4-4. Load results for CUIN & CUOUT with BDL = 0.

Event Date	Pollutant Load (g)											
	TP		TN		OxN		TKN		NH_3		TSS	
	CUIN	CUOUT	CUIN	CUOUT	CUIN	CUOUT	CUIN	CUOUT	CUIN	CUOUT	CUIN	CUOUT
9/25/08	1.70	0	20.15	0	10.74	0	9.42	0	5.65	0	603	0
4/20/09	132.70		379.74		22.46		357.28				45936	
6/3/09	4.50	23.07	193.80	198.03	26.18	24.99	167.62	173.03	84.51	38.45	1089	961
8/21/09	17.95	6.21	227.76	47.67	48.31	11.62	179.45	36.05	69.02	0.00	3451	40
9/11/09	3.20	0	22.57	0	0.39	0	22.18	0	14.54	0	27	0
9/26/09	1.17		19.42		1.94		17.48		3.88		78	
10/15/09	1.66	0	25.52	0	6.10	0	19.41	0	0.00	0	166	0
10/24/09	14.00		164.94		32.68		132.26		0.00		2178	
10/27/09	4.16		60.99		0.92		60.07		13.86		416	
11/11/09	6.83	0	290.08	0	147.89	0	142.20	0	51.19	0	512	0
12/2/09	2.39	0	31.47	0	4.11	0	27.37	0	5.13	0	103	0
3/11/10	6.84	0.07	43.62	0.78	5.99	0.43	37.63	0.35	8.55	0.12	3250	7
3/28/10	21.51	1.12	106.42	8.37	2.80	1.96	103.62	6.41	11.27	1.20	13385	56
7/8/11	11.49	0.27	104.83	3.37	32.88	1.38	71.95	1.99	19.59	0.31	1581	2
8/13/11	1.73	0	24.76	0	5.18	0	19.58	0	9.21	0	23	0
8/27/11	4.62	0	23.50	0	1.67	0	21.84	0	0.00	0	360	0
9/5/11	188.79	70.70	653.14	645.52	39.03	215.17	614.11	430.35	3348.64	0.00	66932	8914
9/23/11	0.63	0	16.61	0	9.30	0	7.31	0	0.00	0	94	0
10/12/11	91.49	30.56	486.86	381.94	12.12	213.89	474.75	168.05	42.74	0.00	56022	1528
12/6/11	89.43	35.31	656.14	195.66	0.00	19.12	656.14	176.53	50.45	0.00	87818	4708
1/11/12	17.24	3.41	127.99	30.32	3.56	12.25	124.43	18.07	7.65	0.00	10557	562
1/26/12	0.57	0	2.52	0	0.21	0	2.31	0	0.63	0	357	0
2/29/12	96.47	30.42	389.71	140.20	13.61	41.00	376.09	99.20	31.35	13.23	29727	3836
3/24/12	1.48	0	14.83	0	2.97	0	11.87	0	4.45	0	252	0
4/21/12	10.55	0.59	78.01	2.23	5.06	0.89	72.96	1.34	15.29	0.00	3446	17

Blank cells are indicative of a storm event which was sampled for water quality but not for that particular water quality constituent.

Table 4-4. Load results for CUIN & CUOUT with BDL = 0 (Continued).

	Pollutant Load (g)											
Event Date	COD		TDS		Cu		Cd		Zn		Pb	
	CUIN	CUOUT	CUIN	CUOUT	CUIN	CUOUT	CUIN	CUOUT	CUIN	CUOUT	CUIN	CUOUT
9/25/08					0.000	0	0.000	0	1.375	0	0.000	0
4/20/09					5.921		0.000		183.743		3.267	
6/3/09					0.431	0.663	0.000	0.000	3.497	1.923	0.000	0.000
8/21/09					0.773	0.196	0.000	0.000	7.592	1.863	0.000	0.000
9/11/09					0.015	0	0.000	0	0.059	0	0.000	0
9/26/09					0.054		0.000		0.000		0.000	
10/15/09					0.061	0	0.000	0	0.527	0	0.000	0
10/24/09					1.089		0.000		3.890		0.163	
10/27/09					0.162		0.000		1.525		0.000	
11/11/09					0.279	0	0.000	0	1.820	0	0.000	0
12/2/09					0.092	0	0.000	0	0.291	0	0.000	0
3/11/10					0.411	0.002	0.034	0.000	1.608	0.016	0.239	0.000
3/28/10					1.143	0.037	0.078	0.002	3.643	0.148	0.557	0.000
7/8/11	2192	42	2172	92	0.275		0.000		4.069		0.000	
8/13/11	956	0	219	0	0.082	0	0.000	0	0.461	0	0.000	0
8/27/11	527	0	0	0	0.180	0	0.013	0	0.437	0	0.000	0
9/5/11	40968	21517	16743	22132	18.421	1.814	0.000	0.000	18.186	0.000	2.086	0.000
9/23/11	366	0	0	0	0.136	0	0.007	0	0.762	0	0.125	0
10/12/11	29850	5653	10213	11764	6.113	0.978	0.000	0.000	15.388	2.903	1.316	0.000
12/6/11	31743	6473	5796	10151	10.329	1.103	0.065	0.000	29.684	3.384	2.677	0.000
1/11/12	5271	442	1405	1084	0.888	0.151	0.000	0.000	4.900	0.402	0.553	0.000
1/26/12	252	0	0	0	0.032	0	0.000	0	0.210	0	0.044	0
2/29/12	20582	4365	10779	5026	4.161	0.661	0.000	0.000	12.532	1.323	1.599	0.000
3/24/12	593	0	0	0	0.000	0	0.015	0	0.445	0	0.000	0
4/21/12	3900	57	936	163	0.515	0.010	0.000	0.000	3.069	0.034	0.304	0.000

Blank cells are indicative of a storm event which was sampled for water quality but not for that particular water quality constituent.

Table 4-4. Load results for CUIN & CUOUT with BDL = 0 (Continued).

Event Date	Pollutant Load (g)									
	O&G		TPH		Alk		Hard		OP	
	CUIN	CUOUT	CUIN	CUOUT	CUIN	CUOUT	CUIN	CUOUT	CUIN	CUOUT
9/25/08					414	0	678	0	0.942	0
4/20/09	4287									
6/3/09	538	0			1155	2403	4300	10574	2.395	17.303
8/21/09	0	0			276	1042	276	40	13.804	3.405
9/11/09	0	0			30	0	99	0	2.144	0
9/26/09	0				39		0		0.777	
10/15/09	0	0			333	0	0	0	0.555	0
10/24/09	0				622		934		6.224	
10/27/09	0				370		0		2.310	
11/11/09	0	0			0	0	1706	0	2.844	0
12/2/09	0	0			103	0	1505	0	1.539	0
3/11/10	0	0			2908	29	513	5	0.000	0.054
3/28/10	0	0			587	192	3626	401	0.555	0.801
7/8/11	0	0								
8/13/11	0	0								
8/27/11	0	0								
9/5/11	0	1783								
9/23/11	0	0								
10/12/11	0	2139								
12/6/11			0	0						
1/11/12			0	0						
1/26/12			0	0						
2/29/12			0	0						
3/24/12			0	0						
4/21/12			0	0						

Blank cells are indicative of a storm event which was sampled for water quality but not for that particular water quality constituent.

Table 4-5. Sample number and percent censoring for loads at influent and effluent sampler locations.

CUIN																	
	TP	TN	OxN	TKN	NH_3	TSS	COD	TDS	Cu	Cd	Zn	Lead	O&G	TPH	Alk	Hard	OP
Censored Observations	0	0	1	0	4	0	0	4	2	19	1	13	16	6	1	3	1
Total Observations	25	25	25	25	24	25	12	12	25	25	24	25	18	6	12	12	12
Percent Censored	0%	0%	4%	0%	17%	0%	0%	33%	8%	76%	4%	52%	89%	100%	8%	25%	8%
CUOUT																	
	TP	TN	OxN	TKN	NH_3	TSS	COD	TDS	Cu	Cd	Zn	Lead	O&G	TPH	Alk	Hard	OP
Censored Observations	0	0	0	0	6	0	0	0	0	9	1	10	0	4	0	0	0
Total Observations	11	11	11	10	11	11	7	7	10	10	10	10	2	4	4	4	4
Percent Censored	0%	0%	0%	0%	55%	0%	0%	0%	0%	90%	10%	100%	0%	100%	0%	0%	0%
CUOUT-ZF (CUOUT Loads including events with no discharge at the outfall and therefore no effluent loads)																	
	TP	TN	OxN	TKN	NH_3	TSS	COD	TDS	Cu	Cd	Zn	Lead	O&G	TPH	Alk	Hard	OP
Censored Observations	0	0	0	0	6	0	0	0	0	9	1	10	0	4	0	0	0
Total Observations	21	21	21	20	21	21	12	12	20	20	20	20	7	9	9	9	9
Percent Censored	0%	0%	0%	0%	29%	0%	0%	0%	0%	45%	5%	50%	0%	44%	0%	0%	0%

4.5 Discussion

4.5.1 Rainfall

Table 4-6 presents the minimum, maximum and average rainfall depths, rates and durations for events that produced discharge at the LID facility outfall, as well as those that did not.

Table 4-6. Rainfall depths, rates and durations that did and did not produce outfall discharge.

Events Producing Discharge at LID facility outfall				
	Minimum	Maximum	Average	Median
Rainfall Depths (in.)	0.12	5.13	0.86	0.59
Rainfall Rates (in./hr.)	0.02	0.23	0.07	0.05
Storm Event Durations (hr.)	2.0	95.5	19.1	12.9
Events Without Discharge at LID facility outfall				
	Minimum	Maximum	Average	Median
Rainfall Depths (in.)	0.01	1.09	0.14	0.07
Rainfall Rates (in./hr.)	0.004	0.60	0.05	0.03
Storm Event Durations (hr.)	0.17	49.3	5.8	2.4

As may be seen in the table, considerable variability exists between the discharge producing and non-discharge producing events. In fact, it may be seen that the maximum event not producing discharge was nearly an order of magnitude larger than the smallest event producing discharge. This is certainly within the realm of the possible, because storage in the facility would be expected to have direct effects on whether a given event produced discharge. The minimum rainfall depth to produce discharge at the outfall occurred on September 19, 2011 with 0.12 inches of rainfall and 0.00013 inches of discharge recorded. This occurrence may seem anomalous considering the numerous storm events recorded with greater rainfall depths which produced no discharge at the outfall. However, taking antecedent conditions into account sheds some light on the occurrence of discharge from this relatively small event. A storm event on September 18, 2011 with 1.00 inches of rainfall and 0.01 inches of discharge immediately preceded the September 19, 2011 event. Presumably, the LID facility did not have enough time to fully infiltrate the stormwater runoff from the prior event into the surrounding subsoils before the September 19, 2011 event began. With this in mind, the occurrence of discharge during the relatively small September 19, 2011 event seems reasonable. Unfortunately, this may not be directly examined, because the inflow sampling equipment did not permit *in situ* observation of flows, and it was not possible to compute a reliable long-term water balance for the facility.

The rainfall data were, however, directly observed, and Figure 4-8 displays an x-y scatter plot of reported runoff from observed events at the LID facility outfall (expressed as inches over the catchment) as a function of reported rainfall in inches. The reported data for both monitoring periods were included in the figure. The 1:1 line was included to illustrate any anomalous cases where inaccuracies in flow measurement or the presence of unaccounted-for water (*e.g.* groundwater or irrigation) may have produced more runoff than rainfall.

Examination of Figure 4-8 shows that, throughout both monitoring periods, little runoff was generated for storm events where less than 0.5–0.75 inches of rain occurred. For events greater than 0.75 inches, the depth of runoff was only about 40% of the rainfall, indicating that the Cub Run LID facility was effectively reducing the stormwater runoff volume through infiltration and evapotranspiration mechanisms. Figure 4-8 also shows the extreme event in the database: Tropical Storm Lee (which was also sampled for water quality) and occurred from September 5-9, 2011. Tropical Storm Lee had 5.13 inches of rainfall and a catchment runoff depth of 1.87 inches discharged at the outfall, indicating that the facility retained 64% of the incident rainfall.

For the 183 storm events monitored during the two monitoring periods, a rainfall total of 59.03 inches was reported, along with a total LID facility discharge of 8.56 inches, expressed as a depth over the catchment. The long-term facility rainfall retention evident from this comparison is 85%.

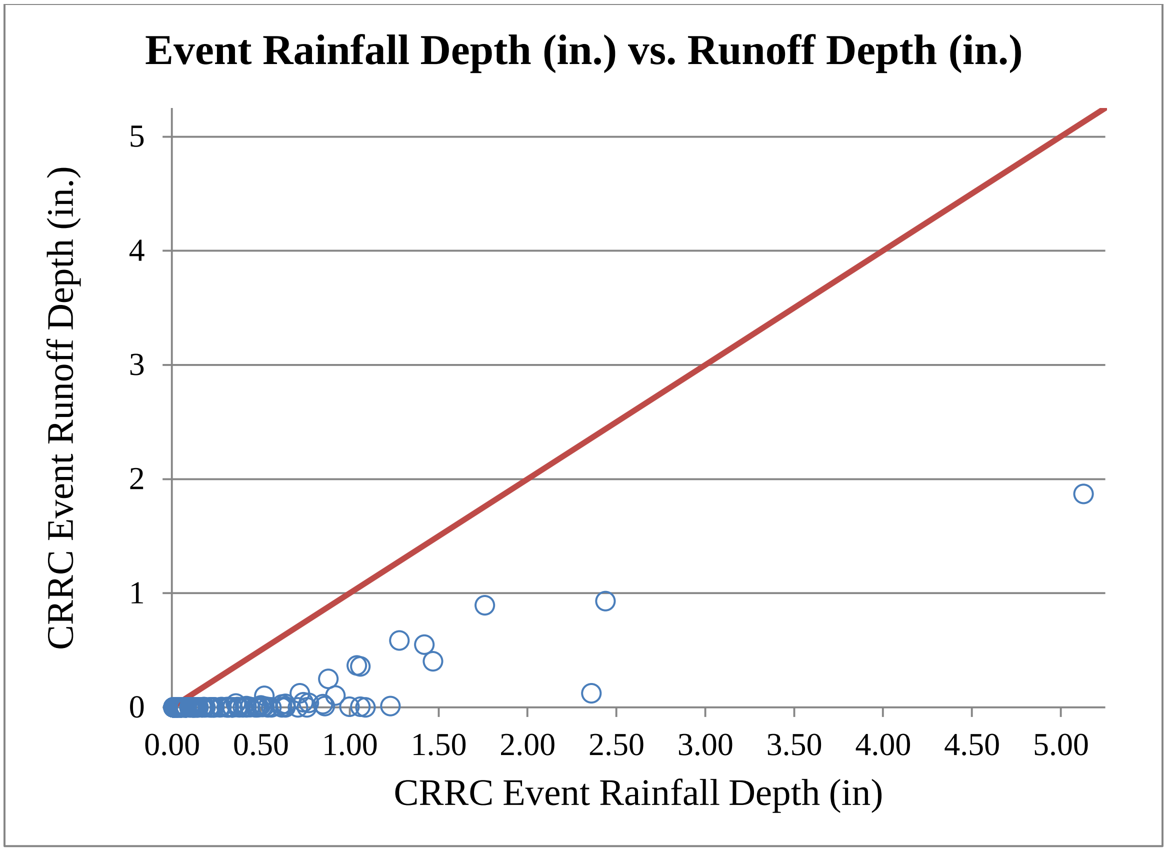


Figure 4-8. Event rainfall depth vs. runoff depth at the Cub Run Recreation Center for all storm events.

4.5.2 Pollutant Removal Mechanisms

Phosphorus and Nitrogen Removal

Reports in the literature on the removal of phosphorus and nitrogen in bioretention facilities exhibit great variability due to the complex physical, chemical and biological interactions present in stormwater BMP environments. Additionally, differences in site design and other management practices may also be expected to affect nutrient removal performance (Davis et al., 2006; Davis et al., 2009; Li and Davis, 2009; Lucas, W. and Greenway, M., 2011; Lucas, W. C. and Greenway, M., 2011).

In general, the effectiveness of phosphorus removal is closely related to the phosphorus content of the soil media used in the bioretention cell. If a bioretention cell media has a relatively high initial phosphorus content, then the ability of the facility to remove dissolved phosphorus is reduced. If the media has a relatively low initial phosphorus content, the dissolved phosphorus in the influent may sorb to iron and aluminum oxides in the soil media. Particle-bound phosphorus is removed through settling and filtration processes along with suspended solids and is generally more related to the total suspended solids removal (Davis et al., 2006; Hunt et al., 2006; Davis, 2007; Davis et al., 2009; Li and Davis, 2009; Lucas, W. and Greenway, M., 2011).

Nitrogen interactions in the aquatic environment are complex, and removal or conversion in stormwater BMPs may be expected to be highly dependent on the forms present, and the oxidation-reduction (REDOX) environment of the system. It is important to note that nitrogen removals are best calculated on a total nitrogen (TN) basis because of the many pathways for conversion of species that exist in the nitrogen cycle. TN is expressed as the sum of total Kjeldahl nitrogen (TKN) and oxidized nitrogen (OxN), TKN is the sum of ammonia, ammonium, and organic nitrogen (TKN=NH_3-N+NH_4^+-N+organic-N) and oxidized nitrogen is the sum of nitrite and nitrate (OxN=NO_2^--N+NO_3^--N) (Li and Davis, 2009; Rice, 2012). To illustrate some of the conversion pathways, a simplified version of the nitrogen cycle (Grady, 2011) is depicted in Figure 4-9:

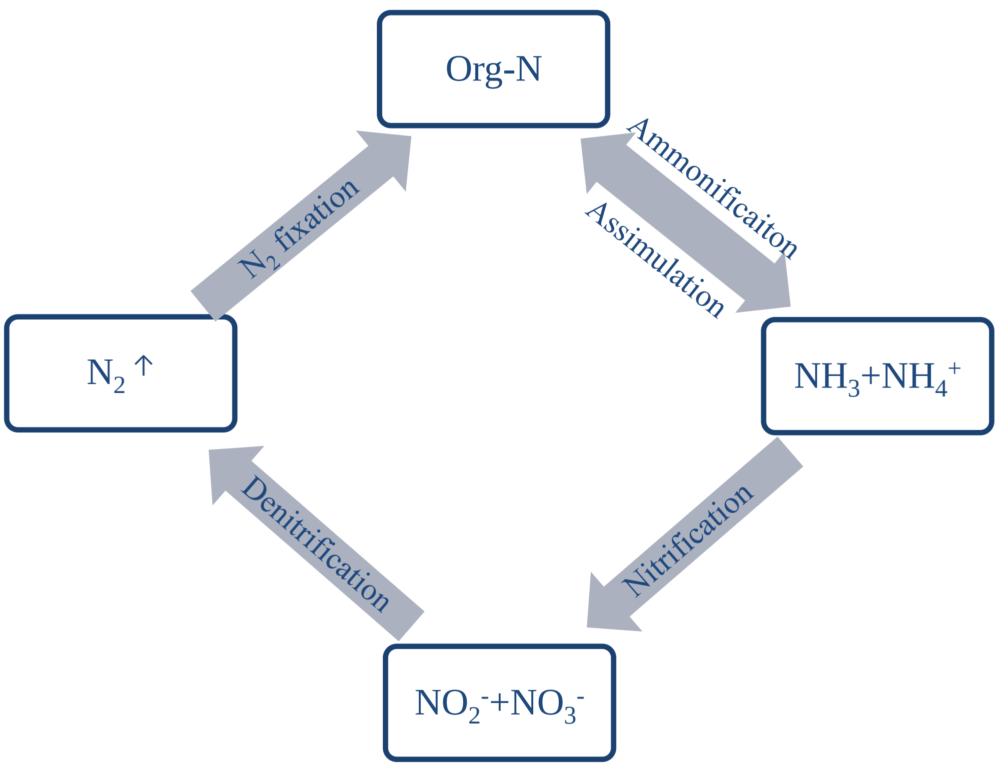


Figure 4-9. Simplified Nitrogen Cycle, Based on: Grady (2011).

Organic nitrogen is microbially converted into ammonia/ammonium and then nitrite/nitrate through the processes of ammonification and nitrification, respectively. These are the dominant microbial processes which occur under aerobic conditions in most stormwater BMPs. Denitrification, or the conversion of oxidized nitrogen to gaseous nitrogen, which may be lost to the atmosphere, can only occur when anoxic, or oxygen deprived, conditions are established (Davis et al., 2006; Hunt et al., 2006; Davis, 2007; Lucas, W. C. and Greenway, M., 2011). Such anoxic conditions may occur naturally in small pockets within a conventionally drained stormwater BMP or may be engineered into the BMP as an internal water storage zone which promotes the conditions necessary for denitrification to occur (Davis et al., 2006; Hunt et al., 2006; Davis, 2007). Without the periodic presence of anoxic zones, microbes within stormwater BMPs may be expected to continuously oxidize available organic nitrogen and ammonia to nitrite and nitrate. In addition, because oxidized nitrogen forms are present as anions and are highly soluble, they do not readily sorb to the negatively charged soil media, and are usually lost from the BMP in a subsequent discharge (Benjamin, 2002; Burton, 2002; Davis et al., 2006; Davis et al., 2009). The exception, of course, occurs when anoxic conditions (in the presence of sufficient organic matter) are subsequently established in the BMP. It should be noted however, that even with the continuous conversion of organic nitrogen and ammonia nitrogen to oxidized nitrogen, total Kjeldahl nitrogen still typically dominates the total nitrogen balance within many stormwater BMPs (Davis et al., 2006).

In general, stormwater BMPs have been found to reduce total nitrogen loads mainly through the sorption of organic nitrogen to organic matter in the media. However, increases in oxidized nitrogen are frequently noted in the literature. When managed properly, the uptake of nutrients by vegetation within a BMP may also play a significant role in the removal of nutrients from incoming stormwater runoff (Davis et al., 2006; Davis et al., 2009; Lucas, W. C. and Greenway, M., 2011).

Total Suspended Solids Removal

Total suspended solids (TSS) removal is typically very high in stormwater BMPs which are designed to utilize sedimentation and infiltration processes (Davis, 2007; Davis et al., 2009). It should be noted that during an initial stabilization period in bioretention BMPs, TSS and other particulate-bound pollutants tend to be produced, instead of reduced, as fine soil media are washed out during the first few events (Davis, 2007).

Trace Metals Removal

Trace metals such as copper, cadmium, zinc and lead may be present in both dissolved and particulate forms in urban stormwater, and tend to be efficiently removed in bioretention BMPs. Particulate-bound metals will be removed through filtration and sedimentation processes. Depending on the physical and chemical composition of the media, dissolved metals such as copper, zinc and lead will also typically sorb to organic matter and soils present in the upper surface layers of the BMP media (Davis, 2007; Li and Davis, 2008; Davis et al., 2009).

Oil & Grease and Total Petroleum Hydrocarbons Removal

Oil and Grease components, including total petroleum hydrocarbons, typically exhibit high removals from stormwater runoff in bioretention BMPs. Oil and Grease components are initially removed through filtration and sorption to organic matter present in the media, followed by microbial degradation (Hsieh and Davis, 2005; Hsieh and Davis, 2005; Hong et al., 2006; Davis et al., 2009).

Chemical Oxygen Demand Removal

Chemical oxygen demand (COD) is often used as a surrogate measure for the removal efficiency of organic matter from stormwater runoff (Benjamin, 2002; Rice, 2012). The COD test provides a relatively quick, consistent estimate of the maximum oxygen (O_2) consumption that could be expected from the degradation of (mostly) organic constituents within a stormwater BMP (Benjamin, 2002). COD may be taken as indicative of the removal of organic matter through the processes of filtration and biological degradation. Conversely, if the stormwater BMP is leaching oxidizable materials such as organic matter, then increases in COD may be observed in the effluent (Ergas et al., 2010). Removal of biochemically oxidizable compounds from stormwater runoff is important to ensure that the potential oxygen demand is not exerted in downstream aquatic environments (Burton, 2002; Miller, 2002).

Total Dissolved Solids, Alkalinity and Hardness Removal

Total dissolved solids (TDS) is a measure of the nonvolatile dissolved species, principally comprised of the ions of inorganic salts such as calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^{+}), potassium (K^{+}), bicarbonate (HCO_3^{-}), chloride (Cl^{-}), nitrate (NO_3^{-}) and sulfate (SO_4^{2-}) in stormwater runoff (Benjamin, 2002; Burton, 2002; Davis et al., 2009). High concentrations of some inorganic salts, such as sodium chloride (NaCl), may be expected in the runoff generated from roads, parking lots and sidewalks in regions that experience snow and ice during the winter season (Burton, 2002; Davis et al., 2009). The removal of such dissolved solids from stormwater is difficult due to their highly soluble nature (Benjamin, 2002; Burton, 2002). Some dissolved solids, however, may be more readily be removed from solution through processes such as precipitation, ion-exchange, absorption and biological transformation, depending on the physical and biogeochemical conditions within the BMP (Burton, 2002). Generally, little removal is expected, except for transformations due to pH change and REDOX reactions.

Alkalinity is a measure of the capacity of a water to resist changes in pH resulting from the introduction of acidic species. While most natural systems contain a variety of species capable of neutralizing acids, the dominant forms present in most natural systems are the carbonate (CO_3^{2-}) and bicarbonate (HCO_3^-) species. For computational simplicity, alkalinity is reported as mg/L as $CaCO_3$ (Benjamin, 2002; Rice, 2012). Increases or decreases in alkalinity within a stormwater BMP may be indicative of other processes occurring. For example, because the process of nitrification ($NH_4^+ \rightarrow NO_2^- \rightarrow NO_3^-$) consumes alkalinity and the process of denitrification ($NO_3^- \rightarrow N_2$) produces alkalinity (Grady, 2011), the analysis of alkalinity changes within a practice may give some insights into whether either process is occurring. If increases in oxidized nitrogen are occurring concurrently with decreases in alkalinity, the hypothesis of nitrification is strengthened. If alkalinity is not decreasing, then nitrification is not likely the dominant process by which oxidized nitrogen is being produced within the BMP. Conversely, if oxidized nitrogen is decreasing within the BMP, the hypothesis that denitrification is the dominate mechanism removing oxidized nitrogen from the BMP would be strengthened if increases in alkalinity were also observed. It should be noted that if both nitrification and denitrification are occurring within a BMP, the net change in alkalinity will likely be smaller than if either process was occurring alone.

Hardness is defined as the sum (expressed as mg/L of $CaCO_3$) of polyvalent cations present in a water sample. As a practical matter, this is most often taken to be the sum of the calcium (Ca^{2+}) and magnesium (Mg^{2+}) ions, because these are the most abundant. Depending on the alkalinity, the total hardness may be distributed between carbonate and non-carbonate) forms (Rice, 2012).

Hardness may be removed or produced within a stormwater BMP through processes such as ion-exchange, sorption and biological transformation of calcium and magnesium ions, and is largely dependent on the biogeochemical soil conditions present in the BMP media (Clark et al., 2009).

4.5.3 Performance Analysis by Summation of Loads Method

Table 4-7 presents the results from the Summation of Loads performance analysis for all parameters of interest using three common substitution methods: (1) setting below detection limit (BDL) observations to zero, (2) setting BDL observations to one-half the detection limit, and (3) setting BDL observations to the detection limit. Additionally, Table 4-7 includes the percent censoring for each water quality parameter of the CUIN and CUOUT load datasets, as previously presented in Table 4-5, to facilitate understanding how the level of censoring affected the performance results when substitution methods were used. It was previously noted that substitution methods may introduce bias into data analysis when considering the attributes of a distribution (Helsel, 2012). However, they may be useful in establishing the upper and lower bounds of BMP performance when BDL observations are present for parameters of interest.

Examination of Table 4-7 shows that positive performance for monitored constituents was found for: total phosphorus (TP), total nitrogen (TN), total Kjeldahl nitrogen (TKN), ammonia (NH_3), total suspended solids (TSS), chemical oxygen demand (COD), copper (Cu), cadmium (Cd), zinc (Zn), Lead (Pb), total petroleum hydrocarbons (TPH), alkalinity (Alk), hardness (Hard) and orthophosphate phosphorus (OP). Negative performance was observed for: oxidized nitrogen (OxN), total dissolved solids (TDS) and oil & grease (O&G).

The Summation of Load results from the Cub Run site are within the range of results found in the literature for LID facilities employing vegetated infiltration based stormwater management BMPs such as bioretention cells and grass swales. Pollutant removal is typically accomplished through a combination of processes including sedimentation, filtration, sorption, ion-exchange and various biological processes such as plant uptake and microbial degradation (Davis et al., 2006; Davis, 2007).

Comparison of the Summation of Loads values using each substitution method along with the percent censoring for CUIN and CUOUT load datasets suggests that the higher the level of censoring for a particular water quality parameter, the greater the effect of the chosen substitution value. This is most evident when viewing the Summation of Loads results for O&G with the three methods of substitution for BDL values of concentration. It should be noted that the level of censoring for the CUIN and CUOUT load datasets was 89% and 0%, respectively. Substituting a value of zero for censored data resulted in a -629% removal according to the Summation of Loads method, while substituting values of one-half the detection limit and the detection limit itself resulted in removals of -14% and +38%, respectively. Clearly, the value chosen to substitute for censored observations completely controlled the Summation of Loads results for O&G. Similar, although less extreme, patterns may be seen for most other constituents with censored observations including: OxN, NH_3, TDS, Cd, Zn, Pb, and TPH.

It should be noted that the Summation of Loads results did not change across the substitution methods for Cu, Alk, hardness, and OP, although censoring was present for all, albeit not at the levels observed for O&G.

Performance Comparisons to Other Reports in the Literature

Table 4-8 presents summaries of reported bioretention performance from some recent studies reported in the literature, and provides a basis for comparison to the CRRC performance data shown previously in Table 4-7 for TP, TN, TSS, Cu, Zn, and Pb. As may be seen from the individual studies in the table, wide ranges of pollutant removal performance are not uncommon for the constituents listed.

As was noted for TP, TN, and TSS, there was no censoring of the data for the water quality events monitored, and the mass-based constituent removals computed by the SOL method were 65%, 53%, and 93%, respectively. In examining the results from the literature in Table 4-8, it may be seen that the median percent removals for TP, TN, and TSS were 56%, 52%, and 71%, respectively. The performance of the CRRC facility with respect to TP appears to be somewhat better than reported in the studies cited. The TN removal was quite comparable to the median value of 52% in the studies cited. With respect to TSS removal, the CRRC facility performance was greater than the median value of 71% in the 5 studies cited.

In the CRRC stormwater quality monitoring database, there was a very low level of censoring of the data for Cu and Zn due to the presence of concentrations below the analytical detection limits (Table 4-7). For these trace metals, the substitution approach had little effect on the computed removal performance. Using the conservative assumption of the BDL values being equal to the detection limit, the removals of Cu and Zn computed with the SOL method were found to be 87% and 86%, respectively. When compared to median performance values from the literature for the same trace metals, removals of 63% and 95% were reported (Table 4-8). For Cu, the CRRC facility performance was better than the reported median, but within the range of the three studies. For Zn, the CRRC facility performance was somewhat lower than the range of the three studies cited. It is not known if any galvanized pipe is present within the drainage network of the facility, but this possibility should be ruled out before attaching too much significance to the observed removals. For Pb, the level of censoring in the CRRC water quality database was quite high (52% inflow; 50% outflow). Using the conservative approach of substituting the analytical detection limit for any BDL value, the SOL performance computation gave an estimated performance of 85% removal, which compares quite favorably to the range of 81%-86% in the three studies cited in Table 4-8.

Table 4-7. Cub Run LID facility pollutant removal efficiencies for Summation of Loads Method and percent censoring.

	TP	TN	OxN	TKN	NH_3	TSS	COD	TDS	Cu	Cd	Zn	Pb	O&G	TPH	Alk	Hard	OP
Below Detection Limit Observations set as 0 (BDL = 0)																	
Summation of Loads	65%	53%	-44%	65%	99%	93%	72%	-4%	87%	99%	89%	100%	-629%	n/a[1]	37%	13%	13%
Below Detection Limit Observations set as one-half the detection limit (BDL = ½ DL)																	
Summation of Loads	65%	53%	-43%	65%	97%	93%	72%	-1%	87%	64%	88%	92%	-14%	30%	37%	13%	13%
Below Detection Limit Observations set as the detection limit (BDL = DL)																	
Summation of Loads	65%	53%	-42%	65%	95%	93%	72%	3%	87%	56%	86%	85%	38%	30%	37%	13%	14%
Percent Censoring of CUIN and CUOUT Loads (from Table 4-5**).**																	
CUIN	0%	0%	4%	0%	17%	0%	0%	33%	8%	76%	4%	52%	89%	100%	8%	25%	8%
CUOUT	0%	0%	0%	0%	29%	0%	0%	0%	0%	45%	5%	50%	0%	44%	0%	0%	0%

[1]Cannot Divide by zero: When below detection limit (BDL) observations are substituted with zero (0) values, all the TPH input observations equal 0. Because of this, the Summation of Loads performance metric cannot be computed for TPH because it would require dividing by 0.

Table 4-8. Reported TP, TN, TSS, Cu, Zn, and Pb removals in bioretention BMPs by Summation of Loads Method.

Location	Percent TP Removal mass basis	Reference
Total Phosphorus		
Greensboro, North Carolina	-240%	Hunt et al. (2006)
Chapel Hill, North Carolina	65%	Hunt et al. (2006)
Nashville, North Carolina	5%	Brown and Hunt III (2011a)
Nashville, North Carolina	44%	Brown and Hunt III (2011a)
College Park, Maryland	80%	Li and Davis (2009)
Silver Spring, Maryland	58%	Li and Davis (2009)
CRRC LID facility, Virginia	65%	This report
Total Nitrogen		
Greensboro, North Carolina	40%	Hunt et al. (2006)
Chapel Hill, North Carolina	40%	Hunt et al. (2006)
Nashville, North Carolina	12%	Brown and Hunt III (2011a)
Nashville, North Carolina	13%	Brown and Hunt III (2011a)
College Park, Maryland	73%	Li and Davis (2009)
Silver Spring, Maryland	63%	Li and Davis (2009)
CRRC LID facility, Virginia	53%	This report
Total Suspended Solids		
Greensboro, North Carolina	-170%	Hunt et al. (2006)
Nashville, North Carolina	71%	Brown and Hunt III (2011a)
Nashville, North Carolina	84%	Brown and Hunt III (2011a)
College Park, Maryland	97%	Li and Davis (2009)
Silver Spring, Maryland	93%	Li and Davis (2009)
CRRC LID facility, Virginia	93%	This report
Copper		
Greensboro, North Carolina	99%	Hunt et al. (2006)
College Park, Maryland	72%	Li and Davis (2009)
Silver Spring, Maryland	63%	Li and Davis (2009)
CRRC LID facility, Virginia	87%	This report
Zinc		
Greensboro, North Carolina	98%	Hunt et al. (2006)
College Park, Maryland	94%	Li and Davis (2009)
Silver Spring, Maryland	95%	Li and Davis (2009)
CRRC LID facility, Virginia	86%[1]	This report
Lead		
Greensboro, North Carolina	81%	Hunt et al. (2006)

Table 4-8. Reported TP, TN, TSS, Cu, Zn, and Pb removals in bioretention BMPs by Summation of Loads Method (Continued).

Location	Percent TP Removal mass basis	Reference
College Park, Maryland	86%	Li and Davis (2009)
Silver Spring, Maryland	83%	Li and Davis (2009)
CRRC LID facility, Virginia	85%[1]	This report

[1]The SOL method results reported for Zn and Pb are based on substituting the detection limit for below detection limit observations, which in this case provided a more conservative estimate of performance.

4.6 Conclusions

The Cub Run Recreation Center LID retrofit was monitored during September 2008 – June 2010 and March 2011 – May 2012. During the two periods, 183 storm events were observed with a rainfall total of 59.03 inches and a total LID facility discharge of 8.56 inches, expressed as a depth over the catchment. The long-term facility rainfall retention evident from this comparison was 85%.

The LID facility was monitored for water quality during 25 storm events over the course of the two monitoring periods. The 25 monitored events represented 1/3 of all storm events meeting the minimum precipitation eligibility criterion of 0.2 inches.

Continuous meteorological and hydrologic monitoring data, along with water quality monitoring during selected storm events were used to assess the LID facility pollutant removal performance. It is important to note that water quality benefits from LID practices and other infiltration-based stormwater best management practices (BMPs) are a function of physical, chemical, and biological processes as well as reductions in stormwater runoff volumes (Davis et al., 2006; Davis, 2007; Geosyntec and WWE, 2009). For this reason, performance metrics based on changes in the total pollutant load over the monitoring period were chosen to assess the pollutant removal performance of the facility (Davis, 2007; Geosyntec and WWE, 2009). The Summation of Loads method (Minton, 2005; Hunt et al., 2006; Cates et al., 2009; Chi-Feng et al., 2009; Geosyntec and WWE, 2009; Williams et al., 2009; McNett et al., 2011) was chosen for analysis of pollutant removal performance.

The Summation of Loads (SOL) method was used to compare influent and effluent loads at the LID facility. Table 4-7 presented the results from the SOL performance analysis using three common substitution methods for censored data. Additionally, Table 4-7 included the percent censoring for each water quality constituent in both the influent and effluent load datasets to facilitate understanding the effects of censoring on performance results when substitution methods were used. The results suggested that the higher the level of censoring for a given water quality parameter, the greater the effect of the chosen substitution value.

The SOL results from the Cub Run site were within the range of results found in the literature for LID facilities employing vegetated infiltration based stormwater management BMPs such as bioretention cells and grass swales. Overall, the Summation of Loads method showed positive performance for total phosphorus (TP), total nitrogen (TN), total Kjeldahl nitrogen (TKN), ammonia (NH_3), total suspended solids (TSS), chemical oxygen demand (COD), copper (Cu), cadmium (Cd), zinc (Zn), lead (Pb), total petroleum hydrocarbons (TPH), alkalinity (Alk), hardness (Hard) and orthophosphate phosphorus (OP). Negative performance was observed for: oxidized nitrogen (OxN), total dissolved solids (TDS) and Oil & Grease (O&G).

4.7 References

Barber, M. E., King, S. G., Yonge, D. R. and Hathhorn, W. E. (2003). “Ecology Ditch: A Best Management Practice for Storm Water Runoff Mitigation.” Journal of Hydrologic Engineering **8**(3): 111-122.

Bedient, P. B. H., Wayne C. (2002). Hydrology and Floodplain Analysis, Third Edition. Upper Saddle River, NJ, Prentice Hall.

Benjamin, M. M. (2002). Water Chemistry, McGraw-Hill.

Beyerlein, D. (2008). LID Analysis Considerations in Western Washington. Low Impact Development for Urban Ecosystem and Habitat Protection**:** 1-9.

Brown, R. and Hunt III, W. (2011a). “Impacts of Media Depth on Effluent Water Quality and Hydrologic Performance of Undersized Bioretention Cells.” Journal of Irrigation and Drainage Engineering **137**(3): 132-143.

Brown, R. and Hunt III, W. (2011b). “Underdrain Configuration to Enhance Bioretention Exfiltration to Reduce Pollutant Loads.” Journal of Environmental Engineering **137**(11): 1082-1091.

Burton, G. A., Jr.; Pitt, Robert E. (2002). Stormwater Effects Handbook, Lewis Publishers.

Carpenter, D. D. and Hallam, L. (2010). “Influence of Planting Soil Mix Characteristics on Bioretention Cell Design and Performance.” Journal of Hydrologic Engineering **15**(6): 404-416.

Carpenter, D. D. and Kaluvakolanu, P. (2011). "Effect of Roof Surface Type on Storm-Water Runoff from Full-Scale Roofs in a Temperate Climate." Journal of Irrigation and Drainage Engineering **137**(3): 161-169.

Cates, E. L., Westphal, M. J., Cox, J. H., Calabria, J. and Patch, S. C. (2009). "Field Evaluation of a Proprietary Storm-Water Treatment System: Removal Efficiency and Relationships to Peak Flow, Season, and Dry Time." Journal of Environmental Engineering **135**(7): 511-517.

Chi-Feng, C., Jen-Yang, L., Chih-Hong, H., Way-Ling, C. and Nai-Ling, C. (2009). "Performance evaluation of a full-scale natural treatment system for nonpoint source and point source pollution removal." Environmental Monitoring & Assessment **157**(1-4): 391-406.

Chung, W., Wang, I. and Wang, R. (2010). "Theory-Based SCS-CN Method and Its Applications." Journal of Hydrologic Engineering **15**(12): 1045-1058.

Clark, S. E., Mikula, J. B., Baker, K. H. and Treese, D. P. (2009). Pollutant Transport within the Vadose Zone: Interactions of Soil Horizon Chemistry on Water Quality. World Environmental and Water Resources Congress 2009**:** 1-9.

Clark, S. E. and Pitt, R. (2010). Considerations in Selecting a (Bio)Filtration Media to Optimize Lifespan and Pollutant Removal, ASCE.

Clary, J., Quigley, M., Poresky, A., Earles, A., Strecker, E., Leisenring, M. and Jones, J. (2011). "Integration of Low-Impact Development into the International Stormwater BMP Database." Journal of Irrigation and Drainage Engineering **137**(3): 190-198.

Davis, A. P. (2007). "Field Performance of Bioretention: Water Quality." Environmental Engineering Science **24**(8): 1048-1064.

Davis, A. P. (2008). "Field Performance of Bioretention: Hydrology Impacts." Journal of Hydrologic Engineering **13**(2): 90-95.

Davis, A. P., Hunt, W. F., Traver, R. G. and Clar, M. (2009). "Bioretention Technology: Overview of Current Practice and Future Needs." Journal of Environmental Engineering **135**(3): 109-117.

Davis, A. P., Shokouhian, M., Sharma, H. and Minami, C. (2006). "Water Quality Improvement through Bioretention Media: Nitrogen and Phosphorus Removal." Water Environment Research **78**(3): 284-293.

DeBusk, K. M., Hunt, W. F. and Line, D. E. (2011). "Bioretention Outflow: Does It Mimic Nonurban Watershed Shallow Interflow?" Journal of Hydrologic Engineering **16**(3): 274-279.

EPA, U. S. (2007). "Reducing Stormwater Costs through Low Impact Development (LID) Strategies and Practices." Nonpoint Source Control Branch.

Ergas, S., Sengupta, S., Siegel, R., Pandit, A., Yao, Y. and Yuan, X. (2010). "Performance of Nitrogen-Removing Bioretention Systems for Control of Agricultural Runoff." Journal of Environmental Engineering **136**(10): 1105-1112.

Geosyntec and WWE, Geosyntec Consultants, Wright Water Engineers, Inc. (2009) "Urban Stormwater BMP Performance Monitoring" U.S. Environmental Protection Agency Prepared with support from the U.S. EPA, Water Environmental Research Foundation, Federal Highway Administration, and the Environmental and Water Resources Institute of the American Society of Civil Engineers, http://www.bmpdatabase.org

Giacomoni, M. H., Zechman, E. M. and Brumbelow, K. (2012). "Hydrologic Footprint Residence: Environmentally Friendly Criteria for Best Management Practices." Journal of Hydrologic Engineering **17**(1): 99-108.

GIS and Mapping Services (2011) "Soils Map 33-4" Fairfax County, D. o. I. T., Enterprise Services Division, GIS and Mapping Services

GKY, GKY & Associates (2012). Retrieved 10/25/2012, from http://www.gky.com/products/.

Google Maps (2013). "Cub Run Rec Center Satellite Image Google Maps, Used under fair use, 2013.". Retrieved 2/15/2013, from http://goo.gl/maps/LzirW, Fair use determination attached.

Grady, C. P. L., Jr; Daigger, Glen T.; Love, Nancy G.; Filipe, Carlos D.M. (2011). Biological Wastewater Treatment, IWA Publishing.

Grizzard, T. and Le Bel, P. (2013). Analysis of Monitoring Data at Cub Run Recreation Center Stormwater Improvements Fairfax County, Virginia, Virginia Tech.

Guo, J. C. Y. (2008). "Volume-Based Imperviousness for Storm Water Designs." Journal of Irrigation and Drainage Engineering **134**(2): 193-196.

Guo, J. C. Y. (2010). "Preservation of Watershed Regime for Low-Impact Development through Detention." Journal of Hydrologic Engineering **15**(1): 15-19.

Guo, J. C. Y. and Cheng, J. Y. C. (2008). "Retrofit Storm Water Retention Volume for Low Impact Development." Journal of Irrigation and Drainage Engineering **134**(6): 872-876.

Hass, J. W., Maurice D.; Thomas, George B, Jr. (2007). University Calculus, Pearson Addison Wesley.

He, Z. and Davis, A. P. (2009). Unit Process Modeling of Stormwater Flow and Pollutant Sorption in a Bioretention Cell, ASCE.

Helsel, D. R. (2012). "Statistics for Censored Environmental Data Using Minitab and R."

Helsel, D. R. and Hirsch, R. M. (2002). "Statistical Methods in Water Resources Techniques of Water Resources Investigations." U.S. Geological Survey **Book 4**(chapter A3).

Hong, E., Seagren, E. A. and Davis, A. P. (2006). "Sustainable Oil and Grease Removal from Synthetic Stormwater Runoff Using Bench-Scale Bioretention Studies." Water Environment Research **78**(2): 141-155.

Hsieh, C.-h. and Davis, A. P. (2003). Evaluation of Bioretention for Treatment of Urban Storm Water Runoff, ASCE.

Hsieh, C.-h. and Davis, A. P. (2005). "Evaluation and Optimization of Bioretention Media for Treatment of Urban Storm Water Runoff." Journal of Environmental Engineering **131**(11): 1521-1531.

Hsieh, C. H. and Davis, A. P. (2005). "Multiple-event study of bioretention for treatment of urban storm water runoff." Water Science & Technology **51**(3/4): 177-181.

Hunt, W. F., Jarrett, A. R., Smith, J. T. and Sharkey, L. J. (2006). "Evaluating Bioretention Hydrology and Nutrient Removal at Three Field Sites in North Carolina." Journal of Irrigation and Drainage Engineering **132**(6): 600-608.

ISCO, T. I.-. (2012). Retrieved 10/25/2012, from http://www.isco.com/products/products1.asp?PL=201.

Jones, T. (2013). Personal Communications with Tom Jones of Versar, Inc.

Kim, H., Seagren, E. A. and Davis, A. P. (2003). "Engineered Bioretention for Removal of Nitrate from Stormwater Runoff." Water Environment Research **75**(4): 355-367.

Lamont, S., Eli, R. and Fletcher, J. (2008). "Continuous Hydrologic Models and Curve Numbers: A Path Forward." Journal of Hydrologic Engineering **13**(7): 621-635.

LeFevre, N.-J. B., David W. Watkins, J., Gierke, J. S. and Brophy-Price, J. (2010). "Hydrologic Performance Monitoring of an Underdrained Low-Impact Development Storm-Water Management System." Journal of Irrigation and Drainage Engineering **136**(5): 333-339.

Li, H. and Davis, A. (2009). "Water Quality Improvement through Reductions of Pollutant Loads Using Bioretention." Journal of Environmental Engineering **135**(8): 567-576.

Li, H. and Davis, A. P. (2008). "Heavy Metal Capture and Accumulation in Bioretention Media." Environmental Science & Technology **42**(14): 5247-5253.

Lucas, W. and Greenway, M. (2011). "Phosphorus Retention by Bioretention Mesocosms Using Media Formulated for Phosphorus Sorption: Response to Accelerated Loads." Journal of Irrigation and Drainage Engineering **137**(3): 144-153.

Lucas, W. C. (2010). “Design of Integrated Bioinfiltration-Detention Urban Retrofits with Design Storm and Continuous Simulation Methods.” Journal of Hydrologic Engineering **15**(6): 486-498.

Lucas, W. C. and Greenway, M. (2011). “Hydraulic Response and Nitrogen Retention in Bioretention Mesocosms with Regulated Outlets: Part IINitrogen Retention.” Water Environment Research **83**(8): 703-713.

McCuen, R. H. (2003). “Smart Growth: Hydrologic Perspective.” Journal of Professional Issues in Engineering Education and Practice **129**(3): 151-154.

McCuen, R. H. (2004). Hydrologic Analysis and Design, Pearson Prentice Hall.

McGarity, A. E. (2012). “Storm-Water Investment Strategy Evaluation Model for Impaired Urban Watersheds.” Journal of Water Resources Planning and Management **138**(2): 111-124.

McNett, J. K., Hunt, W. F. and Davis, A. P. (2011). “Influent Pollutant Concentrations as Predictors of Effluent Pollutant Concentrations for Mid-Atlantic Bioretention.” Journal of Environmental Engineering **137**(9): 790-799.

Meyer, S. C. (2005). “Analysis of base flow trends in urban streams, northeastern Illinois, USA.” Hydrogeology journal **13**(5-6): 871-885.

Miller, G. T., Jr. (2002). Living in the Environment, Brooks/Cole Thomas Learning.

Minton, G. (2005). Stormwater Treatment - Biological, Chemical, and Engineering Principles, Resource Planning Associates.

NRCS, USDA Natural Resources Conservation Service (1986). “Urban Hydrology for Small Watersheds TR-55.”

O'Neill, S. W. and Davis, A. P. (2010). Analysis of Bioretention Media Specifications and Relationships to Overall Performance, ASCE.

Ogden, F. L., Downer, C. W., Pradhan, N. R. and Nelson, E. J. (2011). Predicting Hydrologic Effects of Land-Use Change: Problems with the Curve Number Approach. World Environmental and Water Resources Congress 2011**:** 4801-4810.

Onset, Onset Computer Corporation (2012). Retrieved 10/25/2012, from http://www.onsetcomp.com/.

Palhegyi, G. E. (2010a). “Designing Storm-Water Controls to Promote Sustainable Ecosystems: Science and Application.” Journal of Hydrologic Engineering **15**(6): 504-511.

Palhegyi, G. E. (2010b). “Modeling and Sizing Bioretention Using Flow Duration Control.” Journal of Hydrologic Engineering **15**(6): 417-425.

Pitt, R., Clark, S. and Steets, B. (2010). Evaluation of the Contaminant Removal Potential of Biofiltration Media, ASCE.

Ponce, V. and Hawkins, R. (1996). “Runoff Curve Number: Has It Reached Maturity?” Journal of Hydrologic Engineering **1**(1): 11-19.

Quigley, M. M., Strecker, E. W., Leisenring, M., Huber, W. C., Heaney, J., Weinstein, N., Sansalone, J. and Bodine, D. (2005). The Integrated Unit Process Design Approach for Urban Water Quality Design, ASCE.

Reichold, L., Zechman, E. M., Brill, E. D. and Holmes, H. (2010). “Simulation-Optimization Framework to Support Sustainable Watershed Development by Mimicking the Predevelopment Flow Regime.” Journal of Water Resources Planning and Management **136**(3): 366-375.

Rice, E. B., Rodger; Eaton, Andrew; Clesceri, Lenore (2012). Standard Methods For the Examination of Water and Wastewater, American Public Health Association; American Water Works Association; Water Environment Federation.

Roesner, L. A., Bledsoe, B. P. and Brashear, R. W. (2001). “Are Best-Management-Practice Criteria Really Environmentally Friendly?” Journal of Water Resources Planning and Management **127**(3): 150-154.

Sansalone, J., Kuang, X. and Ranieri, V. (2008). “Permeable Pavement as a Hydraulic and Filtration Interface for Urban Drainage.” Journal of Irrigation and Drainage Engineering **134**(5): 666-674.

Sansalone, J., Liu, B. and Ying, G. (2010). “Volumetric Filtration of Rainfall Runoff. II: Event-Based and Interevent Nutrient Fate.” Journal of Environmental Engineering **136**(12): 1331-1340.

Sansalone, J. and Teng, Z. (2004). “In Situ Partial Exfiltration of Rainfall Runoff. I: Quality and Quantity Attenuation.” Journal of Environmental Engineering **130**(9): 990-1007.

Traver, R. G., Davis, A. P., Hunt, W. F. and Cheng, M.-S. (2008). Stormwater Concepts --- No Adverse Impact, ASCE.

Versar, I. (2011). “Performance Monitoring [Volume Reduction and Water Quality] At Cub Run Recenter Stormwater Improvements, Fairfax County, Virginia.”

VT-OWML, Virginia Tech Occoquan Watershed Monitoring Laboratory (2012). Fairfax County-Performance Assessment of LID Practices Data Repository. Scholar, Virginia Tech, Versar, Inc.; Fairfax County Government; Virginia Tech Faculty and Students.

Williams, E. S. and Wise, W. R. (2009). “Economic Impacts of Alternative Approaches to Storm-Water Management and Land Development.” Journal of Water Resources Planning and Management **135**(6): 537-546.

Williams, G., Roseen, R. M., Lenhart, J. H. and Kayhanian, M. (2009). Potential Data Analysis Methodology to Evaluate the Performance of Manufactured BMPs. World Environmental and Water Resources Congress 2009**:** 1-10.

5 MANUSCRIPT II: “PERFORMANCE EVALUATION OF A LOW IMPACT DEVELOPMENT RETROFIT EMPLOYING AN EFFLUENT PROBABILITY METHOD ANALYSIS”

5.1 Abstract

The goal of Low Impact Development (LID) is to mimic the pre-development hydrologic regime of a catchment through infiltration, filtration, storage, evaporation, and detention of post-development runoff using small-scale hydrologic controls close to the source. A LID facility was examined for pollutant removal and hydrologic performance. The facility treatment train included four in-line grass swales followed by a bioretention cell with a gravel base. The LID facility retained 85% of the rainfall. Influent and effluent pollutant loads were compared using the Effluent Probability Method (EPM). The Kaplan-Meier method was used to account for censored, or below detection limit, observations within the influent and effluent datasets in place of more common substitution methods. The EPM analysis showed statistically significant ($p \leq 0.05$) pollutant load removal performance over the entire range of sampled events for total suspended solids, total phosphorus, total nitrogen, total Kjeldahl nitrogen, ammonia nitrogen, chemical oxygen demand, copper, zinc and alkalinity. EPM analysis did not show significant removals of oxidized nitrogen, total dissolved solids, orthophosphate phosphorus and hardness.

5.2 Introduction

5.2.1 Urbanization

Undeveloped lands typically generate relatively little stormwater runoff because most of the precipitation during storm events infiltrates into the soil where it will be available for evapotranspiration, groundwater recharge, shallow interflow, or any number of other natural processes in the hydrologic cycle. As a watershed is developed, or urbanized, land areas which were formerly forested or pastoral in nature are increasingly covered by impervious surfaces such as roads, parking lots, roofs, driveways and sidewalks. This increase in imperviousness fundamentally changes the hydrologic response of the urbanized site when compared to its pre-development condition. For a given rainfall event, the urbanized site will exhibit increased frequency of runoff, runoff volume, peak flows, temperatures and pollutant loads compared to its pre-development condition. The increased magnitude and frequency of stormwater runoff and consequent pollutant loads generated by urbanized watersheds can cause severe environmental degradation including channel erosion, increased flooding, decreased water quality and degraded or destroyed aquatic habitats in water bodies such as streams, rivers, lakes, estuaries and wetlands. Stormwater runoff due to urbanization is one of the leading sources of pollution for all water body types in the United States (Roesner et al., 2001; Barber et al., 2003; Hsieh and Davis, 2003; McCuen, 2003; Sansalone and Teng, 2004; Meyer, 2005; Davis, 2007; EPA, 2007; Guo, 2008; Guo and Cheng, 2008; Li and Davis, 2008; Sansalone et al., 2008; Li and Davis, 2009; Palhegyi, 2010b; Palhegyi, 2010a; Reichold et al., 2010; Carpenter and Kaluvakolanu, 2011; DeBusk et al., 2011; Giacomoni et al., 2012; McGarity, 2012).

5.2.2 Best Management Practices

In the context of urban stormwater management, best management practices (BMPs) include a range of structural, non-structural and site design practices intended to remove, reduce, retard or prevent stormwater runoff and its associated pollutants from reaching receiving waters in an urbanized or otherwise developed environment. Structural BMPs rely on a wide range of hydrological, physical, biological and chemical processes. Non-Structural BMPs typically involve community education and outreach programs. Overall site designs such as Low Impact Development (LID), Cluster Development, No Adverse Impact (NAI) and smart growth strategies combine a variety of structural and non-structural BMPs in order to reduce the environmental impacts associated with urbanization and development (Hsieh and Davis, 2003; McCuen, 2003; Quigley et al., 2005; Traver et al., 2008; Geosyntec and WWE, 2009; Williams and Wise, 2009; Clary et al., 2011).

5.2.3 Low Impact Development

Low Impact Development (LID) is a comprehensive land planning and engineering design approach to managing stormwater runoff. The goal of LID is to mimic the pre-development hydrologic regime of a watershed through infiltration, filtration, storage, evaporation and detention of post-development runoff using small-scale hydrologic controls close to the source. Urban developments which employ LID practices are expected to produce outflow hydrographs similar to those that would be found at the site during its predevelopment condition. LID practices may also be retrofitted into existing, traditional stormwater conveyance systems. LID BMPs include practices such as bioretention cells and rain gardens, bioswales, infiltration basins and trenches, stormwater wetlands, vegetated rooftops or green roofs, rain barrels or cisterns, permeable pavers, porous pavement, tree planters and site design practices such as narrow streets, reduced imperviousness, minimal curb and gutter use and preservation of natural areas (Hsieh and Davis, 2003; Davis, 2007; EPA, 2007; Beyerlein, 2008; Davis, 2008; Guo and Cheng, 2008; Traver et al., 2008; Geosyntec and WWE, 2009; Carpenter and Hallam, 2010; Guo, 2010; O'Neill and Davis, 2010; Palhegyi, 2010b; Palhegyi, 2010a; Brown and Hunt III, 2011; Clary et al., 2011; DeBusk et al., 2011).

Infiltration practices are used to route surface runoff into subsurface soils or media where it is temporarily held in pore spaces before evaporating, transpiring from vegetation, exfiltrating into surrounding subsoils and groundwater, discharging as interflow or exiting through underdrains. Infiltration BMPs include bioretention cells or rain gardens, bioswales and vegetated filter strips, infiltration basins and trenches, and tree planters, among others. In addition to infiltration, some practices include specialized media and/or internal water storage zones which promote the removal of some important dissolved pollutants such as orthophosphate phosphorus or nitrate and nitrite nitrogen. Pollutant removal is achieved through processes such as settling, filtration, sorption and other biogeochemical interactions (Hsieh and Davis, 2003; Kim et al., 2003; Sansalone and Teng, 2004; Davis et al., 2006; Hunt et al., 2006; EPA, 2007; Davis, 2008; Li and Davis, 2008; Davis et al., 2009; Geosyntec and WWE, 2009; He and Davis, 2009; Clark and Pitt, 2010; Lucas, 2010; Sansalone et al., 2010; Brown and Hunt III, 2011). Evidence suggests that infiltration BMP performance for dissolved constituents (e.g., nitrate/nitrite, orthophosphate and dissolved metals) capture may be highly dependent on the hydraulic residence time within the practice, along with media depth and other characteristics including media organic matter content, cation exchange capacity, pH, and initial chemical composition (Hsieh and Davis, 2003; Hunt et al., 2006; Davis et al., 2009; Li and Davis, 2009; Clark and Pitt, 2010; O'Neill and Davis, 2010; Pitt et al., 2010; Sansalone et al., 2010; Brown and Hunt III, 2011). A variety of vegetation types, including grasses, shrubs and small trees may be used to promote evapotranspiration, maintain soil porosity and encourage biological uptake and or degradation of some pollutants. It should be noted that nutrient and micronutrient uptake by vegetation will reduce pollutant loads only if new growth is regularly harvested (usually annually) to remove excess biomass before decay and decomposition can result in re-release to the watershed (Kim et al., 2003; Davis et al., 2006; EPA, 2007; Davis, 2008; Li and Davis, 2008; Davis et al., 2009; Geosyntec and WWE, 2009; He and Davis, 2009; Lucas, 2010). Pollutant build-up and removal may be of concern for infiltration BMPs. However, particulate-bound pollutants are typically captured in the upper soil horizon and may be removed by replacing the topsoil (Davis et al., 2006; EPA, 2007; Li and Davis, 2008; Davis et al., 2009).

5.2.4 CRRC Low Impact Development Facility Monitoring Project

The Cub Run Recreation Center (CRRC) LID study site is an urban stormwater management retrofit located within the Cub Run watershed in the community of Chantilly, in western Fairfax County, Virginia. The facility is adjacent to a parking lot serving the CRRC and Westfield High School, and serves a total drainage area of 1.6 acres including 0.63 acres of asphalt parking lot, 0.86 acres of grassy-wooded area, and 0.11 acres of the LID facility itself (Versar, 2011; VT-OWML, 2012). The treatment train is gravity flow, and includes four in-line grass swales followed by a bioretention cell with a gravel base. Stormwater runoff enters the grass swales from the parking lot to the north and the grassy and wooded area to the south, as shown in Figure 5-1. The grass swales were designed to allow water ponding deeper than six inches in any swale to overflow into the next cell. The bioretention cell was designed to allow water ponding deeper than six inches to discharge by means of an overflow in to an adjacent 15 inch PVC pipe from which samples were taken. The pipe discharged into a curb inlet that received additional parking lot drainage. Outflows from the curb inlet were routed to a conventional detention pond (Versar, 2011).

Versar, Inc. under contract with the Fairfax County Department of Public Works and Environmental Services (DPWES) monitored the CRRC LID facility during two periods from September 2008 – June 2010 and March 2011 – May 2012. Installation of the monitoring equipment took place during August 2008. Continuous flow monitoring (at the LID facility outfall only), meteorological data, soil moisture and storm monitoring was performed by ATR Associates, Inc. under subcontract to Versar, Inc. from September 2008 to July 2009 and solely by Versar, Inc. from July 2009 to June 2010 and again from March 2011 to May 2012 (Versar, 2011). In July, 2011, Virginia Tech entered into an agreement with DPWES to conduct a performance analysis of the LID stormwater retrofit. Faculty, staff, and students of the Departments of Biological Systems Engineering and Civil and Environmental Engineering were involved in the project, and contributed to the performance analysis.

The collected datasets, provided by Versar (2011), consisted of continuous monitoring for meteorology and hydrology, along with discrete sampling, and subsequent analysis for selected water quality parameters during targeted storm events. The LID facility was monitored for water quality during 25 storm events over the course of the two monitoring periods. Passive and automated devices were used to collect samples that facilitated comparisons of water quality and flows at inflow and outflow locations, respectively. The water quality monitoring included post-storm analyses for the event mean concentrations of nutrients such as phosphorus and nitrogen, trace metals such as copper and zinc, and other important water quality parameters such as total suspended solids and total dissolved solids. The water quality data were then used along with the meteorological and hydrologic data to calculate inflow and outflow loadings for constituents of interest. Flow estimates were made using different techniques at the inflow and outflow points.

Water quality benefits from LID practices and other infiltration-based stormwater BMPs are a function of physical, chemical, and biological processes as well as reductions in stormwater runoff volumes (Davis et al., 2006; Davis, 2007; Geosyntec and WWE, 2009). For this reason, metrics based on changes in the total pollutant load over the monitoring period were chosen to assess the pollutant removal performance of the facility (Davis, 2007; Geosyntec and WWE, 2009). The Effluent Probability Method (Strecker et al., 2001; Geosyntec and WWE, 2009; Williams et al., 2009) was chosen for constituent load reduction analyses.

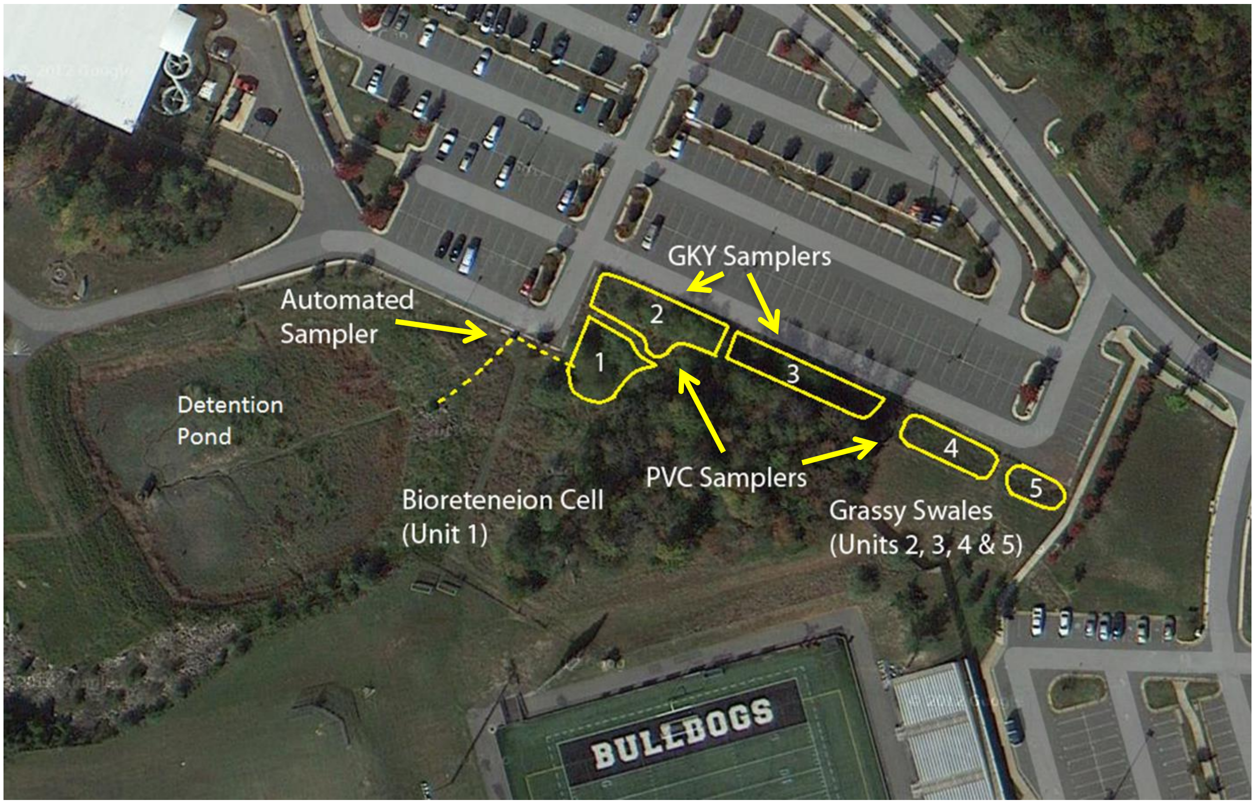


Figure 5-1. Aerial view of the Cub Run Recreation Center LID facility with approximate outlines for the bioretention cell, grass swales and sampler locations (VT-OWML, 2012; Google Maps, 2013) Used under fair use, 2013.

5.3 CRRC LID Facility Methodology

5.3.1 Flow Rate Monitoring and Flow Volume Estimates

LID facility outflows were continuously monitored using a depth sensor and a 60^0 V-notch weir located within the outfall pipe from the bioretention cell (Versar, 2011). Continuous flow data were logged electronically and integrated using the trapezoidal method over the duration of a storm event to arrive at outflow discharge volume estimates (Versar, 2011). Inflow discharge volumes were estimated using the Soil Conservation Service (SCS) runoff curve number method as outlined by Technical Release 55 (TR-55) by the United States Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS, 1986).

5.3.1.1 Inflow Volume Estimates

SCS Runoff Curve Number Method

TR-55 presents a simplified procedure for estimating storm runoff volumes, peak discharge rates, hydrographs and storage volumes required for floodwater reservoirs. The so-called SCS runoff curve number method has been widely used to estimate inflows when actual monitoring data are unavailable (LeFevre et al., 2010; Giacomoni et al., 2012).

The SCS runoff equation (NRCS, 1986) is given as:

$$Q = \frac{(P - I_a)^2}{(P - I_a) + S}$$

Where: Q = runoff (in), P = rainfall (in), S = potential maximum retention after runoff begins (in), I_a = initial abstraction (in) = all losses before runoff begins (in)

Initial abstraction (I_a) may be approximated by the following empirical equation based on SCS watershed studies (NRCS, 1986; Bedient, 2002):

$$I_a = 0.2S$$

Where: $S = \frac{1000}{CN} - 10$

Substituting 0.2S for I_a in the original runoff equation gives:

$$Q = \frac{(P - 0.2S)^2}{(P + 0.8S)}$$

The curve number (CN) has a range from 0 to 100 and depends on the soil and cover conditions of the watershed, which include the hydrologic soil group, cover type, treatment, hydrologic condition and antecedent runoff condition (NRCS, 1986). In essence, the CN may be viewed as a surrogate for watershed imperviousness, and, therefore, hydrologic response.

Versar (2011) conducted a previous performance analysis of the LID facility and reported the curve numbers of 98 and 69.5, respectively, for the adjacent parking lot and grassy and wooded areas. While the curve number of 98 remained a valid estimate for the parking lot, the grassy and wooded area curve number was updated to reflect a more recent soil survey map provided by Fairfax County (2011). The updated soil survey map designated the grassy and wooded area soils adjacent to the LID facility as hydrologic soil group (HSG) D. Taking the new HSG D designation into account, the grassy and wooded area weighted curve number was determined to be 79, which is an area-weighted composite of the curve numbers for a fully developed urban area consisting of open space in good condition (CN 80) and an agricultural land comprised of woods in good condition (CN 77) (NRCS, 1986).

Limitations of the SCS Runoff Curve Number Method

Because the initial abstraction term includes all losses before runoff begins, the curve number method assumes that runoff does not occur until the precipitation depth exceeds the initial abstraction depth. Because the initial abstraction may be calculated as a function of the curve number, it may be assumed that, for any given curve number, there is a precipitation depth that must be exceeded before which the SCS runoff curve number calculation would produce realistic runoff values. By setting runoff (Q) in the curve number method equation to zero and applying the curve number of interest, the precipitation depth threshold required to satisfy the $P \geq 0.2S$ constraint may be found (McCuen, 2004). For the CRRC parking lot (CN=98), the threshold precipitation depth was found to be approximately 0.04 inches, while for the grassy and wooded area (CN=79), the threshold precipitation depth was found to be approximately 0.53 inches.

The minimum precipitation threshold may be assumed to have no appreciable effect on parking lot runoff volume estimates, because samples were not collected until at least 0.2 inches of rain was expected (Versar, 2011). However, it may be seen to have a pronounced effect on runoff estimates for the grassy and wooded areas. The curve number method restricts the production of surface runoff to storms with rainfall depths of 0.53 inches and greater. Six of the sixteen (37.5%) events with samples taken from the grassy and wooded areas were found to have had rainfall depths less than 0.53 inches. A clear, but not easily quantified, bias in the dataset appears to have resulted from setting the total runoff volume from these events to zero for the grassy and wooded area. The zero-flow value is not reflective of reality because inflow water quality samples were retrieved following each of the events. Nevertheless, the observation that flows did occur when none were predicted may argue for a re-assessment of the appropriateness of using the SCS runoff curve number method for flow estimation in this case. Absent a flow to associate with samples collected in events with rainfall less than 0.53 inches, the inflow loads from the grassy and wooded areas were assumed to be zero, and those inputs removed from the dataset provided by Versar (2011). It should be noted, however, that because of the often dispersed nature of inflows to LID practices, it is not always feasible to physically monitor all the BMP inflows, and estimating such ungaged flows is not an uncommon practice.

While the simple nature of the curve number method allows its application with minimal data requirements (storm depth and curve numbers), the approach also creates some challenges and limitations with regards to its ability to predict event-scale hydrologic response in real world applications (Ponce and Hawkins, 1996). While the method provides prediction for average conditions that are useful for design purposes, the modeling accuracy has been observed to decrease for actual rain events, because of the inability to account for effects of rainfall duration or intensity (NRCS, 1986; Ponce and Hawkins, 1996; Lamont et al., 2008; Chung et al., 2010). The method has also been observed to be less accurate when runoff depth is less than 0.5 inches (NRCS, 1986). Several investigators have also found the often assumed initial abstraction ratio of 0.2S may not accurately reflect specific watershed conditions present at every site of interest (Ponce and Hawkins, 1996; Lamont et al., 2008; Chung et al., 2010). The absence of clear guidance on how to account for variability in antecedent moisture conditions (Ponce and Hawkins, 1996; Chung et al., 2010), spatial scale effects (Ponce and Hawkins, 1996) and land use changes (Ogden et al., 2011), have all been cited as potential barriers to application of the method.

Given the potential problems with down-scaling the curve number method for use in runoff predictions for individual events on small catchments, it is not surprising that the accuracy of the BMP inflow load predictions at the CRRC LID facility is subject to some uncertainty. In BMP performance assessments, the flow balance is always important. However, in practices where infiltration may be responsible for a significant fraction of the constituent removal efficiency, direct measurements of surface inflows and infiltration become critical. Because of this, performance assessments developed from the analysis of the CRRC monitoring program data must take into account the uncertainty introduced by (as yet) unvalidated estimation methods.

5.3.1.2 Outflow Volume Calculations

Flows exiting the LID facility were measured with a 60^0 V-notch plywood weir installed at the end of the 15-inch PVC outlet pipe where it entered a catch basin. An ISCO Model 720 integrated flow module with integrated pressure transducer was used to measure flows. The pressure transducer sensor was installed upstream of the weir to record the head on the weir notch, and the flow module logged static head data at 10-minute intervals. Using the appropriate weir equation, static head was converted to flow rate with proprietary ISCO Flowlink Software. The flow module provided an activation signal to an attached automated sampler during runoff events (Versar, 2011; ISCO, 2012). Storm event flow volumes were calculated by integrating the 10-minute flow data during events using the trapezoidal rule (Hass, 2007).

5.3.2 Sampling

5.3.2.1 LID Facility Inflow Samplers

The LID facility received sheet flow from the adjacent parking area, grassy area and wooded area. Sheet flow samples from the parking area were collected using two GKY 'First-Flush' samplers (Versar, 2011; GKY, 2012). The GKY samplers received sheet flow from the adjacent parking lot area as it flowed into the LID facility at Swale 2 and Swale 3 as shown in Figure 5-1. A schematic of the GKY samplers is provided in Figure 5-2.

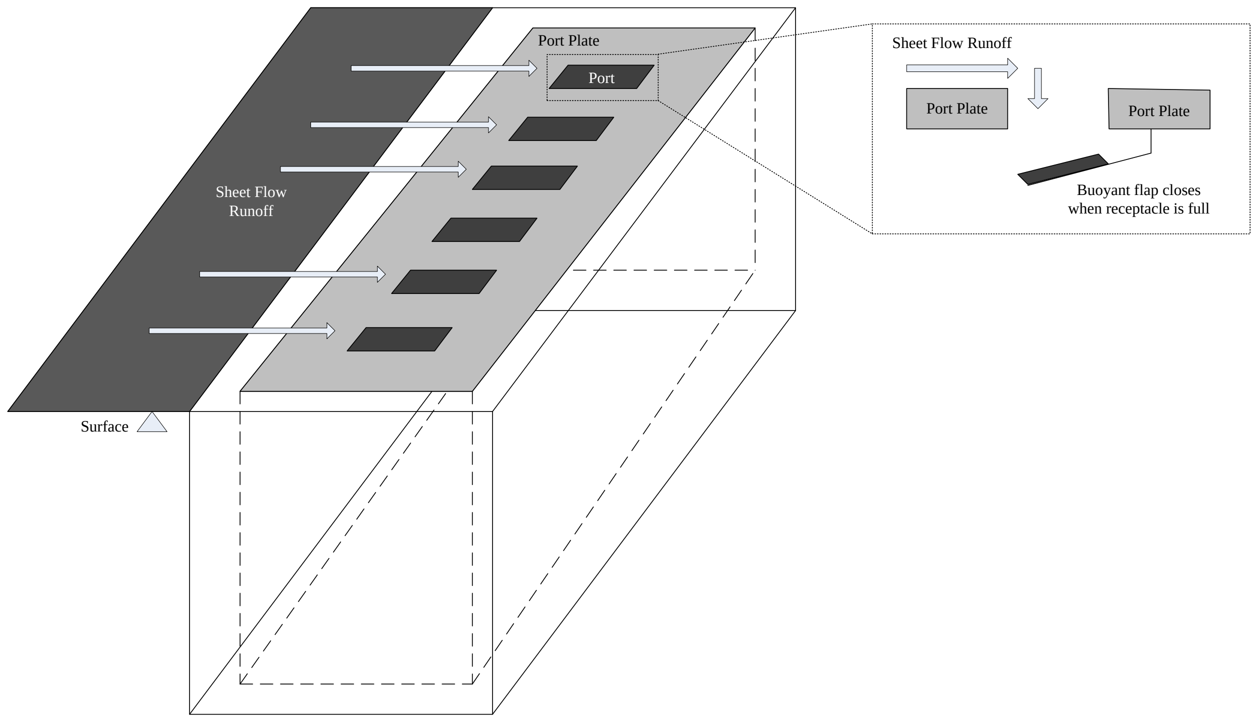


Figure 5-2. Schematic of a GKY First Flush Sampler.

Sheet flow samples from the grassy and wooded areas were taken with samplers constructed by Versar (2011) with two 5-foot sections of 4-inch PVC pipe capped at the ends and installed normal to the fall line. The runoff entered the samplers through a ½ inch slot and a Plexiglas lip attached to the lower edge of the opening to direct runoff into the pipes. The samplers were placed into shallow trenches with cement aprons to mold the Plexiglas lip against the surrounding turf. The PVC samplers receiving drainage from the grassy area and wooded areas were located at the edge of the BMP at Swale 2 and Swale 3, respectively, as shown in Figure 5-1. A schematic of the PVC Samplers is provided in Figure 5-3.

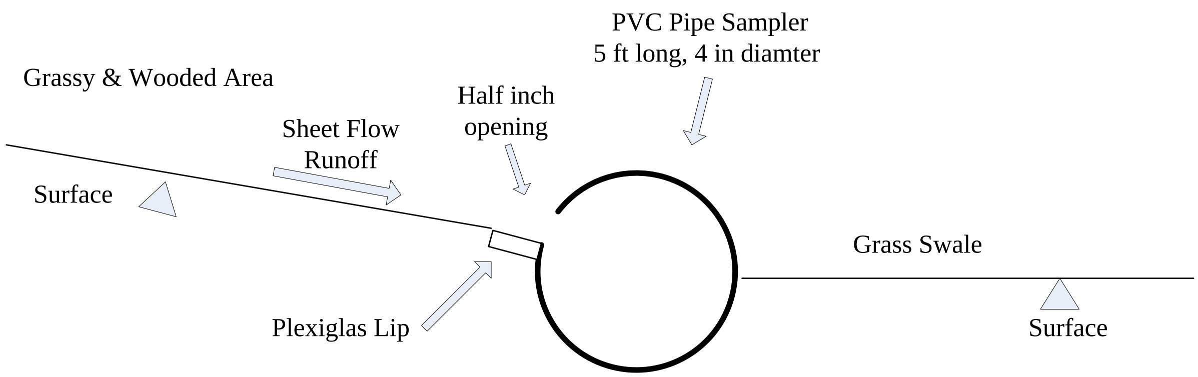


Figure 5-3. Side view schematic of a PVC sampler.

The sheet flow samples were assumed to be composites representative of the runoff from the contributing drainage areas (Versar, 2011). The available data did not make it possible to estimate the lost flow (if any) for events where the sheet flow samplers were filled and had no additional void capacity to store water. In spite of this, it may be concluded that the performance data are conservative, and the actual removals are likely to be somewhat higher.

5.3.2.2 LID Facility Infiltration Sampler

A lysimeter sampler was buried under Swale 4 to collect infiltrated stormwater using a receptacle bucket (Versar, 2011; VT-OWML, 2012). Samples were taken from the lysimeter each day following a targeted storm event until no additional leachate was observed. Due to the expectation that flow into the lysimeter sampler would be relatively small, the sample volumes collected each day after a storm event were simply added together to make an overall composite sample (VT-OWML, 2012). The lysimeter sampler was installed on June 15, 2011 (Versar, 2011). Consequently, no samples were taken during the first monitoring period.

5.3.2.3 LID Facility Outfall Sampler

Samples of the outflow discharge were taken from the LID facility outlet pipe using an ISCO model 6712 portable automated sampler (Versar, 2011; ISCO, 2012). The automated sampler had a collection capacity of 24 1 L water samples in polypropylene bottles and was housed in a nearby equipment shelter constructed of plywood and secured with a padlock (Versar, 2011). A polypropylene sample strainer was placed behind the 60^0 V-notch weir in the PVC outlet pipe and was connected to the sampler through flexible vinyl tubing (Versar, 2011). During targeted storm events, the sampler was activated when the water level in the PVC outlet pipe exceeded 0.54 inches. The sampler was programmed to take discrete samples at time intervals, usually between 45 minutes to 2 hours, to maximize the number of samples obtained while the outfall discharged runoff and account for the extended time the bioretention area dewatered (Versar, 2011; Jones, 2013).The sampler retrieved aliquots that could be combined into a flow-weighted composite at a later time (Versar, 2011; ISCO, 2012). The resulting storm sample composites were taken to be representative of the event mean concentration (EMC) values for any constituents subsequently analyzed. The automated sampler was located above the catch basin receiving outflow from the bioretention cell, as shown in Figure 5-1. A schematic of the sampling apparatus at the LID facility outfall is provided in Figure 5-4.

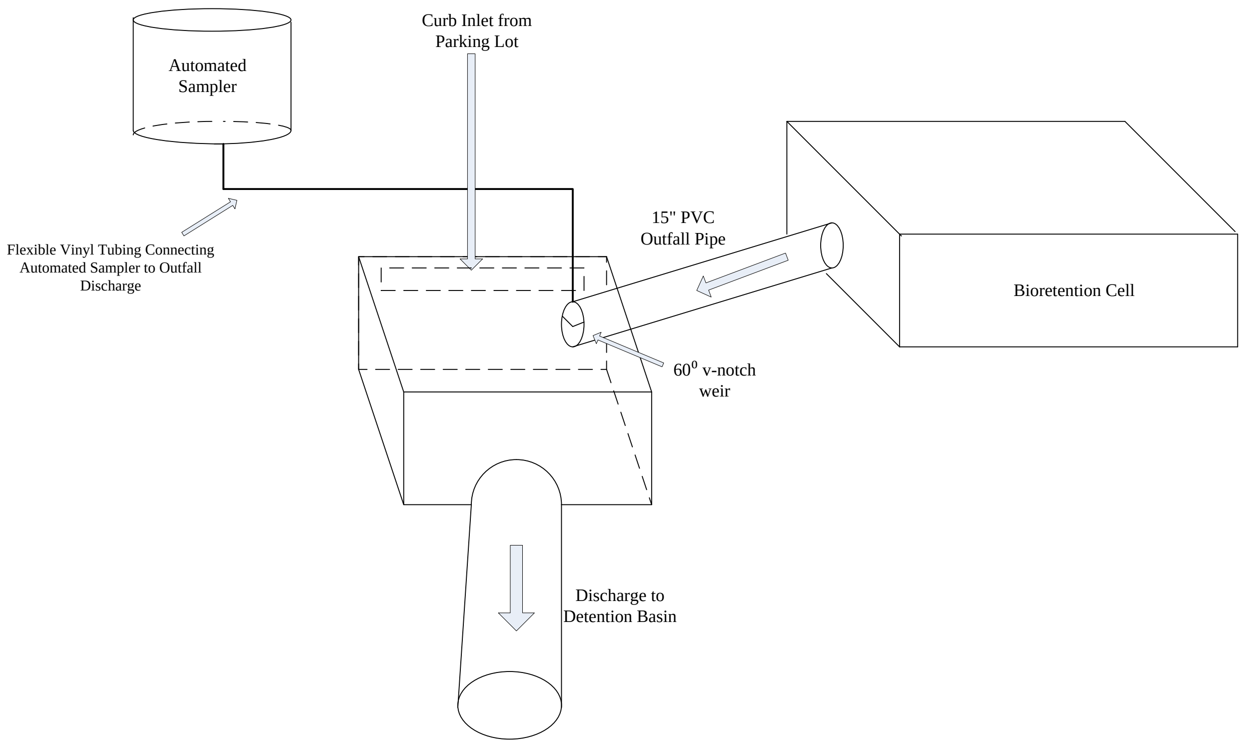


Figure 5-4. Schematic of the sampling apparatus at the LID facility outfall.

5.3.2.4 Water Quality Constituents Monitored

During targeted storm events, sample analyses included total phosphorus (TP), oxidized nitrogen (OxN), total Kjeldahl nitrogen (TKN), ammonia nitrogen (NH_3), total suspended solids (TSS), chemical oxygen demand (COD), total dissolved solids (TDS), copper (Cu), cadmium (Cd), zinc (Zn), lead (Pb), oil and grease (O&G), total petroleum hydrocarbons (TPH), alkalinity (Alk), hardness (Hard) and orthophosphate phosphorus (OP) (Versar, 2011; VT-OWML, 2012).

Table 5-1 lists the water quality parameters monitored on a discrete basis for targeted storm events for the two monitoring periods. The table also shows the analytical methods reported and the applicable reporting limits (Versar, 2011; VT-OWML, 2012).

Table 5-1. Discrete water quality parameters monitored for targeted storm events.

Monitoring Period	September 2008 – June 2010		March 2011- May 2012	
Parameter	**Reportable Detection Limit (mg/L)**	**Method**	**Reportable Detection Limit (mg/L)**	**Method**
Total Phosphorus	0.01	SM 4500P-E	0.01	SM 4500P-E
Oxidized Nitrogen	0.02	SM 4500NO3-H	0.02	SM 4500NO3-H
Total Kjeldahl Nitrogen	0.5	SM 4500NH3-C	0.5	SM 4500NH3-C
Ammonia Nitrogen	0.2	SM 4500NH3-C	0.2	SM 4500NH3-C
Total Suspended Solids	1	SM 2540 D	1	SM 2540 D
Chemical Oxygen Demand[1]			10	EPA 410.4 & SM 5220-D
Total Dissolved Solids[1]			10	SM 2540C
Copper[3]	0.01	EPA 200.8	0.002	EPA 200.8
Cadmium	0.0005	EPA 200.8	0.0005	EPA 200.8
Zinc	0.01	EPA 200.8	0.01	EPA 200.8
Lead[3]	0.01 & 0.002	EPA 200.8	0.002	EPA 200.8
Oil and Grease	5	EPA 1664	5	EPA 1664
Total Petroleum Hydrocarbons[1]			5	EPA 1664
Alkalinity[2]	1	SM 2320 B		
Hardness[2]	1	SM 2340 B		
Orthophosphate Phosphorus[2]	0.01	SM 4500P-E		

[1] Chemical Oxygen Demand (COD), Total Dissolved Solids (TDS) and Total Petroleum Hydrocarbons (TPH) were not tested for during the first monitoring period September 2008 – June 2010. [2] Alkalinity, Hardness and Orthophosphate Phosphorus were not tested for during the most recent monitoring period March 2011- May 2012. [3] Copper and Lead had different reporting limits for the two monitoring periods.

5.3.2.5 Continuous Meteorological and Water Quality Parameters

An Onset Model H21-001 (Onset, 2012) weather station was installed to record continuous meteorological and water temperature data for the entire project period. The station was tripod-mounted and secured with guy wires adjacent to the downstream section of the bioretention cell. As with flow, meteorological and water temperature data were recorded at 10-minute intervals by an associated data logger. The weather station was configured to record precipitation, air temperature, relative humidity, wind speed, wind gust speed, solar radiation, soil moisture at three different depths, temperature of LID facility discharge water, and temperature of water discharging from non-LID areas at the western end of the parking lot (Versar, 2011).

5.3.3 Storm Monitoring

Decisions on storm selection for water quality monitoring were taken after closely monitoring rainfall predictions on available weather services, including NOAA (Versar, 2011). Field staff acted on high-probability weather predictions by traveling to the site with appropriate equipment for targeted storms that were predicted to deliver at least 0.2 inches of rainfall. Of the 25 storm events monitored in the two monitoring periods, nine were reported to produce no flow at the LID facility outfall (Versar, 2011). To prepare for storm sampling, field technicians programmed the automated sampler to obtain time-paced water samples at intervals corresponding to the predicted duration of rainfall. Staff also installed pre-cleaned sample receipt tubs into the GKY samplers, and checked the PVC pipe samplers for cleanliness and proper alignment with the concrete apron (Versar, 2011).

Once storm sampling was underway, field staff checked online weather resources (e.g., http://www.wunderground.com/wundermap) to ensure the minimum required rainfall had taken place. If so, staff visited the site with previously prepared bottles to collect and transport the water samples. At the site, level data were downloaded from the ISCO equipment to facilitate constructing tables of discharge volume per discrete sample to be used to construct volume-weighted composite samples. Samples were also retrieved from the GKY samplers, and the vessels were examined to compare collected volumes. Sub-samples from the GKY samplers were proportionally combined into one-liter, parameter-specific collection and transport bottles. The PVC pipe samplers were removed from the trenches and emptied into a pre-cleaned bucket, mixed, and subsequently poured into one-liter, parameter-specific bottles (Versar, 2011).

Following a sampled storm event, staff removed the discrete sample carrier from the automated sampler, and the individual one-liter bottles were capped and transported to Versar, Inc. facilities to prepare for analysis (Versar, 2011). Flows were computed from the recorded 10-minute level data using the appropriate weir equation with ISCO Flowlink software. Versar (2011) described the compositing procedure where "[t]he flow rate data were then integrated over the sampling interval time to obtain total discharge volume per discrete bottle. The discharge volume-proportional subsample amount from each bottle was poured off and combined to form one composite sample." As with the sheet flow samples, the composite sample was also split between one-liter parameter specific bottles (Versar, 2011).

Lysimeter samples were reported to be collected each day following a storm event until no further leachate was observed. The daily sample volumes were combined to construct an overall lysimeter composite sample, which could then be analyzed for total phosphorus, oxidized nitrogen and total Kjeldahl nitrogen (Versar, 2011). Because influent flows were estimated using the SCS runoff curve number method, an accurate description of the water balance, including infiltration and evapotranspiration, at the LID facility was not possible. While lysimeter samples were analyzed and reported for TP, OxN and TKN concentrations, further evaluation of the lysimeter samples was limited due to uncertainties in the water balance at the LID facility.

5.3.4 Site Maintenance

Staff visited the CRRC site on a biweekly basis between storm events to ensure the monitoring equipment was working properly. Site maintenance was also reported as taking place on an as-needed basis while staff were on site to prepare for a storm event, or to collect samples from a storm event (Versar, 2011).

Regular maintenance of the site was reported to include checking the overall condition of the equipment; checking power-up status of equipment; exchanging batteries if needed; downloading accumulated meteorological, water temperature, and water level data to a field laptop computer; repairing or securing equipment as needed; and filling out equipment status field data reports (Versar, 2011). Weather station and water temperature data were downloaded by staff using Hoboware Pro software from Onset (2012). Water level and flow data were downloaded using Flowlink version 4.15 software from ISCO (2012). A log of site visits between July 2009 – June

2010 and March 2011 – May 2012 was provided by Versar and is available in the performance analysis reports prepared by Versar (2011) and Grizzard and Le Bel (2013).

5.3.5 Accounting for Censored Observations

Analysis of Censored Data

Nondetects in environmental datasets are values reported to be only below an analytical reporting limit, and typically result in censored datasets. Nondetects in water quality data are typically low-level concentrations of chemicals with values known only to be somewhere between zero and the analytical detection/reporting limits (Helsel, 2002; Geosyntec and WWE, 2009; Helsel, 2012). Substitution methods such as replacing censored data with values equal to one-half the detection limit are common in the environmental engineering literature. However, substitution methods have been shown by Helsel (2012) to introduce "invasive" patterns and signals not present in the original dataset. Substitution methods arbitrarily change the distribution of datasets and may cause artificial relationships to be inferred between variables. Helsel (2012) demonstrated that substitution methods are not neutral, but instead "invasive," because such methods may introduce a pattern or signal to the data which is different than the native pattern of the original dataset, and thereby not reflective of reality. Helsel (2012) recommends the use of three data analysis approaches when censored data are present: (1) using nonparametric methods after censoring at the highest reporting limit; (2) using the maximum likelihood estimation (MLE) method which is a survival analysis procedure assuming a specific distribution; (3) and using a nonparametric survival analysis procedure such as the Kaplan-Meier (KM) and Turnbull methods. Helsel (2012) has also recommended imputation methods such as robust regression on ordered statistics (ROS) and robust MLE when the level of censoring within a dataset is greater than 50% but less than 80%. When used correctly, these approaches avoid the introduction of invasive patterns and signals associated with other (and often more commonly used) substitution methods (Helsel, 2012).

5.3.5.1 Robust Regression on Ordered Statistics

Regression on ordered statistics (ROS) methods calculate summary statistics using a least-squares regression on a probability plot. For robust ROS, summary statistics are calculated by imputing values for censored observations based on a parametric model and combining those imputed estimates with the uncensored data (Helsel, 2012). A probability plot is used to fit a regression equation using the uncensored observations within a dataset. The normal scores for censored observations are then used with the previously defined regression equation to assign values for the censored observations. The assigned values may then be imputed and combined with the uncensored observations enabling the computation of summary statistics as though no censoring was present within the dataset. The process avoids transformation bias because it does not require transforming summary statistics (such as the mean and standard deviation) across scales (Helsel, 2012). Robust ROS was used in the analysis of the CRRC LID facility data to produce probability plots, also called quantile-quantile or Q-Q plots, which account for any censored observations.

5.3.5.2 Kaplan-Meier Method

The nonparametric Kaplan-Meier method is the standard method for estimating summary statistics of censored survival data (right-censored) and may also be applied to left-censored environmental data (Helsel, 2012). The Kaplan-Meier method produces estimates of the survival probability function 'S' for right-censored data but may be applied to environmental data (typically left-censored and bounded by 0) by 'flipping' the data by subtracting every observation by a value that is greater than the maximum value within the dataset. The survival probability function applied to left-censored data essentially produces an empirical distribution function (EDF) of the data and is able to incorporate censored (or below detection limit) observations in environmental data (Helsel, 2012). Using the Kaplan-Meier method to estimate summary statistics for censored environmental data, including the EDF, makes it possible to utilize the Effluent Probability Method (Strecker et al., 2001; Geosyntec and WWE, 2009; Williams et al., 2009) to compare influent and effluent loads at the CRRC LID facility while still incorporating the effects of below detection limit observations (Helsel, 2012).

5.3.5.3 Limitations of the Kaplan-Meier Method and Robust ROS

It should be noted that the Kaplan-Meier method is not recommended for datasets which have greater than 50% censoring (Helsel, 2012). For data sets with 50-80% censoring, Helsel (2012) recommends methods such as robust regression on ordered statistics, robust maximum likelihood estimation or multiple imputation may be used to estimate summary statistics. For data sets with greater than 80% censoring, summary statistics cannot be accurately estimated and the analysis is found to be more limited. In such cases, analysis may be limited to reporting the percentage of observations above or below the maximum reporting limit (Helsel, 2012).

5.3.6 Methods of Calculating BMP Efficiency

5.3.6.1 Mass-Based Methods for Assessing Stormwater BMPs

Water quality benefits and load reductions from LID practices and other BMPs are a function of both water quality treatment processes (such as filtration of particle-bound pollutants, removal of dissolved pollutants through amended media, and nutrient uptake by vegetation) and stormwater runoff volume reductions (Davis et al., 2006; Davis, 2007; Geosyntec and WWE, 2009). Because of this, performance metrics based on the total pollutant load removal over a representative period of the meteorological and hydrologic record are more representative measures of the overall system efficiency and are consequently more appropriate for assessing pollutant reduction performance of a LID site (Davis, 2007; Geosyntec and WWE, 2009). The Effluent Probability Method (Strecker et al., 2001; Geosyntec and WWE, 2009; Williams et al., 2009) was chosen for constituent load reduction analyses.

5.3.6.2 LID Facility Load Calculations

LID Facility Inlet Load Calculations

To facilitate the use of the Effluent Probability Method as a performance analysis metric for the CRRC LID facility, volume-weighted event mean concentration (EMC) and load were calculated to represent the total inlet load for any combination of storm event and water quality parameter. The total inlet EMC or load at the Cub Run LID facility was designated as 'CUIN' to maintain consistency with previous performance evaluations. CUIN for each storm event and discrete water quality parameter was calculated by determining the total loads flowing into the LID facility as measured by the GKY and PVC samplers, identified as CUGKY and CUPVC, respectively. The load from each sampler was calculated by multiplying the EMC by the total inflow volume from the respective drainage areas for the GKY and PVC samplers as estimated by the SCS runoff curve number method. The loads from the GKY and PVC samplers were then summed to give the total load delivered to the LID facility. A volume-weighted EMC for CUIN was then obtained by dividing the total load by the total inflow volume calculated by summing the inflows from the parking lot and grassy and wooded areas. The equations describing the CUIN EMC and loads are as follows:

$$CUIN_{Load} = \left(\left(EMC_{GKY} x Inflow_{Parking\ Lot} \right) + \left(EMC_{PVC} x Inflow_{Grassy\ \&\ Wooded\ Area} \right) \right) x \frac{1\ g}{1000mg}$$

$$CUIN_{EMC} = \frac{\left(EMC_{GKY} x Inflow_{Parking\ Lot}\right) + \left(EMC_{PVC} x Inflow_{Grassy\ \&\ Wooded\ Area}\right)}{\left(Inflow_{Parking\ Lot} + Inflow_{Grassy\ \&\ Wooded\ Area}\right)}$$

Where:

- $CUIN_{Load}$ = Total load delivered to the LID facility (grams) from sheet flow runoff from both the parking lot and the grassy and wooded areas;
- $CUIN_{EMC}$ = Volume-weighted EMC for CUIN (mg/L);
- EMC_{GKY} = EMC reported from GKY sampler (mg/L);
- EMC_{PVC} = EMC reported from PVC sampler (mg/L);
- $Inflow_{Parking\ Lot}$ = Volume of runoff entering LID facility from the parking lot (L);
- $Inflow_{Grassy\ \&\ Wooded\ Area}$ = Volume of runoff entering LID facility from the grassy and wooded areas (L).

LID Facility Outlet Loads Calculations

LID facility outlet loads for any combination of water quality parameter and storm event were calculated as the product of the water quality parameter EMC reported at the outfall, designated CUOUT for the Cub Run outfall, and the storm event total discharge at the outlet (Davis et al., 2006; Davis, 2007; Li and Davis, 2009), or:

$$CUOUT_{Load} = EMC_{OUT} x Outflow_{LID\ Facility} x \frac{1g}{1000mg}$$

Where:

- $CUOUT_{Load}$ = Total load discharging from the LID facility outfall (grams);
- EMC_{OUT} = EMC reported from outfall sampler (mg/L);
- $Outflow_{LID\ Facility}$ = Volume of runoff discharging from the LID facility outfall (L).

5.3.6.3 Effluent Probability Method

The Effluent Probability Method (EPM) was used to compare influent and effluent loads at the LID facility. The EPM analysis was not performed on Cd, Pb, O&G, and TPH due to the high level of censoring in their respective datasets. For data sets with greater than 80% censoring, summary statistics could not be accurately estimated and the analysis was limited to reporting the percentage of observations above or below the maximum reporting limit (Helsel, 2012). Application of the Effluent Probability Method consists of three principal steps (Strecker et al., 2001; Geosyntec and WWE, 2009; Williams et al., 2009):

- A distributional adherence test to determine if the data follow a particular distribution (environmental data most often follow the lognormal distribution);
- Statistical tests to determine if any perceived differences between the influent and effluent EMCs or loads are statistically significant;
- Plotting the log-transformed data of influent and effluent EMCs or loads for all storm events on a normal probability plot.

The assumptions of the Effluent Probability Method include:

- The rank of the pollution concentration in influent is consistent with that in the effluent (Chi-Feng et al., 2009);
- The lognormal distribution is an appropriate approximation for the sample data (Strecker et al., 2001; Chi-Feng et al., 2009; Geosyntec and WWE, 2009).

Accounting for Storm Events with no Discharge

An analysis dataset was created to include all observations in the CUOUT load dataset in addition to all storm events which produced no discharge at the outfall and, consequently, no effluent load. This dataset was named CUOUT-ZF to represent the CUOUT load dataset with the zero flow events included. CUOUT-ZF is important because without the inclusion of all storm events where no discharge occurred at the outfall and therefore an effluent load of zero may be assumed, the stormwater BMP performance would be unduly affected in a negative manner. Omitting storm events with no discharge (and no loads) at the outfall would bias the water quality data toward only large events that produce flow (Davis et al., 2006; Davis, 2007).

5.4 Results

5.4.1 Representativeness of Dataset

5.4.1.1 Duration of Study

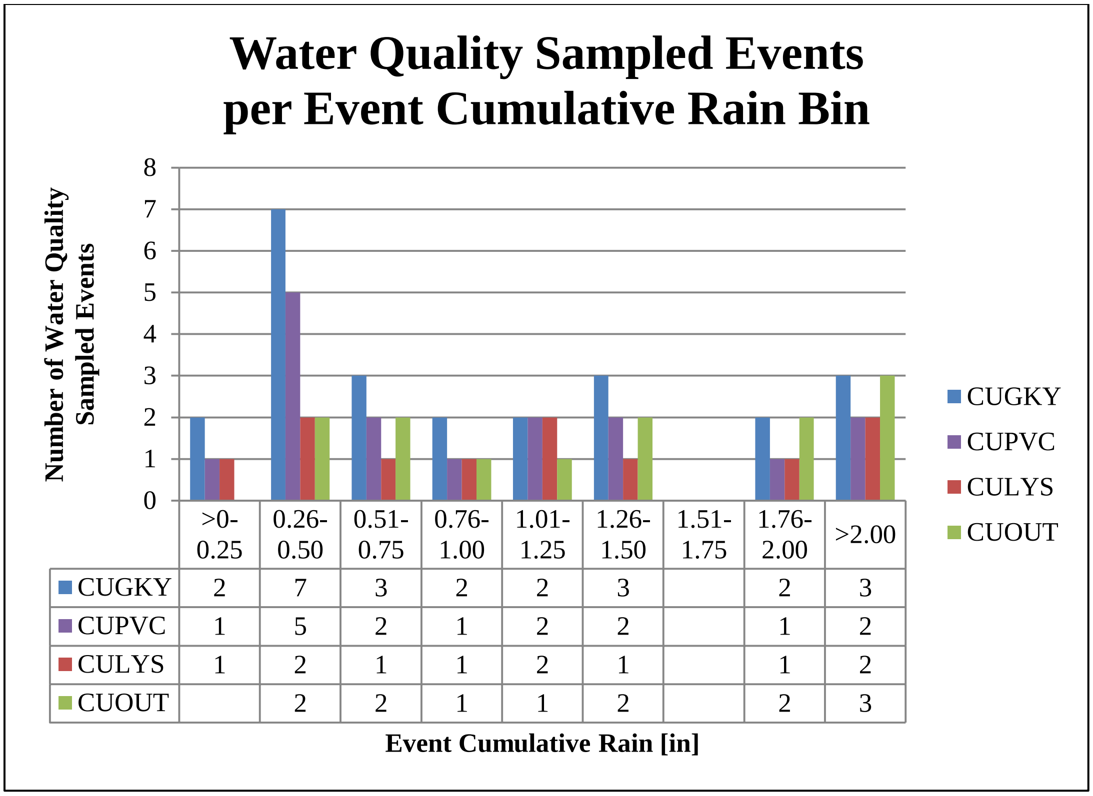
The Cub Run Recreation Center LID facility was monitored during two distinct monitoring periods. The first period ranged from September, 2008 to June, 2010 and the second monitoring period ranged from March, 2011 to May, 2012. During each period, continuous flow monitoring (at the LID facility outfall only), continuous meteorological data, and continuous soil moisture data were collected. Discrete water quality sampling for targeted storm events was also conducted (Versar, 2011).

5.4.1.2 Number of Storm Events and Water Quality Monitored Events

During the two monitoring periods, 183 events were reported where at least 0.01 inches of precipitation occurred (Versar, 2011; VT-OWML, 2012). Of these 183 events, 73 events had precipitation depths equal to or greater than 0.2 inches, which was the minimum pre-storm prediction required to mobilize field staff to sample an event (Versar, 2011). Two events, on 9/11/2009 and 1/26/2011, were monitored for water quality even though their precipitation depths were less than the threshold.

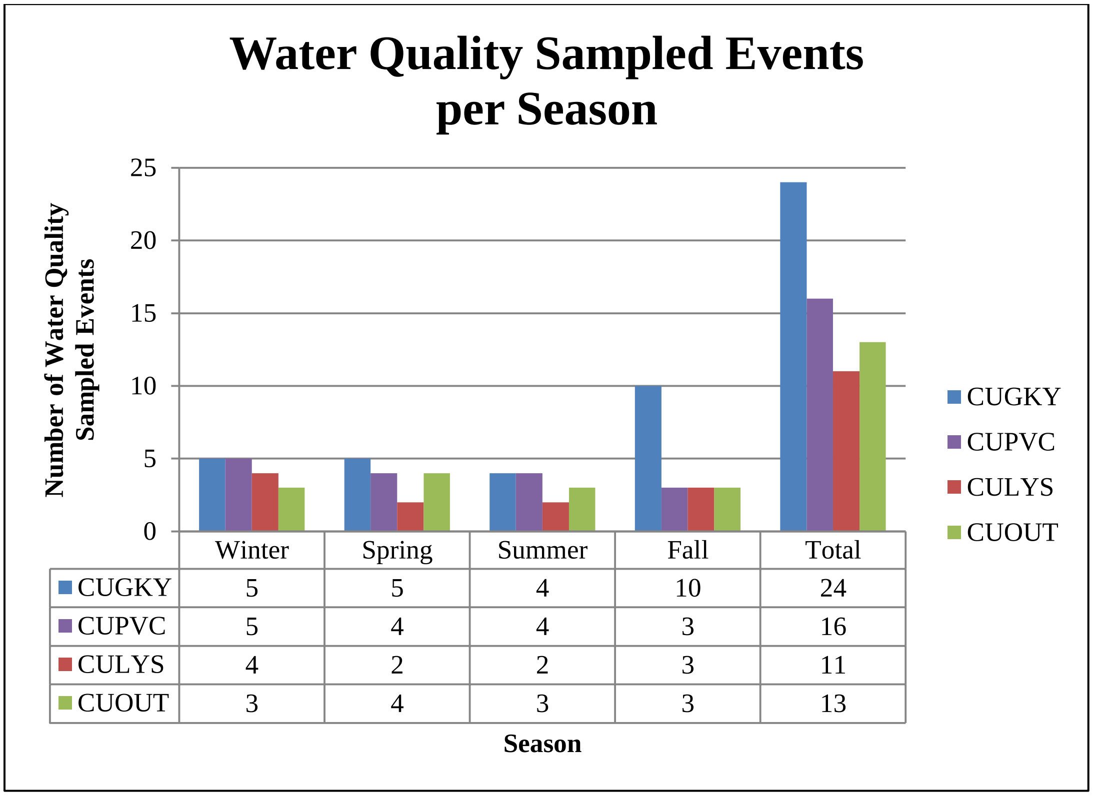
During the two monitoring periods, 25 storm events were monitored for water quality. When the 9/11/2009 and 1/26/2011 storm events were included, the number of events with qualifying precipitation depths increased to 75. From this, it may be seen that 1/3 of all eligible storm events, based on a precipitation depth of 0.2 inches or greater, were monitored for water quality.

Figures 5-5 and 5-6 show a summary of the rainfall event size and seasonal distribution of the events sampled for water quality. For the analysis, winter was defined as December – February; spring as March – May; summer as June – August; and fall as September – November. The water quality events sampled were rather evenly distributed across both rainfall depth and season, although there was a noticeable spike in events sampled with the GKY and PVC samplers at lesser rainfall depths. This is consistent with the previous observation that smaller events were less likely to produce outflow at the LID facility discharge (CUOUT).



	>0-0.25	0.26-0.50	0.51-0.75	0.76-1.00	1.01-1.25	1.26-1.50	1.51-1.75	1.76-2.00	>2.00
CUGKY	2	7	3	2	2	3		2	3
CUPVC	1	5	2	1	2	2		1	2
CULYS	1	2	1	1	2	1		1	2
CUOUT		2	2	1	1	2		2	3

Figure 5-5. Water quality sampled events per cumulative rain amount bar graph.



	Winter	Spring	Summer	Fall	Total
CUGKY	5	5	4	10	24
CUPVC	5	4	4	3	16
CULYS	4	2	2	3	11
CUOUT	3	4	3	3	13

Figure 5-6. Water quality sampled events per season bar graph.

5.4.2 Assessment of Monitoring System Equipment Performance

In the 2011 performance monitoring report produced by Versar (2011), the monitoring equipment design was found to have been adequate for capturing inflows and outflows and generally functioned as designed. Occasional equipment failures were found to have occurred.

Most of the difficulties with monitoring system integrity were due to a variety of problems associated with snow disposal on the Cub Run Recreation Center parking lot. Freezing of the GKY and PVC samplers in the winter of 2009-2010, and limited access due to snow accumulation were both reported to limit the number of sampling attempts (Versar, 2011). In examining the data provided in the much milder winter of 2011, it was apparent that the weather had a much decreased impact on sampling.

A comprehensive examination of equipment failures during the two monitoring periods may be found in Grizzard and Le Bel (2013).

5.4.3 Monitoring Data

5.4.3.1 Rainfall and Runoff Statistics for Storm Events Monitored for Water Quality

Rainfall and runoff statistics for the 25 monitored storm events for the Cub Run Recreation Center LID facility are provided in Table 5-2. The table includes data previously reported by Versar (2011) from the first monitoring period, and data reported to Virginia Tech for the second monitoring period (VT-OWML, 2012). As has been previously noted, the SCS runoff curve number method was used to estimate runoff volumes for the parking lot area and the grassy and wooded area.

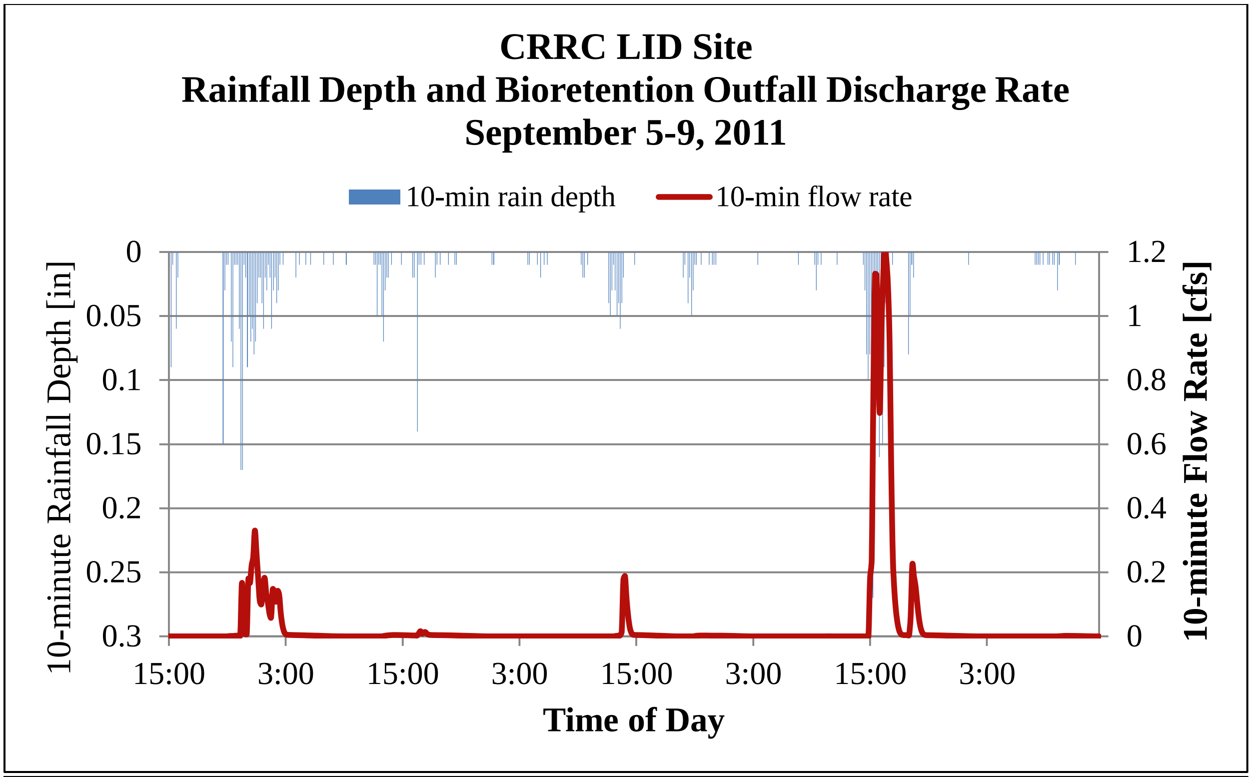
5.4.3.2 Storm Event Hydrographs and Total Flow Volume Time Series Plots

Ten-minute rainfall intensity, flow rate at the LID facility outfall, accumulated flow volume at the outfall and available precipitation volume is presented in Figure 5-7 for the water quality monitored storm event which occurred September 5 – 9, 2011. This event was chosen for display because of the relatively high rainfall total (5.13 inches) and duration (93.2 hours). Available precipitation volume was taken as the product of event rainfall and catchment area. Storm event hydrographs and hyetographs for all 25 water quality monitored events may be found in Figures A-8 – A-32 in Appendix A.

Table 5-2. Storm and runoff statistics for valid storms monitored at Cub Run Recreation Center LID facility.

	Measured Values		Calculated Values		Values Estimated by SCS Runoff CN Method				Measured and Calculated Values						
Event Date	**Total Rain (in.)**	**Outfall Volume (ft^3)**	**Outfall Equivalent Rain (in.)**	**Rain Retained (%)**	**Total Runoff Pavement (ft^3)**	**Runoff with CN Pavement (in.)**	**Total runoff Grassy/ Wooded (ft^3)**	**Runoff with CN Grassy/ Wooded (in.)**	**Dry Time (hr.)**	**Rainfall Duration (hr.)**	**Elevated Flow Duration (hr.)**	**Average Rainfall Rate (in./hr.)**	**Amount of Rain Before Flow (in.)**	**Time Before Flow (hr.)**	**Rainfall Rate Before Flow (in./hr.)**
9/25/08	0.47	0.00	0.00	100%	665	0.29	0	0.00	298.9[2]	18.42	N.R.	0.026	N.R.	N.R.	N.R.
4/20/09	1.80[1]	N.D.	N.D.	N.D.	3605	1.58	1279	0.00	98.8	25.67	N.D.	0.070	N.D.	N.D.	N.D.
6/3/09	1.28[1]	3394.73	0.58	54%	2433	1.06	513	0.00	85.9	1.50	4.00	0.853	0.43	0.33	1.303
8/21/09	2.36[1]	707.31	0.16	95%	4875	2.13	2326	0.22	368.5	15.50	6.17	0.152	1.62	7.67	0.211
9/11/09	0.15	0.00	0.00	100%	87	0.04	0	0.05	69.5	6.83	N.R.	0.022	N.R.	N.R.	N.R.
9/26/09	0.48	N.D.	N.D.	N.D.	686	0.30	0	0.10	30.1	31.17	N.R.	0.015	N.R.	N.R.	N.R.
10/15/09	0.62	0.00	0.00	100%	979	0.43	9	0.00	8.3	30.50	N.R.	0.020	N.R.	N.R.	N.R.
10/24/09	1.42	3178.18	0.73	61%	2747	1.20	695	0.00	151.7	5.83	3.00	0.243	0.21	2.67	0.079
10/27/09	0.92	602.35	0.14	89%	1632	0.71	155	0.00	10.7	13.00	3.00	0.071	0.55	7.83	0.070
11/11/09	1.09	0.00	0.00	100%	2009	0.88	303	0.09	230.1	35.50	N.R.	0.031	N.R.	N.R.	N.R.
12/2/09	0.44	4.20	0.001	100%	604	0.26	0	0.00	42.7	14.17	0.67	0.031	0.35	10.50	0.033
3/11/10	0.44	13.70	0.003	99%	604	0.26	0	0.15	217.3	9.33	4.83	0.047	0.43	6.83	0.063
3/28/10	0.62	141.49	0.03	96%	979	0.43	9	2.91	58.0	7.00	9.50	0.089	0.31	1.67	0.186
7/8/11	1.06	27.03	0.005	100%	1942	0.85	273	0.00	438.8	2.3	5.3	0.172	0.61	0.83	0.732
8/13/11	0.34	0.00	0.00	100%	407	0.18	0	0.80	140.5	33.5	N.R.	0.010	N.R.	N.R.	N.R.
8/27/11	1.23	67.79	0.01	99%	2321	1.01	454	0.39	44.0	19.7	15.8	0.056	0.46	6.00	0.077
9/5/11	5.13	10855.3	1.87	64%	11190	4.89	9097	0.01	51.2	93.2	89.5	0.054	0.37	6.00	0.062
9/23/11	0.32	0.00	0.00	100%	369	0.16	0	0.00	29.5	49.3	N.R.	0.006	N.R.	N.R.	N.R.
10/12/11	2.44	5395.19	0.93	62%	5057	2.21	2490	0.24	7.0	47.8	37.2	0.045	0.48	16.50	0.029
12/6/11	1.76	5195.13	0.89	49%	3514	1.54	1212	0.00	153.7	43.7	24.2	0.034	0.48	27.67	0.017
1/11/12	0.72	709.20	0.12	83%	1194	0.52	39	0.04	23.7	16.5	9.8	0.031	0.42	13.50	0.031
1/26/12	0.14	0.00	0.00	100%	74	0.03	0	0.00	58.8	29.7	N.R.	0.005	N.R.	N.R.	N.R.
2/29/12	1.47	2335.43	0.4	73%	2860	1.25	764	0.00	110.8	64.5	67.8	0.021	0.43	2.83	0.152
3/24/12	0.40	0.00	0.00	100%	524	0.23	0	0.00	508.3	15.5	N.R.	0.026	N.R.	N.R.	N.R.
4/21/12	0.86	59.28	0.01	99%	1500	0.66	113	0.22	65.8	44.8	7.7	0.019	0.51	24.50	0.021

N.R. = not applicable due to no runoff from the outfall pipe.
N.D. = data unavailable
[1] = Total rainfall determined from KVACHANT3 gauge located in Chantilly, VA.
[2] = Antecedent dry time determined from KIAD gauge located at Dulles International Airport.



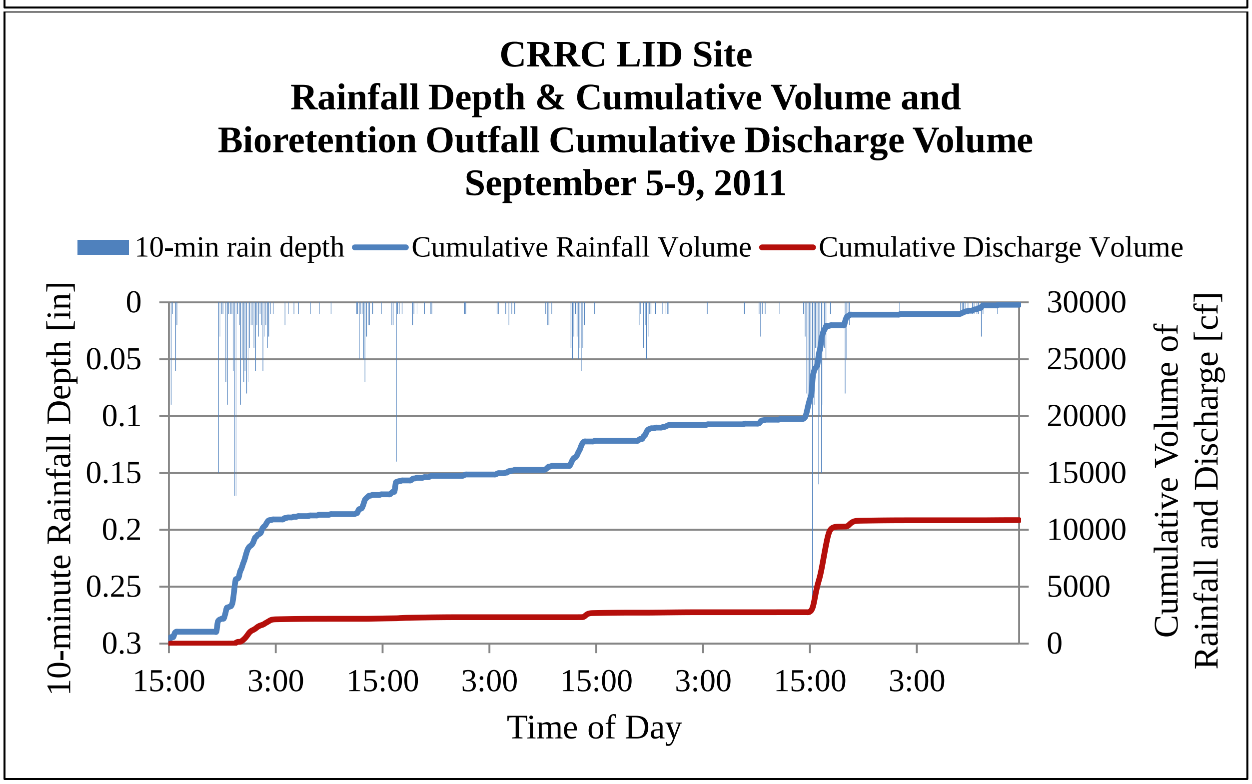


Figure 5-7. Hydrograph and hyetograph of Sept 5-9, 2011 storm event.
Dry time = 51.2 hrs.

5.4.3.3 Water Quality Results

Event Mean Concentration Results for Individual Storm Events

The computed event mean concentration (EMC) results for each sampled storm event in both monitoring periods are presented in Table 5-3.

Load Results for Individual Storm Events for CUIN & CUOUT

Table 5-4 presents the loads for CUIN and CUOUT for each sampled storm event. The loads were calculated as previously described. The loads in Table 5-4 were calculated substituting the detection limit for any censored, or below detection limit, observations. The influent and effluent load datasets were then analyzed using the Kaplan-Meier method to estimate summary statistics, evaluate censored datasets for statistically significant differences and produce Effluent Probability Method plots comparing influent and effluent loads, while accounting for any censored observations. Robust regression on ordered statistics was used to produce Q-Q plots to test for distributional adherence of the influent and effluent load datasets.

Percent Censoring for Each Water Quality Parameter

Table 5-5 presents the percent censoring for each measured water quality parameter for the CUIN, CUOUT and CUOUT-ZF load datasets.

Table 5-3. Analytical results for monitored storm events.

Event Date	Pollutant Concentration (mg/L)																			
	Total Phosphorus					Total Nitrogen[2]					Oxidized Nitrogen					Total Kjeldahl Nitrogen				
	GKY	PVC	IN[1]	LYS[3]	OUT	GKY	PVC	IN[1]	LYS[3]	OUT	GKY	PVC	IN[1]	LYS[3]	OUT	GKY	PVC	IN[1]	LYS[3]	OUT
9/25/08	0.09		0.09			1.07		1.07			0.57		0.57			0.5		0.50		
4/20/09	1.3		0.96		0.28	3.72		2.75			0.22		0.16		0.25	3.5		2.58		2
6/3/09	0.04	0.12	0.05		0.24	2.18	3.02	2.32		2.06	0.38	<0.02	0.32		0.26	1.8	3	2.01		1.8
8/21/09	0.13		0.09		0.31	1.65		1.12		0.58	0.35		0.24		0.58	1.3		0.88		1.8
9/11/09	1.3		1.30			9.16		9.16			0.16		0.16			9		9.00		
9/26/09	0.06		0.06			1.00		1.00			0.1		0.10			0.9		0.90		
10/15/09	0.06		0.06			0.92		0.91			0.22		0.22			0.7		0.69		
10/24/09	0.18		0.14			2.12		1.69			0.42		0.34			1.7		1.36		
10/27/09	0.09		0.08			1.32		1.21			0.02		0.02			1.3		1.19		
11/11/09	0.12		0.10			5.10		4.43			2.6		2.26			2.5		2.17		
12/2/09	0.14	2.4	0.14			1.84		1.84			0.24	<0.02	0.24			1.6	11	1.60		
3/11/10	0.4	0.6	0.40		0.19	2.55		2.55		2.00	0.35	<0.02	0.35		1.1	2.2	3.7	2.20		0.9
3/28/10	0.77	0.63	0.77		0.28	3.80	4.11	3.80		2.09	0.1	0.11	0.10		0.49	3.7	4	3.70		1.6
7/8/11	0.04	1.2	0.18	0.74	0.35	1.16	5.30	1.67	28.40	4.40	0.26	2.40	0.52	20.00	1.80	0.90	2.90	1.15	8.40	2.60
8/13/11	0.15	4.7	0.15			2.15		2.15			0.45	5.70	0.45			1.70	17.00	1.70		
8/27/11		0.36	0.06	1.3			1.83	0.30	23.60			0.13	0.02	18.00			1.70	0.28	5.60	
9/5/11	0.23	0.45	0.33	0.32	0.23	0.85	1.49	1.14	1.92	2.10	0.05	0.09	0.07	0.52	0.70	0.80	1.40	1.07	1.40	1.40
9/23/11	0.06	0.72	0.06	0.72		1.59		1.59	5.10		0.89	6.90	0.89	1.70		0.70	3.50	0.70	3.40	
10/12/11	0.25	0.79	0.43	0.36	0.2	1.16	4.55	2.28	3.20	2.50	0.06	0.05	0.06	1.1	1.4	1.1	4.5	2.22	2.1	1.1
12/6/11	0.64	0.75	0.67	0.33	0.24	4.82	5.22	4.92	1.16	1.33	<0.02	<0.02	<0.02	0.16	0.13	4.8	5.2	4.90	1	1.2
1/11/12	0.48	0.91	0.49	0.35	0.17	3.60	5.66	3.66	2.90	1.51	0.1	0.16	0.10	1.3	0.61	3.5	5.5	3.56	1.6	0.9
1/26/12	0.27	1.4	0.27	0.64		1.20		1.20	2.60		0.1	0.06	0.10	0.6		1.1	4.4	1.10	2	
2/29/12	0.63	2.1	0.94	0.41	0.46	2.92	7.08	3.80	3.20	2.12	0.12	0.18	0.13	1.3	0.62	2.8	6.9	3.66	1.9	1.5
3/24/12	0.1	2	0.10	0.44		1.00		1.00	4.06		0.2	0.35	0.20	0.36		0.8	27	0.80	3.7	
4/21/12	0.21	0.51	0.23	0.37	0.35	1.58	3.42	1.71	3.50	1.33	0.08	0.52	0.11	1.3	0.53	1.5	2.9	1.60	2.2	0.8

[1]IN refers to the volume-weighted CUIN as discussed earlier in the report. [2]Total Nitrogen = $(OxN_{Load} + TKN_{Load})$/(Vol. of Runoff for Sampler's Drainage Area)
[3]Lysimeter samples were only taken for TP, OxN and TKN. Lysimeter samples were only taken during the 2nd monitoring period.
Blank cells are indicative of a storm event which was sampled for water quality but not for that particular water quality constituent.

Table 5-3. Analytical results for monitored storm events (Continued).

Event Date	Pollutant Concentration (mg/L)															
	Ammonia Nitrogen				Total Suspended Solids				Chemical Oxygen Demand[4]				Total Dissolved Solids[4]			
	GKY	PVC	IN[1]	OUT	GKY	PVC	IN[1]	OUT	GKY	PVC	IN[1]	OUT	GKY	PVC	IN[1]	OUT
9/25/08	0.3		0.30		32		32									
4/20/09					450		332	74								
6/3/09	1.1	0.6	1.01	0.4	4	56	13	10								
8/21/09	0.5		0.34	<0.2	25		17	2								
9/11/09	5.9		5.90		11		11									
9/26/09	0.2		0.20		4		4									
10/15/09	<0.2		<0.20		6		6									
10/24/09	<0.2		<0.16		28		22									
10/27/09	0.3		0.27		9		8									
11/11/09	0.9		0.78		9		8									
12/2/09	0.3	1	0.30		6	1600	6									
3/11/10	0.5	0.6	0.50	0.3	190	280	190	19								
3/28/10	0.4	0.7	0.40	0.3	480	290	478	14								
7/8/11	0.30	0.40	0.31	0.40	2	190	25	2	30	70	35	55	24	110	35	120
8/13/11	0.80	0.80	0.80		2		2		83		83		19		19	
8/27/11		<0.2	<0.03			28	5			41	7			<10	<1.7	
9/5/11	<0.2	13.00	5.88	<0.2	8	250	117	29	48	100	71	70	<10	65	32	72
9/23/11	<0.2	0.70	<0.2		9		9		35	50	35		<10		<10	
10/12/11	0.2	0.2	0.20	<0.2	150	490	262	10	110	200	140	37	28	88	48	77
12/6/11	0.3	0.6	0.38	<0.2	610	790	656	32	250	200	237	44	51	21	43	69
1/11/12	0.2	0.8	0.22	<0.2	290	680	302	28	150	180	151	22	39	78	40	54
1/26/12	0.3	0.4	0.30		170	580	170		120	170	120		<10	130	<10	
2/29/12	0.2	0.7	0.31	0.2	180	700	290	58	190	240	201	66	85	180	105	76
3/24/12	0.3	1.4	0.30		17	1300	17		40	310	40		<10	<10	<10	
4/21/12	0.3	0.8	0.33	<0.2	74	95	75	10	85	91	85	34	17	67	20	97

[1]IN refers to the volume-weighted EMC referred to as CUIN and discussed in previous sections.
[4]COD and TDS were not tested for during 1st monitoring period.
Blank cells are indicative of a storm event which was sampled for water quality but not for that particular water quality constituent.

Table 5-3. Analytical results for monitored storm events (Continued).

Event Date	Pollutant Concentration (mg/L)											
	Copper				Cadmium				Zinc			
	GKY	PVC	IN[1]	OUT	GKY	PVC	IN[1]	OUT	GKY	PVC	IN[1]	OUT
9/25/08	<0.01		<0.01		<0.0005		<0.0005		0.073		0.07	
4/20/09	0.058		0.0428	<0.01	<0.0005		<0.0004	<0.0005	1.8			0.064
6/3/09	0.0033	0.014	0.0052	0.0069	<0.0005	<0.0005	<0.0005	<0.0005	0.044	0.032	0.04	0.02
8/21/09	0.0056		0.0038	0.0098	<0.0005		<0.0003	<0.0005	0.055		0.04	0.093
9/11/09	0.0062		0.0062		<0.0005		<0.0005		0.024		0.02	
9/26/09	0.0028		0.0028		<0.0005		<0.0005		<0.01		<0.01	
10/15/09	0.0022		0.0022		<0.0005		<0.0005		0.019		0.019	
10/24/09	0.014		0.0112		<0.0005		<0.0004		0.05		0.040	
10/27/09	0.0035		0.0032		<0.0005		<0.0005		0.033		0.030	
11/11/09	0.0049		0.0043		<0.0005		<0.0004		0.032		0.028	
12/2/09	0.0054	0.125	0.0054		<0.0005	0.0015	<0.0005		0.017	0.17	0.017	
3/11/10	0.024	0.018	0.0240	0.0051	0.002	<0.0005	0.0020	<0.0005	0.094	0.041	0.094	0.04
3/28/10	0.041	0.024	0.0408	0.0093	0.0028	<0.0005	0.0028	0.00055	0.13	0.15	0.130	0.037
7/8/11	0.005		0.0044		<0.0005		<0.0004		0.074		0.065	
8/13/11	0.0071	0.104	0.0071		<0.0005	0.0019	<0.0005		0.04	0.15	0.040	
8/27/11		0.014	0.0023			0.001	0.0002			0.034	0.006	
9/5/11	0.00692	0.063	0.0321	0.0059	<0.0005	<0.0005	<0.0005	<0.0005	0.02	0.046	0.032	<0.01
9/23/11	0.013	0.035	0.0130		0.00065	0.00083	0.0007		0.073	0.089	0.073	
10/12/11	0.023	0.04	0.0286	0.0064	<0.0005	<0.0005	<0.0005	<0.0005	0.073	0.07	0.072	0.019
12/6/11	0.08	0.069	0.0772	0.0075	0.00065	<0.0005	0.0005	<0.0005	0.25	0.14	0.222	0.023
1/11/12	0.024	0.069	0.0254	0.0075	<0.0005	<0.0005	<0.0005	<0.0005	0.14	0.15	0.140	0.02
1/26/12	0.015	0.034	0.0150		<0.0005	<0.0005	<0.0005		0.1	0.07	0.100	
2/29/12	0.03	0.08	0.0405	0.01	<0.0005	<0.0005	<0.0005	<0.0005	0.12	0.13	0.122	0.02
3/24/12	<0.002		<0.002		0.001		0.0010		0.03	0	0.030	
4/21/12	0.011	0.015	0.0113	0.006	<0.0005	<0.0005	<0.0005	<0.0005	0.07	0.03	0.067	0.02

[1]IN refers to the volume-weighted EMC referred to as CUIN and discussed in previous sections.
Blank cells are indicative of a storm event which was sampled for water quality but not for that particular water quality constituent.

Table 5-3. Analytical results for monitored storm events (Continued).

Event Date	Pollutant Concentration (mg/L)											
	Lead				Oil and Grease				Total Petroleum Hydrocarbons			
	GKY	PVC	IN[1]	OUT	GKY	PVC	IN[1]	OUT	GKY	PVC	IN[1]	OUT
9/25/08	<0.01		<0.01									
4/20/09	0.032		0.024	<0.01	42		31.0					
6/3/09	<0.002	<0.002	<0.002	<0.002	5.7	10	6.4					
8/21/09	<0.002		<0.001	<0.002	<5		<3.38					
9/11/09	<0.002		<0.002		<5		<5					
9/26/09	<0.002		<0.002		<5		<5					
10/15/09	<0.002		<0.002		<5		<4.96					
10/24/09	0.0021		0.002		<5		<3.99					
10/27/09	<0.002		<0.002		<5		<4.57					
11/11/09	<0.002		<0.002		<5		<4.35					
12/2/09	<0.002	0.022	<0.002		<5		<5					
3/11/10	0.014	0.0057	0.014	<0.002	<5		<5					
3/28/10	0.02	0.009	0.0199	<0.002	<5		<4.96					
7/8/11	<0.002		<0.002		<5		<4.38					
8/13/11	<0.002	0.016	<0.002		<5		<5					
8/27/11		<0.002	<0.0003			<5	<0.82					
9/5/11	<0.002	0.0081	0.004184	<0.002	<5	<5	<5	5.8				
9/23/11	0.012	0.004	0.012		<5		<5					
10/12/11	0.0054	0.0077	0.006	<0.002	<5	<5	<5	14				
12/6/11	0.024	0.0084	0.020	<0.002					<5	<5	<5	<5
1/11/12	0.016	0.011	0.016	<0.002					<5	<5	<5	<5
1/26/12	0.021	0.013	0.021						<5	<5	<5	
2/29/12	0.016	0.014	0.016	<0.002					<5	<5	<5	<5
3/24/12	<0.002	0	<0.002						<5		<5	
4/21/12	0.007	0.002	0.007	<0.002					<5	<5	<5	<5

[1]IN refers to the volume-weighted EMC referred to as CUIN and discussed in previous sections.
Blank cells are indicative of a storm event which was sampled for water quality but not for that particular water quality constituent.

Table 5-3. Analytical results for monitored storm events (Continued).

Event Date	Pollutant Concentration (mg/L)											
	Alkalinity[5]				Hardness[5]				Orthophosphate[5]			
	GKY	PVC	IN[1]	OUT	GKY	PVC	IN[1]	OUT	GKY	PVC	IN[1]	OUT
9/25/08	22		22		36		36		0.05		0.05	
4/20/09												
6/3/09	2	70	14	25	16	220	52	110	0.02	0.07	0.03	0.18
8/21/09	2		1	52	2		1	2	0.10		0.07	0.17
9/11/09	12		12		40		40		0.87		0.87	
9/26/09	2		2		<1			68	0.04		0.04	
10/15/09	12		12		<1		<0.99		0.02		0.02	
10/24/09	8		6		12		10		0.08		0.06	
10/27/09	8		7		<1		<0.91		0.05		0.05	
11/11/09	<1		<0.87		30		26		0.05		0.04	
12/2/09	6	140	6		88	220	88		0.09	0.15	0.09	
3/11/10	170	16	170	76	30	60	30	14	<0.01	<0.01	<0.01	0.14
3/28/10	20	130	21	48	130	80	130	100	0.02	<0.01	0.02	0.20
7/8/11												
8/13/11												
8/27/11												
9/5/11												
9/23/11												
10/12/11												
12/6/11												
1/11/12												
1/26/12												
2/29/12												
3/24/12												
4/21/12												

[1]IN refers to the volume-weighted EMC referred to as CUIN and discussed in previous sections.
[5]Alkalinity, Hardness and Orthophosphate were not sampled for during the 2nd monitoring period.
Blank cells are indicative of a storm event which was sampled for water quality but not for that particular water quality constituent.

Table 5-4. Load results for CUIN & CUOUT with BDL = detection limit.

Event Date	Pollutant Load (g)											
	TP		TN		OxN		TKN		NH_3		TSS	
	CUIN	CUOUT	CUIN	CUOUT	CUIN	CUOUT	CUIN	CUOUT	CUIN	CUOUT	CUIN	CUOUT
9/25/08	1.70	0	20.15	0	10.74	0	9.42	0	5.65	0	603	0
4/20/09	132.70		379.74		22.46		357.28				45936	
6/3/09	4.50	23.07	194.09	198.03	26.47	24.99	167.62	173.03	84.51	38.45	1089	961
8/21/09	17.95	6.21	227.76	47.67	48.31	11.62	179.45	36.05	69.02	4.01	3451	40
9/11/09	3.20	0	22.57	0	0.39	0	22.18	0	14.54	0	27	0
9/26/09	1.17		19.42		1.94		17.48		3.88		78	
10/15/09	1.66	0	25.52	0	6.10	0	19.41	0	5.55	0	166	0
10/24/09	14.00		164.94		32.68		132.26		15.56		2178	
10/27/09	4.16		60.99		0.92		60.07		13.86		416	
11/11/09	6.83	0	290.08	0	147.89	0	142.20	0	51.19	0	512	0
12/2/09	2.39	0	31.47	0	4.11	0	27.37	0	5.13	0	103	0
3/11/10	6.84	0.07	43.62	0.78	5.99	0.43	37.63	0.35	8.55	0.12	3250	7
3/28/10	21.51	1.12	106.42	8.37	2.80	1.96	103.62	6.41	11.27	1.20	13385	56
7/8/11	11.49	0.27	104.83	3.37	32.88	1.38	71.95	1.99	19.59	0.31	1581	2
8/13/11	1.73	0	24.76	0	5.18	0	19.58	0	9.21	0	23	0
8/27/11	4.62	0	23.50	0	1.67	0	21.84	0	2.57	0	360	0
9/5/11	188.79	70.70	653.14	645.52	39.03	215.17	614.11	430.35	3412.01	61.48	66932	8914
9/23/11	0.63	0	16.61	0	9.30	0	7.31	0	2.09	0	94	0
10/12/11	91.49	30.56	486.86	381.94	12.12	213.89	474.75	168.05	42.74	30.56	56022	1528
12/6/11	89.43	35.31	658.82	195.66	2.68	19.12	656.14	176.53	50.45	29.42	87818	4708
1/11/12	17.24	3.41	127.99	30.32	3.56	12.25	124.43	18.07	7.65	4.02	10557	562
1/26/12	0.57	0	2.52	0	0.21	0	2.31	0	0.63	0	357	0
2/29/12	96.47	30.42	389.71	140.20	13.61	41.00	376.09	99.20	31.35	13.23	29727	3836
3/24/12	1.48	0	14.83	0	2.97	0	11.87	0	4.45	0	252	0
4/21/12	10.55	0.59	78.01	2.23	5.06	0.89	72.96	1.34	15.29	0.34	3446	17

Blank cells are indicative of a storm event which was sampled for water quality but not for that particular water quality constituent.

Table 5-4. Load results for CUIN & CUOUT with BDL = detection limit (Continued).

	Pollutant Load (g)											
Event	COD		TDS		Cu		Cd		Zn		Pb	
Date	CUIN	CUOUT	CUIN	CUOUT	CUIN	CUOUT	CUIN	CUOUT	CUIN	CUOUT	CUIN	CUOUT
9/25/08					0.188	0	0.0094	0	1.375	0	0.1884	0
4/20/09					5.921		0.0510		183.743		3.2665	
6/3/09					0.431	0.663	0.0417	0.0481	3.497	1.923	0.1669	0.1923
8/21/09					0.773	0.196	0.0690	0.0100	7.592	1.863	0.2761	0.0401
9/11/09					0.015	0	0.0012	0	0.059	0	0.0049	0
9/26/09					0.054		0.0097		0.194		0.0388	
10/15/09					0.061	0	0.0139	0	0.527	0	0.0555	0
10/24/09					1.089		0.0389		3.890		0.1634	
10/27/09					0.162		0.0231		1.525		0.0924	
11/11/09					0.279	0	0.0284	0	1.820	0	0.1138	0
12/2/09					0.092	0	0.0086	0	0.291	0	0.0342	0
3/11/10					0.411	0.002	0.0342	0.0002	1.608	0.016	0.2395	0.0008
3/28/10					1.143	0.037	0.0778	0.0022	3.643	0.148	0.5569	0.0080
7/8/11	2192	42	2172	92	0.275		0.0275		4.069		0.1100	
8/13/11	956	0	219	0	0.082	0	0.0058	0	0.461	0	0.0230	0
8/27/11	527	0	128	0	0.180	0	0.0128	0	0.437	0	0.0257	0
9/5/11	40968	21517	19912	22132	18.421	1.814	0.2872	0.1537	18.186	3.074	2.7202	0.6148
9/23/11	366	0	104	0	0.136	0	0.0068	0	0.762	0	0.1253	0
10/12/11	29850	5653	10213	11764	6.113	0.978	0.1068	0.0764	15.388	2.903	1.3160	0.3056
12/6/11	31743	6473	5796	10151	10.329	1.103	0.0818	0.0736	29.684	3.384	2.6767	0.2942
1/11/12	5271	442	1405	1084	0.888	0.151	0.0175	0.0100	4.900	0.402	0.5532	0.0402
1/26/12	252	0	21	0	0.032	0	0.0011	0	0.210	0	0.0441	0
2/29/12	20582	4365	10779	5026	4.161	0.661	0.0513	0.0331	12.532	1.323	1.5988	0.1323
3/24/12	593	0	148	0	0.030	0	0.0148	0	0.445	0	0.0297	0
4/21/12	3900	57	936	163	0.515	0.010	0.0228	0.0008	3.069	0.034	0.3037	0.0034

Blank cells are indicative of a storm event which was sampled for water quality but not for that particular water quality constituent.

Table 5-4. Load results for CUIN & CUOUT with BDL = detection limit (Continued).

Event Date	Pollutant Load (g)									
	O&G		TPH		Alk		Hard		OP	
	CUIN	CUOUT	CUIN	CUOUT	CUIN	CUOUT	CUIN	CUOUT	CUIN	CUOUT
9/25/08		0			414	0	678	0	0.942	0
4/20/09	4287									
6/3/09	538	0			1155	2403	4300	10574	2.395	17.303
8/21/09	690	0			276	1042	276	40	13.804	3.405
9/11/09	12	0			30	0	99	0	2.144	0
9/26/09	97				39		19		0.777	
10/15/09	139	0			333	0	28	0	0.555	0
10/24/09	389				622		934		6.224	
10/27/09	231				370		46		2.310	
11/11/09	284	0			57	0	1706	0	2.844	0
12/2/09	86	0			103	0	1505	0	1.539	0
3/11/10	86	0			2908	29	513	5	0.171	0.054
3/28/10	139	0			587	192	3626	401	0.557	0.801
7/8/11	275	0								
8/13/11	58	0								
8/27/11	64	0								
9/5/11	2872	1783								
9/23/11	52	0								
10/12/11	1068	2139								
12/6/11			669	736						
1/11/12			175	100						
1/26/12			11	0						
2/29/12			513	331						
3/24/12			74	0						
4/21/12			228	8						

Blank cells are indicative of a storm event which was sampled for water quality but not for that particular water quality constituent.

Table 5-5. Sample number and percent censoring for loads at influent and effluent sampler locations.

CUIN																	
	TP	TN	OxN	TKN	NH_3	TSS	COD	TDS	Cu	Cd	Zn	Lead	O&G	TPH	Alk	Hard	OP
Censored Observations	0	0	1	0	4	0	0	4	2	19	1	13	16	6	1	3	1
Total Observations	25	25	25	25	24	25	12	12	25	25	24	25	18	6	12	12	12
Percent Censored	0%	0%	4%	0%	17%	0%	0%	33%	8%	76%	4%	52%	89%	100%	8%	25%	8%
CUOUT																	
	TP	TN	OxN	TKN	NH_3	TSS	COD	TDS	Cu	Cd	Zn	Lead	O&G	TPH	Alk	Hard	OP
Censored Observations	0	0	0	0	6	0	0	0	0	9	1	10	0	4	0	0	0
Total Observations	11	11	11	10	11	11	7	7	10	10	10	10	2	4	4	4	4
Percent Censored	0%	0%	0%	0%	55%	0%	0%	0%	0%	90%	10%	100%	0%	100%	0%	0%	0%
CUOUT-ZF (CUOUT Loads including events with no discharge at the outfall and therefore no effluent loads)																	
	TP	TN	OxN	TKN	NH_3	TSS	COD	TDS	Cu	Cd	Zn	Lead	O&G	TPH	Alk	Hard	OP
Censored Observations	0	0	0	0	6	0	0	0	0	9	1	10	0	4	0	0	0
Total Observations	21	21	21	20	21	21	12	12	20	20	20	20	7	9	9	9	9
Percent Censored	0%	0%	0%	0%	29%	0%	0%	0%	0%	45%	5%	50%	0%	44%	0%	0%	0%

5.5 Discussion

5.5.1 Rainfall

Table 5-6 presents the minimum, maximum and average rainfall depths, rates and durations for events that produced discharge at the LID facility outfall, as well as those that did not.

Table 5-6. Rainfall depths, rates and durations that did and did not produce outfall discharge.

Events Producing Discharge at LID facility outfall				
	Minimum	Maximum	Average	Median
Rainfall Depths (in.)	0.12	5.13	0.86	0.59
Rainfall Rates (in./hr.)	0.02	0.23	0.07	0.05
Storm Event Durations (hr.)	2.0	95.5	19.1	12.9
Events Without Discharge at LID facility outfall				
	Minimum	Maximum	Average	Median
Rainfall Depths (in.)	0.01	1.09	0.14	0.07
Rainfall Rates (in./hr.)	0.004	0.60	0.05	0.03
Storm Event Durations (hr.)	0.17	49.3	5.8	2.4

As may be seen in the table, considerable variability exists between the discharge producing and non-discharge producing events. In fact, it may be seen that the maximum event not producing discharge was nearly an order of magnitude larger than the smallest event producing discharge. This is certainly within the realm of the possible, because storage in the facility would be expected to have direct effects on whether a given event produced discharge. The minimum rainfall depth to produce discharge at the outfall occurred on September 19, 2011 with 0.12 inches of rainfall and 0.00013 inches of discharge recorded. This occurrence may seem anomalous considering the numerous storm events recorded with greater rainfall depths which produced no discharge at the outfall. However, taking antecedent conditions into account sheds some light on the occurrence of discharge from this relatively small event. A storm event on September 18, 2011 with 1.00 inches of rainfall and 0.01 inches of discharge immediately preceded the September 19, 2011 event. Presumably, the LID facility did not have enough time to fully infiltrate the stormwater runoff from the prior event into the surrounding subsoils before the September 19, 2011 event began. With this in mind, the occurrence of discharge during the relatively small September 19, 2011 event seems reasonable. Unfortunately, this may not be directly examined, because the inflow sampling equipment did not permit *in situ* observation of flows, and it was not possible to compute a reliable long-term water balance for the facility.

The rainfall data were, however, directly observed, and Figure 5-8 displays an x-y scatter plot of reported runoff from observed events at the LID facility outfall (expressed as inches over the catchment) as a function of reported rainfall in inches. The reported data for both monitoring periods were included in the figure. The 1:1 line was included to illustrate any anomalous cases where inaccuracies in flow measurement or the presence of unaccounted-for water (*e.g.* groundwater or irrigation) may have produced more runoff than rainfall.

Examination of Figure 5-8 shows that, throughout both monitoring periods, little runoff was generated for storm events where less than 0.5–0.75 inches of rain occurred. For events greater than 0.75 inches, the depth of runoff was only about 40% of the rainfall, indicating that the Cub Run LID facility was effectively reducing the stormwater runoff volume through infiltration and evapotranspiration mechanisms. Figure 5-8 also shows the extreme event in the database: Tropical Storm Lee (which was also sampled for water quality) and occurred from September 5-9, 2011. Tropical Storm Lee had 5.13 inches of rainfall and a catchment runoff depth of 1.87 inches discharged at the outfall, indicating that the facility retained 64% of the incident rainfall.

For the 183 storm events monitored during the two monitoring periods, a rainfall total of 59.03 inches was reported, along with a total LID facility discharge of 8.56 inches, expressed as a depth over the catchment. The long-term facility rainfall retention evident from this comparison is 85%.

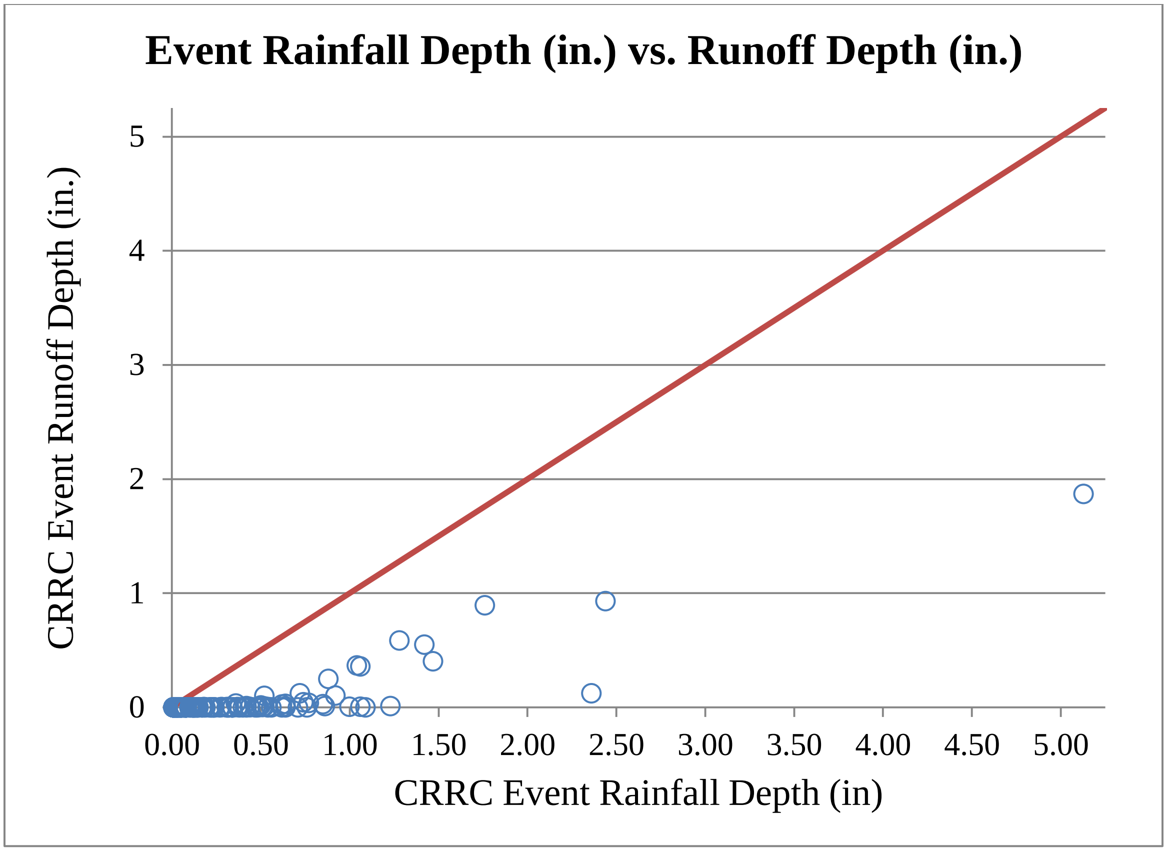


Figure 5-8. Event rainfall depth vs. runoff depth at the Cub Run Recreation Center for all storm events.

5.5.2 Pollutant Removal Mechanisms

Phosphorus and Nitrogen Removal

Reports in the literature on the removal of phosphorus and nitrogen in bioretention facilities exhibit great variability due to the complex physical, chemical and biological interactions present in stormwater BMP environments. Additionally, differences in site design and other management practices may also be expected to affect nutrient removal performance (Davis et al., 2006; Davis et al., 2009; Li and Davis, 2009; Lucas, W. and Greenway, M., 2011; Lucas, W. C. and Greenway, M., 2011).

In general, the effectiveness of phosphorus removal is closely related to the phosphorus content of the soil media used in the bioretention cell. If a bioretention cell media has a relatively high initial phosphorus content, then the ability of the facility to remove dissolved phosphorus is reduced. If the media has a relatively low initial phosphorus content, the dissolved phosphorus in the influent may sorb to iron and aluminum oxides in the soil media. Particle-bound phosphorus is removed through settling and filtration processes along with suspended solids and is generally more related to the total suspended solids removal (Davis et al., 2006; Hunt et al., 2006; Davis, 2007; Davis et al., 2009; Li and Davis, 2009; Lucas, W. and Greenway, M., 2011).

Nitrogen interactions in the aquatic environment are complex, and removal or conversion in stormwater BMPs may be expected to be highly dependent on the forms present, and the oxidation-reduction (REDOX) environment of the system. It is important to note that nitrogen removals are best calculated on a total nitrogen (TN) basis because of the many pathways for conversion of species that exist in the nitrogen cycle. TN is expressed as the sum of total Kjeldahl nitrogen (TKN) and oxidized nitrogen (OxN), TKN is the sum of ammonia, ammonium, and organic nitrogen ($TKN=NH_3\text{-}N+NH_4^+\text{-}N+organic\text{-}N$) and oxidized nitrogen is the sum of nitrite and nitrate ($OxN=NO_2^-\text{-}N+NO_3^-\text{-}N$) (Li and Davis, 2009; Rice, 2012). To illustrate some of the conversion pathways, a simplified version of the nitrogen cycle (Grady, 2011) is depicted in Figure 5-9:

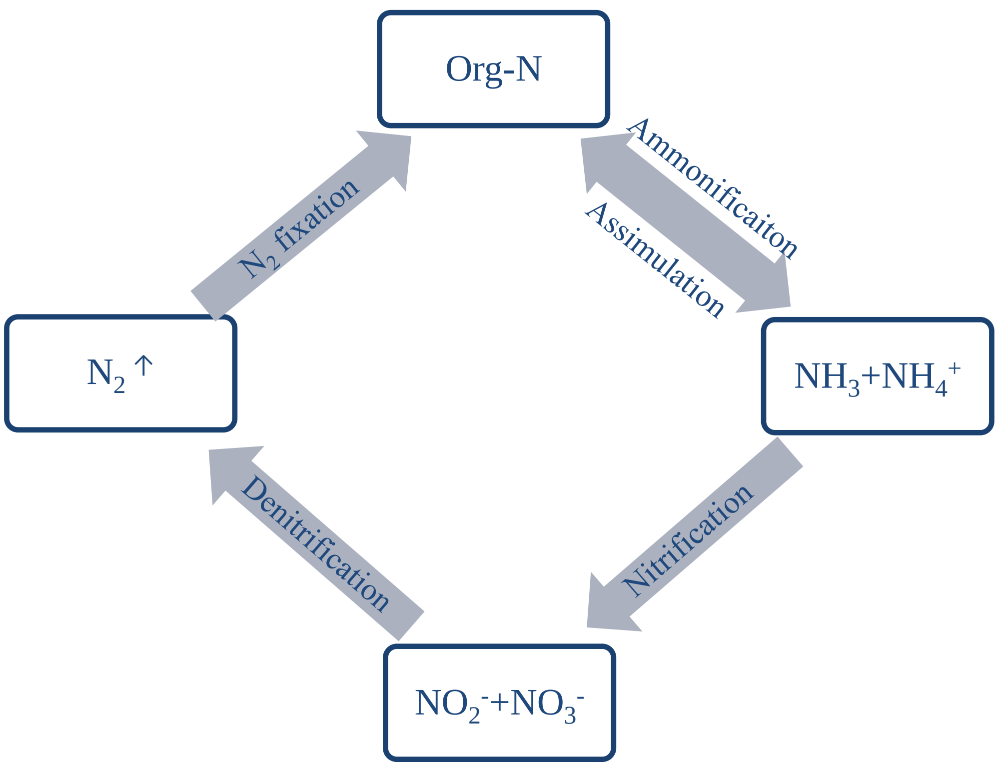


Figure 5-9. Simplified Nitrogen Cycle, Based on: Grady (2011).

Organic nitrogen is microbially converted into ammonia/ammonium and then nitrite/nitrate through the processes of ammonification and nitrification, respectively. These are the dominant microbial processes which occur under aerobic conditions in most stormwater BMPs. Denitrification, or the conversion of oxidized nitrogen to gaseous nitrogen, which may be lost to the atmosphere, can only occur when anoxic, or oxygen deprived, conditions are established (Davis et al., 2006; Hunt et al., 2006; Davis, 2007; Lucas, W. C. and Greenway, M., 2011). Such anoxic conditions may occur naturally in small pockets within a conventionally drained stormwater BMP or may be engineered into the BMP as an internal water storage zone which promotes the conditions necessary for denitrification to occur (Davis et al., 2006; Hunt et al., 2006; Davis, 2007). Without the periodic presence of anoxic zones, microbes within stormwater BMPs may be expected to continuously oxidize available organic nitrogen and ammonia to nitrite and nitrate. In addition, because oxidized nitrogen forms are present as anions and are highly soluble, they do not readily sorb to the negatively charged soil media, and are usually lost from the BMP in a subsequent discharge (Benjamin, 2002; Burton, 2002; Davis et al., 2006; Davis et al., 2009). The exception, of course, occurs when anoxic conditions (in the presence of sufficient organic matter) are subsequently established in the BMP. It should be noted however, that even with the continuous conversion of organic nitrogen and ammonia nitrogen to oxidized nitrogen, total Kjeldahl nitrogen still typically dominates the total nitrogen balance within many stormwater BMPs (Davis et al., 2006).

In general, stormwater BMPs have been found to reduce total nitrogen loads mainly through the sorption of organic nitrogen to organic matter in the media. However, increases in oxidized nitrogen are frequently noted in the literature. When managed properly, the uptake of nutrients by vegetation within a BMP may also play a significant role in the removal of nutrients from incoming stormwater runoff (Davis et al., 2006; Davis et al., 2009; Lucas, W. C. and Greenway, M., 2011).

Total Suspended Solids Removal

Total suspended solids (TSS) removal is typically very high in stormwater BMPs which are designed to utilize sedimentation and infiltration processes (Davis, 2007; Davis et al., 2009). It should be noted that during an initial stabilization period in bioretention BMPs, TSS and other particulate-bound pollutants tend to be produced, instead of reduced, as fine soil media are washed out during the first few events (Davis, 2007).

Trace Metals Removal

Trace metals such as copper, cadmium, zinc and lead may be present in both dissolved and particulate forms in urban stormwater, and tend to be efficiently removed in bioretention BMPs. Particulate-bound metals will be removed through filtration and sedimentation processes. Depending on the physical and chemical composition of the media, dissolved metals such as copper, zinc and lead will also typically sorb to organic matter and soils present in the upper surface layers of the BMP media (Davis, 2007; Li and Davis, 2008; Davis et al., 2009).

Oil & Grease and Total Petroleum Hydrocarbons Removal

Oil and Grease components, including total petroleum hydrocarbons, typically exhibit high removals from stormwater runoff in bioretention BMPs. Oil and Grease components are initially removed through filtration and sorption to organic matter present in the media, followed by microbial degradation (Hsieh and Davis, 2005; Hsieh and Davis, 2005; Hong et al., 2006; Davis et al., 2009).

Chemical Oxygen Demand Removal

Chemical oxygen demand (COD) is often used as a surrogate measure for the removal efficiency of organic matter from stormwater runoff (Benjamin, 2002; Rice, 2012). The COD test provides a relatively quick, consistent estimate of the maximum oxygen (O_2) consumption that could be expected from the degradation of (mostly) organic constituents within a stormwater BMP (Benjamin, 2002). COD may be taken as indicative of the removal of organic matter through the processes of filtration and biological degradation. Conversely, if the stormwater BMP is leaching oxidizable materials such as organic matter, then increases in COD may be observed in the effluent (Ergas et al., 2010). Removal of biochemically oxidizable compounds from stormwater runoff is important to ensure that the potential oxygen demand is not exerted in downstream aquatic environments (Burton, 2002; Miller, 2002).

Total Dissolved Solids, Alkalinity and Hardness Removal

Total dissolved solids (TDS) is a measure of the nonvolatile dissolved species, principally comprised of the ions of inorganic salts such as calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+), potassium (K^+), bicarbonate (HCO_3^-), chloride (Cl^-), nitrate (NO_3^-) and sulfate (SO_4^{2-}) in stormwater runoff (Benjamin, 2002; Burton, 2002; Davis et al., 2009). High concentrations of some inorganic salts, such as sodium chloride (NaCl), may be expected in the runoff generated from roads, parking lots and sidewalks in regions that experience snow and ice during the winter season (Burton, 2002; Davis et al., 2009). The removal of such dissolved solids from stormwater is difficult due to their highly soluble nature (Benjamin, 2002; Burton, 2002). Some dissolved solids, however, may be more readily be removed from solution through processes such as precipitation, ion-exchange, absorption and biological transformation, depending on the physical and biogeochemical conditions within the BMP (Burton, 2002). Generally, little removal is expected, except for transformations due to pH change and REDOX reactions.

Alkalinity is a measure of the capacity of a water to resist changes in pH resulting from the introduction of acidic species. While most natural systems contain a variety of species capable of neutralizing acids, the dominant forms present in most natural systems are the carbonate (CO_3^{2-}) and bicarbonate (HCO_3^-) species. For computational simplicity, alkalinity is reported as mg/L as $CaCO_3$ (Benjamin, 2002; Rice, 2012). Increases or decreases in alkalinity within a stormwater BMP may be indicative of other processes occurring. For example, because the process of nitrification ($NH_4^+ \rightarrow NO_2^- \rightarrow NO_3^-$) consumes alkalinity and the process of denitrification ($NO_3^- \rightarrow N_2$) produces alkalinity (Grady, 2011), the analysis of alkalinity changes within a practice may give some insights into whether either process is occurring. If increases in oxidized nitrogen are occurring concurrently with decreases in alkalinity, the hypothesis of nitrification is strengthened. If alkalinity is not decreasing, then nitrification is not likely the dominant process by which oxidized nitrogen is being produced within the BMP. Conversely, if oxidized nitrogen is decreasing within the BMP, the hypothesis that denitrification is the dominate mechanism removing oxidized nitrogen from the BMP would be strengthened if increases in alkalinity were also observed. It should be noted that if both nitrification and denitrification are occurring within a BMP, the net change in alkalinity will likely be smaller than if either process was occurring alone.

Hardness is defined as the sum (expressed as mg/L of $CaCO_3$) of polyvalent cations present in a water sample. As a practical matter, this is most often taken to be the sum of the calcium (Ca^{2+}) and magnesium (Mg^{2+}) ions, because these are the most abundant. Depending on the alkalinity, the total hardness may be distributed between carbonate and non-carbonate forms (Rice, 2012).

Hardness may be removed or produced within a stormwater BMP through processes such as ion-exchange, sorption and biological transformation of calcium and magnesium ions, and is largely dependent on the biogeochemical soil conditions present in the BMP media (Clark et al., 2009).

5.5.3 Performance Analysis by the Effluent Probability Method

Developing performance assessments using the Effluent Probability Method requires three principal steps (Strecker et al., 2001; Geosyntec and WWE, 2009; Williams et al., 2009):

- Distributional adherence test to determine if the data follow a particular distribution;
- Statistical tests to determine if any perceived differences between the influent and effluent EMCs or loads are statistically significant;
- Plotting the log-transformed data of influent and effluent EMCs or loads for all storm events on a normal probability plot.

Section 5.5.3.1 presents and discusses the probability plots, also called quantile-quantile or Q-Q plots, for the CUIN and CUOUT-Zero Flows Included (CUOUT-ZF) load datasets to determine if the datasets follow an assumed distribution, such as the lognormal.

Section 5.5.3.2 presents and discusses the results of the nonparametric generalized Wilcoxon test comparing CUIN and CUOUT-ZF load datasets for significant differences.

Section 5.5.3.3 presents and discusses the results of the Effluent Probability Method plots comparing CUIN and CUOUT-ZF load datasets.

5.5.3.1 Q-Q Plots for CUIN & CUOUT-ZF Testing for Distributional Adherence

Testing for distributional adherence is an important step in the Effluent Probability Method because it reveals the underlying distribution of the data, such as the normal or lognormal. Determining the distribution of the dataset allows for the selection of the proper transform to employ to best represent the influent and effluent concentrations or loads on the normal probability plot. Additionally, the type of statistical test selected to compare datasets is affected largely by the assumed underlying distribution of the datasets (Strecker et al., 2001; Geosyntec and WWE, 2009; Williams et al., 2009). Robust regression on ordered statistics (ROS) was used to produce probability plots which account for any censored (below detection limit) observations in the LID facility water quality data.

An analysis was done for total phosphorus, and Figure 5-10 displays the Q-Q plots for the individual water quality loads for the CUIN, CUOUT and CUOUT-ZF load datasets. The Q-Q plots for all remaining water quality parameters may be found in Figures A-34 – A-46 in Appendix A. Recall that the CUOUT-ZF dataset was created to represent the CUOUT load dataset plus all events where no runoff discharged from the outfall and an effluent load of zero was assumed. For each figure, the left side plot displays the Q-Q plot for the untransformed dataset against the theoretical normal distribution, while the right plot displays the Q-Q plot for the lognormally transformed dataset against the theoretical normal distribution. If the data on the left plot most closely approximate a straight line, the original data distribution may be assumed to be near normal. If the lognormally transformed data on the right side plot most closely approximate a straight line, the original data distribution may be assumed to more likely be lognormal. If neither produces a linear fit on the probability plot, the original dataset distribution cannot be assumed to be either normal or lognormal.

The modified CUOUT-ZF dataset was created with a logarithmic transformation of the original dataset with the zero outflow storm events included. The modification was done because the inclusion of zero loads would not be otherwise possible due to the limitations of the log transformation. This dataset was named CUOUT-MZF and was created by substituting a load value two orders of magnitude lower than the lowest observation in the CUOUT-ZF dataset for each zero load constituent of interest. The substituted value was created by dividing the lowest non-zero observation in each CUOUT-ZF dataset by 100 and substituting the result in for all zero discharge events where the effluent load was assumed to be zero.

For TP, the lognormal transformation was found to provide good fits for the CUIN and CUOUT datasets, as may be seen in the right side plots of Figure 5-10. However, after inclusion of the zero flow events in the CUOUT-MZF dataset, neither the normal nor the log transformation gave a good fit. Nevertheless, it may be seen that a significant area of linearity existed in the log transform plots above the artificially introduced zero load storms, which have served to simply shift the plotted distribution to the right. Q-Q plots for the remaining water quality constituents exhibited similar results and may be found in Figures A-34 through A-46 in Appendix A. Q-Q plots were not generated for cadmium, lead, oil & grease and TPH loads due to the high level of censoring of the data. Analysis of constituent loading datasets with high levels of censoring (above 80%) will be discussed in section 5.5.4.

The distributional adherence test results have an important consequence in conducting further analysis of the LID facility BMP performance. If both the CUIN and CUOUT-ZF datasets had followed the lognormal distribution, parametric statistics could be applied after the appropriate transformation of the datasets. However, the Q-Q plots revealed that the CUOUT-ZF datasets were not closely approximated by either the normal or lognormal distribution. For that reason, it was not possible to apply parametric statistical methods for further analysis. The generalized Wilcoxon test, which is a nonparametric method, was selected to test for significant differences between the influent and effluent datasets for each water quality constituent.

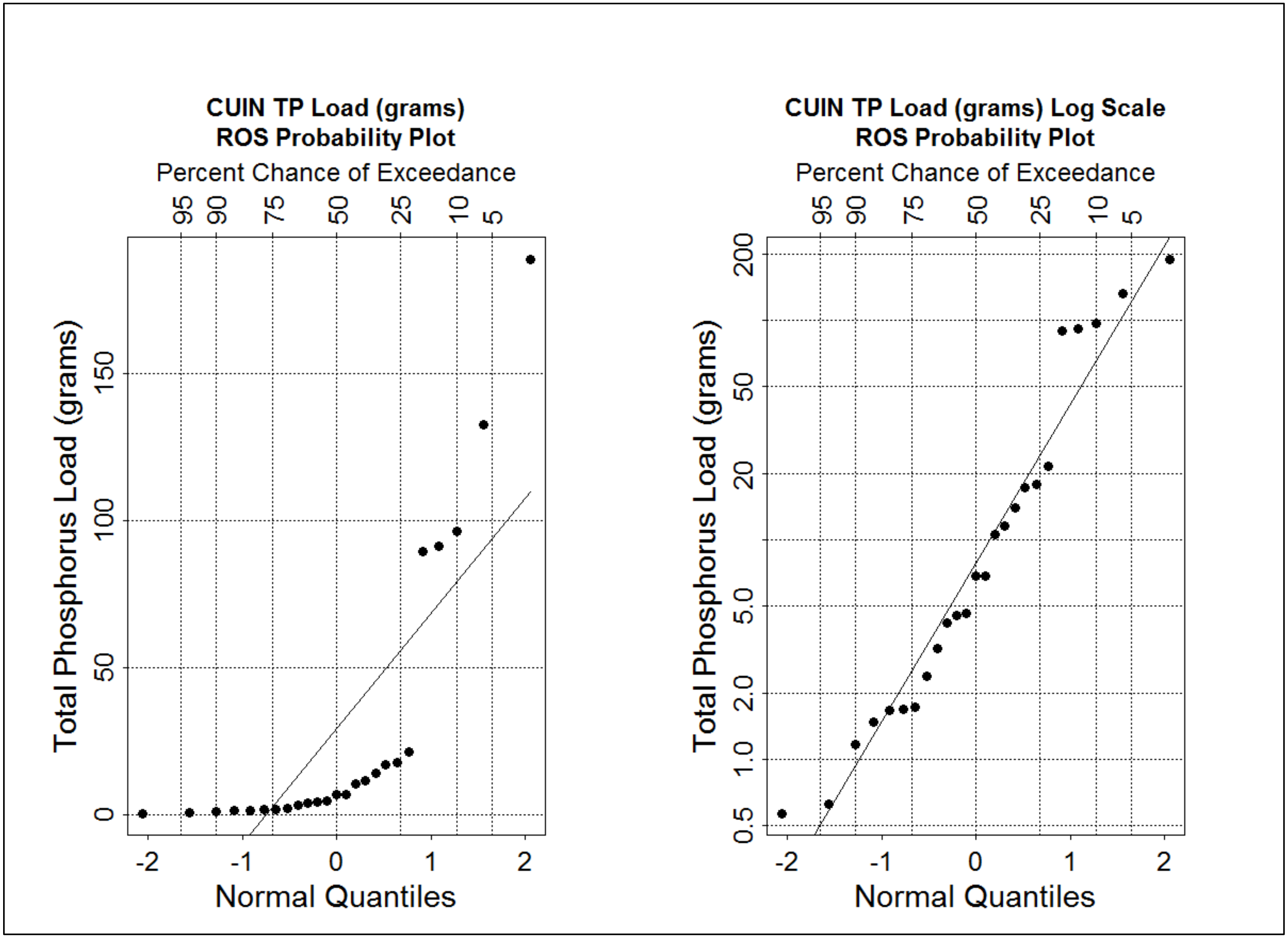


Figure 5-10a. Q-Q Plots of CUIN load dataset for total phosphorus.

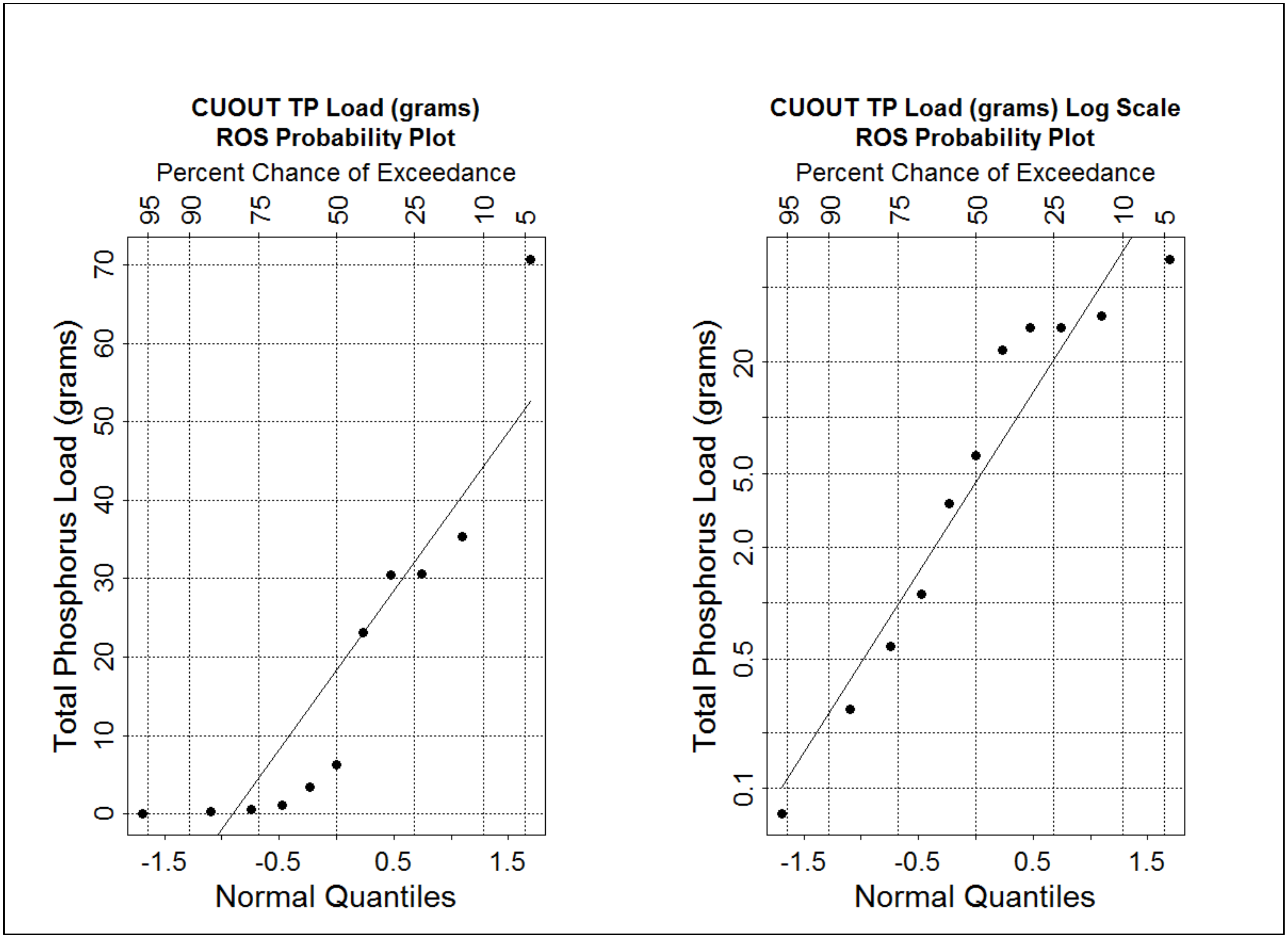


Figure 5-10b. Q-Q Plots of CUOUT load dataset for total phosphorus.

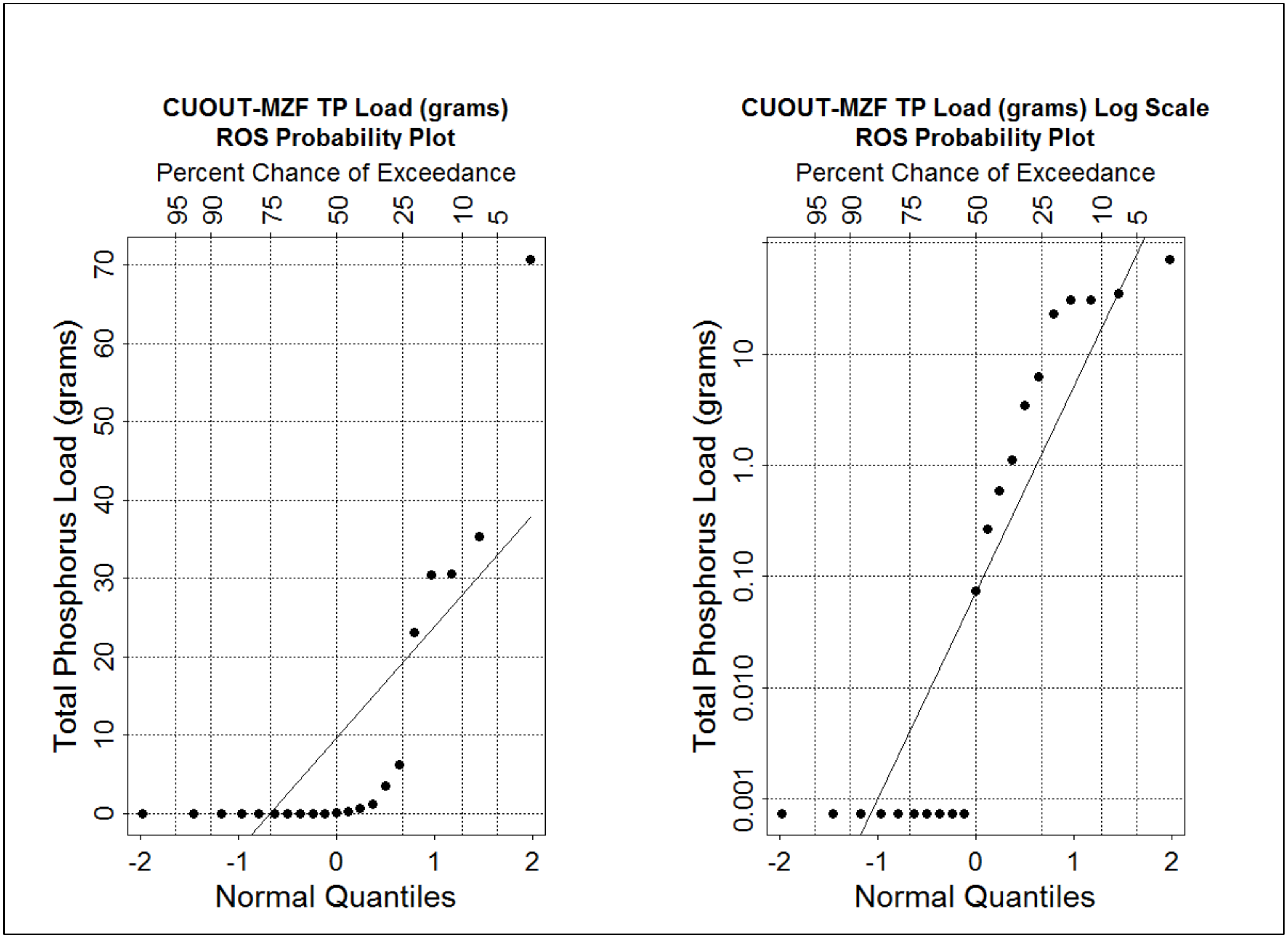


Figure 5-10c. Q-Q Plots of CUOUT-MZF load dataset for total phosphorus.

5.5.3.2 Generalized Wilcoxon Test Results when Comparing CUIN and CUOUT-ZF

Using statistical tests to determine if any perceived differences between the influent and effluent EMCs or loads are statistically significant is another important step in the application of the Effluent Probability Method (Strecker et al., 2001; Geosyntec and WWE, 2009; Williams et al., 2009). Geosyntec and WWE (2009) suggests a 95 percent confidence level ($\alpha = 0.05$) be used when performing appropriate statistical analysis tests comparing the influent and effluent conditions.

The generalized Wilcoxon test, which is also called the Peto–Prentice or Peto–Peto test, is a nonparametric statistical test which determines if there is a significant difference in the cumulative distributions between two or more datasets. The generalized Wilcoxon test takes censored observations into account by using the Kaplan-Meier method to estimate the percentiles of the empirical distribution function for the sample data. (Helsel, 2012).

The generalized Wilcoxon test was used to test for significant differences between LID facility influent and effluent load datasets because of its ability to incorporate censored observations. In addition, it may be successfully applied to datasets from unknown distributions, such as CUOUT-ZF.

Table 5-7 displays the results for the two-sample generalized Wilcoxon two-sided test between the CUIN and CUOUT-ZF load datasets at the 95% confidence level ($\alpha = 0.05$). As may be seen in the table, a significant difference was found between the CUIN and CUOUT-ZF load datasets for all water quality constituents except total dissolved solids, hardness and orthophosphate phosphorus at the 95% confidence level. It should be noted that, while the CUIN and CUOUT-ZF load datasets for hardness and orthophosphate phosphorus were found to be not statistically different at the 95% confidence level, their respective p-values, 0.061 and 0.071, are very close to the tested confidence level ($\alpha = 0.05$). For that reason, the hardness and orthophosphate phosphorus influent and effluent load datasets may be considered to be very close to being statistically different. Generalized Wilcoxon test results were not computed for Cd, Pb, O&G, and TPH due to the high level of censoring in their respective datasets. Analysis of datasets with high levels of censoring (above 80%) is discussed in section 5.5.4.

Table 5-7. Generalized Wilcoxon two-sided test for CUIN & CUOUT-ZF loads.

Water Quality Constituent	Sample	No. Samples	Statistically Different at 95% confidence level?	p-value
Total Phosphorus	CUIN	25	Yes	0.002
	CUOUT-ZF	21		
Total Nitrogen	CUIN	25	Yes	<0.001
	CUOUT-ZF	21		
Oxidized Nitrogen	CUIN	25	Yes	0.023
	CUOUT-ZF	21		
Total Kjeldahl Nitrogen	CUIN	25	Yes	<0.001
	CUOUT-ZF	20		
Ammonia	CUIN	24	Yes	<0.001
	CUOUT-ZF	21		
Total Suspended Solids	CUIN	25	Yes	<0.001
	CUOUT-ZF	21		
Chemical Oxygen Demand	CUIN	12	Yes	0.025
	CUOUT-ZF	12		
Total Dissolved Solids	CUIN	12	No	0.582
	CUOUT-ZF	12		
Copper	CUIN	25	Yes	0.003
	CUOUT-ZF	20		
Zinc	CUIN	24	Yes	<0.001
	CUOUT-ZF	20		
Alkalinity	CUIN	12	Yes	0.053
	CUOUT-ZF	9		
Hardness	CUIN	12	No[2]	0.061
	CUOUT-ZF	9		
Orthophosphate Phosphorus	CUIN	12	No[2]	0.071
	CUOUT-ZF	9		

[2]While the Generalized Wilcoxon Two-Sided Test did not find a significant difference between CUIN and CUOUT-ZF for Hardness and Orthophosphate Phosphorus at the 95% confidence level, their p-values are very close to being significant at p = 0.061 and 0.071, respectively.

5.5.3.3 Effluent Probability Method Results for CUIN & CUOUT-ZF

The last step in applying the Effluent Probability Method (EPM) is to plot the transformed data of influent and effluent EMCs or loads for all storm events on a normal probability plot. The resulting plot allows for a graphical representation of the BMP performance over the range of all influent and effluent conditions observed (Strecker et al., 2001; Chi-Feng et al., 2009; Geosyntec and WWE, 2009; Williams et al., 2009). The plotting position of each datum (an observed concentration or load within the influent or effluent dataset for a particular water quality constituent) is based on the cumulative frequency of that datum as calculated by an empirical distribution function for the individual dataset (Chi-Feng et al., 2009; Geosyntec and WWE, 2009; Helsel, 2012). By comparing the influent and effluent water quality in this manner, the plot promotes a more thorough understanding of how the BMP may be expected to perform over the range of influent concentrations and loadings sampled (Strecker et al., 2001; Geosyntec and WWE, 2009; Williams et al., 2009).

Because the effluent load datasets contained censored data, the probability plots comparing the CUIN and CUOUT-ZF datasets were produced using the empirical distribution function percentile data calculated by the previously discussed Kaplan-Meier method. Use of the Kaplan-Meier method allowed for incorporation of the effects of censored (below detection limit) observations (Helsel, 2012).

The lowest load observation in the dataset has a cumulative frequency, or frequency of non-exceedance, of 0% (Helsel, 2012). Because a probability scale was used on the dependent variable axis for the EPM, 0% and 100% probabilities were not included on the plot because they mathematically extend to negative and positive infinity, respectively, as would be expected in a normal distribution (Montgomery, 1999). Although not shown on the plot, the effect of the extremes of the distribution is still accounted for in the plotting positions of all other points.

As noted in the previous section, the outflow load datasets were not closely approximated by the lognormal distribution when zero outflow events were included as very small, but finite, loads. However, the log-transformed outflow loads for all storm events do demonstrate reasonable linearity on the probability plot for events sufficiently large to produce LID facility outflow, indicating that the non-zero loads may be reasonably characterized by the lognormal distribution.

Figure 5-11 presents the EPM plot comparing the influent and effluent load datasets, CUIN and CUOUT-ZF, for TSS. The EPM plots comparing influent and effluent load datasets for all applicable water quality constituent may be found in Figures A-47 – A-59 in Appendix A. As noted in the previous section, EPM plots were not generated for Cd, Pb, O&G, and TPH, due to the high level of censoring.

Total Suspended Solids Removal

Figure 5-11 displays the EPM plot of influent and effluent loads for TSS. As may be seen, dramatic reductions in TSS loads were achieved throughout the entire range of influent loads. This is visually evidenced by the fact that all the points on the effluent plot lie to the left of the influent plot for comparable percentiles. The EPM plot, coupled with results from the generalized Wilcoxon test show a statistically significant difference between CUIN and CUOUT-ZF load datasets (p-value = <0.001), and suggest that the LID facility was effectively removing total suspended solids over the entire range of sampled events. For events below the 50^{th} percentile, flows were generally completely retained within the facility, and 100% removal occurred. These were also, of course, the storms carrying relatively low TSS loads (< 1 kg). Even during the larger events in the database, however, TSS reductions in excess of 90% were observed. The very effective performance with TSS is likely responsible for much of the performance for other particle-associated species that will be discussed below.

Phosphorus and Nitrogen Removal

The EPM plots of influent and effluent loads for TP and OP may be found in Figures A-48 – A-49 in Appendix A, respectively. It should be remembered that OP was not measured during the second monitoring period, and may not be as representative of overall LID facility performance as for those constituents monitored during both periods. For that reason, the discussion of phosphorus removal performance will focus on TP. Reductions in total phosphorus loads were achieved over the entire range of influent loads. The lowest outflow storm load plotted was near the 50^{th} percentile of the data, indicating that nearly half the observed storms produced no outflow or load. At events above the 70^{th} percentile in the database removals declined dramatically, but improved substantially in larger events. It is not clear if this apparent anomaly is truly reflective of performance, or if it is an artifact of the available stormwater dataset. It would generally be expected that the TP removal performance would have tracked more closely with the observed performance for TSS. Without more information, this cannot be resolved from the existing dataset, particularly for events in the range of the 70^{th} – 80^{th} percentiles of the existing database. Overall, information from the EPM plot, coupled with the generalized Wilcoxon test results show a statistically significant difference between the CUIN and CUOUT-ZF load datasets (p-value = 0.002), and suggest that the LID facility was removing TP over the entire range of sampled events.

Figure A-50 in Appendix A displays the EPM plot for TN. TN load reductions were achieved over the entire range of influent loads. For the upper extremes in the dataset, however, the removals were substantially lower. At the 50^{th} percentile, the TN removal was approximately 90 grams at a removal rate of 98%. During larger events, TN removal percentages declined, and at the 75^{th} percentile event, a removal of nearly 162 g of TN would represent a 59% load reduction. At the maximum event size in the database, removals declined to only 2%. As with TSS and TP, reference back to the generalized Wilcoxon test results shows a statistically significant difference between the inflow-outflow load datasets (p-value = <0.001), suggesting that the LID facility was removing TN over the entire range of sampled events, albeit at declining rates for larger storms.

EPM plots for OxN, TKN, and NH_3 are shown in Figures A-51 to A-53, respectively, in Appendix A. The overall BMP nitrogen removal performance is best characterized with an assessment based on TN, as addressed in the prior paragraph. However, consideration of other species may provide some insights into other nitrogen transformations within the LID facility. The OxN EPM plot suggests that, during events below the 50^{th} percentile, 100% of the influent OxN load is removed. This is consistent with the notion that longer storage intervals are available within the LID system during small storms, and the anoxic conditions that support denitrification are more likely to occur. Examination of the OxN EPM plot seems to indicate that this effect is no longer present at events above the 70^{th} percentile. In fact, beyond that point, the LID facility appears to have little effect on OxN loads. This is not unexpected. The OxN component species, nitrite and nitrate, are both highly soluble anions, and unlikely to sorb to negatively charged particle surfaces. In addition, the large events have reduced detention times, and are less likely to have sufficiently long periods of anoxia to achieve significant denitrification. This is not to suggest that denitrification is absent during large events, but rather, that the mass removed by such a pathway is small relative to the total mass transport through the facility during high flows.

The EPM plot for TKN is shown in Figure A-52 in Appendix A, and displays reductions for the entire range of influent loads. Additionally, it may be seen by comparison to the OxN EPM plot that, generally, TKN loads for a given storm were an order of magnitude greater than OxN loads. This observation helps to explain the relatively good TN removal performance even when OxN loads were relatively unaffected during larger events. In fact, comparison to the TN EPM plot will show that most of the TN load is comprised of TKN, and that the behaviors are similar. Figure A-53 in Appendix A displays the EPM plot for NH_3 loads. As with OxN, the NH_3 loads were generally an order of magnitude lower than the TKN loads. Because TKN = org-N + NH_3-N, this observation emphasizes the importance of organic nitrogen removal, which is largely particulate-associated, for the effective removal of TN within the LID facility.

Chemical Oxygen Demand Removal

Figure A-54 in Appendix A displays the EPM plot for the influent and effluent loads of COD for the events sampled. Although COD was not monitored in the first sampling period, it is included in the discussion because of its importance as a measure of LID facility removal performance on degradable organic matter. Reductions in COD loads were achieved throughout the entire range of sampled events. At events lower than the 50^{th} percentile, essentially 100% removal of COD took place, because (as discussed earlier), these events were completely retained within the LID facility. Removal rates of COD appeared to decline between the median and 70^{th} percentile events, although at a slightly greater rate than observed for TSS. As with the constituents previously discussed, consideration of the EPM plot and the prior result of the generalized Wilcoxon test show a statistically significant difference between CUIN and CUOUT-ZF load datasets (p-value = 0.025), and suggest that the LID facility was effectively removing COD from stormwater runoff for the entire range of sampled events.

Total Dissolved Solids Removal

Figure A-55 in Appendix A displays the EPM plot of influent and effluent loads for TDS. As with some other constituents, TDS was not included in the first monitoring period. The dataset is consequently smaller, and may not be as representative of facility performance. TDS reduction occurred mostly in events below the 50^{th} percentile where (as explained previously) the entire flow was retained within the LID facility. Small reductions occurred for events up to the 60th percentile, and may be partially explained by the loss of alkalinity (mostly bicarbonate). At this juncture, there are insufficient data to completely explain the alkalinity reductions, except to say that it principally occurred in events below the 70th percentile in the database. One cause for consideration in future research may be the destruction of alkalinity in microbial denitrification. Overall, the facility did not exhibit consistent removal of TDS, and this conclusion is borne out by the results of the generalized Wilcoxon test (p = 0.582).

Trace Metals Removal

Figures A-56 and A-57 in Appendix A display the EPM plots of influent and effluent loads for Cu and Zn, respectively. Reductions in copper loads were achieved throughout the entire range of sampled events. As with other constituents, reductions below the 50th percentile of events were at 100% due to retention in the facility, but it may also be seen that the entire range of sampled events did display load reductions. Similar reductions in zinc loads were also achieved throughout the entire range of sampled events. Complete removal was also observed during events below the 50th percentile. The EPM plots, coupled with the generalized Wilcoxon test results, showed statistically significant differences between the CUIN and CUOUT-ZF load datasets for both copper and zinc (p-values = 0.003 and <0.001, respectively), and suggest that the LID facility was effectively removing these trace metals for the entire range of sampled events.

Alkalinity and Hardness Removal

Figures A-58 and A-59 in Appendix A display the EPM plots of influent and effluent loads for alkalinity and hardness, respectively. It should be noted that alkalinity and hardness were not included in the sampling program for the second monitoring period, and as a result, the data may not be as representative of overall LID facility performance. Virtually no removal of alkalinity is observed in the higher ranges of sampled events. Some reduction is seen in events below the 70th percentile, and may be related to denitrification in small events, as was speculated in an earlier section. Because of the changes in small events, the generalized Wilcoxon test results showed a statistically significant difference between the influent and effluent load datasets for alkalinity (p-value = 0.053).

Reductions between influent and effluent loads for hardness are observed for all but one event on the higher end of the sampled storms. The generalized Wilcoxon test result showed that the influent and effluent loads, CUIN and CUOUT-ZF, were not statistically different for hardness. It should be noted however, that while influent and effluent loads were not statistically different at the 95% confidence level ($\alpha = 0.05$), the test p-value (p-value = 0.061) was very close to qualifying the two load datasets as statistically different. Examining the EPM plot shows that fewer effluent data values were available for loads above the 75th percentile, and this may have affected the conclusions.

Summary of EPM Results

The empirical distribution function (EDF) results for the inlet and outlet load datasets were used to estimate mass removals and removal percentages for the minimum, 25th, 50th, 75th and maximum percentile levels on the EPM plots. Linear interpolation was used to estimate each load when an actual observation did not fall on the percentile of interest. Table 5-8 displays the mass removal in grams and removal percentages for each percentile of interest for TSS, TP, TN, COD, Cu and Zn. As discussed previously, for events below the 50th percentile, flows were generally completely retained within the facility, and nearly 100% removal occurred for all constituents. The mass removal performance was more varied at the 75th percentile and maximum observed events, however significant pollutant removal was still observed for most of the water quality constituents analyzed. This suggests that, while the LID facility is achieving pollutant load removals throughout the entire range of sampled events, it is more effective at treating smaller storm events with consequently lower influent loads. This observation emphasizes the importance of stormwater runoff attenuation as an essential mechanism of water quality improvement, and the use of performance metrics based on the total pollutant load removal.

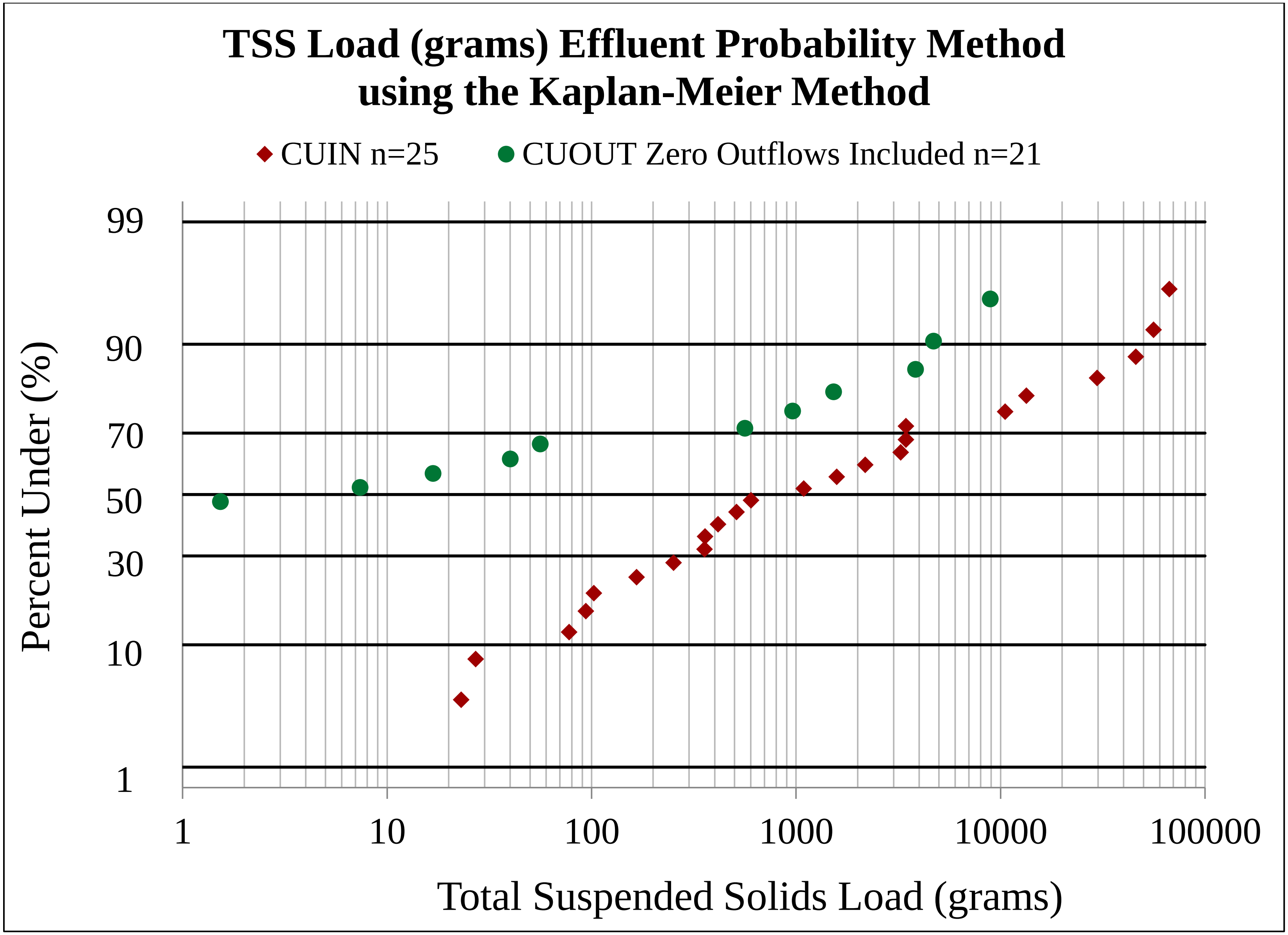


Figure 5-11. Effluent Probability Method plot of CUIN & CUOUT-ZF load datasets for total suspended solids.

Table 5-8. CRRC Load reduction quantiles from Effluent Probability Method with empirical distribution functions calculated from the Kaplan-Meier method.

Percentile	TSS		TP		TN		COD		Cu		Zn	
	Grams Removed	Percent Reduction	Grams Removed	Percent Reduction	Grams Removed	Percent Reduction	Grams Removed	Percent Reduction	Grams Removed	Percent Reduction	Grams Removed	Percent Reduction
Minimum	23	100%	0.57	100%	2.52	100%	252	100%	0.02	100%	0.06	100%
25^{th}	278	100%	1.86	98%	23.4	98%	568	96%	0.09	99%	0.45	98%
50^{th}	1,330	100%	6.66	98%	89.9	98%	3,840	99%	0.34	99%	1.81	99%
75^{th}	11,820	93%	1.77	9%	162	59%	24,200	81%	0.47	41%	3.46	71%
Maximum	78,900	90%	118	63%	13.3	2%	19,450	47%	16.6	90%	26.3	89%

5.5.4 Performance Analysis of Datasets with High Censoring

Tools such as the Kaplan-Meier method may be of significant use in attempts to analyze left-censored data, which are very common in physical/chemical/biological analyses of environmental data. The presence of a non-detect, while depriving the investigation of direct measurements of an analyte, does not necessarily result in the loss of meaningful information. The previously presented EPM analysis for water quality constituent removal in the CRRC LID facility gained considerable power from using techniques that allowed the effects of non-detects to be retained in the dataset(s).

However, there are limits to the utility of such techniques. For data sets with greater than 80% censoring, summary statistics cannot be accurately estimated using methods such as the Kaplan-Meier method or robust regression on ordered statistics. In these cases, analysis may be limited to reporting the percentage of observations above or below the maximum reporting limit. If the sample size is large (>50 observations) estimates of high percentiles such as the 90^{th} or 95^{th} percentiles may be available (Helsel, 2012).

Due to the high level of censoring (>80%) for either the influent or effluent load datasets and small sample sizes (<50 observations), estimations of summary statistics could not be produced for Cd, Pb, O&G, and TPH, and the EPM analysis could not be conducted on those constituents. The percentage of observations below the detection limit for each constituent, in both inflow and outflow datasets, is presented in Table 5-9. The CUOUT load dataset, it should be remembered, includes only those events that produced outflow, while the CUOUT-ZF dataset also included the zero flow events. The apparent lower level of censoring for outflow using the latter dataset was due to the inclusion of the zero flow events as uncensored data.

Overall, the high level of censoring made it difficult to develop any meaningful characterizations of performance for these constituents. The experience may, however, prove to be of value in illustrating the need for lower detection limit requirements for future monitoring programs.

Table 5-9. Percentage of water quality observations below the detection limit (BDL).

CUIN Load				
	Cadmium	**Lead**	**Oil & Grease**	**Total Petroleum Hydrocarbons**
Censored Observations	19	13	16	6
Total Observations	25	25	18	6
Percent BDL	76%	52%	**89%**	**100%**
CUOUT Load				
	Cadmium	**Lead**	**Oil & Grease**	**Total Petroleum Hydrocarbons**
Censored Observations	9	10	0	4
Total Observations	10	10	2	4
Percent BDL	**90%**	**100%**	0%	**100%**
CUOUT-ZF Load				
	Cadmium	**Lead**	**Oil & Grease**	**Total Petroleum Hydrocarbons**
Censored Observations	9	10	0	4
Total Observations	20	20	7	9
Percent BDL	45%	50%	0%	44%

5.6 Conclusions

The Cub Run Recreation Center LID retrofit was monitored during September 2008 – June 2010 and March 2011 – May 2012. During the two periods, 183 storm events were observed with a rainfall total of 59.03 inches and a total LID facility discharge of 8.56 inches, expressed as a depth over the catchment. The long-term facility rainfall retention evident from this comparison was 85%.

The LID facility was monitored for water quality during 25 storm events over the course of the two monitoring periods. The 25 monitored events represented 1/3 of all storm events meeting the minimum precipitation eligibility criterion of 0.2 inches.

Continuous meteorological and hydrologic monitoring data, along with water quality monitoring during selected storm events were used to assess the LID facility pollutant removal performance.

Water quality benefits from LID practices and other infiltration-based stormwater best management practices (BMPs) are a function of physical, chemical, and biological processes as well as reductions in stormwater runoff volumes (Davis et al., 2006; Davis, 2007; Geosyntec and WWE, 2009). For this reason, performance metrics based on changes in the total pollutant load over the monitoring period were chosen to assess the pollutant removal performance of the facility (Davis, 2007; Geosyntec and WWE, 2009). The Effluent Probability Method (Strecker et al., 2001; Geosyntec and WWE, 2009; Williams et al., 2009) was chosen for analysis of pollutant load removal performance.

The Effluent Probability Method (EPM) was used to compare influent and effluent loads at the LID facility. The Effluent Probability Method plots were produced using the empirical distribution function percentile data calculated with the Kaplan-Meier method, which makes it possible to incorporate any censored (below detection limit) observations (Helsel, 2012). Figures A-47 through A-59 in Appendix A presented the EPM plots comparing influent and effluent load datasets for each applicable water quality constituent. EPM plots were not generated for Cd, Pb, O&G, and TPH, due to the high level of censoring in their respective datasets. For data sets with greater than 80% censoring, summary statistics could not be accurately estimated and the analysis was limited to reporting the percentage of observations above or below the maximum reporting limit (Helsel, 2012).

The EPM analysis showed statistically significant positive pollutant load removal performance over the entire range of sampled events for TSS, TP, TN, TKN, NH3, COD, Cu, Zn and alkalinity. While the method also showed positive pollutant load removal performance for the hardness and OP water quality constituents, the generalized Wilcoxon test results showed that there was no statistically significant difference between influent and effluent load datasets at the 95% confidence level ($\alpha = 0.05$) with respective p-values of 0.061 and 0.071. With this in mind, while reductions in pollutant load for hardness and OP cannot be considered statistically significant, their respective p-values and probability plot results suggest there were reductions in pollutant load removal occurring.

The EPM results suggest that, during events below the 50th percentile, 100% of the influent OxN load is removed. This is consistent with the notion that longer storage intervals are available within the LID system during small storms, and the anoxic conditions that support denitrification are more likely to occur. However, the LID facility appears to have little effect on OxN loads above the 70th percentile of events. Still, the generalized Wilcoxon test results show that the influent and effluent load datasets are statistically significantly different with a p-value = 0.023.

The EPM results showed little to no reductions in TDS were achieved throughout the entire range of sampled events. Small reductions occurred for events up to the 60th percentile, and may be partially explained by the loss of alkalinity (mostly bicarbonate). At this juncture, there are insufficient data to completely explain the alkalinity reductions, except to say that it principally occurred in events below the 70th percentile in the database.

It should be noted that most of the EPM plots displayed greater removal performance on the lower end of the sampled range than on the higher end. This suggests that while the LID facility is achieving pollutant load removals throughout the entire range of sampled events, it is more effective at treating smaller storm events with consequently lower influent loads. This observation emphasizes the importance of stormwater runoff attenuation as an essential mechanism of water quality improvement, and the use of performance metrics based on the total pollutant load removal.

5.7 References

Barber, M. E., King, S. G., Yonge, D. R. and Hathhorn, W. E. (2003). "Ecology Ditch: A Best Management Practice for Storm Water Runoff Mitigation." Journal of Hydrologic Engineering **8**(3): 111-122.

Bedient, P. B. H., Wayne C. (2002). Hydrology and Floodplain Analysis, Third Edition. Upper Saddle River, NJ, Prentice Hall.

Benjamin, M. M. (2002). Water Chemistry, McGraw-Hill.

Beyerlein, D. (2008). LID Analysis Considerations in Western Washington. Low Impact Development for Urban Ecosystem and Habitat Protection**:** 1-9.

Brown, R. and Hunt III, W. (2011). "Underdrain Configuration to Enhance Bioretention Exfiltration to Reduce Pollutant Loads." Journal of Environmental Engineering **137**(11): 1082-1091.

Burton, G. A., Jr.; Pitt, Robert E. (2002). Stormwater Effects Handbook, Lewis Publishers.

Carpenter, D. D. and Hallam, L. (2010). "Influence of Planting Soil Mix Characteristics on Bioretention Cell Design and Performance." Journal of Hydrologic Engineering **15**(6): 404-416.

Carpenter, D. D. and Kaluvakolanu, P. (2011). “Effect of Roof Surface Type on Storm-Water Runoff from Full-Scale Roofs in a Temperate Climate.” Journal of Irrigation and Drainage Engineering **137**(3): 161-169.

Chi-Feng, C., Jen-Yang, L., Chih-Hong, H., Way-Ling, C. and Nai-Ling, C. (2009). “Performance evaluation of a full-scale natural treatment system for nonpoint source and point source pollution removal.” Environmental Monitoring & Assessment **157**(1-4): 391-406.

Chung, W., Wang, I. and Wang, R. (2010). “Theory-Based SCS-CN Method and Its Applications.” Journal of Hydrologic Engineering **15**(12): 1045-1058.

Clark, S. E., Mikula, J. B., Baker, K. H. and Treese, D. P. (2009). Pollutant Transport within the Vadose Zone: Interactions of Soil Horizon Chemistry on Water Quality. World Environmental and Water Resources Congress 2009**:** 1-9.

Clark, S. E. and Pitt, R. (2010). Considerations in Selecting a (Bio)Filtration Media to Optimize Lifespan and Pollutant Removal, ASCE.

Clary, J., Quigley, M., Poresky, A., Earles, A., Strecker, E., Leisenring, M. and Jones, J. (2011). “Integration of Low-Impact Development into the International Stormwater BMP Database.” Journal of Irrigation and Drainage Engineering **137**(3): 190-198.

Davis, A. P. (2007). “Field Performance of Bioretention: Water Quality.” Environmental Engineering Science **24**(8): 1048-1064.

Davis, A. P. (2008). “Field Performance of Bioretention: Hydrology Impacts.” Journal of Hydrologic Engineering **13**(2): 90-95.

Davis, A. P., Hunt, W. F., Traver, R. G. and Clar, M. (2009). “Bioretention Technology: Overview of Current Practice and Future Needs.” Journal of Environmental Engineering **135**(3): 109-117.

Davis, A. P., Shokouhian, M., Sharma, H. and Minami, C. (2006). “Water Quality Improvement through Bioretention Media: Nitrogen and Phosphorus Removal.” Water Environment Research **78**(3): 284-293.

DeBusk, K. M., Hunt, W. F. and Line, D. E. (2011). “Bioretention Outflow: Does It Mimic Nonurban Watershed Shallow Interflow?” Journal of Hydrologic Engineering **16**(3): 274-279.

EPA, U. S. (2007). “Reducing Stormwater Costs through Low Impact Development (LID) Strategies and Practices.” Nonpoint Source Control Branch.

Ergas, S., Sengupta, S., Siegel, R., Pandit, A., Yao, Y. and Yuan, X. (2010). “Performance of Nitrogen-Removing Bioretention Systems for Control of Agricultural Runoff.” Journal of Environmental Engineering **136**(10): 1105-1112.

Geosyntec and WWE, Geosyntec Consultants, Wright Water Engineers, Inc. (2009) "Urban Stormwater BMP Performance Monitoring" U.S. Environmental Protection Agency Prepared with support from the U.S. EPA, Water Environmental Research Foundation, Federal Highway Administration, and the Environmental and Water Resources Institute of the American Society of Civil Engineers, http://www.bmpdatabase.org

Giacomoni, M. H., Zechman, E. M. and Brumbelow, K. (2012). "Hydrologic Footprint Residence: Environmentally Friendly Criteria for Best Management Practices." Journal of Hydrologic Engineering **17**(1): 99-108.

GIS and Mapping Services (2011) "Soils Map 33-4" Fairfax County, D. o. I. T., Enterprise Services Division, GIS and Mapping Services

GKY, GKY & Associates (2012). Retrieved 10/25/2012, from http://www.gky.com/products/.

Google Maps (2013). "Cub Run Rec Center Satellite Image Google Maps, Used under fair use, 2013.". Retrieved 2/15/2013, from http://goo.gl/maps/LzirW, Fair use determination attached.

Grady, C. P. L., Jr; Daigger, Glen T.; Love, Nancy G.; Filipe, Carlos D.M. (2011). Biological Wastewater Treatment, IWA Publishing.

Grizzard, T. and Le Bel, P. (2013). Analysis of Monitoring Data at Cub Run Recreation Center Stormwater Improvements Fairfax County, Virginia, Virginia Tech.

Guo, J. C. Y. (2008). "Volume-Based Imperviousness for Storm Water Designs." Journal of Irrigation and Drainage Engineering **134**(2): 193-196.

Guo, J. C. Y. (2010). "Preservation of Watershed Regime for Low-Impact Development through Detention." Journal of Hydrologic Engineering **15**(1): 15-19.

Guo, J. C. Y. and Cheng, J. Y. C. (2008). "Retrofit Storm Water Retention Volume for Low Impact Development." Journal of Irrigation and Drainage Engineering **134**(6): 872-876.

Hass, J. W., Maurice D.; Thomas, George B, Jr. (2007). University Calculus, Pearson Addison Wesley.

He, Z. and Davis, A. P. (2009). Unit Process Modeling of Stormwater Flow and Pollutant Sorption in a Bioretention Cell, ASCE.

Helsel, D. R. (2012). "Statistics for Censored Environmental Data Using Minitab and R."

Helsel, D. R. and Hirsch, R. M. (2002). "Statistical Methods in Water Resources Techniques of Water Resources Investigations." U.S. Geological Survey **Book 4**(chapter A3).

Hong, E., Seagren, E. A. and Davis, A. P. (2006). "Sustainable Oil and Grease Removal from Synthetic Stormwater Runoff Using Bench-Scale Bioretention Studies." Water Environment Research **78**(2): 141-155.

Hsieh, C.-h. and Davis, A. P. (2003). Evaluation of Bioretention for Treatment of Urban Storm Water Runoff, ASCE.

Hsieh, C.-h. and Davis, A. P. (2005). "Evaluation and Optimization of Bioretention Media for Treatment of Urban Storm Water Runoff." Journal of Environmental Engineering **131**(11): 1521-1531.

Hsieh, C. H. and Davis, A. P. (2005). "Multiple-event study of bioretention for treatment of urban storm water runoff." Water Science & Technology **51**(3/4): 177-181.

Hunt, W. F., Jarrett, A. R., Smith, J. T. and Sharkey, L. J. (2006). "Evaluating Bioretention Hydrology and Nutrient Removal at Three Field Sites in North Carolina." Journal of Irrigation and Drainage Engineering **132**(6): 600-608.

ISCO, T. I.-. (2012). Retrieved 10/25/2012, from http://www.isco.com/products/products1.asp?PL=201.

Jones, T. (2013). Personal Communications with Tom Jones of Versar, Inc.

Kim, H., Seagren, E. A. and Davis, A. P. (2003). "Engineered Bioretention for Removal of Nitrate from Stormwater Runoff." Water Environment Research **75**(4): 355-367.

Lamont, S., Eli, R. and Fletcher, J. (2008). "Continuous Hydrologic Models and Curve Numbers: A Path Forward." Journal of Hydrologic Engineering **13**(7): 621-635.

LeFevre, N.-J. B., David W. Watkins, J., Gierke, J. S. and Brophy-Price, J. (2010). "Hydrologic Performance Monitoring of an Underdrained Low-Impact Development Storm-Water Management System." Journal of Irrigation and Drainage Engineering **136**(5): 333-339.

Li, H. and Davis, A. (2009). "Water Quality Improvement through Reductions of Pollutant Loads Using Bioretention." Journal of Environmental Engineering **135**(8): 567-576.

Li, H. and Davis, A. P. (2008). "Heavy Metal Capture and Accumulation in Bioretention Media." Environmental Science & Technology **42**(14): 5247-5253.

Lucas, W. and Greenway, M. (2011). "Phosphorus Retention by Bioretention Mesocosms Using Media Formulated for Phosphorus Sorption: Response to Accelerated Loads." Journal of Irrigation and Drainage Engineering **137**(3): 144-153.

Lucas, W. C. (2010). "Design of Integrated Bioinfiltration-Detention Urban Retrofits with Design Storm and Continuous Simulation Methods." Journal of Hydrologic Engineering **15**(6): 486-498.

Lucas, W. C. and Greenway, M. (2011). “Hydraulic Response and Nitrogen Retention in Bioretention Mesocosms with Regulated Outlets: Part IINitrogen Retention.” Water Environment Research **83**(8): 703-713.

McCuen, R. H. (2003). “Smart Growth: Hydrologic Perspective.” Journal of Professional Issues in Engineering Education and Practice **129**(3): 151-154.

McCuen, R. H. (2004). Hydrologic Analysis and Design, Pearson Prentice Hall.

McGarity, A. E. (2012). “Storm-Water Investment Strategy Evaluation Model for Impaired Urban Watersheds.” Journal of Water Resources Planning and Management **138**(2): 111-124.

Meyer, S. C. (2005). “Analysis of base flow trends in urban streams, northeastern Illinois, USA.” Hydrogeology journal **13**(5-6): 871-885.

Miller, G. T., Jr. (2002). Living in the Environment, Brooks/Cole Thomas Learning.

Montgomery, D. C. and Runger, G. C. (1999). Applied Statistics and Probability for Engineers, John Wiley & Sons, Inc.

NRCS, USDA Natural Resources Conservation Service (1986). “Urban Hydrology for Small Watersheds TR-55.”

O'Neill, S. W. and Davis, A. P. (2010). Analysis of Bioretention Media Specifications and Relationships to Overall Performance, ASCE.

Ogden, F. L., Downer, C. W., Pradhan, N. R. and Nelson, E. J. (2011). Predicting Hydrologic Effects of Land-Use Change: Problems with the Curve Number Approach. World Environmental and Water Resources Congress 2011**:** 4801-4810.

Onset, Onset Computer Corporation (2012). Retrieved 10/25/2012, from http://www.onsetcomp.com/.

Palhegyi, G. E. (2010a). “Designing Storm-Water Controls to Promote Sustainable Ecosystems: Science and Application.” Journal of Hydrologic Engineering **15**(6): 504-511.

Palhegyi, G. E. (2010b). “Modeling and Sizing Bioretention Using Flow Duration Control.” Journal of Hydrologic Engineering **15**(6): 417-425.

Pitt, R., Clark, S. and Steets, B. (2010). Evaluation of the Contaminant Removal Potential of Biofiltration Media, ASCE.

Ponce, V. and Hawkins, R. (1996). “Runoff Curve Number: Has It Reached Maturity?” Journal of Hydrologic Engineering **1**(1): 11-19.

Quigley, M. M., Strecker, E. W., Leisenring, M., Huber, W. C., Heaney, J., Weinstein, N., Sansalone, J. and Bodine, D. (2005). The Integrated Unit Process Design Approach for Urban Water Quality Design, ASCE.

Reichold, L., Zechman, E. M., Brill, E. D. and Holmes, H. (2010). "Simulation-Optimization Framework to Support Sustainable Watershed Development by Mimicking the Predevelopment Flow Regime." Journal of Water Resources Planning and Management **136**(3): 366-375.

Rice, E. B., Rodger; Eaton, Andrew; Clesceri, Lenore (2012). Standard Methods For the Examination of Water and Wastewater, American Public Health Association; American Water Works Association; Water Environment Federation.

Roesner, L. A., Bledsoe, B. P. and Brashear, R. W. (2001). "Are Best-Management-Practice Criteria Really Environmentally Friendly?" Journal of Water Resources Planning and Management **127**(3): 150-154.

Sansalone, J., Kuang, X. and Ranieri, V. (2008). "Permeable Pavement as a Hydraulic and Filtration Interface for Urban Drainage." Journal of Irrigation and Drainage Engineering **134**(5): 666-674.

Sansalone, J., Liu, B. and Ying, G. (2010). "Volumetric Filtration of Rainfall Runoff. II: Event-Based and Interevent Nutrient Fate." Journal of Environmental Engineering **136**(12): 1331-1340.

Sansalone, J. and Teng, Z. (2004). "In Situ Partial Exfiltration of Rainfall Runoff. I: Quality and Quantity Attenuation." Journal of Environmental Engineering **130**(9): 990-1007.

Strecker, E., Quigley, M., Urbonas, B., Jones, J. and Clary, J. (2001). "Determining Urban Storm Water BMP Effectiveness." Journal of Water Resources Planning and Management **127**(3): 144-149.

Traver, R. G., Davis, A. P., Hunt, W. F. and Cheng, M.-S. (2008). Stormwater Concepts --- No Adverse Impact, ASCE.

Versar, I. (2011). "Performance Monitoring [Volume Reduction and Water Quality] At Cub Run Recenter Stormwater Improvements, Fairfax County, Virginia."

VT-OWML, Virginia Tech Occoquan Watershed Monitoring Laboratory (2012). Fairfax County-Performance Assessment of LID Practices Data Repository. Scholar, Virginia Tech, Versar, Inc.; Fairfax County Government; Virginia Tech Faculty and Students.

Williams, E. S. and Wise, W. R. (2009). "Economic Impacts of Alternative Approaches to Storm-Water Management and Land Development." Journal of Water Resources Planning and Management **135**(6): 537-546.

Williams, G., Roseen, R. M., Lenhart, J. H. and Kayhanian, M. (2009). Potential Data Analysis Methodology to Evaluate the Performance of Manufactured BMPs. World Environmental and Water Resources Congress 2009**:** 1-10.

6 SUMMARY AND CONCLUSIONS

The Cub Run Recreation Center (CRRC) low impact development (LID) study site is an urban stormwater management retrofit located within the Cub Run watershed in the community of Chantilly, in western Fairfax County, Virginia. The facility is adjacent to a parking lot serving the CRRC and Westfield High School, and serves a total drainage area of 1.6 acres including 0.63 acres of asphalt parking lot, 0.86 acres of grassy-wooded area, and 0.11 acres of the LID facility itself. The treatment train is gravity flow, and includes four in-line grass swales followed by a bioretention cell with a gravel base. Discharges leaving the facility are routed to a conventional detention pond downstream.

The LID facility was monitored for water quality during 25 storm events over the course of two monitoring periods from September 2008 – June 2010 and March 2011 – May 2012. Continuous meteorological and hydrologic monitoring data, along with water quality monitoring during selected storm events were provided by Versar (2011). Passive and automated devices were used to collect samples that facilitated comparisons of water quality and flows at inflow and outflow locations, respectively. Inflow and outflow load datasets were developed from the water quality and hydrology data. It is important to note that water quality benefits from LID practices and other infiltration-based stormwater best management practices (BMPs) are a function of physical, chemical, and biological processes as well as reductions in stormwater runoff volumes (Davis et al., 2006; Davis, 2007; Geosyntec and WWE, 2009). For this reason, metrics based on changes in the total pollutant load over the monitoring period were chosen to assess the pollutant removal performance of the facility (Davis, 2007; Geosyntec and WWE, 2009). The Summation of Loads method (Minton, 2005; Hunt et al., 2006; Cates et al., 2009; Chi-Feng et al., 2009; Geosyntec and WWE, 2009; Williams et al., 2009; McNett et al., 2011) and the Effluent Probability Method (Strecker et al., 2001; Geosyntec and WWE, 2009; Williams et al., 2009) were chosen for constituent load reduction analyses.

The LID facility was monitored during 183 storm events, during which the monitoring equipment recorded a total rainfall of 59.03 inches and a total LID facility discharge of 8.56 inches, expressed as a depth over the catchment. The long-term facility rainfall retention evident from this comparison was 85%. Little runoff was generated for storm events where less than 0.5–0.75 inches of rain occurred. For events greater than 0.75 inches, the depth of runoff was only about 40% of the rainfall, indicating that the CRRC LID facility was effectively reducing the stormwater runoff volume through infiltration and evapotranspiration mechanisms.

The Summation of Loads (SOL) method was used to compare influent and effluent loads at the LID facility using three common substitution methods for censored observations: (1) setting below detection limit (BDL) observations to zero, (2) setting BDL observations to one-half the detection limit, and (3) setting BDL observations to the detection limit. The SOL method defines the efficiency of a given BMP to remove pollutants as the ratio of the summation of all incoming (inlet) loads to the summation of all outgoing (outlet) loads. The overall change in load for each pollutant over the monitoring period is presented as a percent decrease between the summation of inlet and outlet loads (Minton, 2005; Hunt et al., 2006; Cates et al., 2009; Chi-Feng et al., 2009; Geosyntec and WWE, 2009; Williams et al., 2009; McNett et al., 2011).

The SOL results from the Cub Run site were within the range of results found in the literature for LID facilities employing vegetated infiltration based stormwater management BMPs such as bioretention cells and grass swales. Overall, the Summation of Loads method showed positive performance for total phosphorus (TP), total nitrogen (TN), total Kjeldahl nitrogen (TKN), ammonia nitrogen (NH_3), total suspended solids (TSS), chemical oxygen demand (COD), copper (Cu), cadmium (Cd), zinc (Zn), Lead (Pb), total petroleum hydrocarbons (TPH), alkalinity (Alk), hardness (Hard) and orthophosphate phosphorus (OP). Negative performance was observed for: oxidized nitrogen (OxN), total dissolved solids (TDS) and Oil & Grease (O&G). Comparison of the Summation of Loads values using each substitution method along with the percent censoring for influent and effluent load datasets suggested that the higher the level of censoring for a particular water quality parameter, the greater the effect of the chosen substitution value.

There was no censoring within the TP, TN and TSS load datasets for the water quality events monitored, and the mass-based constituent removals computed by the SOL method were 65%, 53%, and 93%, respectively. In examining summaries of reported bioretention performance from some recent studies reported in the literature, it may be seen that the median percent removals for TP, TN, and TSS were 56%, 52%, and 71%, respectively. The performance of the CRRC LID facility with respect to TP appears to be somewhat better than reported in the studies cited. The TN removal was quite comparable to the median value of 52% in the studies cited.

With respect to TSS removal, the CRRC LID facility performance was greater than the median value of 71% in the 5 studies cited.

In the CRRC stormwater quality monitoring database, there was a very low level of censoring of the data for Cu and Zn due to the presence of concentrations below the analytical detection limits. For these trace metals, the substitution approach had little effect on the computed removal performance. Using the conservative assumption of the BDL values being equal to the detection limit, the removals of Cu and Zn computed with the SOL method were found to be 87% and 86%, respectively. When compared to median performance values from the literature for the same trace metals, removals of 63% and 95% were reported. For Cu, the CRRC LID facility performance was better than the reported median, but within the range of the three studies. For Zn, the CRRC LID facility performance was somewhat lower than the range of the three studies cited. It is not known if any galvanized pipe is present within the drainage network of the facility, but this possibility should be ruled out before attaching too much significance to the observed removals. For Pb, the level of censoring in the CRRC water quality database was quite high (52% inflow; 50% outflow). Using the conservative approach of substituting the analytical detection limit for any BDL value, the SOL performance computation gave an estimated performance of 85% removal, which compares quite favorably to the range of 81%-86% in the three studies cited.

As the level of censoring in influent and effluent load datasets increased, the effect of the chosen substitution value on the SOL method results became more prominent. This is most evident when viewing the SOL results for O&G with the three methods of substitution for BDL values of concentration. It should be noted that the level of censoring for the influent and effluent load datasets was 89% and 0%, respectively. Substituting a value of zero for censored data resulted in a -629% removal according to the Summation of Loads method, while substituting values of one-half the detection limit and the detection limit itself resulted in removals of -14% and +38%, respectively. Clearly, the value chosen to substitute in for censored observations completely controlled the Summation of Loads results for O&G. Similar, although less extreme, patterns may be seen for most other constituents with censored observations including: OxN, NH_3, TDS, Cd, Zn, Pb, and TPH. It should be noted that the Summation of Loads results did not change across the substitution methods for Cu, alkalinity, hardness, and OP, although censoring was present for all, albeit not at the levels observed for O&G. This observation emphasizes the importance of appropriately accounting for censored observations, or the effects of substitution methods, when using performance metrics such as the Summation of Loads method.

The Effluent Probability Method (EPM) was also used to compare influent and effluent loads at the LID facility. The EPM analysis was not performed on Cd, Pb, O&G, and TPH due to the high level of censoring in their respective datasets. For data sets with greater than 80% censoring, summary statistics could not be accurately estimated and the analysis was limited to reporting the percentage of observations above or below the maximum reporting limit (Helsel, 2012). Developing performance assessments using the Effluent Probability Method requires three principal steps (Strecker et al., 2001; Geosyntec and WWE, 2009; Williams et al., 2009):

- Distributional adherence test to determine if the data follow a particular distribution;
- Statistical tests to determine if any perceived differences between the influent and effluent EMCs or loads are statistically significant;
- Plotting the log-transformed data of influent and effluent EMCs or loads for all storm events on a normal probability plot.

Testing for distributional adherence is an important step in the Effluent Probability Method because it reveals the underlying distribution of the data, such as the normal or lognormal. Determining the distribution of the dataset allows for the selection of the proper transform to employ to best represent the influent and effluent concentrations or loads on the normal probability plot. Additionally, the type of statistical test selected to compare datasets is affected largely by the assumed underlying distribution of the datasets (Strecker et al., 2001; Geosyntec and WWE, 2009; Williams et al., 2009). Robust regression on ordered statistics (ROS) was used to produce probability plots, also called Q-Q plots, which account for any censored (below detection limit) observations in the LID facility water quality data.

The Q-Q plots revealed that while the lognormal transformation provided good fits for the influent load datasets, neither the normal nor the lognormal transformations provided good fits for the effluent load datasets because of the inclusion of events with no discharge at the outfall. If both the influent and effluent load datasets had followed the lognormal distribution, parametric statistics may have been applied after the appropriate transformation of the datasets. Because the effluent load datasets were not closely approximated by either the normal or lognormal distribution it was not possible to apply parametric statistical methods for further analysis. Consequently, the generalized Wilcoxon test, which is a nonparametric method, was selected to test for significant differences between the influent (CUIN) and effluent (CUOUT-ZF) load datasets for each water quality constituent.

The generalized Wilcoxon test is a nonparametric statistical test which determines if there is a significant difference in the cumulative distributions between two or more datasets. The generalized Wilcoxon test takes censored observations into account by using the Kaplan-Meier method to estimate the percentiles of the empirical distribution function for the sample data (Helsel, 2012). The generalized Wilcoxon test was used to test for significant differences between LID facility influent and effluent load datasets because of its ability to incorporate censored observations. In addition, it may be successfully applied to datasets from unknown distributions, such as CUOUT-ZF.

Two-sample generalized Wilcoxon two-sided tests between the CUIN and CUOUT-ZF load datasets at the 95% confidence level ($\alpha = 0.05$) revealed statistically significant differences for all water quality constituents except TDS, hardness and OP. It should be noted that, while the CUIN and CUOUT-ZF load datasets for hardness and OP were found to be not statistically different at the 95% confidence level, their respective p-values, 0.061 and 0.071, are very close to the tested confidence level ($\alpha = 0.05$). For that reason, the hardness and OP influent and effluent load datasets may be considered to be very close to being statistically different.

The last step in applying the EPM is to plot the transformed data of influent and effluent EMCs or loads for all storm events on a normal probability plot. The resulting plot allows for a graphical representation of the BMP performance over the range of all influent and effluent conditions observed (Strecker et al., 2001; Chi-Feng et al., 2009; Geosyntec and WWE, 2009; Williams et al., 2009). The plotting position of each datum (an observed concentration or load within the influent or effluent dataset for a particular water quality constituent) is based on the cumulative frequency of that datum as calculated by an empirical distribution function for the individual dataset (Chi-Feng et al., 2009; Geosyntec and WWE, 2009; Helsel, 2012). By comparing the influent and effluent water quality in this manner, the plot promotes a more thorough understanding of how the BMP may be expected to perform over the range of influent concentrations and loadings sampled (Strecker et al., 2001; Geosyntec and WWE, 2009; Williams et al., 2009). Because the load datasets contained censored data, the probability plots comparing the CUIN and CUOUT-ZF datasets were produced using the empirical distribution function percentile data calculated by the Kaplan-Meier method which allowed for incorporation of the effects of censored (below detection limit) observations (Helsel, 2012).

The EPM analysis showed statistically significant ($p \leq 0.05$) positive pollutant load removal performance over the entire range of sampled events for TSS, TP, TN, TKN, NH_3, COD, Cu, Zn and alkalinity. While the method also showed positive pollutant load removal performance for the hardness and OP water quality constituents, the generalized Wilcoxon test results showed that there was no statistically significant difference between influent and effluent load datasets at the 95% confidence level ($\alpha = 0.05$) with respective p-values of 0.061 and 0.071. With this in mind, while reductions in pollutant load for hardness and OP cannot be considered statistically significant, their respective p-values and probability plot results suggest there were reductions in pollutant load removal occurring.

The EPM results suggest that, during events below the 50^{th} percentile, 100% of the influent OxN load is removed. This is consistent with the notion that longer storage intervals are available within the LID system during small storms, and the anoxic conditions that support denitrification are more likely to occur. However, the LID facility appears to have little effect on OxN loads above the 70^{th} percentile of events. Still, the generalized Wilcoxon test results show that the influent and effluent load datasets are statistically significantly different with a p-value = 0.023.

The EPM results showed little to no reductions in TDS were achieved throughout the entire range of sampled events. Small reductions occurred for events up to the 60^{th} percentile, and may be partially explained by the loss of alkalinity (mostly bicarbonate). At this juncture, there are insufficient data to completely explain the alkalinity reductions, except to say that it principally occurred in events below the 70^{th} percentile in the database.

It should be noted that most of the EPM plots displayed greater removal performance on the lower end of the sampled range than on the higher end. This suggests that while the LID facility is achieving pollutant load removals throughout the entire range of sampled events, it is more effective at treating smaller storm events with consequently lower influent loads. This observation emphasizes the importance of stormwater runoff attenuation as an essential mechanism of water quality improvement, and the use of performance metrics based on the total pollutant load removal.

Tools such as the Kaplan-Meier method may be of significant use in attempts to analyze left-censored data, which are very common in physical/chemical/biological analyses of environmental data. The presence of a non-detect, while depriving the investigation of direct measurements of an analyte, does not necessarily result in the loss of meaningful information. The EPM analysis for water quality constituent removal in the CRRC LID facility gained considerable power from using techniques that allowed the effects of non-detects to be retained in the dataset(s). However, there are limits to the utility of such techniques. For data sets with greater than 80% censoring, summary statistics cannot be accurately estimated using methods such as the Kaplan-Meier method or robust regression on ordered statistics. In these cases, analysis may be limited to reporting the percentage of observations above or below the maximum reporting limit. If the sample size is large (>50 observations) estimates of high percentiles such as the 90^{th} or 95^{th} percentiles may be available (Helsel, 2012). Due to the high level of censoring (>80%) for either the influent or effluent load datasets and small sample sizes (<50 observations), estimations of summary statistics could not be produced for Cd, Pb, O&G, and TPH, and the EPM analysis could not be conducted on those constituents. Overall, the high level of censoring made it difficult to develop any meaningful characterizations of performance for these constituents. The experience may, however, prove to be of value in illustrating the need for lower detection limit requirements for future monitoring programs.

Working with the datasets developed for the CRRC LID retrofit made it possible to consider changes that might be implemented in future monitoring projects of this type with a view to improving the quality of performance estimates. A major (and unquantified) source of uncertainty arose from the need to estimate storm event scale flows from the parking lot and the grassy-wooded area sub-catchments. It is well-recognized that the dispersed nature of inflows to LID practices makes it difficult to monitor all inflows (Geosyntec and WWE, 2009). However, the limitations of the SCS runoff curve number method in providing reliable discharge data on a storm event temporal scale have also been well-documented. Instrumenting the 2 sub-catchment inflows would have been difficult, made the site more attractive to vandalism, and increased operational costs, but in hindsight, may well have improved the program outcomes. While it would have been difficult to fully instrument the sub-catchments of both the impervious and pervious portions of the site drainage, it would have been possible to, at least, monitor a sub-catchment of the parking lot drainage. Because the parking lot was the major source of inflow, having measured data would have substantially decreased the uncertainty in the water balance and inflow loads. Another area of concern is that runoff velocity can have short-term impacts on drainage area, particularly from impervious surfaces. Direct observation of flow movement during a range of storm event intensities could document (or disprove) this phenomenon. Finally, it was observed that flow sometimes bypassed most of the LID facility and directly entered the swale adjacent to the bioretention cell, which created some uncertainty about residence times in the upstream swales. Taking steps to ensure that all flows entered the practice at the desired locations would help to remove another area of uncertainty in data interpretation.

The monitoring program was conducted during a period shortly after the installation of the LID retrofit, and for that reason, it may not have been truly indicative of the performance of a mature system. In addition, the monitoring program did not take place during a period near the end of a scheduled maintenance interval. Nutrient and micronutrient uptake by vegetation can effect pollutant load reductions only if the net new growth is harvested to remove excess biomass before decay and decomposition can result in the re-release of nutrients and micronutrients to the watershed. Many investigators have recommended that such maintenance activities should occur on a regular, usually annual, basis (Kim et al., 2003; Davis et al., 2006; EPA, 2007; Davis, 2008; Li and Davis, 2008; Davis et al., 2009; Geosyntec and WWE, 2009; He and Davis, 2009; Lucas, 2010).

6.1 References

Cates, E. L., Westphal, M. J., Cox, J. H., Calabria, J. and Patch, S. C. (2009). "Field Evaluation of a Proprietary Storm-Water Treatment System: Removal Efficiency and Relationships to Peak Flow, Season, and Dry Time." Journal of Environmental Engineering **135**(7): 511-517.

Chi-Feng, C., Jen-Yang, L., Chih-Hong, H., Way-Ling, C. and Nai-Ling, C. (2009). "Performance evaluation of a full-scale natural treatment system for nonpoint source and point source pollution removal." Environmental Monitoring & Assessment **157**(1-4): 391-406.

Davis, A. P. (2007). “Field Performance of Bioretention: Water Quality.” Environmental Engineering Science **24**(8): 1048-1064.

Davis, A. P. (2008). “Field Performance of Bioretention: Hydrology Impacts.” Journal of Hydrologic Engineering **13**(2): 90-95.

Davis, A. P., Hunt, W. F., Traver, R. G. and Clar, M. (2009). “Bioretention Technology: Overview of Current Practice and Future Needs.” Journal of Environmental Engineering **135**(3): 109-117.

Davis, A. P., Shokouhian, M., Sharma, H. and Minami, C. (2006). “Water Quality Improvement through Bioretention Media: Nitrogen and Phosphorus Removal.” Water Environment Research **78**(3): 284-293.

EPA, U. S. (2007). “Reducing Stormwater Costs through Low Impact Development (LID) Strategies and Practices.” Nonpoint Source Control Branch.

Geosyntec and WWE, Geosyntec Consultants, Wright Water Engineers, Inc. (2009) “Urban Stormwater BMP Performance Monitoring” U.S. Environmental Protection Agency Prepared with support from the U.S. EPA, Water Environmental Research Foundation, Federal Highway Administration, and the Environmental and Water Resources Institute of the American Society of Civil Engineers, http://www.bmpdatabase.org

He, Z. and Davis, A. P. (2009). Unit Process Modeling of Stormwater Flow and Pollutant Sorption in a Bioretention Cell, ASCE.

Helsel, D. R. (2012). “Statistics for Censored Environmental Data Using Minitab and R.”

Hunt, W. F., Jarrett, A. R., Smith, J. T. and Sharkey, L. J. (2006). “Evaluating Bioretention Hydrology and Nutrient Removal at Three Field Sites in North Carolina.” Journal of Irrigation and Drainage Engineering **132**(6): 600-608.

Kim, H., Seagren, E. A. and Davis, A. P. (2003). “Engineered Bioretention for Removal of Nitrate from Stormwater Runoff.” Water Environment Research **75**(4): 355-367.

Li, H. and Davis, A. P. (2008). “Heavy Metal Capture and Accumulation in Bioretention Media.” Environmental Science & Technology **42**(14): 5247-5253.

Lucas, W. C. (2010). “Design of Integrated Bioinfiltration-Detention Urban Retrofits with Design Storm and Continuous Simulation Methods.” Journal of Hydrologic Engineering **15**(6): 486-498.

McNett, J. K., Hunt, W. F. and Davis, A. P. (2011). “Influent Pollutant Concentrations as Predictors of Effluent Pollutant Concentrations for Mid-Atlantic Bioretention.” Journal of Environmental Engineering **137**(9): 790-799.

Minton, G. (2005). Stormwater Treatment - Biological, Chemical, and Engineering Principles, Resource Planning Associates.

Strecker, E., Quigley, M., Urbonas, B., Jones, J. and Clary, J. (2001). "Determining Urban Storm Water BMP Effectiveness." Journal of Water Resources Planning and Management **127**(3): 144-149.

Versar, I. (2011). "Performance Monitoring [Volume Reduction and Water Quality] At Cub Run Recenter Stormwater Improvements, Fairfax County, Virginia."

Williams, G., Roseen, R. M., Lenhart, J. H. and Kayhanian, M. (2009). Potential Data Analysis Methodology to Evaluate the Performance of Manufactured BMPs. World Environmental and Water Resources Congress 2009**:** 1-10.

CONSOLIDATED REFERENCES

Barber, M. E., King, S. G., Yonge, D. R. and Hathhorn, W. E. (2003). "Ecology Ditch: A Best Management Practice for Storm Water Runoff Mitigation." Journal of Hydrologic Engineering **8**(3): 111-122.

Bedient, P. B. H., Wayne C. (2002). Hydrology and Floodplain Analysis, Third Edition. Upper Saddle River, NJ, Prentice Hall.

Benjamin, M. M. (2002). Water Chemistry, McGraw-Hill.

Beyerlein, D. (2008). LID Analysis Considerations in Western Washington. Low Impact Development for Urban Ecosystem and Habitat Protection**:** 1-9.

Brown, R. and Hunt III, W. (2010). "Impacts of Construction Activity on Bioretention Performance." Journal of Hydrologic Engineering **15**(6): 386-394.

Brown, R. and Hunt III, W. (2011a). "Impacts of Media Depth on Effluent Water Quality and Hydrologic Performance of Undersized Bioretention Cells." Journal of Irrigation and Drainage Engineering **137**(3): 132-143.

Brown, R. and Hunt III, W. (2011b). "Underdrain Configuration to Enhance Bioretention Exfiltration to Reduce Pollutant Loads." Journal of Environmental Engineering **137**(11): 1082-1091.

Burton, G. A., Jr.; and Pitt, R. E. (2001). Stormwater Effects Handbook: A Toolbox for Watershed Managers, Scientists, and Engineers. Lewis Publishers.

Burton, G. A., Jr.; Pitt, Robert E. (2002). Stormwater Effects Handbook, Lewis Publishers.

Carpenter, D. D. and Hallam, L. (2010). "Influence of Planting Soil Mix Characteristics on Bioretention Cell Design and Performance." Journal of Hydrologic Engineering **15**(6): 404-416.

Carpenter, D. D. and Kaluvakolanu, P. (2011). "Effect of Roof Surface Type on Storm-Water Runoff from Full-Scale Roofs in a Temperate Climate." Journal of Irrigation and Drainage Engineering **137**(3): 161-169.

Cates, E. L., Westphal, M. J., Cox, J. H., Calabria, J. and Patch, S. C. (2009). "Field Evaluation of a Proprietary Storm-Water Treatment System: Removal Efficiency and Relationships to Peak Flow, Season, and Dry Time." Journal of Environmental Engineering **135**(7): 511-517.

Chi-Feng, C., Jen-Yang, L., Chih-Hong, H., Way-Ling, C. and Nai-Ling, C. (2009). "Performance evaluation of a full-scale natural treatment system for nonpoint source and point source pollution removal." Environmental Monitoring & Assessment **157**(1-4): 391-406.

Chung, W., Wang, I. and Wang, R. (2010). "Theory-Based SCS-CN Method and Its Applications." Journal of Hydrologic Engineering **15**(12): 1045-1058.

Clark, S. E., Mikula, J. B., Baker, K. H. and Treese, D. P. (2009). Pollutant Transport within the Vadose Zone: Interactions of Soil Horizon Chemistry on Water Quality. World Environmental and Water Resources Congress 2009**:** 1-9.

Clark, S. E. and Pitt, R. (2010). Considerations in Selecting a (Bio)Filtration Media to Optimize Lifespan and Pollutant Removal, ASCE.

Clary, J., Quigley, M., Poresky, A., Earles, A., Strecker, E., Leisenring, M. and Jones, J. (2011). "Integration of Low-Impact Development into the International Stormwater BMP Database." Journal of Irrigation and Drainage Engineering **137**(3): 190-198.

Davis, A. P. (2007). "Field Performance of Bioretention: Water Quality." Environmental Engineering Science **24**(8): 1048-1064.

Davis, A. P. (2008). "Field Performance of Bioretention: Hydrology Impacts." Journal of Hydrologic Engineering **13**(2): 90-95.

Davis, A. P., Hunt, W. F., Traver, R. G. and Clar, M. (2009). "Bioretention Technology: Overview of Current Practice and Future Needs." Journal of Environmental Engineering **135**(3): 109-117.

Davis, A. P., Shokouhian, M., Sharma, H. and Minami, C. (2006). "Water Quality Improvement through Bioretention Media: Nitrogen and Phosphorus Removal." Water Environment Research **78**(3): 284-293.

Davis, A. P., Shokouhian, M., Sharma, H., Minami, C. and Winogradoff, D. (2003). "Water Quality Improvement through Bioretention: Lead, Copper, and Zinc Removal." Water Environment Research **75**(1): 73-82.

DeBusk, K. M., Hunt, W. F. and Line, D. E. (2011). "Bioretention Outflow: Does It Mimic Nonurban Watershed Shallow Interflow?" Journal of Hydrologic Engineering **16**(3): 274-279.

Denich, C. and Bradford, A. (2010). "Estimation of Evapotranspiration from Bioretention Areas Using Weighing Lysimeters." Journal of Hydrologic Engineering **15**(6): 522-530.

Emerson, C. H. and Traver, R. G. (2008). "Multiyear and Seasonal Variation of Infiltration from Storm-Water Best Management Practices." Journal of Irrigation and Drainage Engineering **134**(5): 598-605.

EPA, U. S. (1999) "Preliminary Data Summary of Urban Stormwater Best Management Practices"

EPA, U. S. (2000). "Low Impact Development (LID) - A Literature Review."

EPA, U. S. (2007). "Reducing Stormwater Costs through Low Impact Development (LID) Strategies and Practices." Nonpoint Source Control Branch.

EPA, U. S. E. P. A. (1983). "Results of the Nationwide Urban Runoff Program: Volume 1 - Final Report."

EPA, U. S. E. P. A. (1992). "National Pollutant Discharge Elimination System Stormwater Sampling Guidance Document."

Ergas, S., Sengupta, S., Siegel, R., Pandit, A., Yao, Y. and Yuan, X. (2010). "Performance of Nitrogen-Removing Bioretention Systems for Control of Agricultural Runoff." Journal of Environmental Engineering **136**(10): 1105-1112.

Gallagher, D. (2011). "VT CEE 5724 Environmental Monitoring and Sampling Lecture Spring 2011."

Geosyntec and WWE, Geosyntec Consultants, Wright Water Engineers, Inc. (2009) "Urban Stormwater BMP Performance Monitoring" U.S. Environmental Protection Agency Prepared with support from the U.S. EPA, Water Environmental Research Foundation, Federal Highway Administration, and the Environmental and Water Resources Institute of the American Society of Civil Engineers, http://www.bmpdatabase.org

Giacomoni, M. H., Zechman, E. M. and Brumbelow, K. (2012). "Hydrologic Footprint Residence: Environmentally Friendly Criteria for Best Management Practices." Journal of Hydrologic Engineering **17**(1): 99-108.

GIS and Mapping Services (2011) "Soils Map 33-4" Fairfax County, D. o. I. T., Enterprise Services Division, GIS and Mapping Services

GKY, GKY & Associates (2012). Retrieved 10/25/2012, from http://www.gky.com/products/.

Google Maps (2013). "Cub Run Rec Center Satellite Image Google Maps, Used under fair use, 2013.". Retrieved 2/15/2013, from http://goo.gl/maps/LzirW, Fair use determination attached.

Grady, C. P. L., Jr; Daigger, Glen T.; Love, Nancy G.; Filipe, Carlos D.M. (2011). Biological Wastewater Treatment, IWA Publishing.

Grizzard, T. and Le Bel, P. (2013). Analysis of Monitoring Data at Cub Run Recreation Center Stormwater Improvements Fairfax County, Virginia, Virginia Tech.

Guo, J. C. Y. (2008). "Volume-Based Imperviousness for Storm Water Designs." Journal of Irrigation and Drainage Engineering **134**(2): 193-196.

Guo, J. C. Y. (2010). "Preservation of Watershed Regime for Low-Impact Development through Detention." Journal of Hydrologic Engineering **15**(1): 15-19.

Guo, J. C. Y., Blackler, G. E., Earles, T. A. and MacKenzie, K. (2010). "Incentive Index Developed to Evaluate Storm-Water Low-Impact Designs." Journal of Environmental Engineering **136**(12): 1341-1346.

Guo, J. C. Y. and Cheng, J. Y. C. (2008). "Retrofit Storm Water Retention Volume for Low Impact Development." Journal of Irrigation and Drainage Engineering **134**(6): 872-876.

Hass, J. W., Maurice D.; Thomas, George B, Jr. (2007). University Calculus, Pearson Addison Wesley.

He, Z. and Davis, A. P. (2009). Unit Process Modeling of Stormwater Flow and Pollutant Sorption in a Bioretention Cell, ASCE.

Helsel, D. R. (2012). "Statistics for Censored Environmental Data Using Minitab and R."

Helsel, D. R. and Hirsch, R. M. (2002). "Statistical Methods in Water Resources Techniques of Water Resources Investigations." U.S. Geological Survey **Book 4**(chapter A3).

Hong, E., Seagren, E. A. and Davis, A. P. (2006). "Sustainable Oil and Grease Removal from Synthetic Stormwater Runoff Using Bench-Scale Bioretention Studies." Water Environment Research **78**(2): 141-155.

Houdeshel, C. D., Pomeroy, C. A., Hair, L. and Moeller, J. (2011). "Cost-Estimating Tools for Low-Impact Development Best Management Practices: Challenges, Limitations, and Implications." Journal of Irrigation and Drainage Engineering **137**(3): 183-189.

Hsieh, C.-h. and Davis, A. P. (2003). Evaluation of Bioretention for Treatment of Urban Storm Water Runoff, ASCE.

Hsieh, C.-h. and Davis, A. P. (2005). "Evaluation and Optimization of Bioretention Media for Treatment of Urban Storm Water Runoff." Journal of Environmental Engineering **131**(11): 1521-1531.

Hsieh, C. H. and Davis, A. P. (2005). "Multiple-event study of bioretention for treatment of urban storm water runoff." Water Science & Technology **51**(3/4): 177-181.

Hunt, W. F., Jarrett, A. R., Smith, J. T. and Sharkey, L. J. (2006). "Evaluating Bioretention Hydrology and Nutrient Removal at Three Field Sites in North Carolina." Journal of Irrigation and Drainage Engineering **132**(6): 600-608.

Hunt, W. F., Smith, J. T., Jadlocki, S. J., Hathaway, J. M. and Eubanks, P. R. (2008). "Pollutant Removal and Peak Flow Mitigation by a Bioretention Cell in Urban Charlotte, N.C." Journal of Environmental Engineering **134**(5): 403-408.

ISCO, T. I.-. (2012). Retrieved 10/25/2012, from http://www.isco.com/products/products1.asp?PL=201.

Jones, T. (2013). Personal Communications with Tom Jones of Versar, Inc.

Kim, H., Seagren, E. A. and Davis, A. P. (2003). “Engineered Bioretention for Removal of Nitrate from Stormwater Runoff.” Water Environment Research **75**(4): 355-367.

Lamont, S., Eli, R. and Fletcher, J. (2008). “Continuous Hydrologic Models and Curve Numbers: A Path Forward.” Journal of Hydrologic Engineering **13**(7): 621-635.

Lee, J. G., Selvakumar, A., Alvi, K., Riverson, J., Zhen, J. X., Shoemaker, L. and Lai, F.-h. (2012). “A watershed-scale design optimization model for stormwater best management practices.” Environmental Modelling & Software **37**(0): 6-18.

LeFevre, N.-J. B., David W. Watkins, J., Gierke, J. S. and Brophy-Price, J. (2010). “Hydrologic Performance Monitoring of an Underdrained Low-Impact Development Storm-Water Management System.” Journal of Irrigation and Drainage Engineering **136**(5): 333-339.

Lenhart, H. A. and Hunt, W. F. (2011). “Evaluating Four Storm-Water Performance Metrics with a North Carolina Coastal Plain Storm-Water Wetland.” Journal of Environmental Engineering **137**(2): 155-162.

Lenhart, J. H. (2007). BMP Performance Expectation Functions – A Simple Method for Evaluating Stormwater Treatment BMP Performance Data. 9th Biennial Conference on Stormwater Research & Watershed Management.

Li, H. and Davis, A. (2009). “Water Quality Improvement through Reductions of Pollutant Loads Using Bioretention.” Journal of Environmental Engineering **135**(8): 567-576.

Li, H. and Davis, A. P. (2008). “Heavy Metal Capture and Accumulation in Bioretention Media.” Environmental Science & Technology **42**(14): 5247-5253.

Linden, K. V. and Stone, M. (2009). “Treatment Performance of an Extensive Vegetated Roof in Waterloo, Ontario.” Water Quality Research Journal of Canada **44**(1): 26-32.

Lucas, W. and Greenway, M. (2011). “Phosphorus Retention by Bioretention Mesocosms Using Media Formulated for Phosphorus Sorption: Response to Accelerated Loads.” Journal of Irrigation and Drainage Engineering **137**(3): 144-153.

Lucas, W. C. (2010). “Design of Integrated Bioinfiltration-Detention Urban Retrofits with Design Storm and Continuous Simulation Methods.” Journal of Hydrologic Engineering **15**(6): 486-498.

Lucas, W. C. and Greenway, M. (2011). "Hydraulic Response and Nitrogen Retention in Bioretention Mesocosms with Regulated Outlets: Part IINitrogen Retention." Water Environment Research **83**(8): 703-713.

Ma, J., Kang, J., Kayhanian, M. and Stenstrom, M. (2009). "Sampling Issues in Urban Runoff Monitoring Programs: Composite versus Grab." Journal of Environmental Engineering **135**(3): 118-127.

McCuen, R. H. (2003). "Smart Growth: Hydrologic Perspective." Journal of Professional Issues in Engineering Education and Practice **129**(3): 151-154.

McCuen, R. H. (2004). Hydrologic Analysis and Design, Pearson Prentice Hall.

McGarity, A. E. (2012). "Storm-Water Investment Strategy Evaluation Model for Impaired Urban Watersheds." Journal of Water Resources Planning and Management **138**(2): 111-124.

McNett, J. K., Hunt, W. F. and Davis, A. P. (2011). "Influent Pollutant Concentrations as Predictors of Effluent Pollutant Concentrations for Mid-Atlantic Bioretention." Journal of Environmental Engineering **137**(9): 790-799.

Meyer, S. C. (2005). "Analysis of base flow trends in urban streams, northeastern Illinois, USA." Hydrogeology journal **13**(5-6): 871-885.

Miller, G. T., Jr. (2002). Living in the Environment, Brooks/Cole Thomas Learning.

Minton, G. (2005). Stormwater Treatment - Biological, Chemical, and Engineering Principles, Resource Planning Associates.

Montgomery, D. C. and Runger, G. C. (1999). Applied Statistics and Probability for Engineers, John Wiley & Sons, Inc.

NRCS, USDA Natural Resources Conservation Service (1986). "Urban Hydrology for Small Watersheds TR-55."

O'Neill, S. W. and Davis, A. P. (2010). Analysis of Bioretention Media Specifications and Relationships to Overall Performance, ASCE.

Ogden, F. L., Downer, C. W., Pradhan, N. R. and Nelson, E. J. (2011). Predicting Hydrologic Effects of Land-Use Change: Problems with the Curve Number Approach. World Environmental and Water Resources Congress 2011**:** 4801-4810.

Onset, Onset Computer Corporation (2012). Retrieved 10/25/2012, from http://www.onsetcomp.com/.

Palhegyi, G. E. (2010a). "Designing Storm-Water Controls to Promote Sustainable Ecosystems: Science and Application." Journal of Hydrologic Engineering **15**(6): 504-511.

Palhegyi, G. E. (2010b). “Modeling and Sizing Bioretention Using Flow Duration Control.” Journal of Hydrologic Engineering **15**(6): 417-425.

Pitt, R., Clark, S. and Steets, B. (2010). Evaluation of the Contaminant Removal Potential of Biofiltration Media, ASCE.

Pitt, R., Nara, Y., Kirby, J. and Durrans, S. R. (2007). Particulate Transport in Grass Swales, ASCE.

Ponce, V. and Hawkins, R. (1996). “Runoff Curve Number: Has It Reached Maturity?” Journal of Hydrologic Engineering **1**(1): 11-19.

Quigley, M. M., Strecker, E. W., Leisenring, M., Huber, W. C., Heaney, J., Weinstein, N., Sansalone, J. and Bodine, D. (2005). The Integrated Unit Process Design Approach for Urban Water Quality Design, ASCE.

Reichold, L., Zechman, E. M., Brill, E. D. and Holmes, H. (2010). “Simulation-Optimization Framework to Support Sustainable Watershed Development by Mimicking the Predevelopment Flow Regime.” Journal of Water Resources Planning and Management **136**(3): 366-375.

Rice, E. B., Rodger; Eaton, Andrew; Clesceri, Lenore (2012). Standard Methods For the Examination of Water and Wastewater, American Public Health Association; American Water Works Association; Water Environment Federation.

Roesner, L. A., Bledsoe, B. P. and Brashear, R. W. (2001). “Are Best-Management-Practice Criteria Really Environmentally Friendly?” Journal of Water Resources Planning and Management **127**(3): 150-154.

Roseen, R. M., Ballestero, T. P., Houle, J. J., Avellaneda, P., Briggs, J., Fowler, G. and Wildey, R. (2009). “Seasonal Performance Variations for Storm-Water Management Systems in Cold Climate Conditions.” Journal of Environmental Engineering **135**(3): 128-137.

Roseen, R. M., Ballestero, T. P., Houle, J. J., Briggs, J. F. and Houle, K. M. (2012). “Water Quality and Hydrologic Performance of a Porous Asphalt Pavement as a Storm-Water Treatment Strategy in a Cold Climate.” Journal of Environmental Engineering **138**(1): 81-89.

Sansalone, J., Kuang, X. and Ranieri, V. (2008). “Permeable Pavement as a Hydraulic and Filtration Interface for Urban Drainage.” Journal of Irrigation and Drainage Engineering **134**(5): 666-674.

Sansalone, J., Liu, B. and Ying, G. (2010). “Volumetric Filtration of Rainfall Runoff. II: Event-Based and Interevent Nutrient Fate.” Journal of Environmental Engineering **136**(12): 1331-1340.

Sansalone, J. and Teng, Z. (2004). “In Situ Partial Exfiltration of Rainfall Runoff. I: Quality and Quantity Attenuation.” Journal of Environmental Engineering **130**(9): 990-1007.

Sansalone, J. J. and Cristina, C. M. (2004). “First Flush Concepts for Suspended and Dissolved Solids in Small Impervious Watersheds.” Journal of Environmental Engineering **130**(11): 1301-1314.

She, N. and Pang, J. (2010). “Physically Based Green Roof Model.” Journal of Hydrologic Engineering **15**(6): 458-464.

Strecker, E., Quigley, M., Urbonas, B., Jones, J. and Clary, J. (2001). “Determining Urban Storm Water BMP Effectiveness.” Journal of Water Resources Planning and Management **127**(3): 144-149.

Teemusk, A. and Mander, Ü. (2011). “The Influence of Green Roofs on Runoff Water Quality: A Case Study from Estonia.” Water Resources Management **25**(14): 3699-3713.

Traver, R. G., Davis, A. P., Hunt, W. F. and Cheng, M.-S. (2008). Stormwater Concepts --- No Adverse Impact, ASCE.

Van Buren, M. A., Watt, W. E. and Marsalek, J. (1997). “Application of the log-normal and normal distributions to stormwater quality parameters.” Water Research **31**(1): 95-104.

Van Seters, T., Rocha, L., Smith, D. and MacMillan, G. (2009). “Evaluation of Green Roofs for Runoff Retention, Runoff Quality, and Leachability.” Water Quality Research Journal of Canada **44**(1): 33-47.

Versar, I. (2011). “Performance Monitoring [Volume Reduction and Water Quality] At Cub Run Recenter Stormwater Improvements, Fairfax County, Virginia.”

Virginia Department of Conservation and Recreation (2011) “Virginia DCR Stormwater Design Spec. No. 9, Bioretention, Version 1.9” Recreation, V. D. o. C. a.

Voyde, E., Fassman, E., Simcock, R. and Wells, J. (2010). “Quantifying Evapotranspiration Rates for New Zealand Green Roofs.” Journal of Hydrologic Engineering **15**(6): 395-403.

VT-OWML, Virginia Tech Occoquan Watershed Monitoring Laboratory (2012). Fairfax County-Performance Assessment of LID Practices Data Repository. Scholar, Virginia Tech, Versar, Inc.; Fairfax County Government; Virginia Tech Faculty and Students.

Water Environment Research Foundation (2009). User's Guide to the BMP and LID Whole Life Cost Models. Water Environment Research Foundation. **Version 2.0**.

WEF and ASCE, Water Environment Federation, American Society of Civil Engineers, Environmental & Water Resource Institute, (2012). Design of Urban Stormwater Controls, McGraw Hill.

Welker, A. L. and Wadzuk, B. M. (2011). Development of a Stormwater Control Measure Microcosm to Measure Evapotranspiration. Geo-Frontiers 2011**:** 3068-3076.

Williams, E. S. and Wise, W. R. (2009). "Economic Impacts of Alternative Approaches to Storm-Water Management and Land Development." Journal of Water Resources Planning and Management **135**(6): 537-546.

Williams, G., Roseen, R. M., Lenhart, J. H. and Kayhanian, M. (2009). Potential Data Analysis Methodology to Evaluate the Performance of Manufactured BMPs. World Environmental and Water Resources Congress 2009**:** 1-10.

Yu, S. L. and Stanford, R. L. (2007). Field Evaluation of a Stormwater Bioretention Filtration System. World Environmental and Water Resources Congress 2007**:** 1-10.

APPENDIX A List of Figures

List of Figures

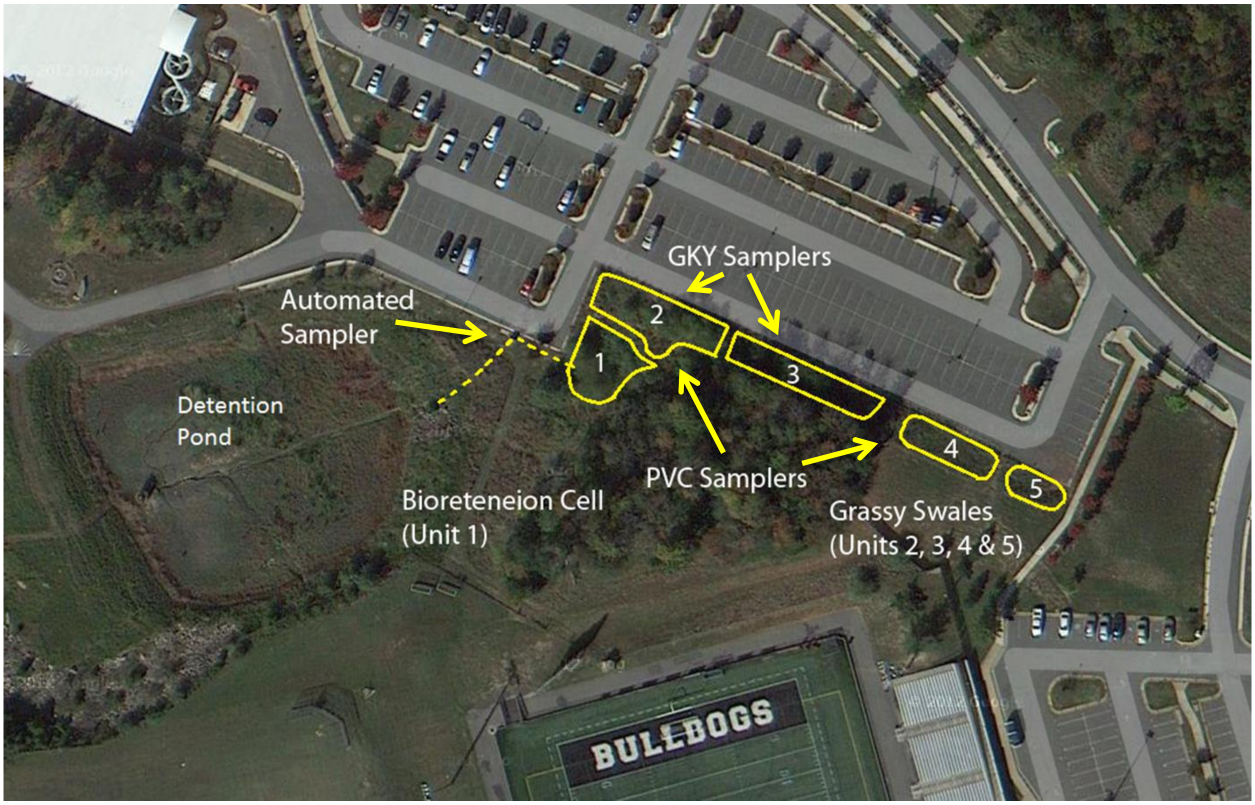


Figure A-1. Aerial view of the Cub Run Recreation Center LID facility with approximate outlines for the bioretention cell, grass swales and sampler locations (VT-OWML, 2012; Google Maps, 2013) Used under fair use, 2013.

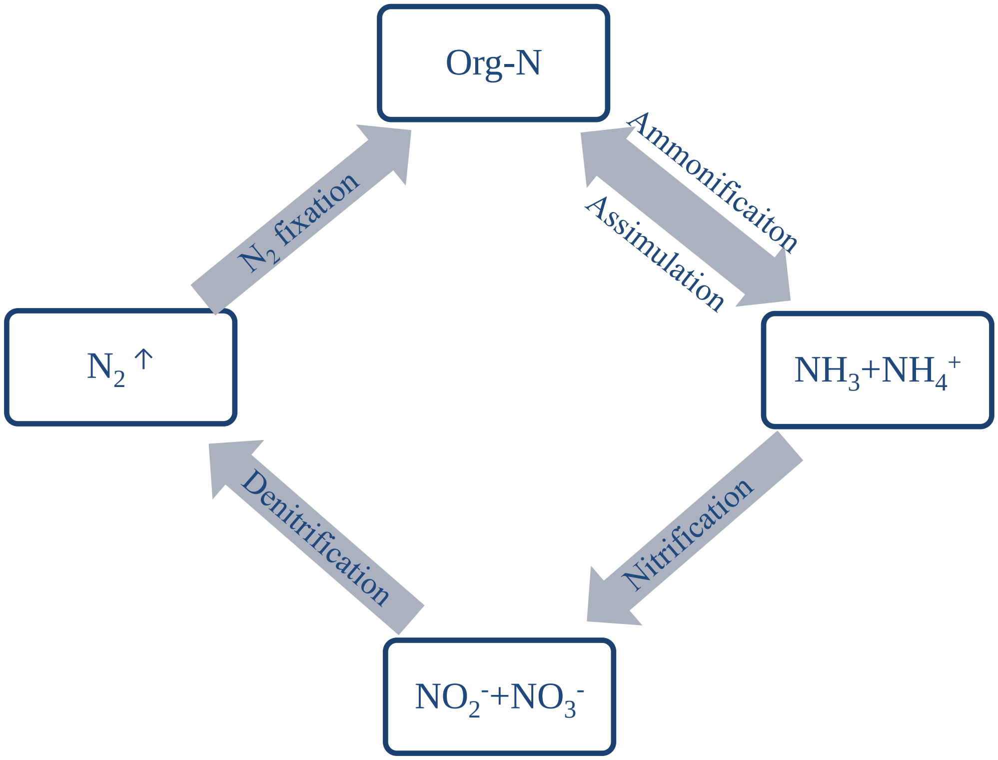


Figure A-2. Simplified Nitrogen Cycle, Based on: Grady (2011).

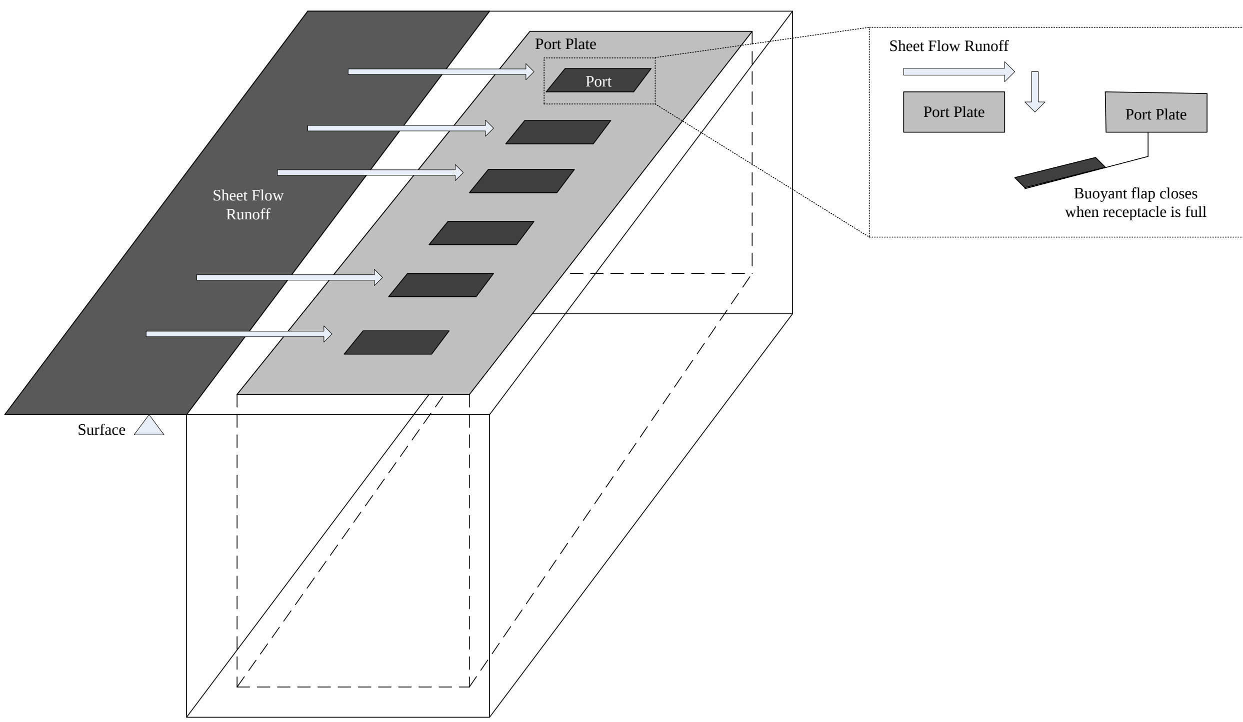


Figure A-3. Schematic of a GKY First Flush Sampler.

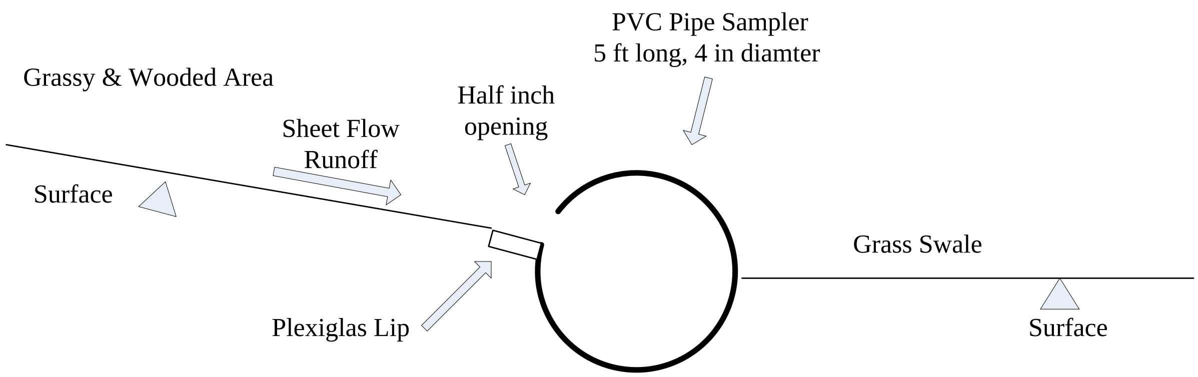


Figure A-4. Side view schematic of a PVC Sampler.

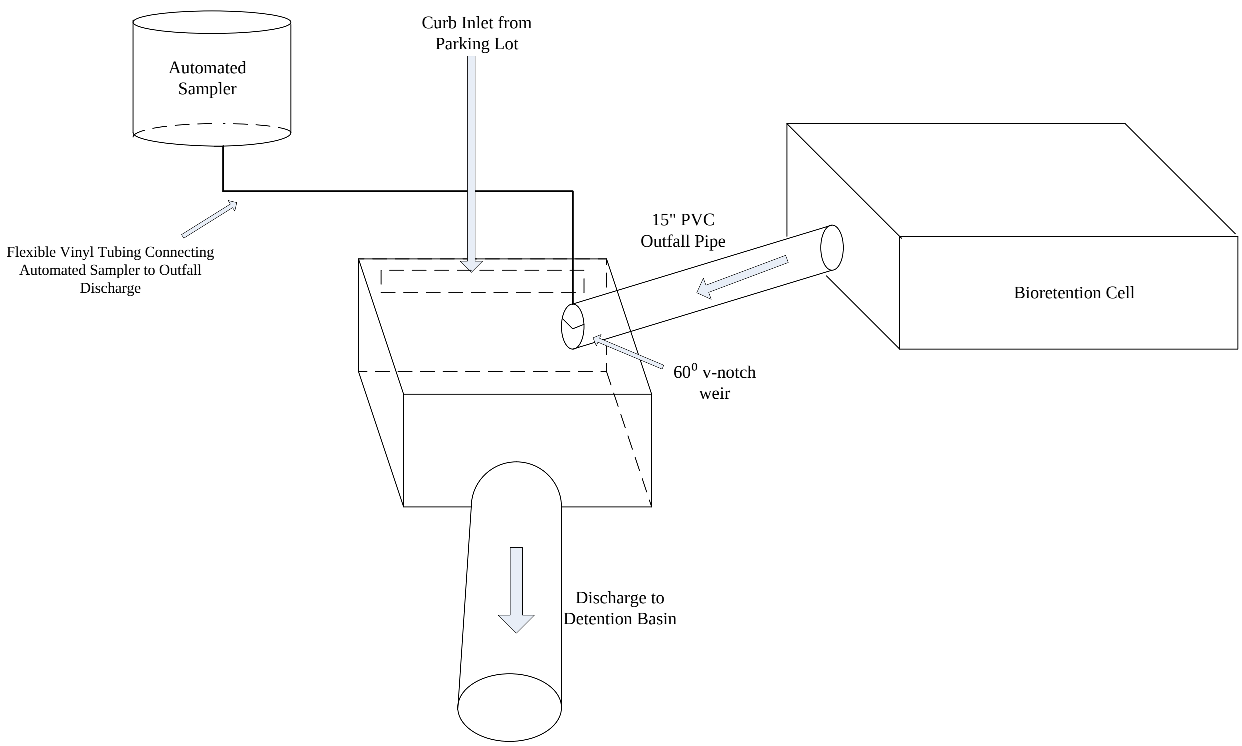
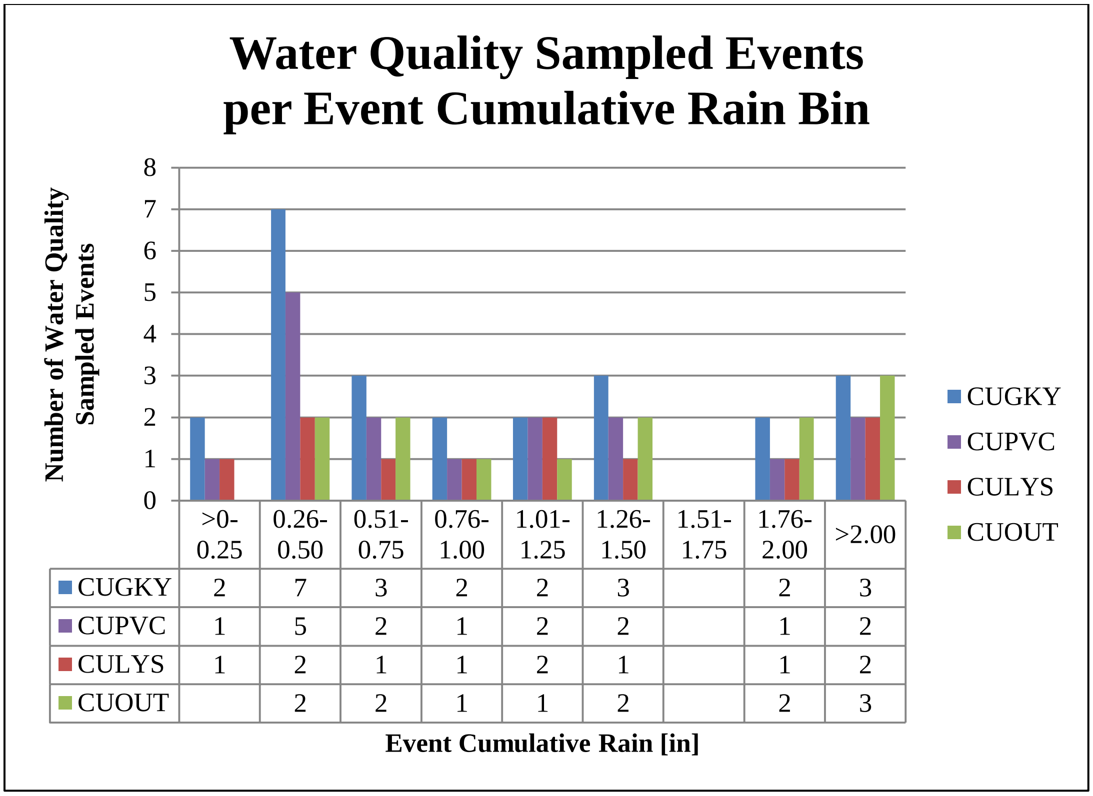
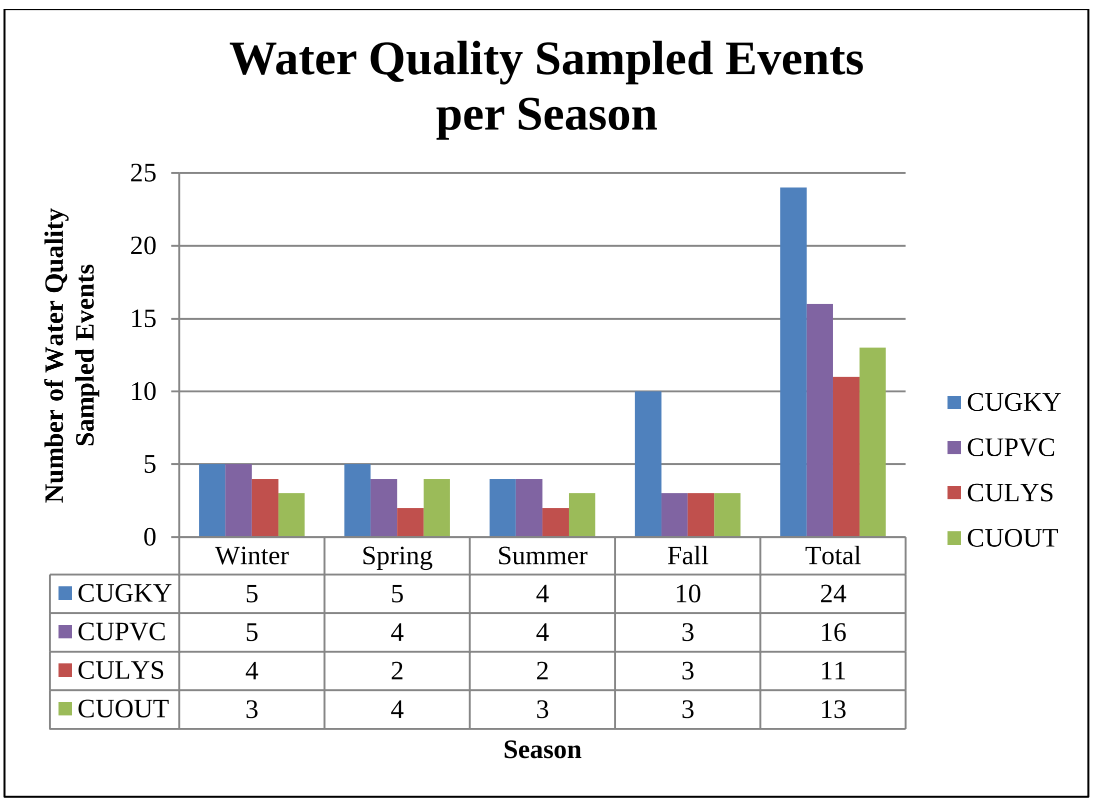


Figure A-5. Schematic of the sampling apparatus at the LID facility outfall.



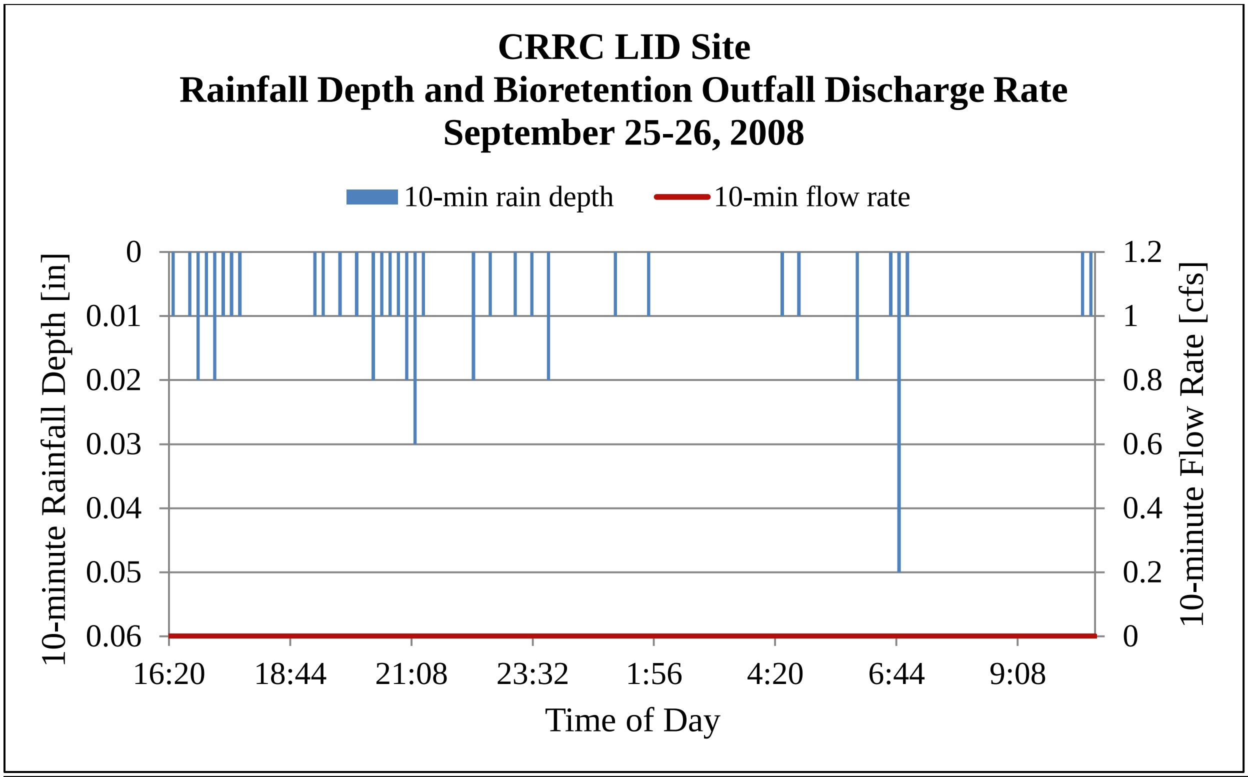
	>0-0.25	0.26-0.50	0.51-0.75	0.76-1.00	1.01-1.25	1.26-1.50	1.51-1.75	1.76-2.00	>2.00
CUGKY	2	7	3	2	2	3		2	3
CUPVC	1	5	2	1	2	2		1	2
CULYS	1	2	1	1	2	1		1	2
CUOUT		2	2	1	1	2		2	3

Figure A-6. Water quality sampled events per cumulative rain amount bar graph.



	Winter	Spring	Summer	Fall	Total
CUGKY	5	5	4	10	24
CUPVC	5	4	4	3	16
CULYS	4	2	2	3	11
CUOUT	3	4	3	3	13

Figure A-7. Water quality sampled events per season bar graph.



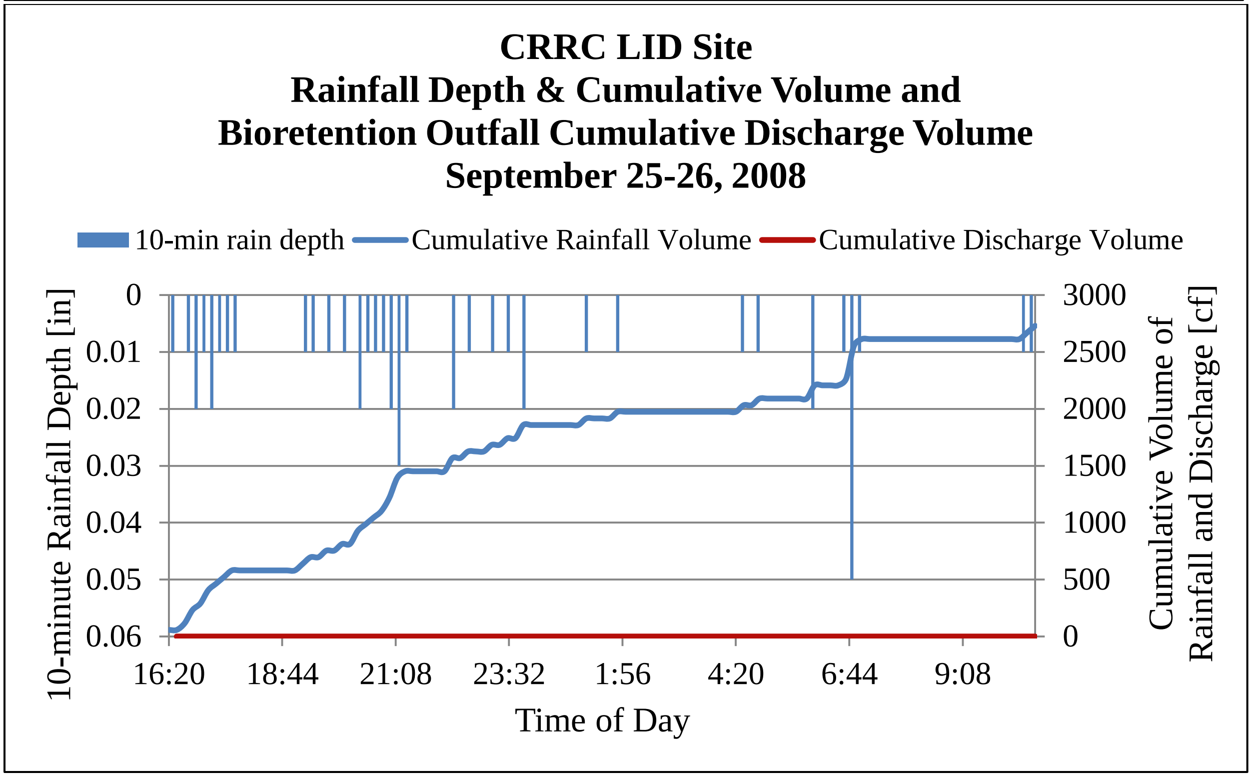
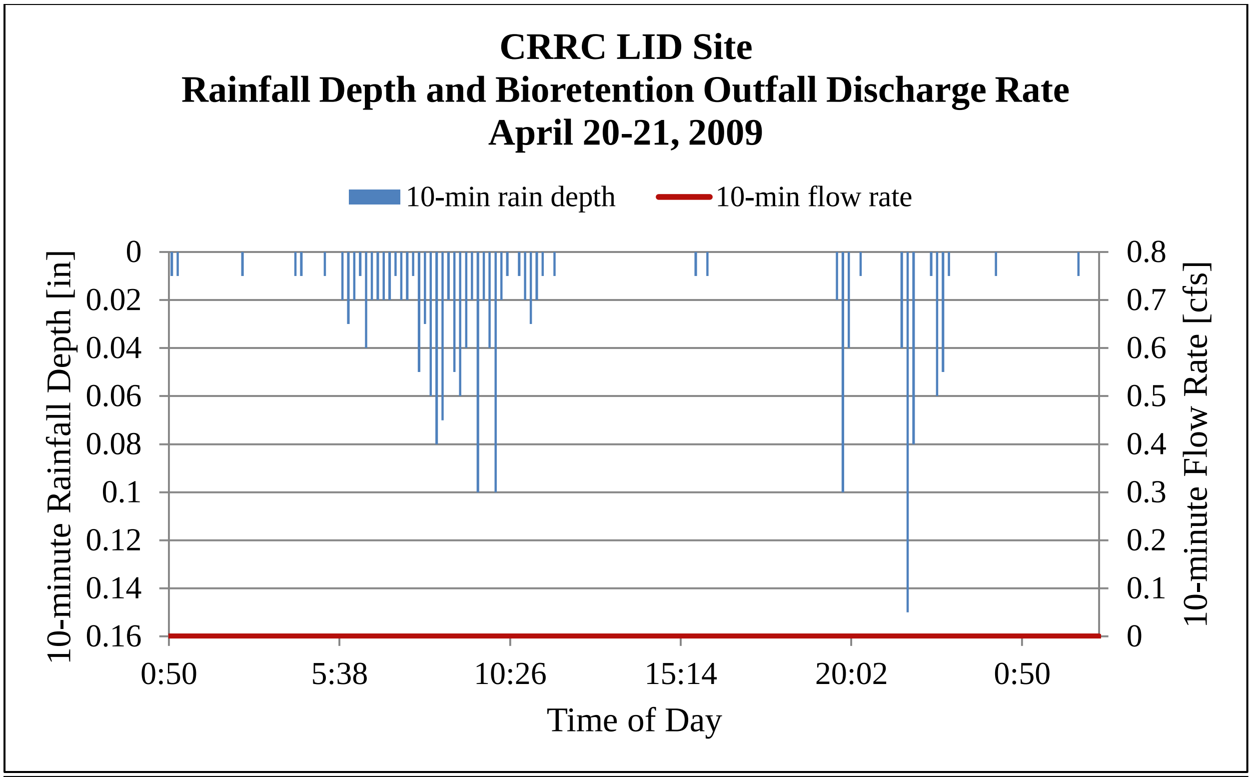


Figure A-8. Hydrograph and hyetograph of Sept 25-26, 2008 storm event.
Dry time=298.9 hrs.



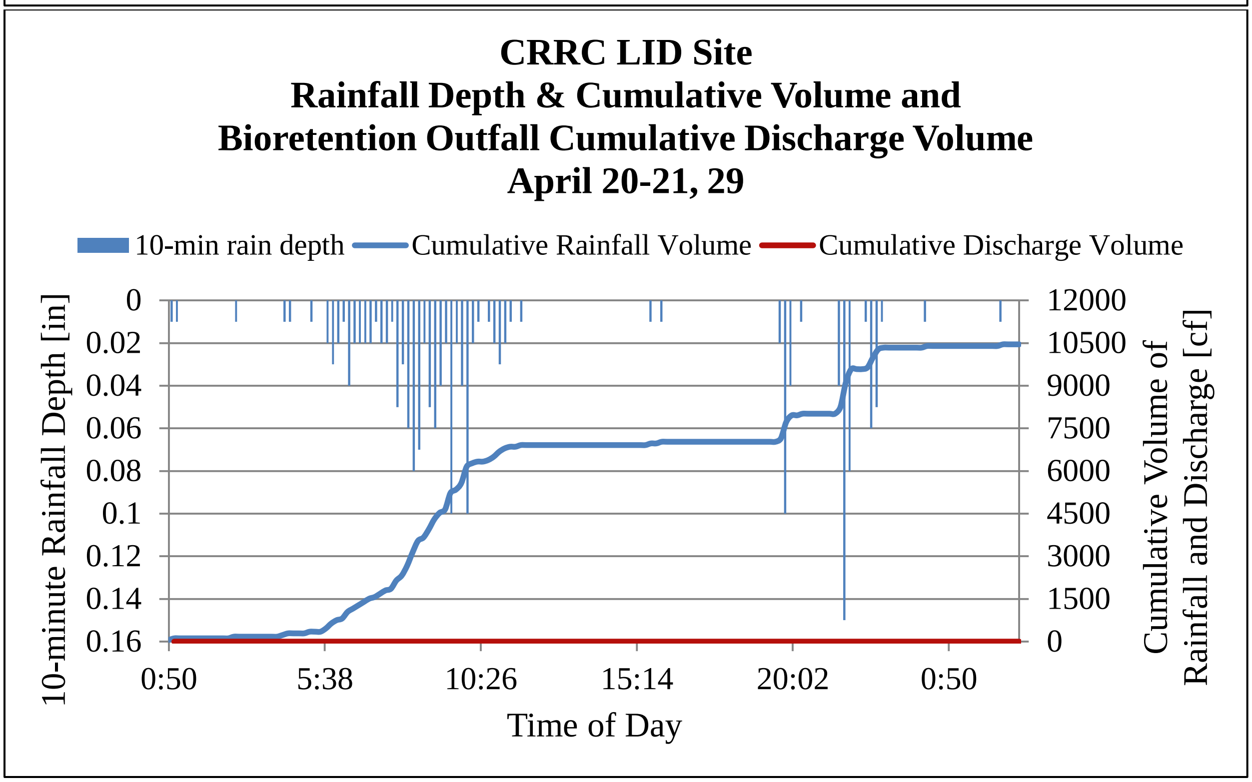
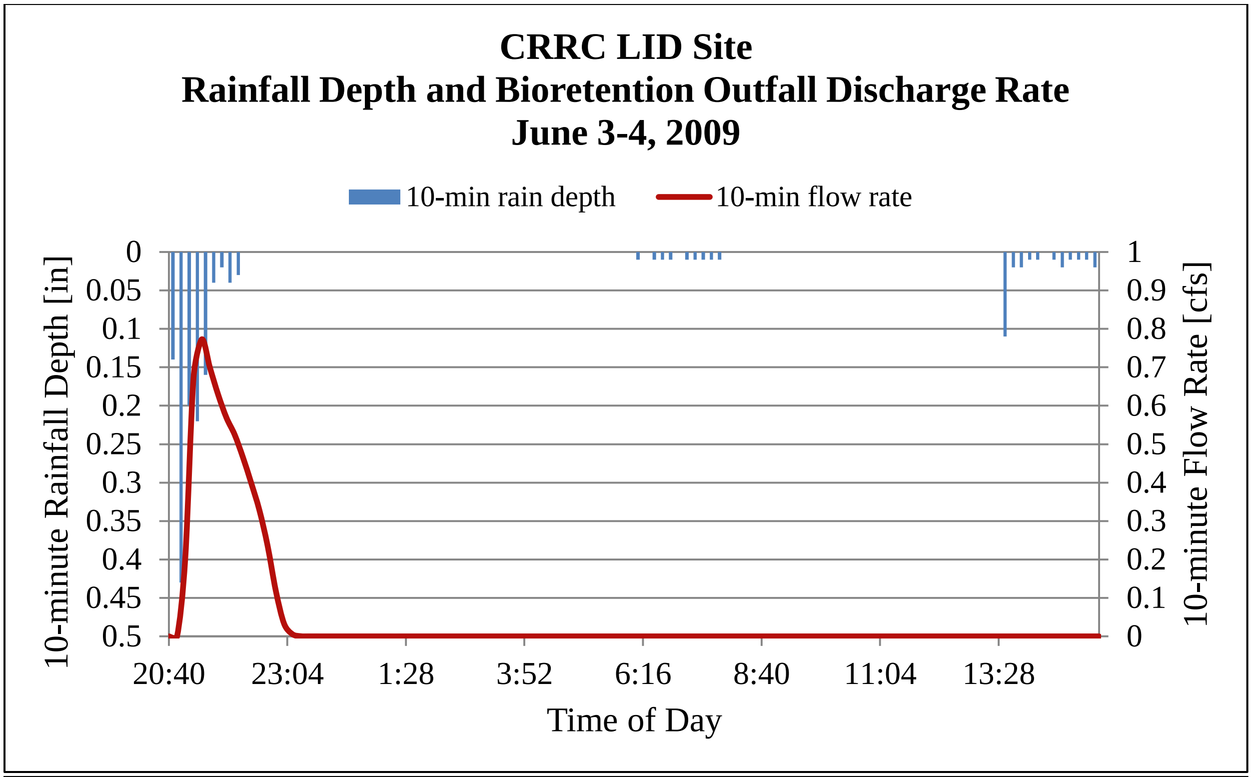


Figure A-9. Hydrograph and hyetograph of Apr 20-21, 2009 storm event.
Dry time= 98.8 hrs.



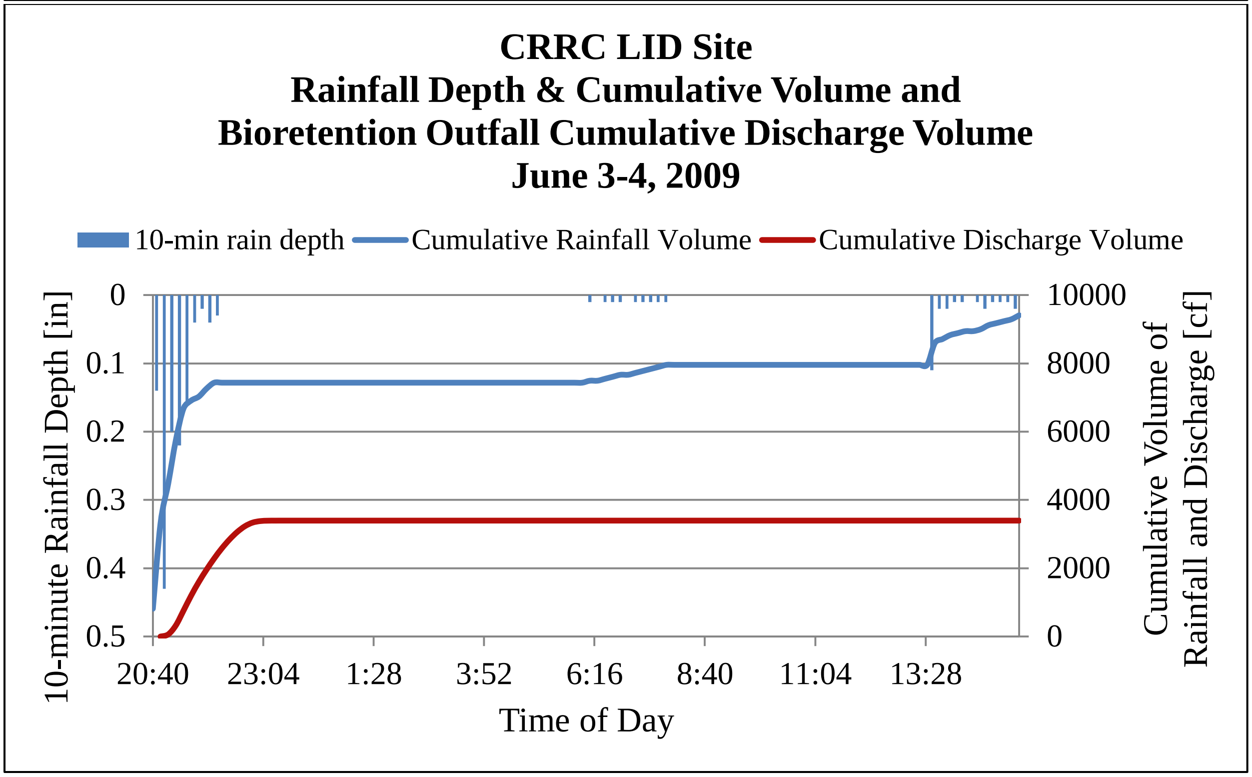
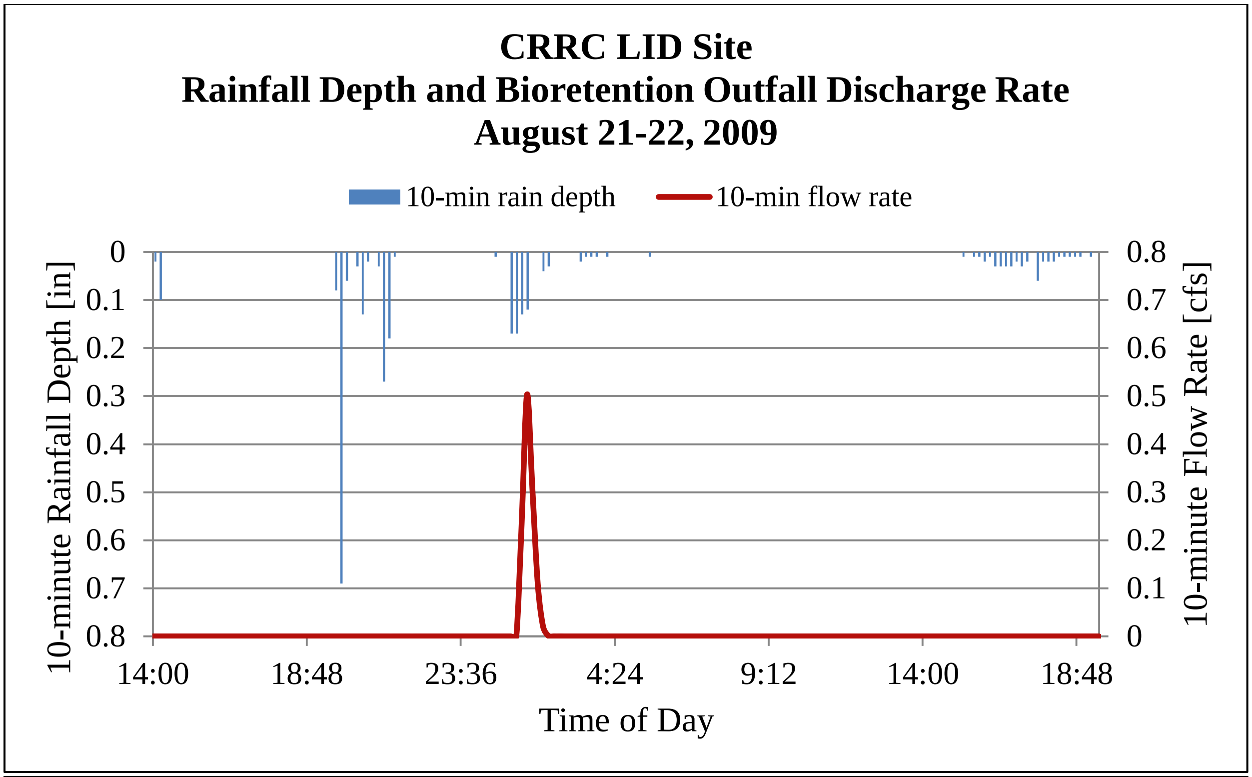


Figure A-10. Hydrograph and hyetograph of Jun 3-4, 2009 storm event.
Dry time= 85.9 hrs.



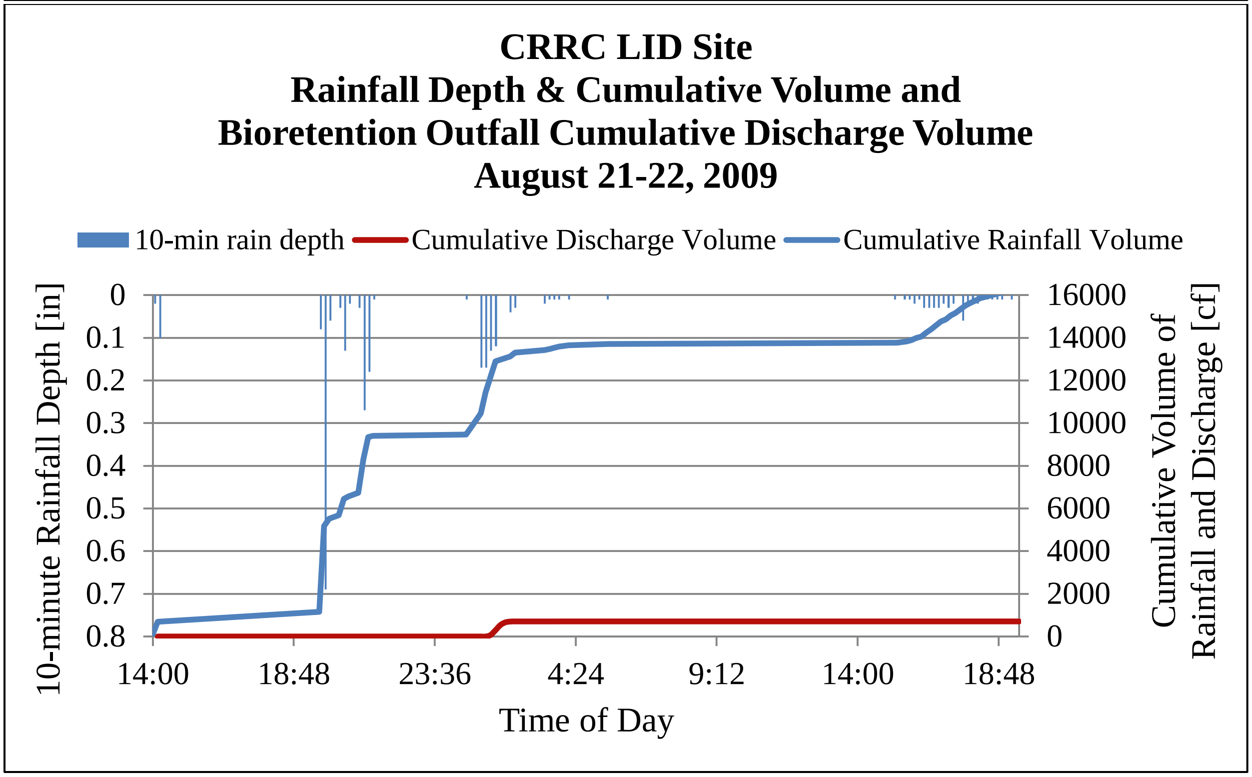
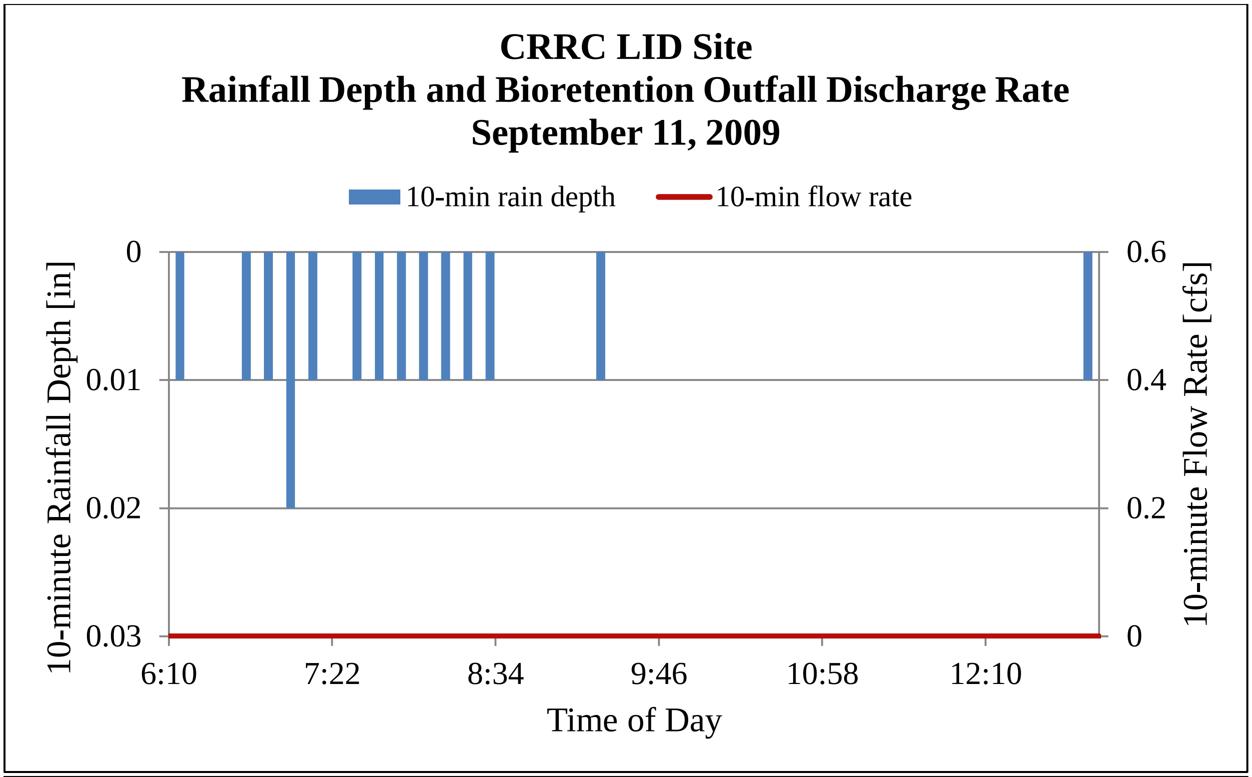


Figure A-11. Hydrograph and hyetograph of Aug 21-22, 2009 storm event.
Dry time= 368.5 hrs.



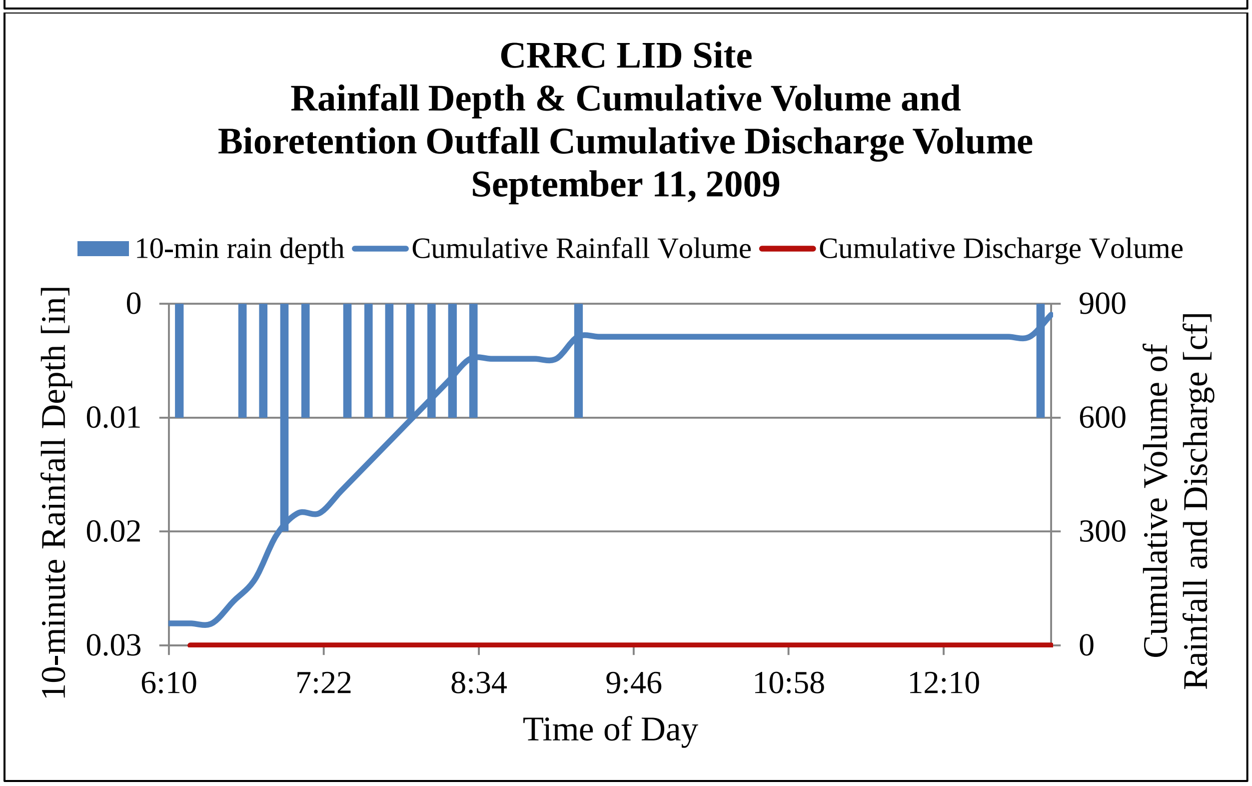
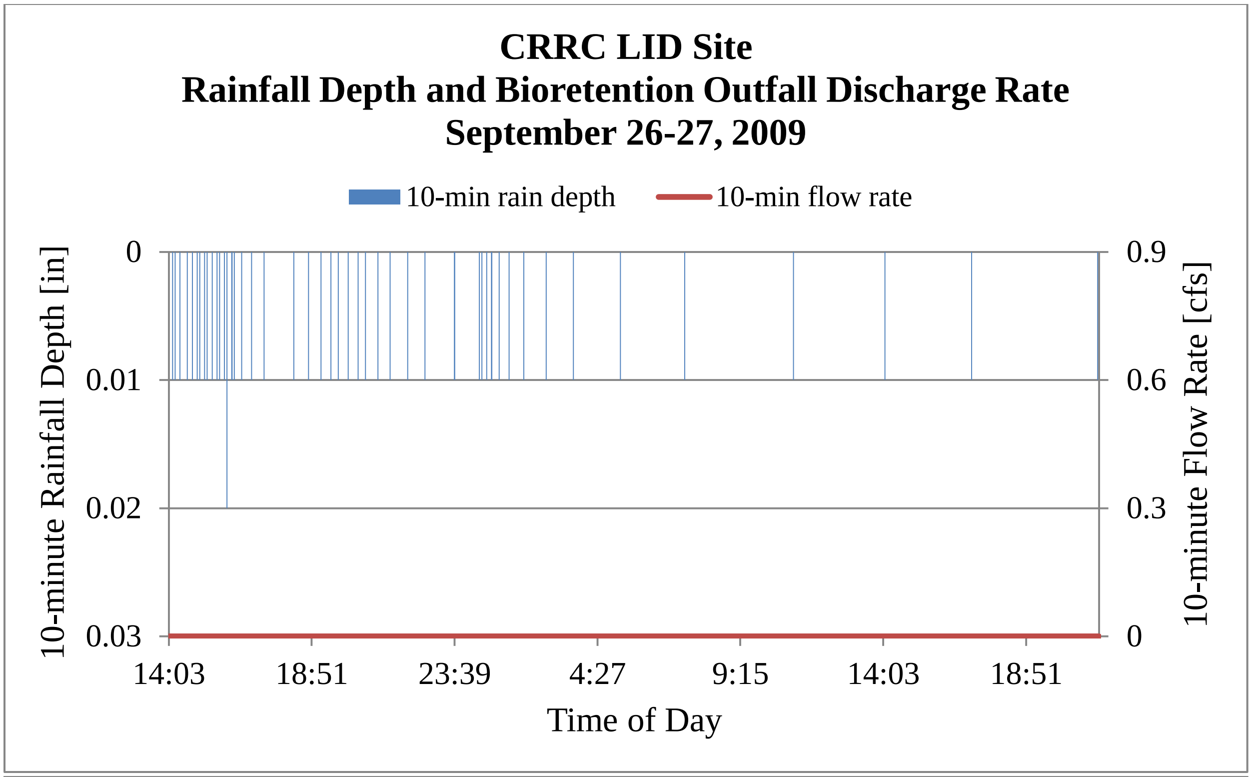


Figure A-12. Hydrograph and hyetograph of Sept 11, 2009 storm event.
Dry time= 69.5 hrs.



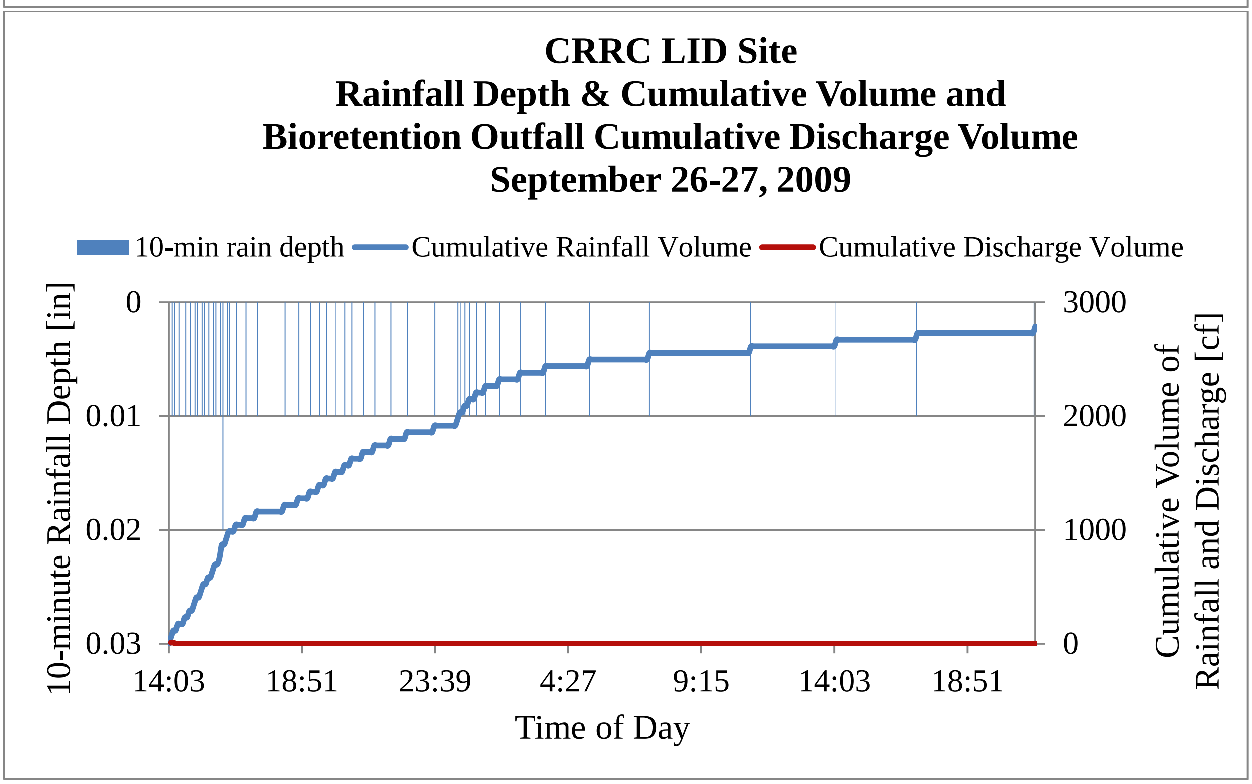
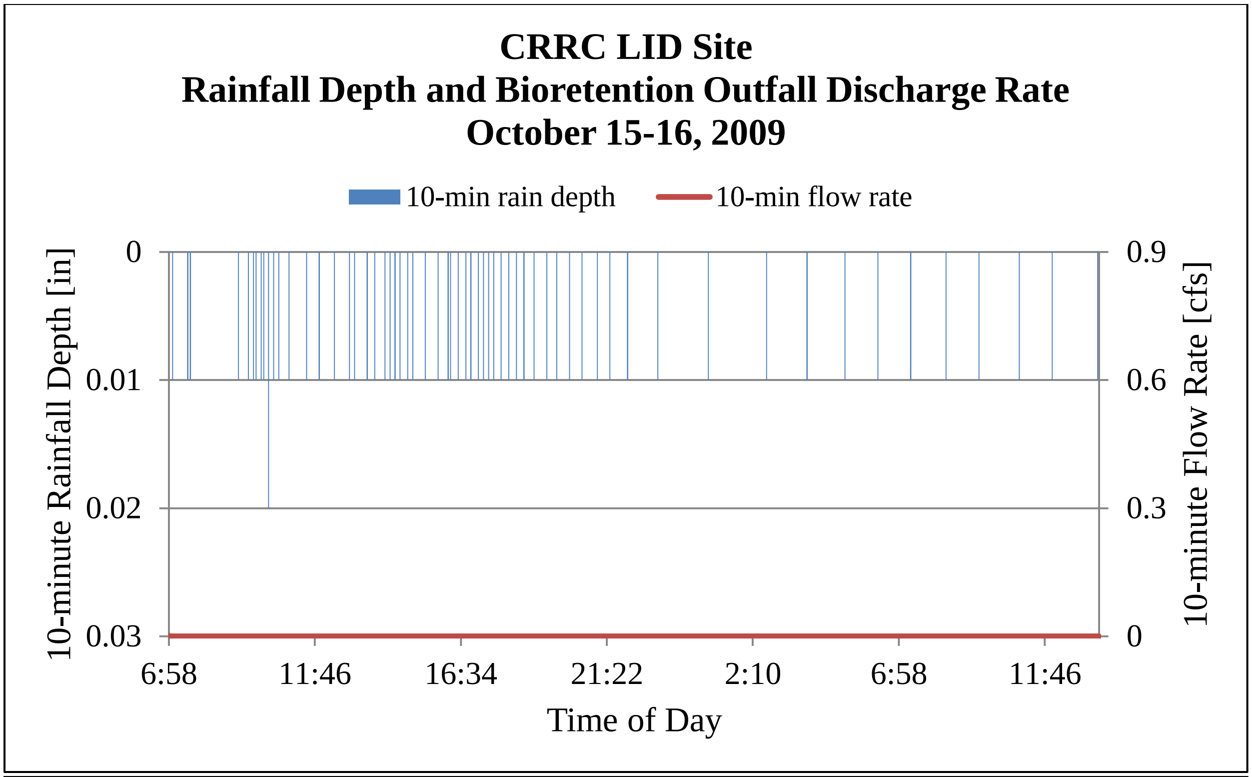


Figure A-13. Hydrograph and hyetograph of Sept 26-27, 2009 storm event.
Dry time = 30.1 hrs.



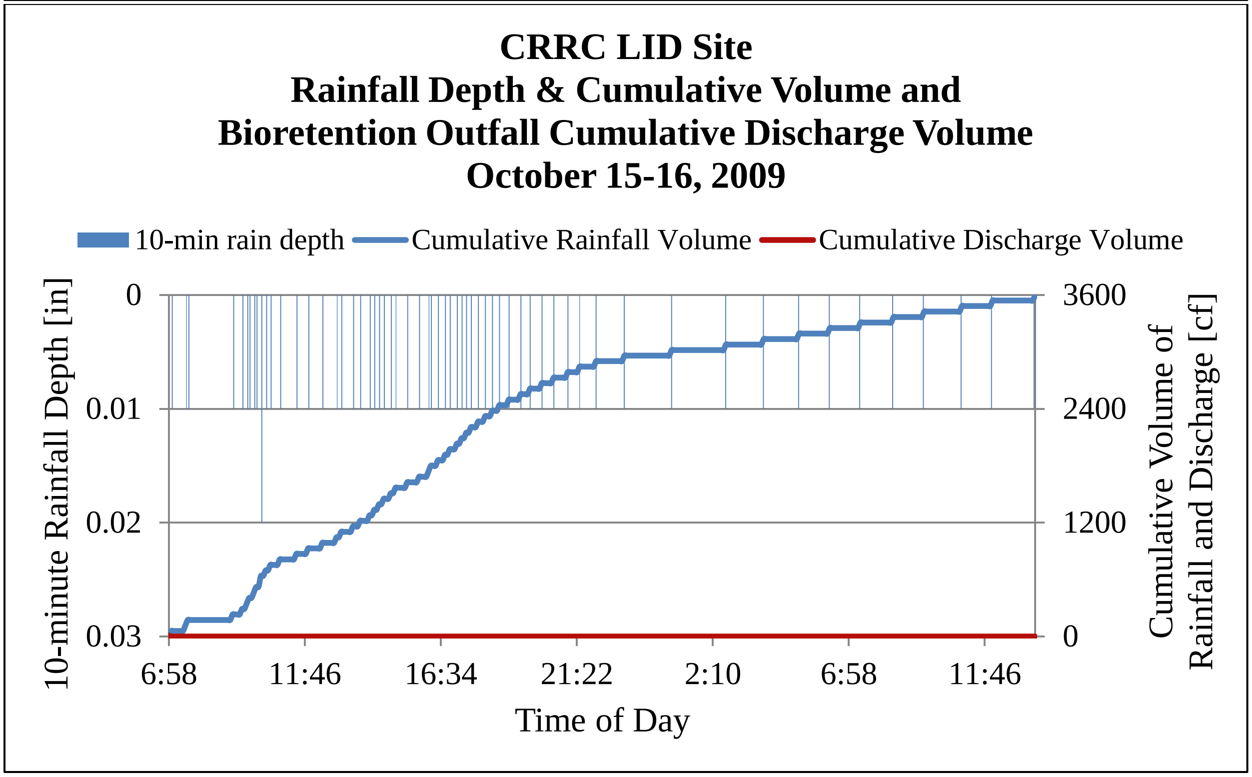
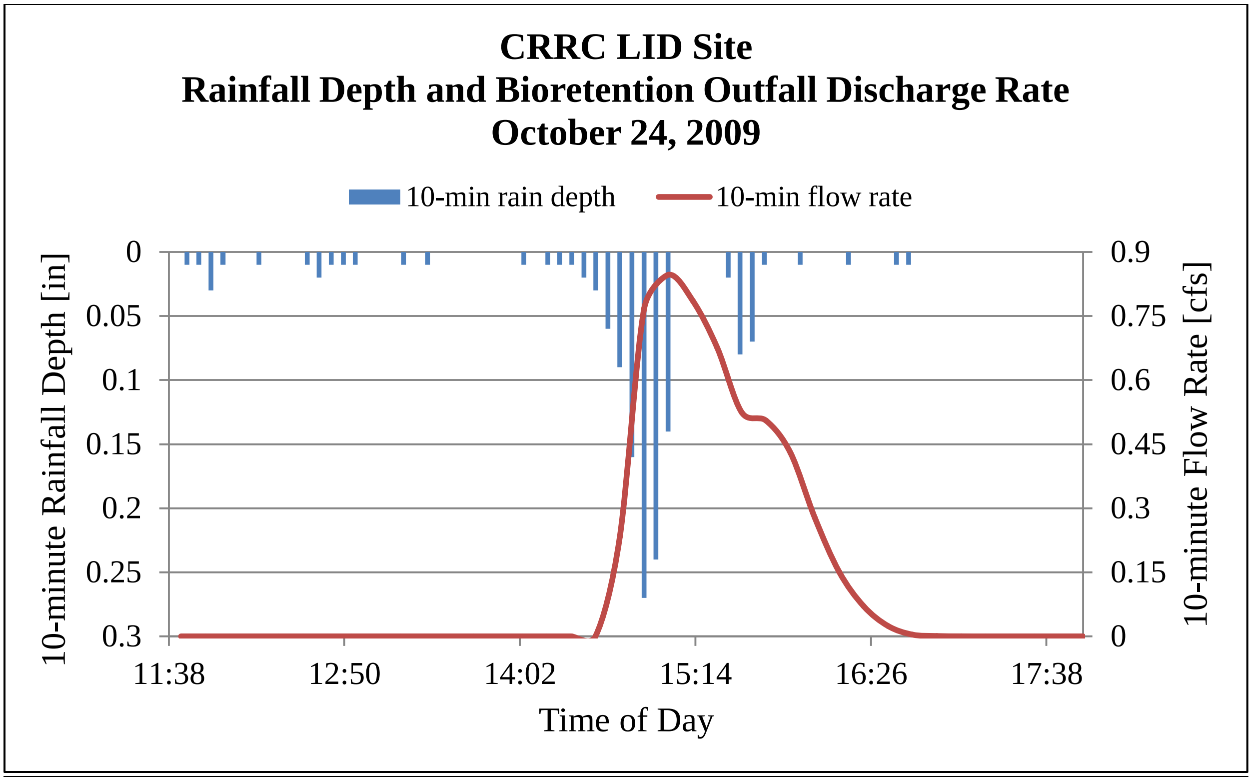


Figure A-14. Hydrograph and hyetograph of Oct 15-16, 2009 storm event.
Dry time = 8.3 hrs.



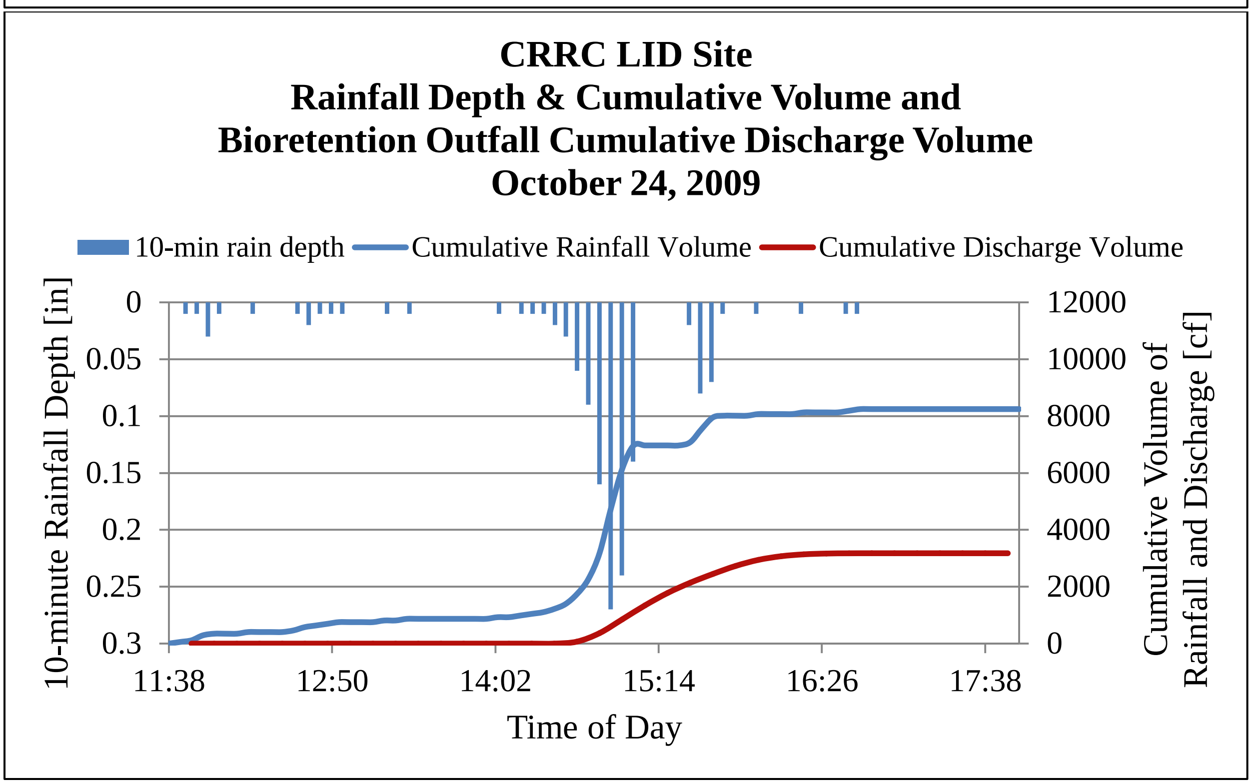
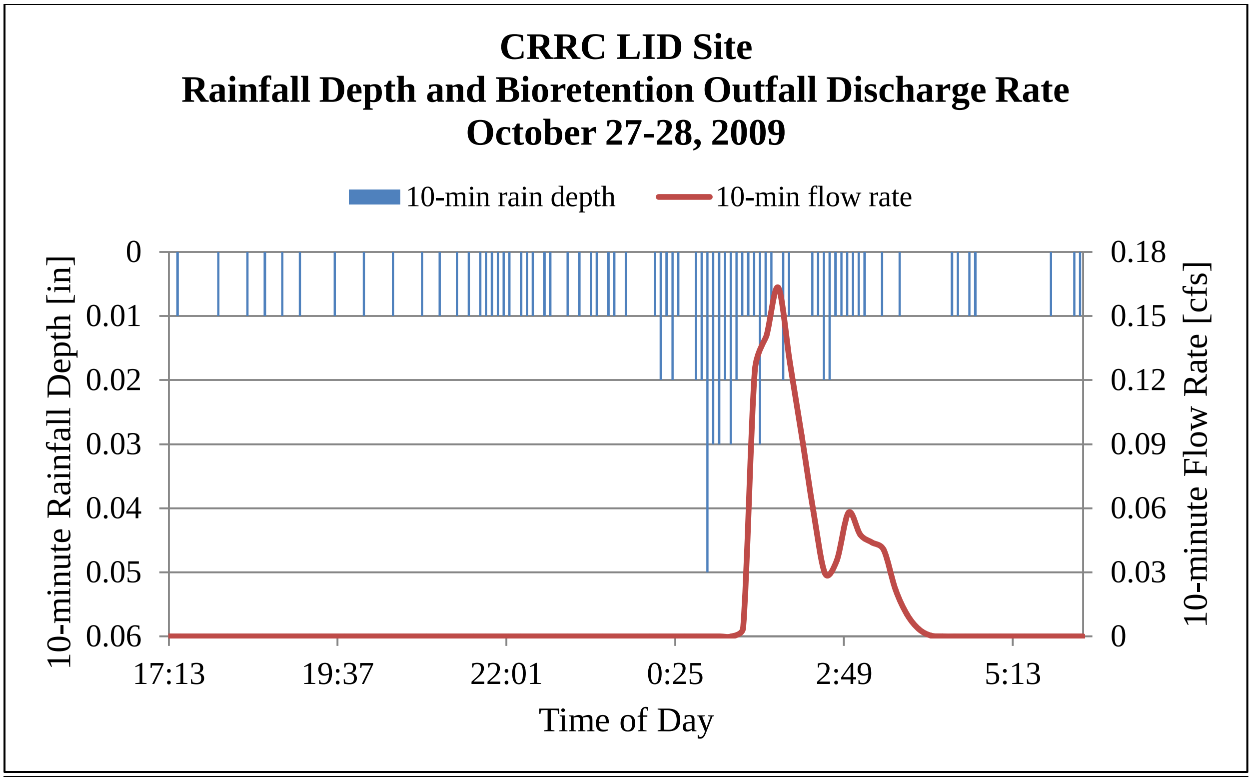


Figure A-15. Hydrograph and hyetograph of Oct 24, 2009 storm event.
Dry time = 151.7 hrs.



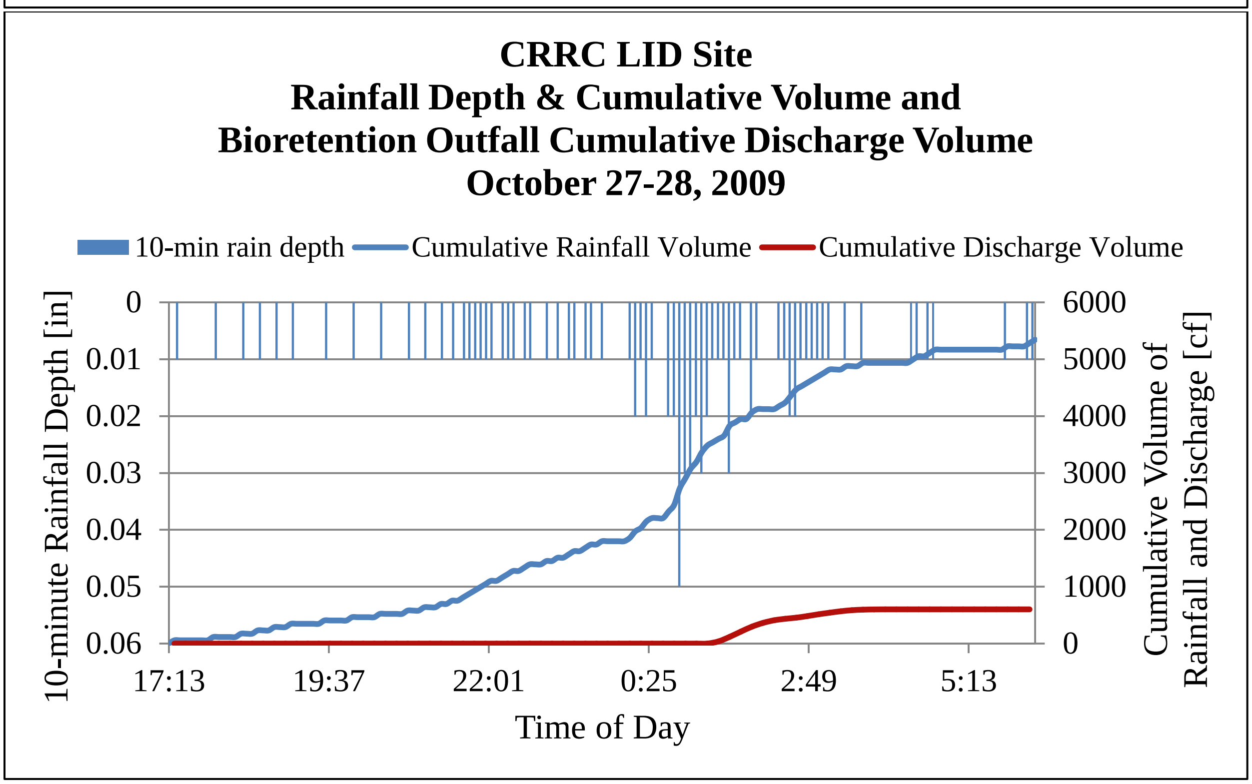
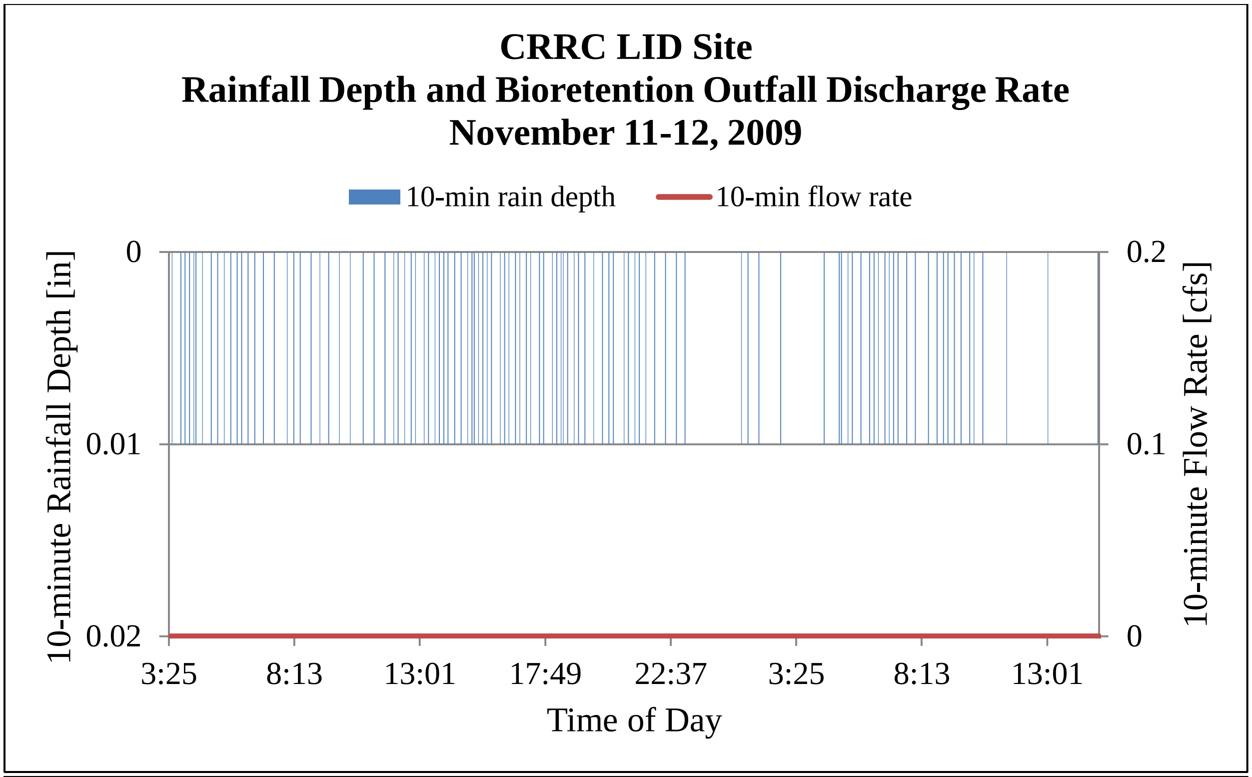


Figure A-16. Hydrograph and hyetograph of Oct 27-28, 2009 storm event.
Dry time = 10.7 hrs.



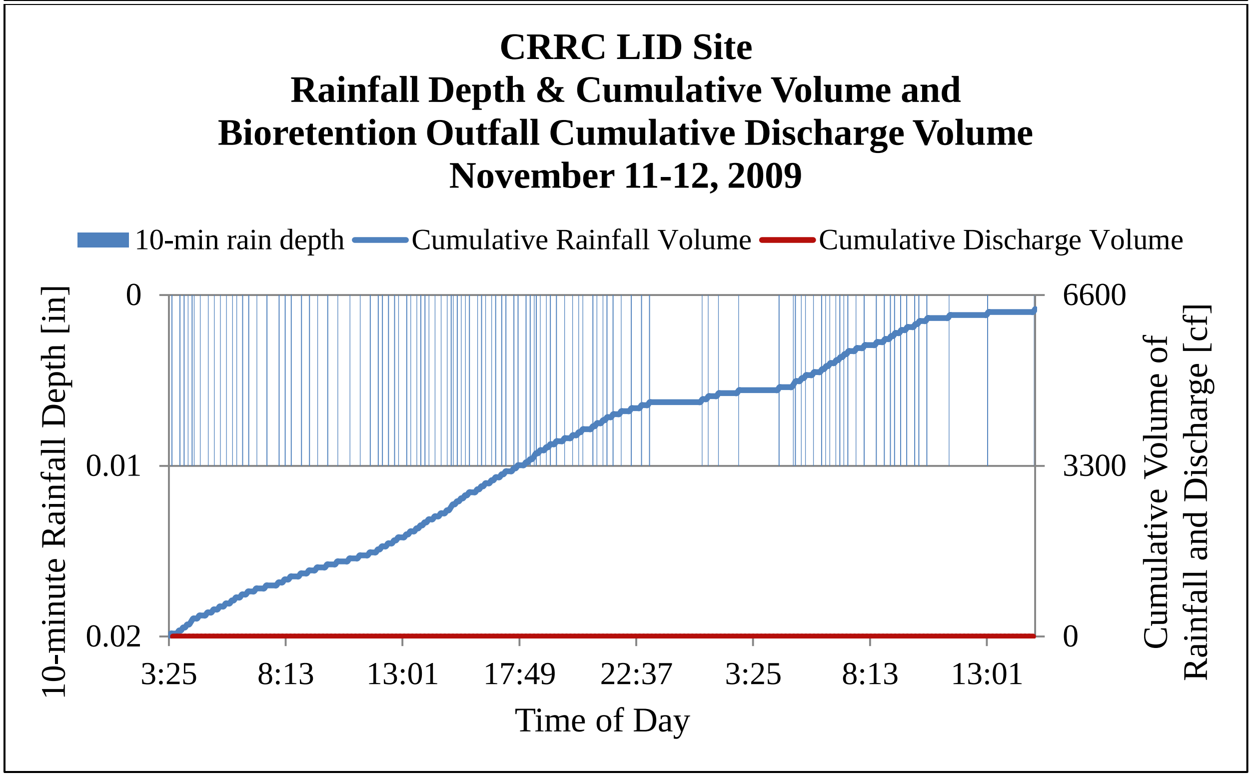
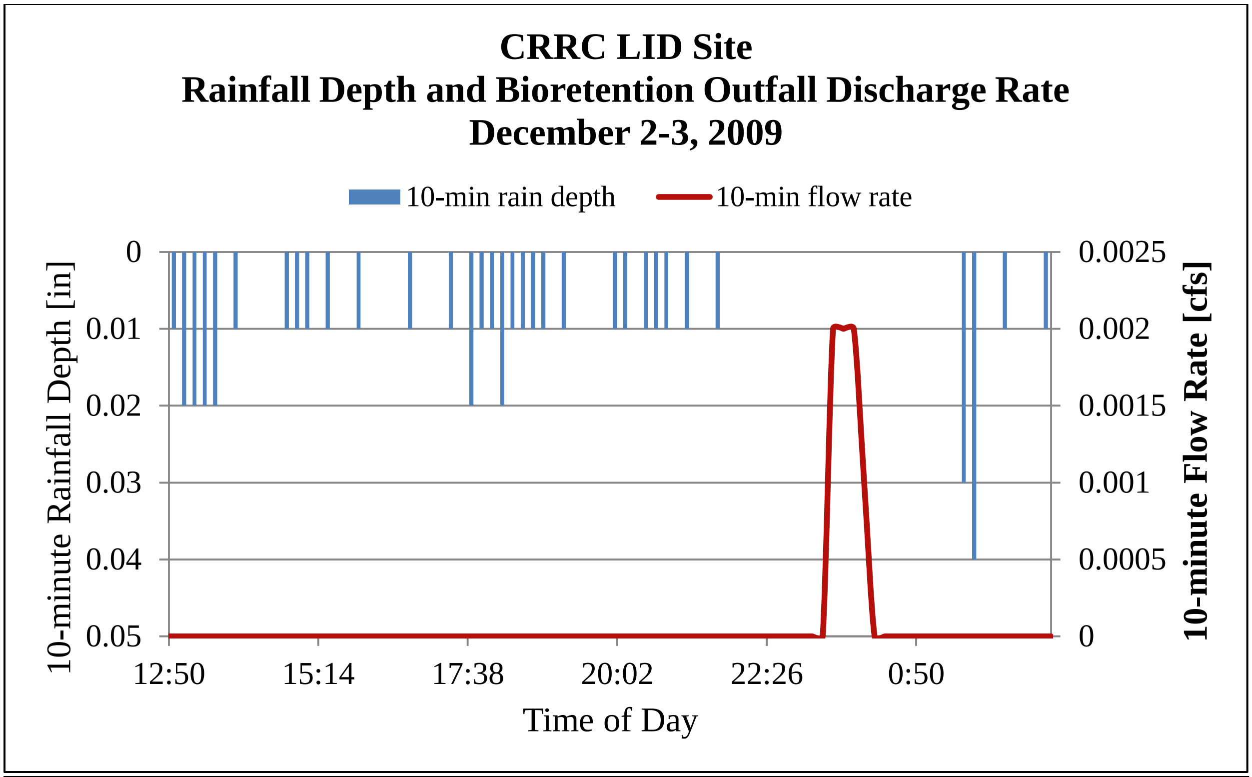


Figure A-17. Hydrograph and hyetograph of Nov 11-12, 2009 storm event.
Dry time = 230.1 hrs.



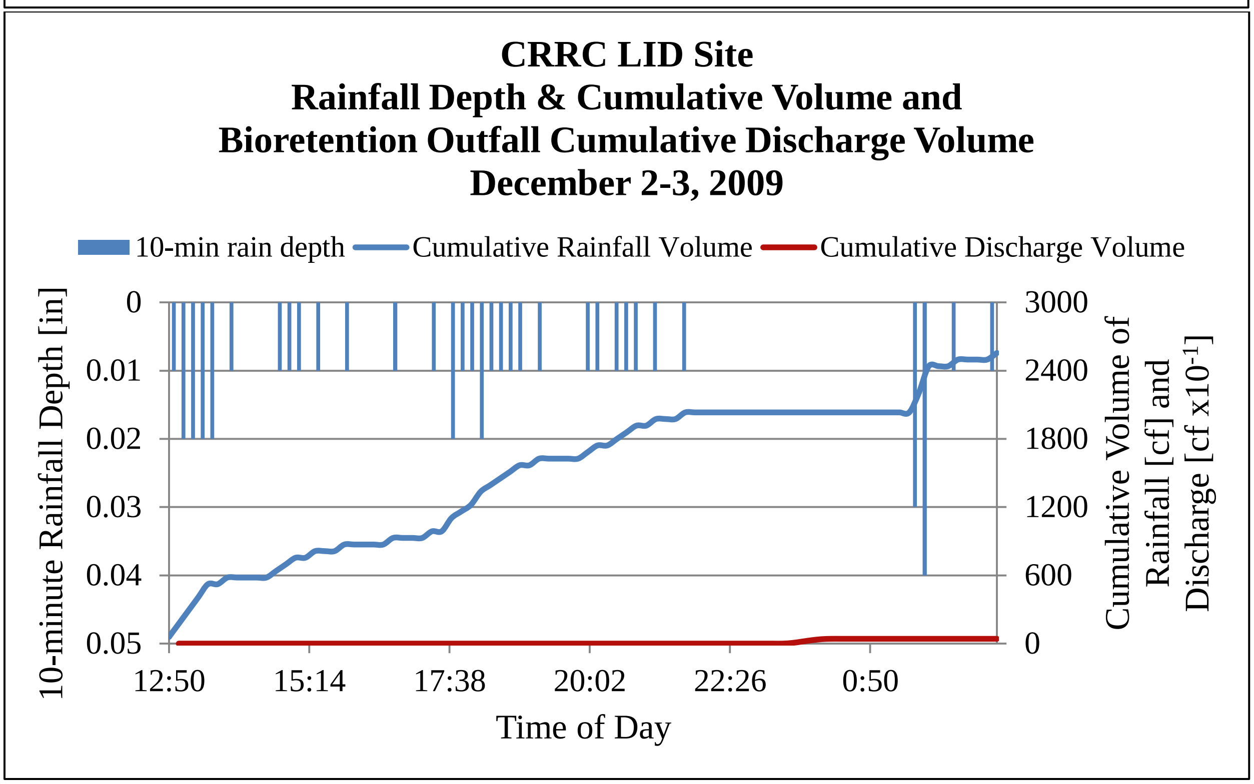
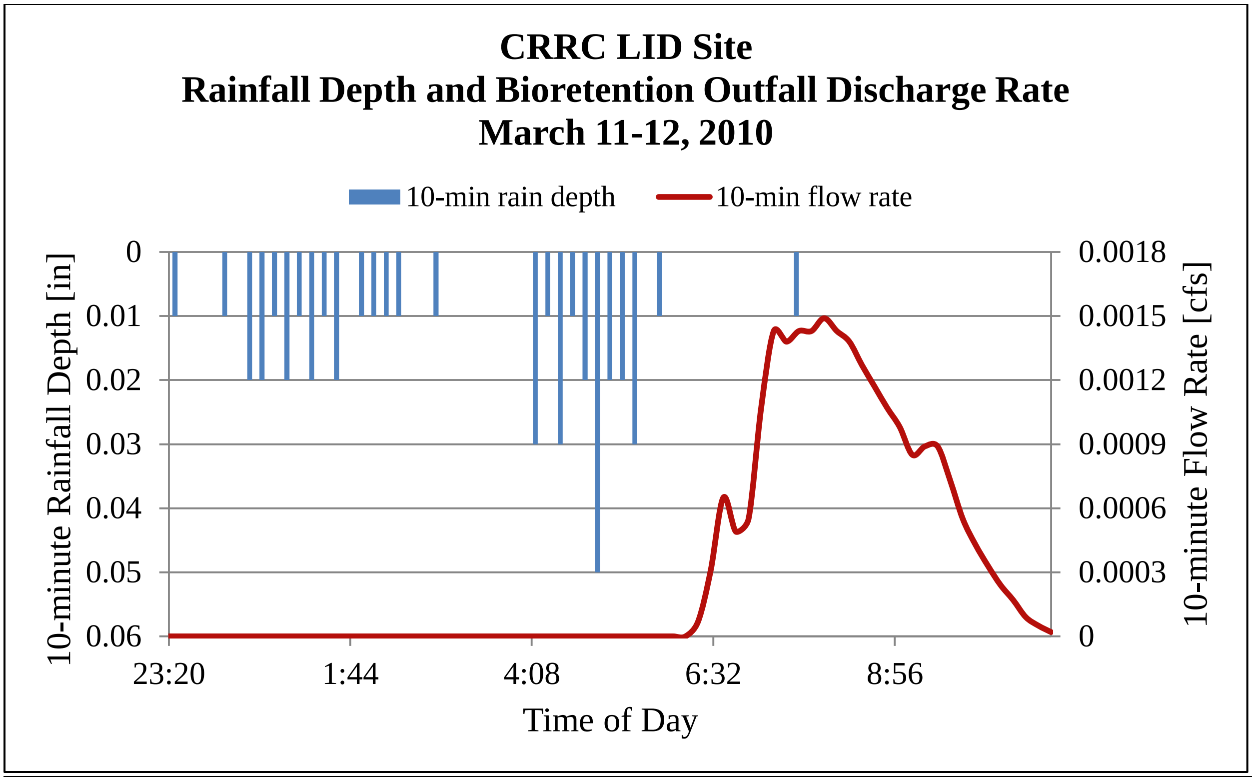


Figure A-18. Hydrograph and hyetograph of Dec 2-3, 2009 storm event.
Dry time = 42.7 hrs.



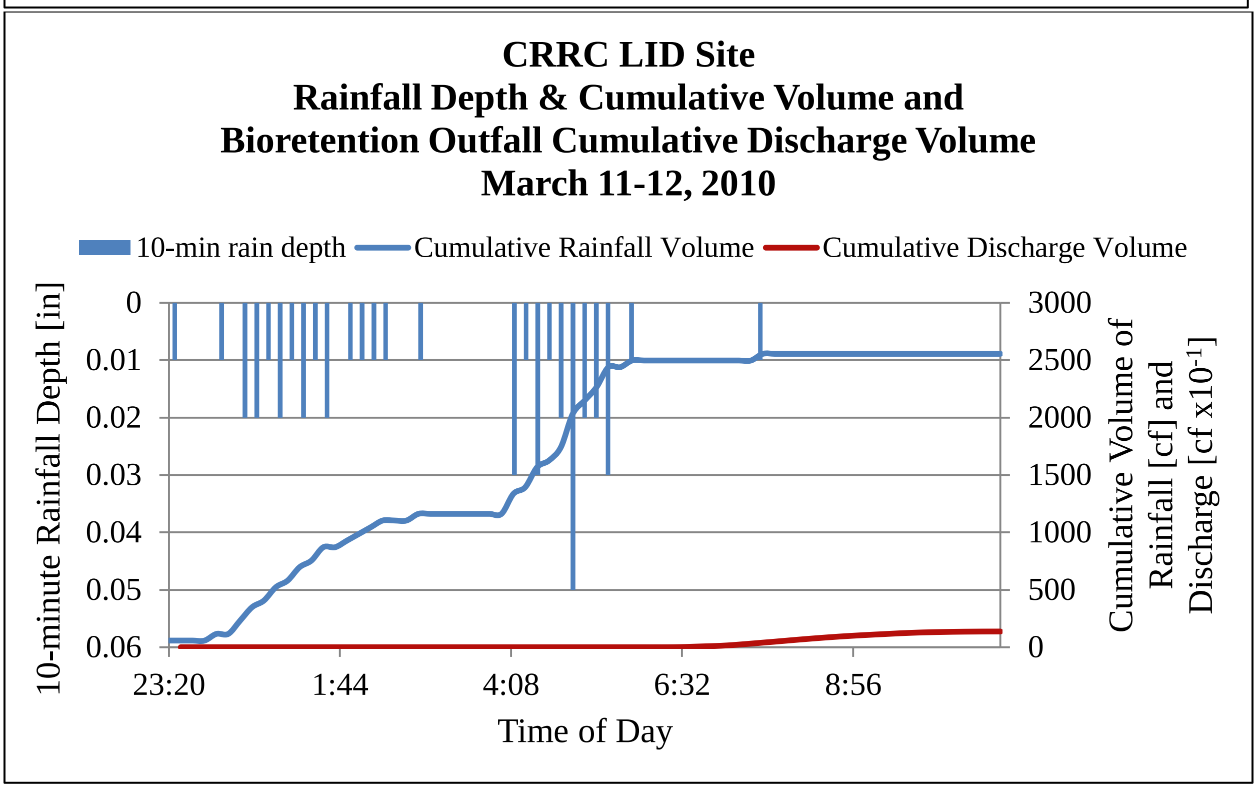
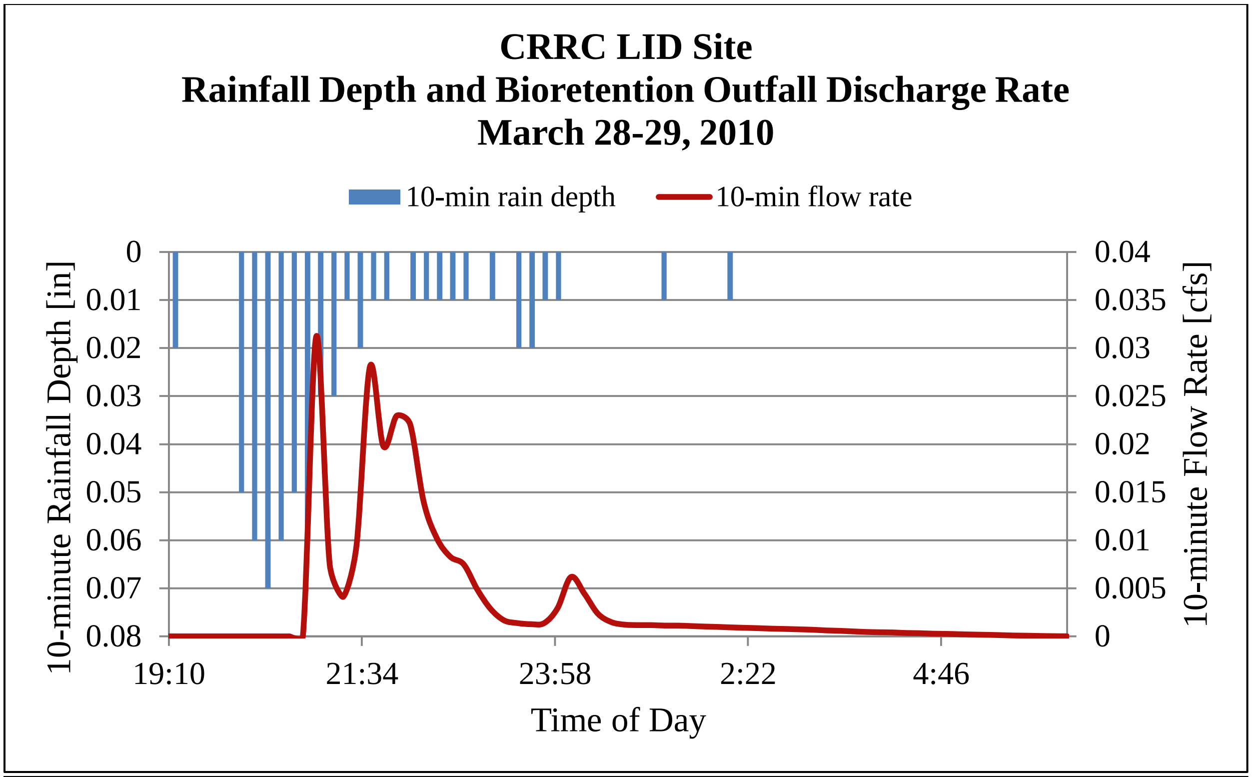


Figure A-19. Hydrograph and hyetograph of Mar 11-12, 2010 storm event.
Dry time = 217.3 hrs.



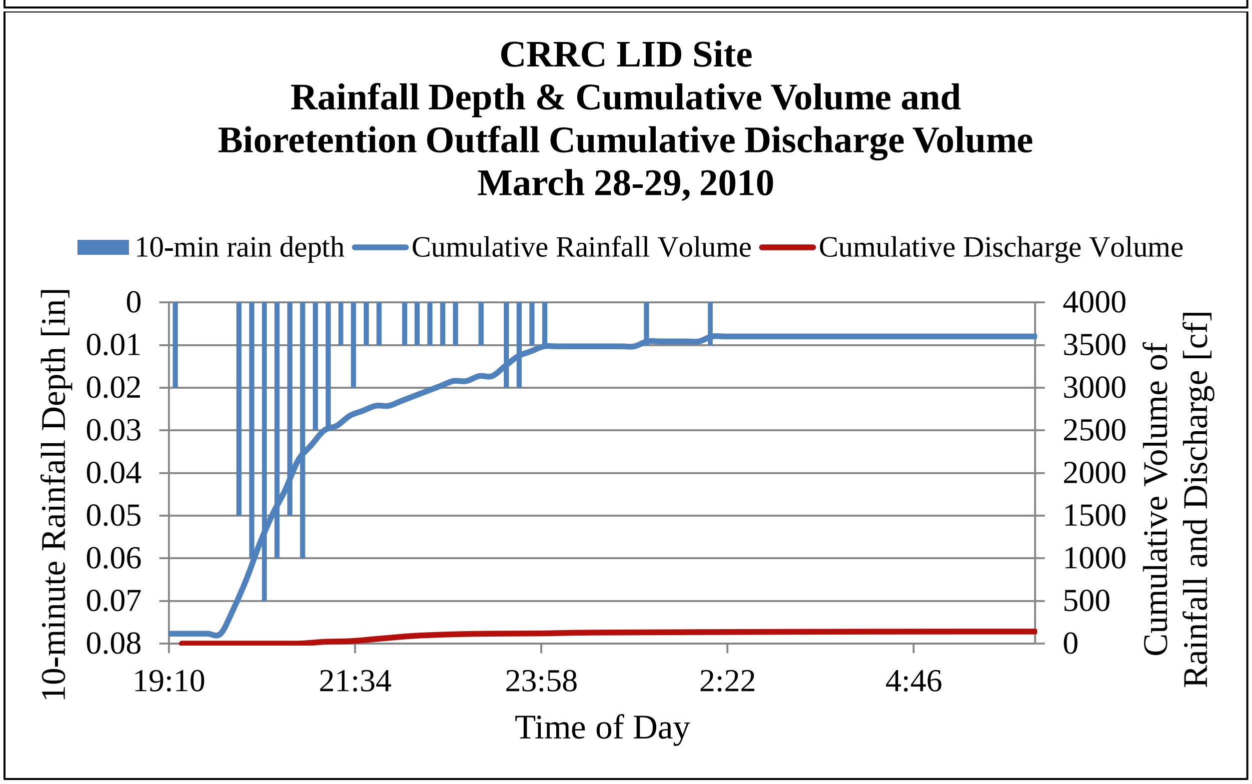
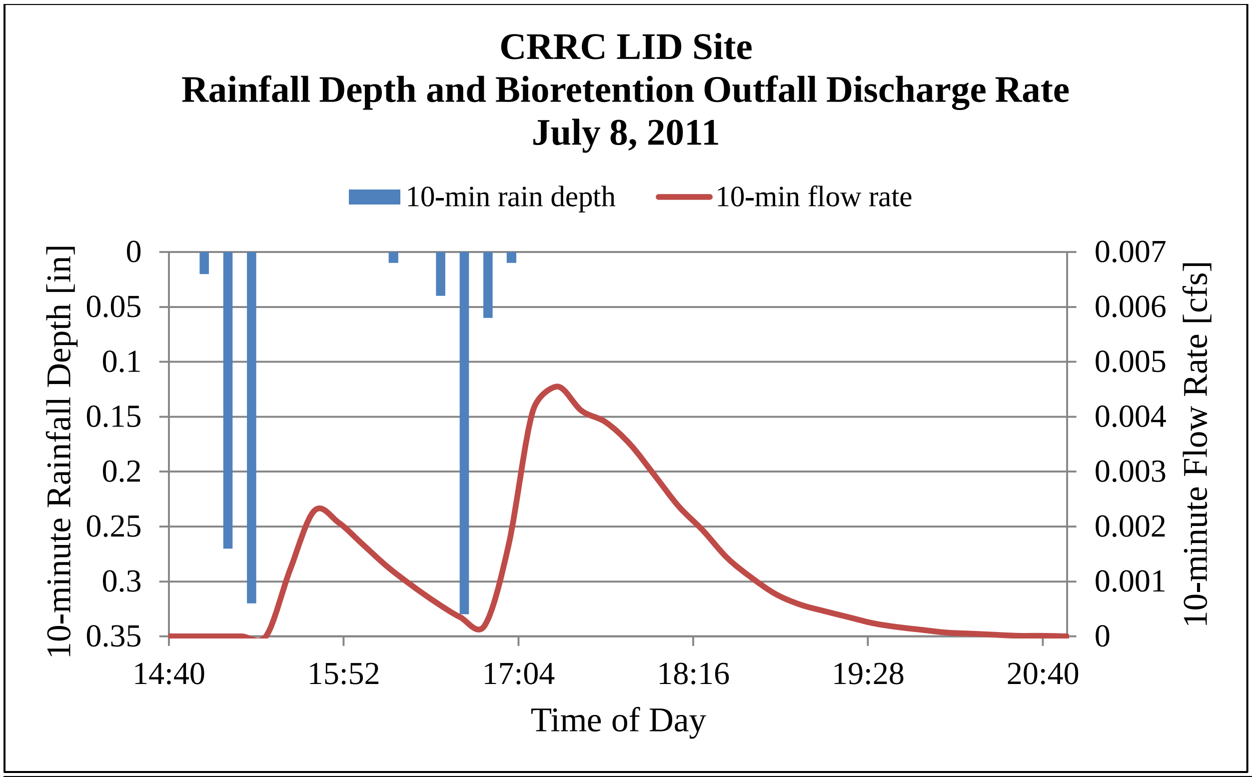


Figure A-20. Hydrograph and hyetograph of Mar 28-29, 2010 storm event.
Dry time = 58.0 hrs.



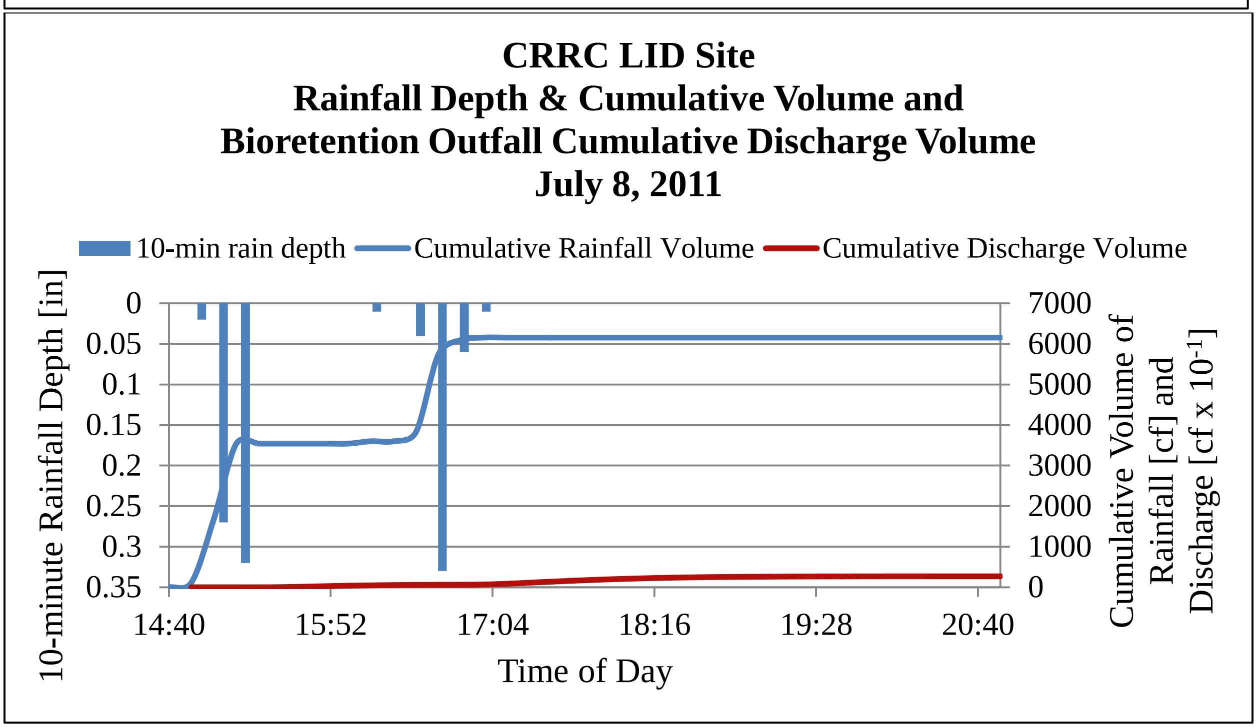
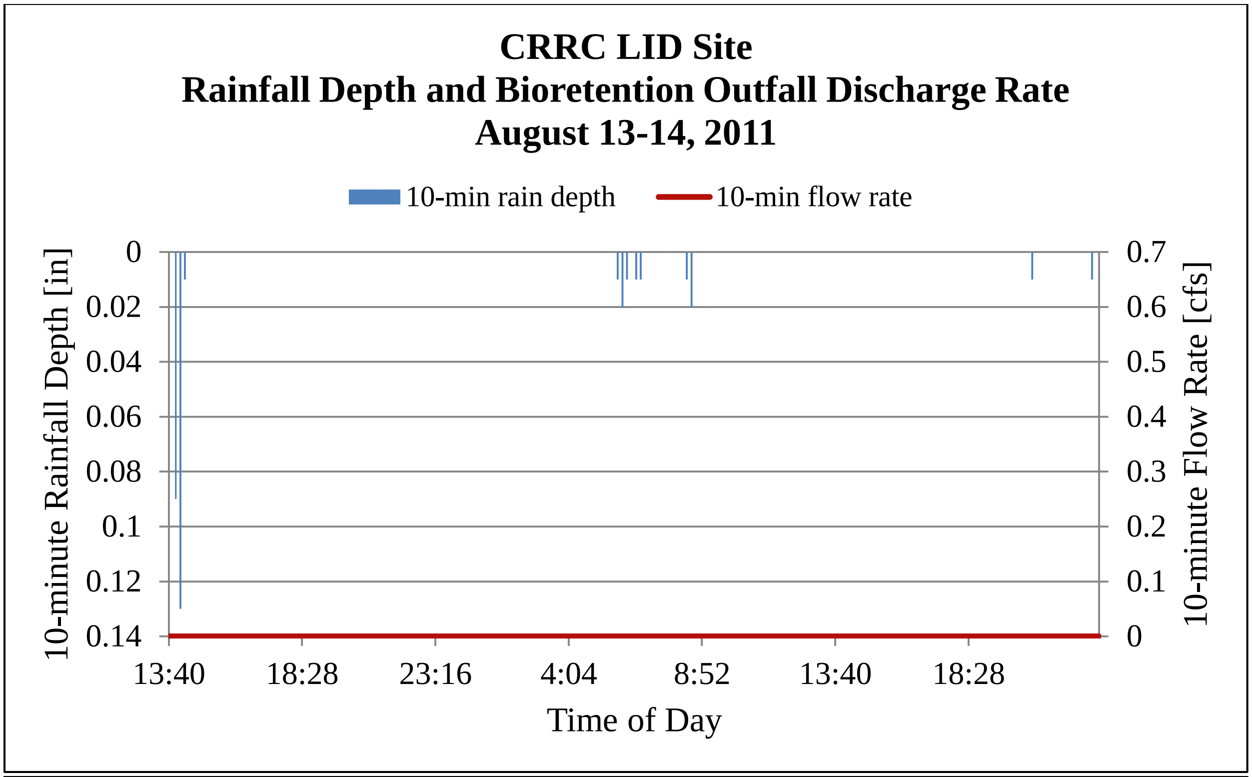


Figure A-21. Hydrograph and hyetograph of Jul 8, 2011 storm event.
Dry time = 438.8 hrs.



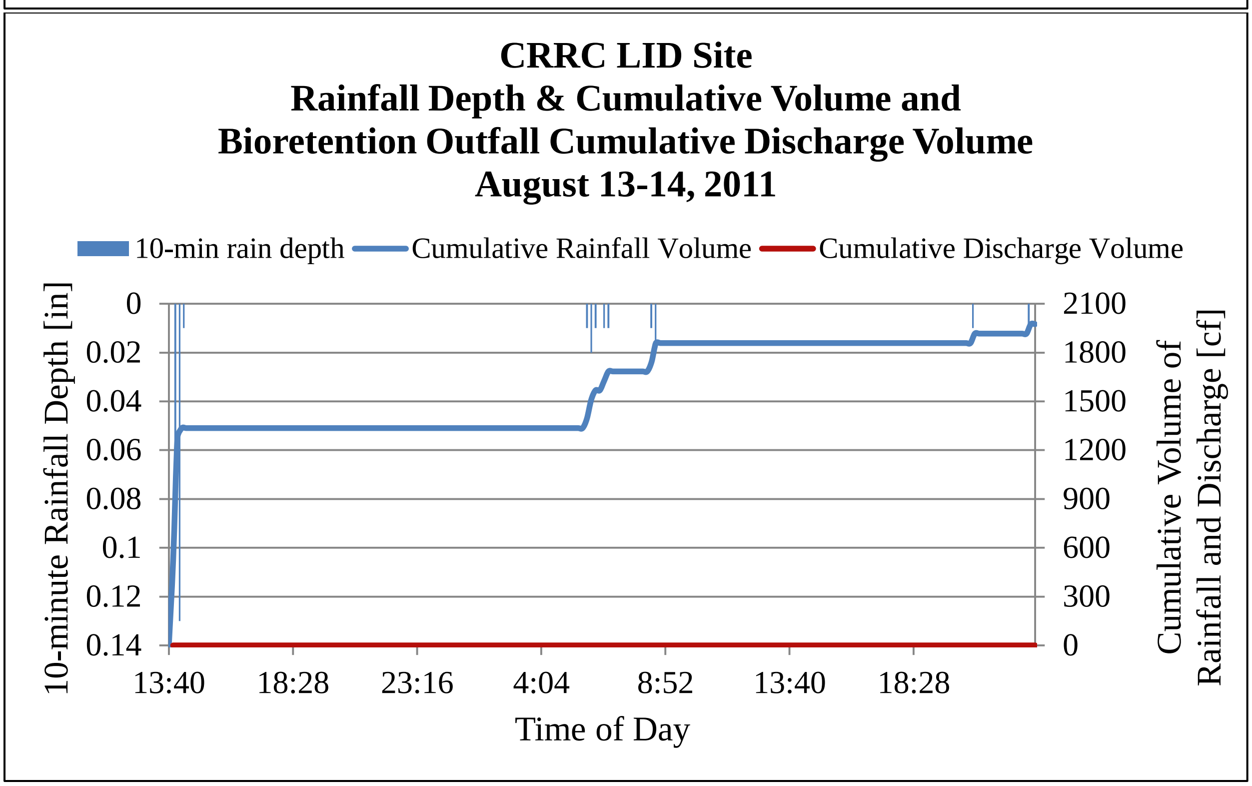
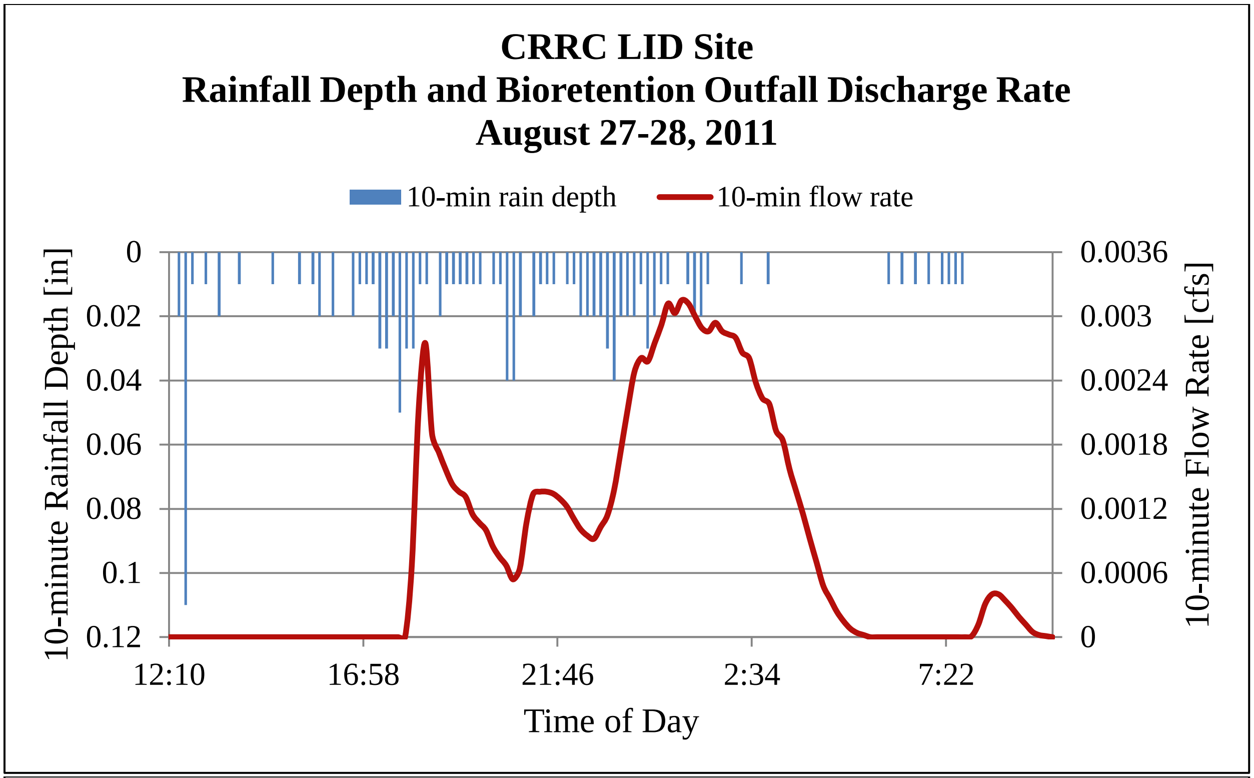


Figure A-22. Hydrograph and hyetograph of Aug 13-14, 2011 storm event.
Dry time = 140.5 hrs.



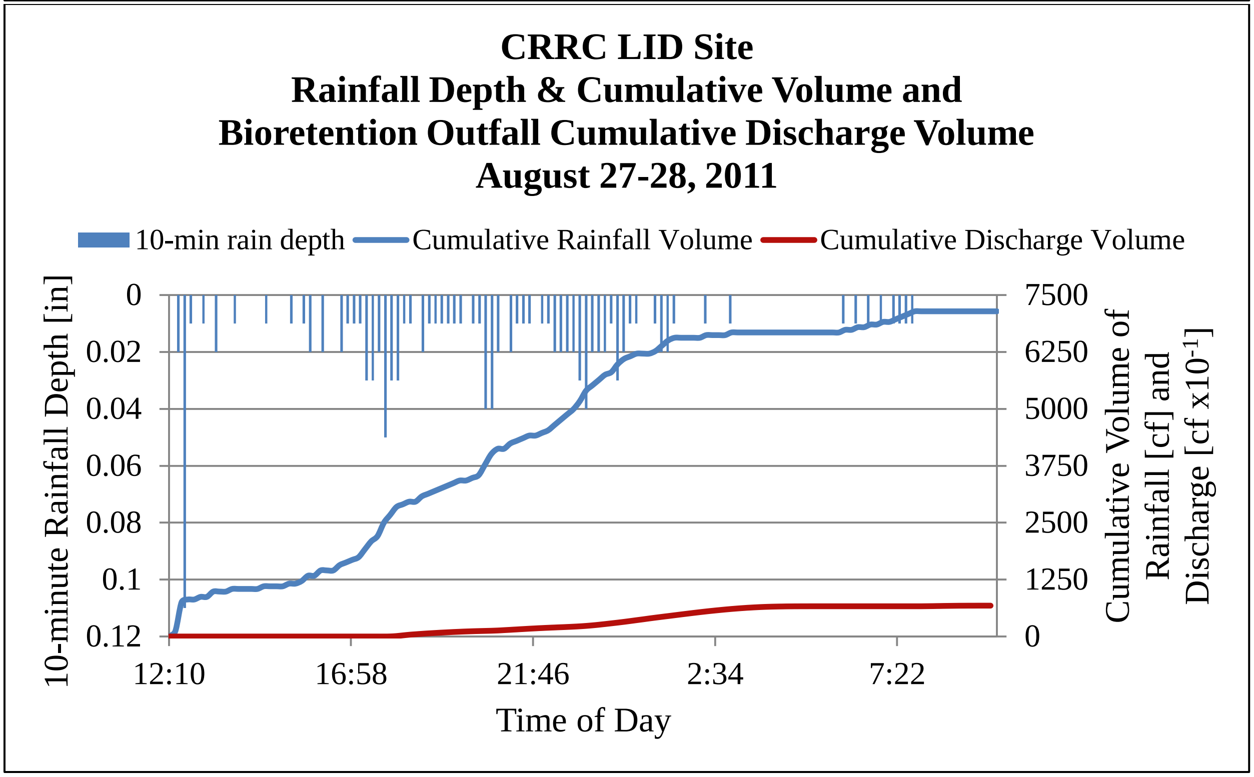
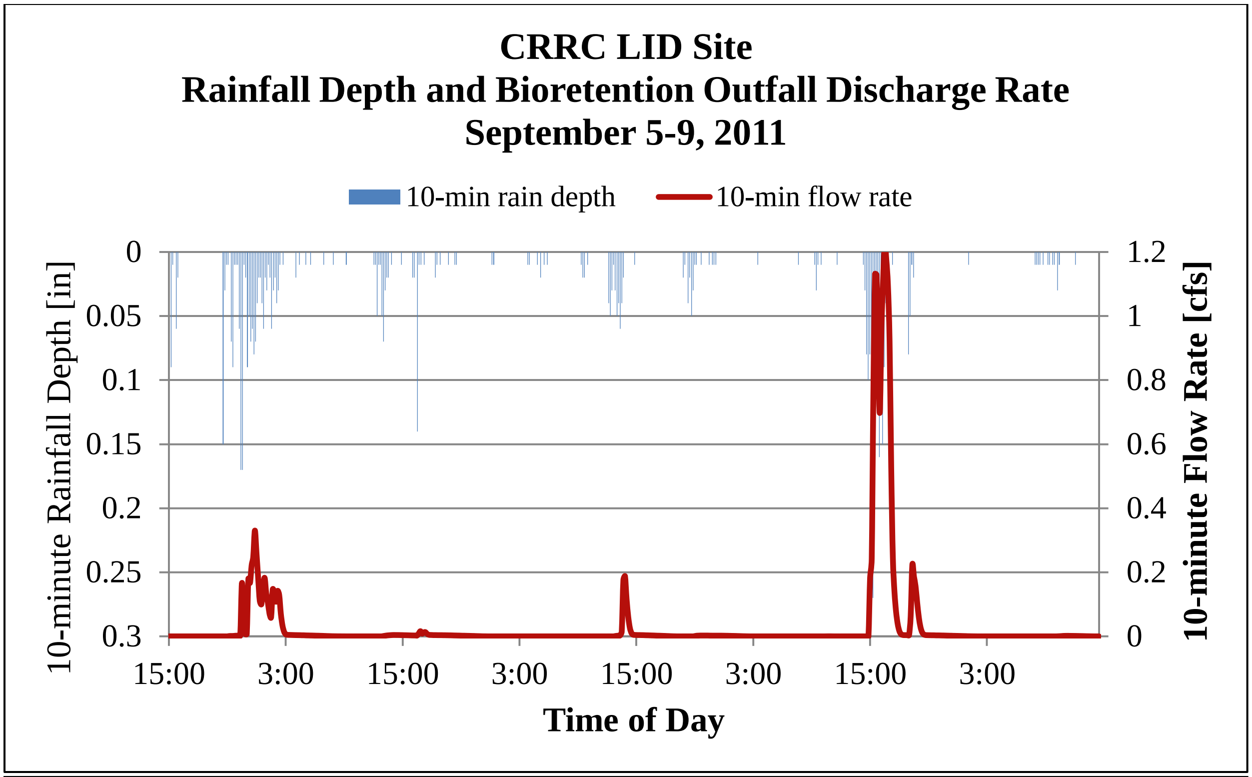


Figure A-23. Hydrograph and hyetograph of Aug 27-28, 2011 storm event.
Dry time = 44.0 hrs.



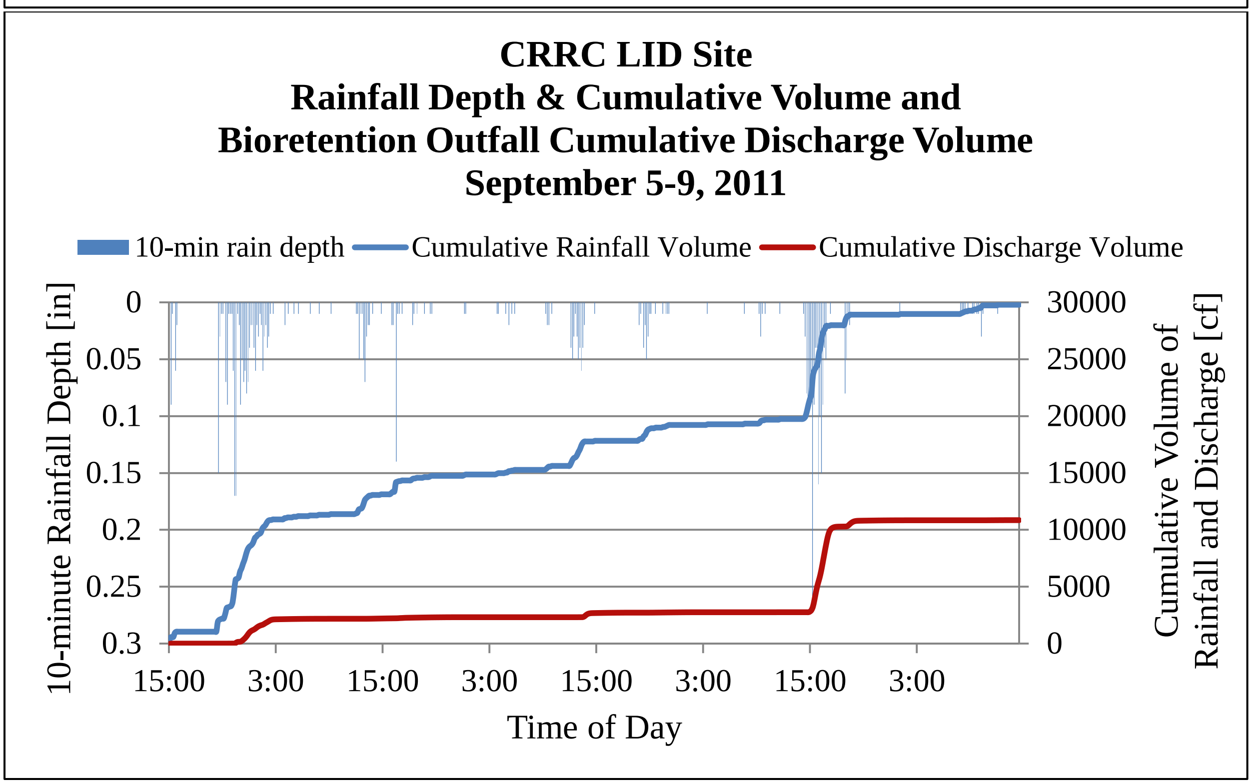
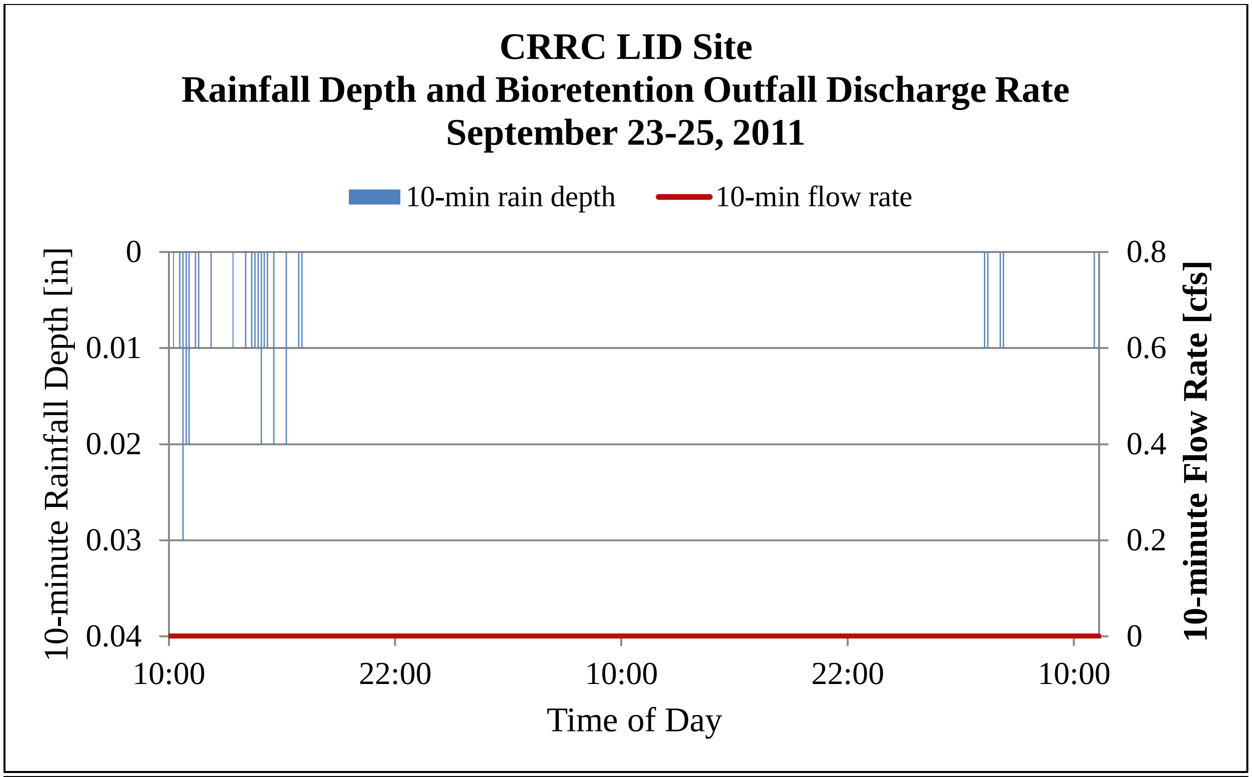


Figure A-24. Hydrograph and hyetograph of Sept 5-9, 2011 storm event.
Dry time = 51.2 hrs.



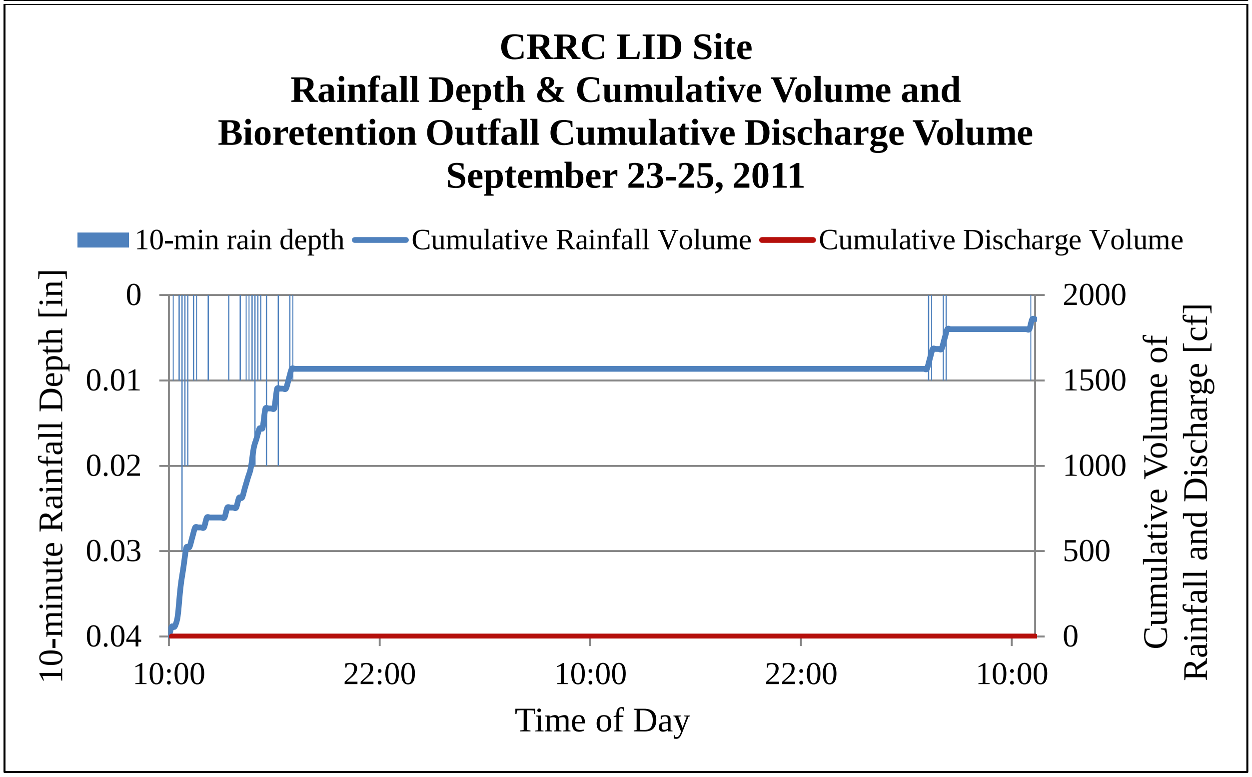
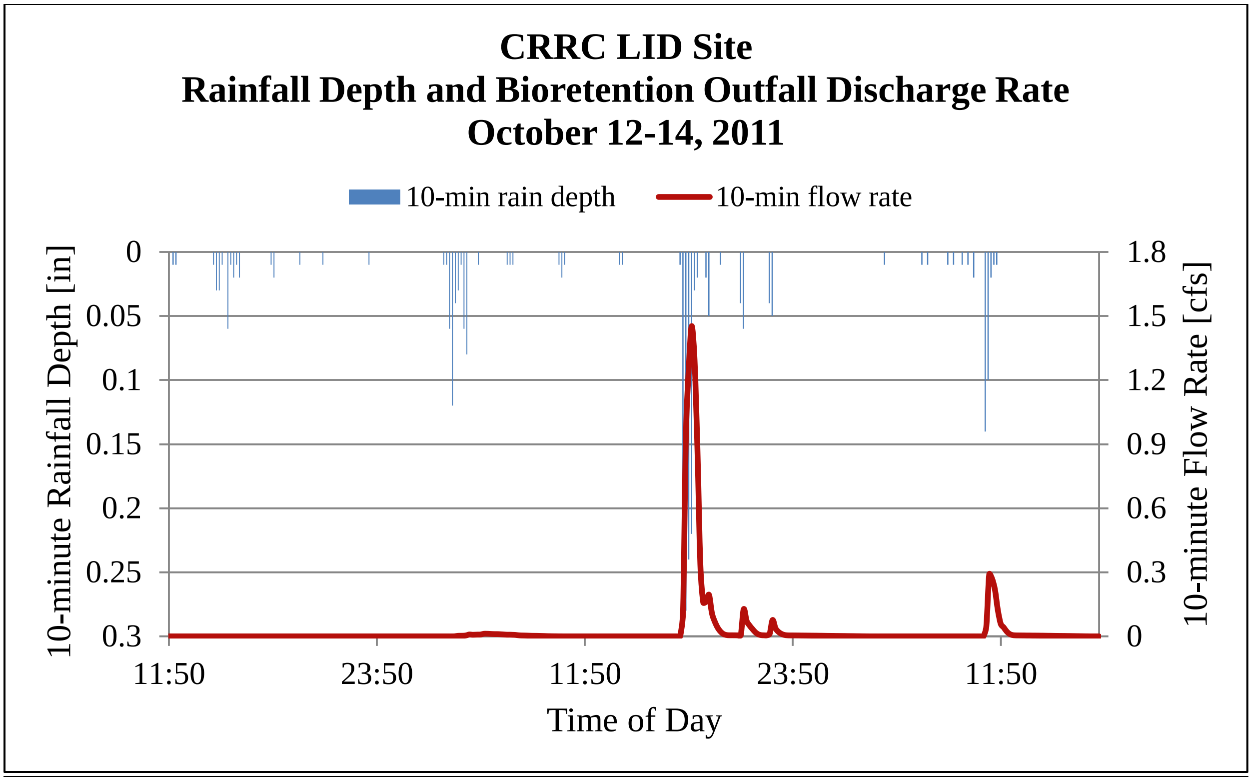


Figure A-25. Hydrograph and hyetograph of Sept 23-25, 2011 storm event.
Dry time = 29.5 hrs.



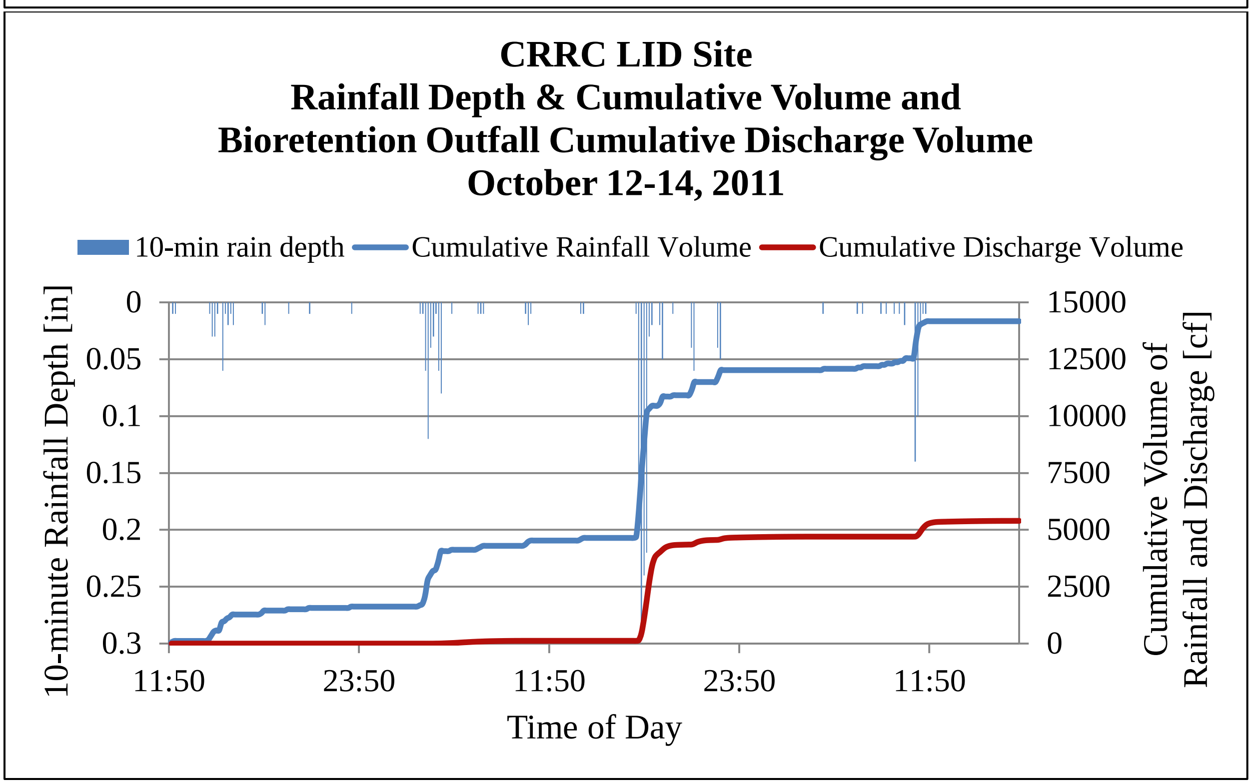
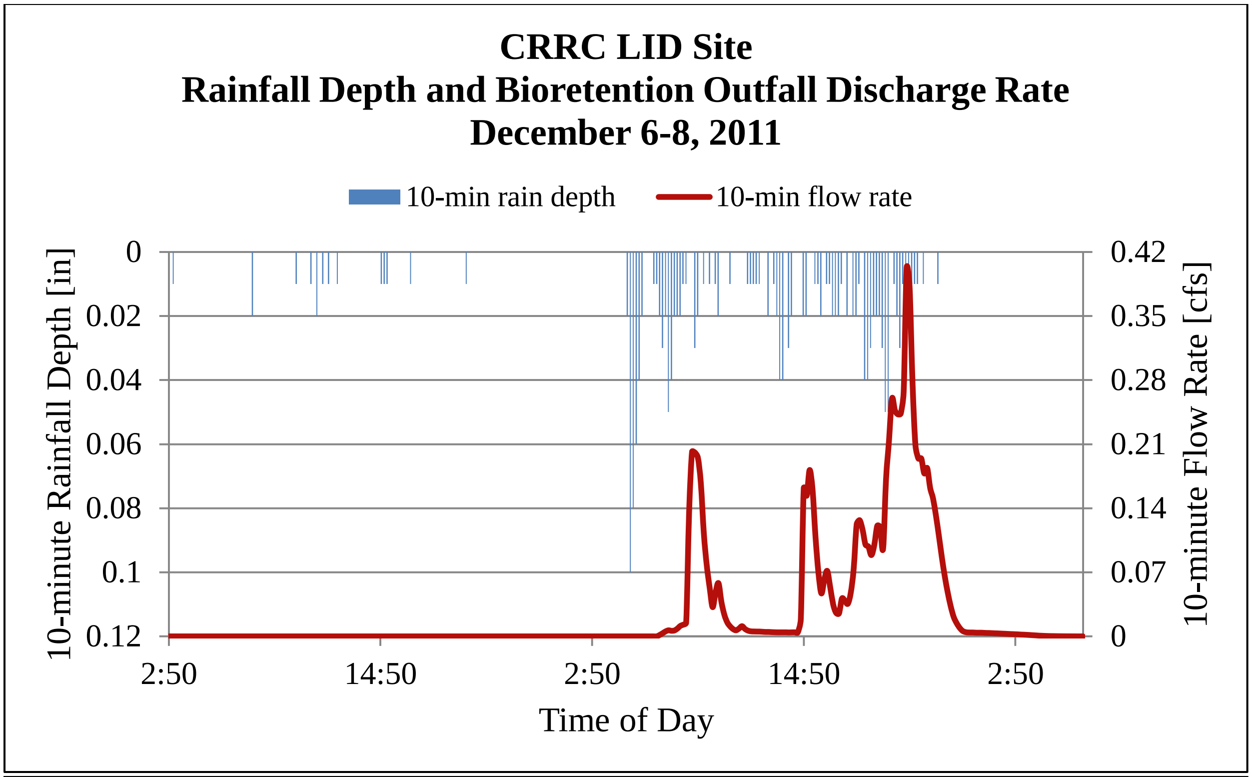


Figure A-26. Hydrograph and hyetograph of Oct 12-14, 2011 storm event.
Dry time = 7.0 hrs.



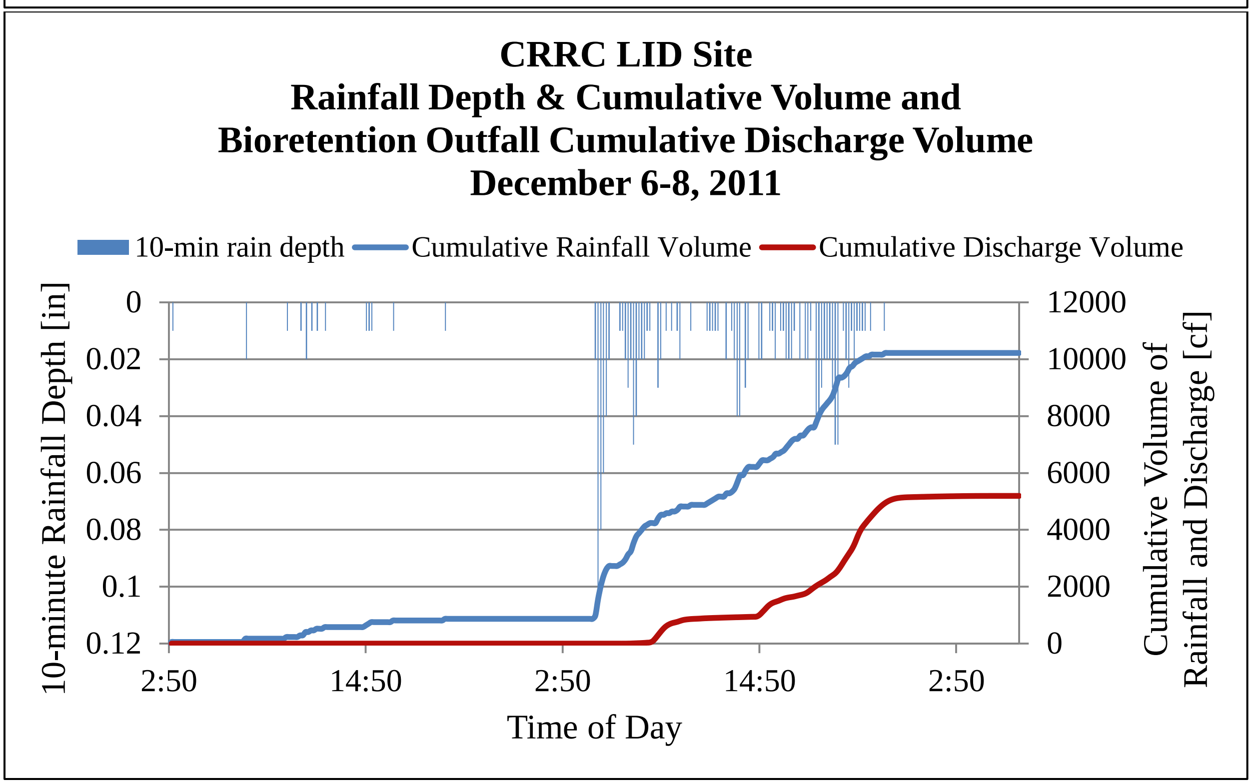
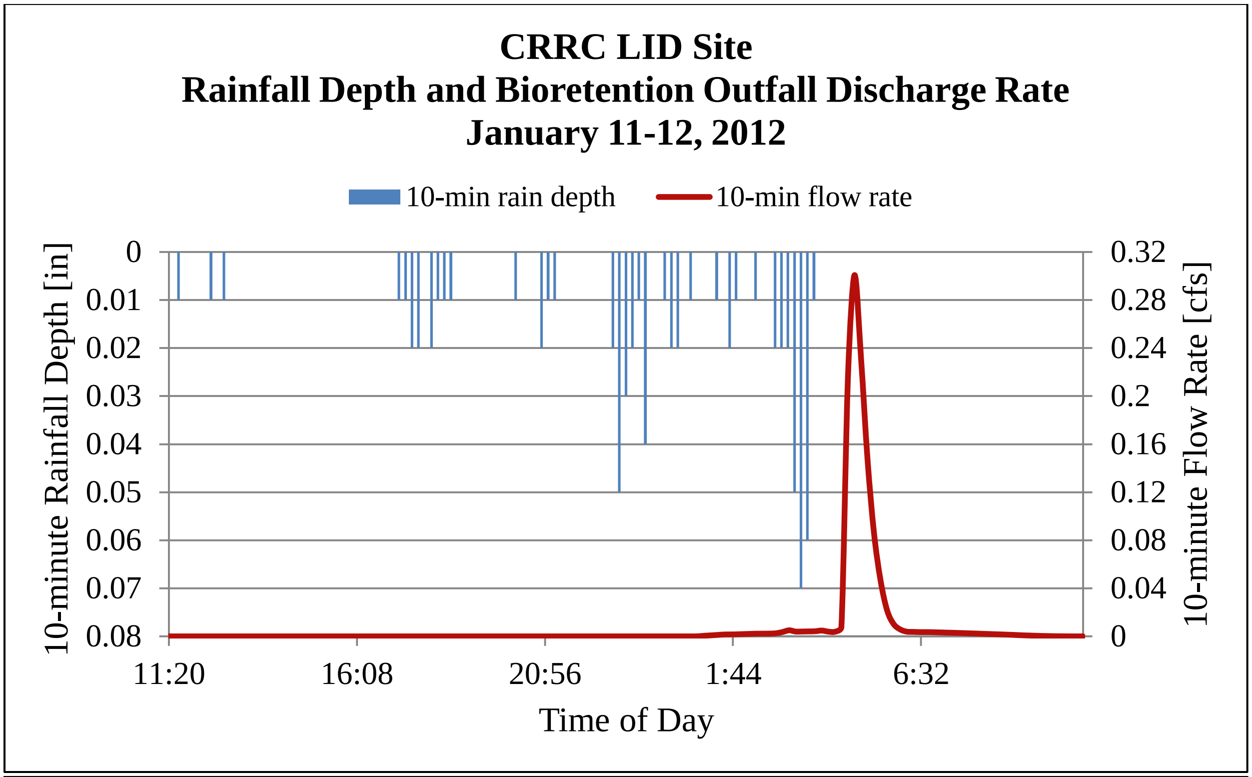


Figure A-27. Hydrograph and hyetograph of Dec 6-8, 2011 storm event.
Dry time = 153.7 hrs.



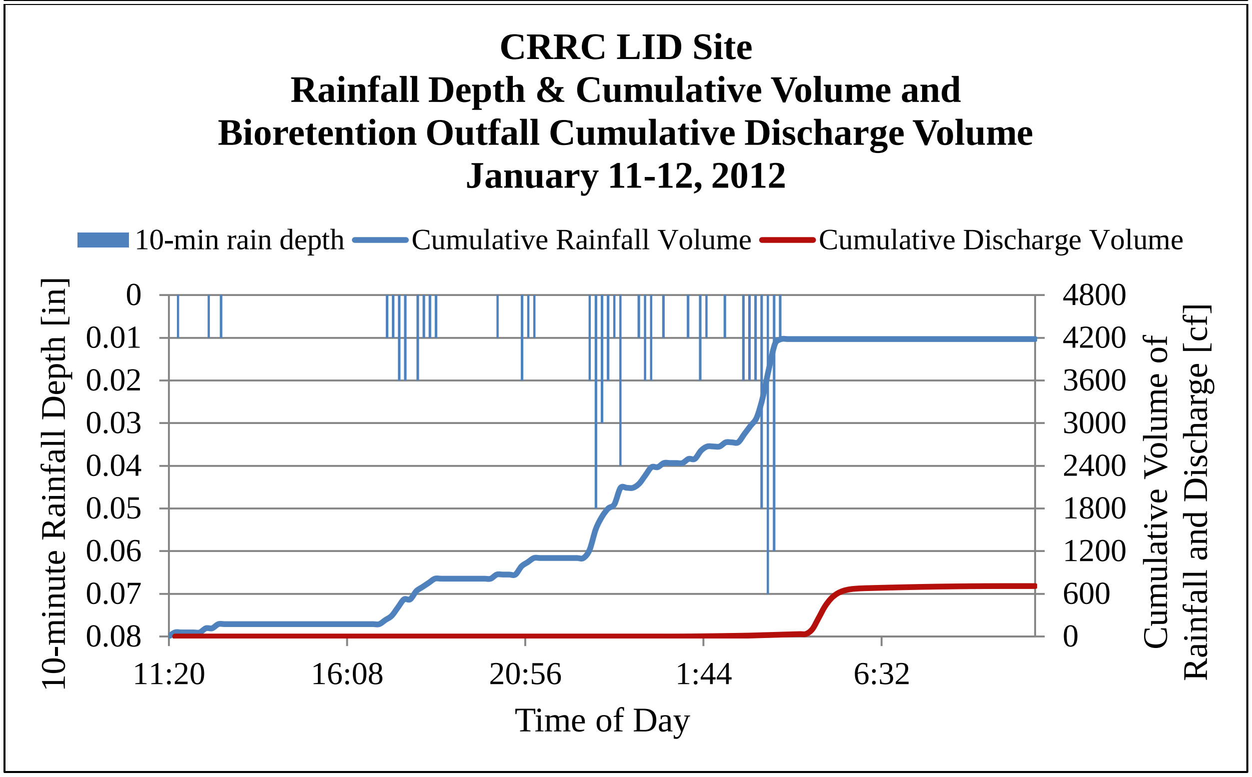
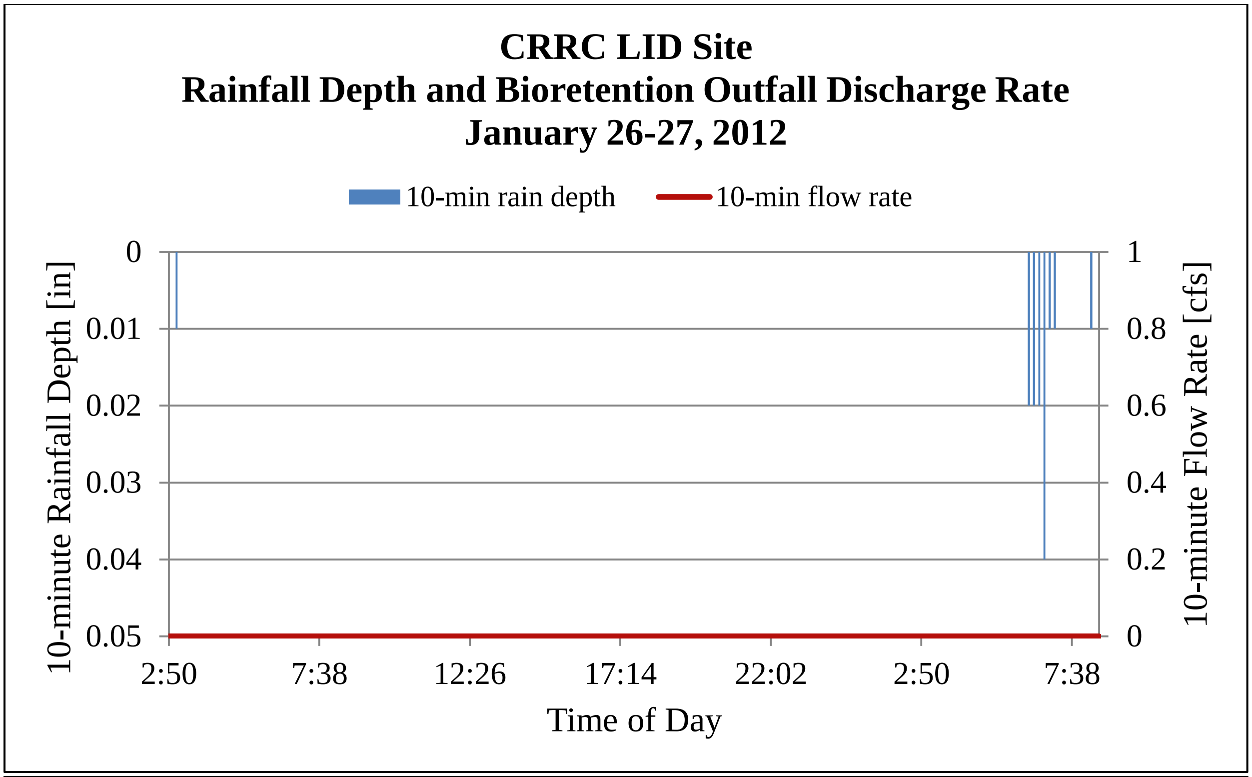


Figure A-28. Hydrograph and hyetograph of Jan 11-12, 2012 storm event.
Dry time = 23.7 hrs.



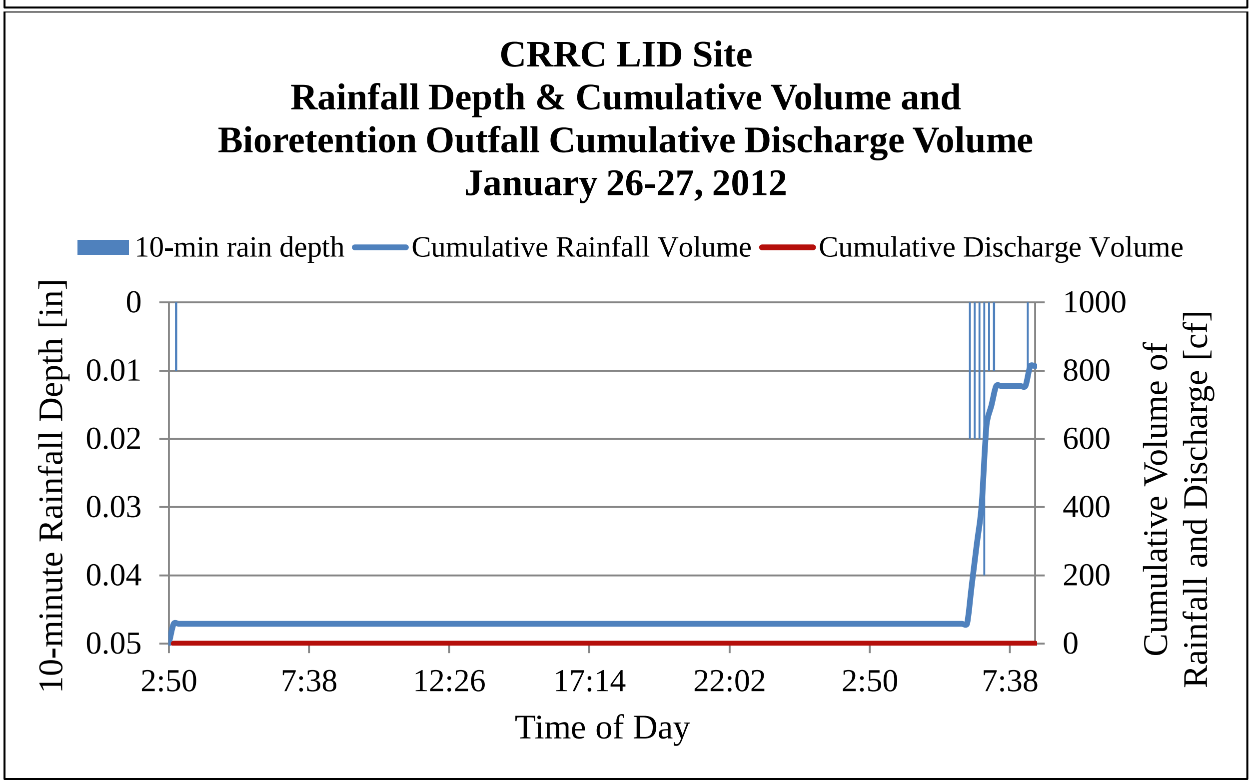
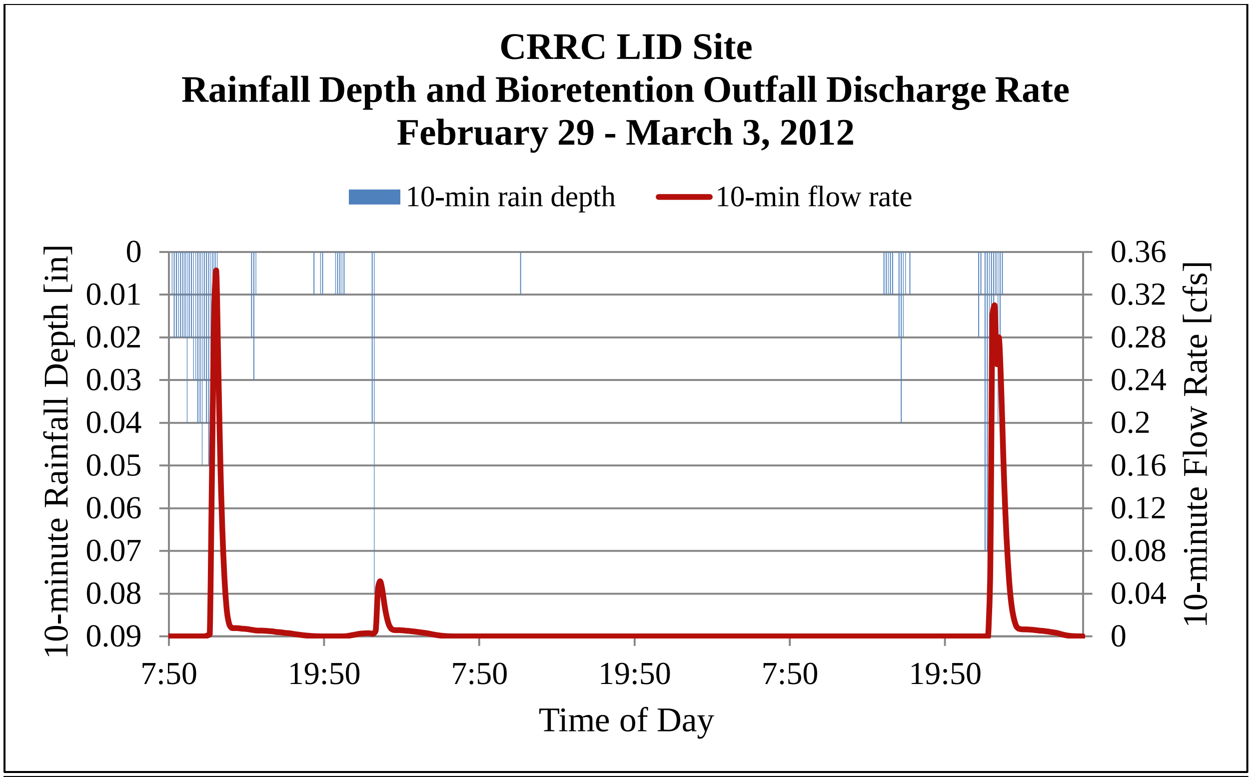


Figure A-29. Hydrograph and hyetograph of January 26-27, 2012 storm event.
Dry time = 58.8 hours



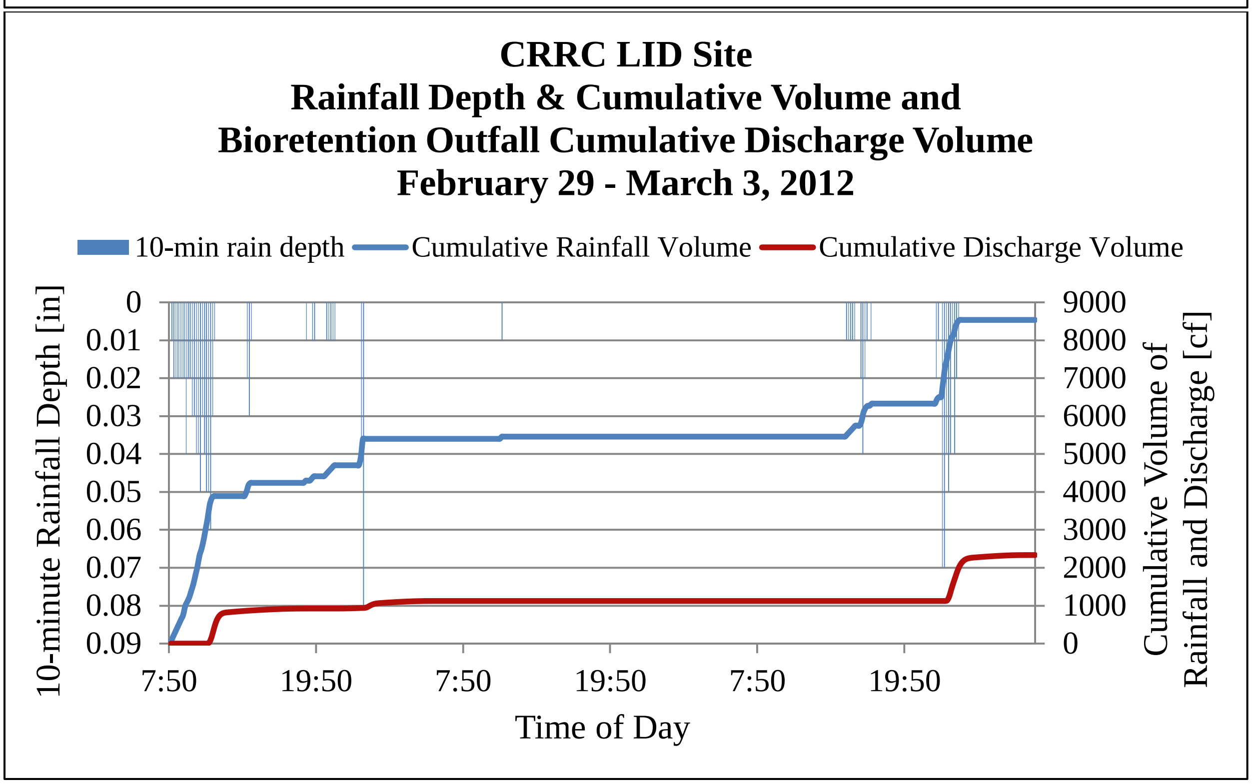
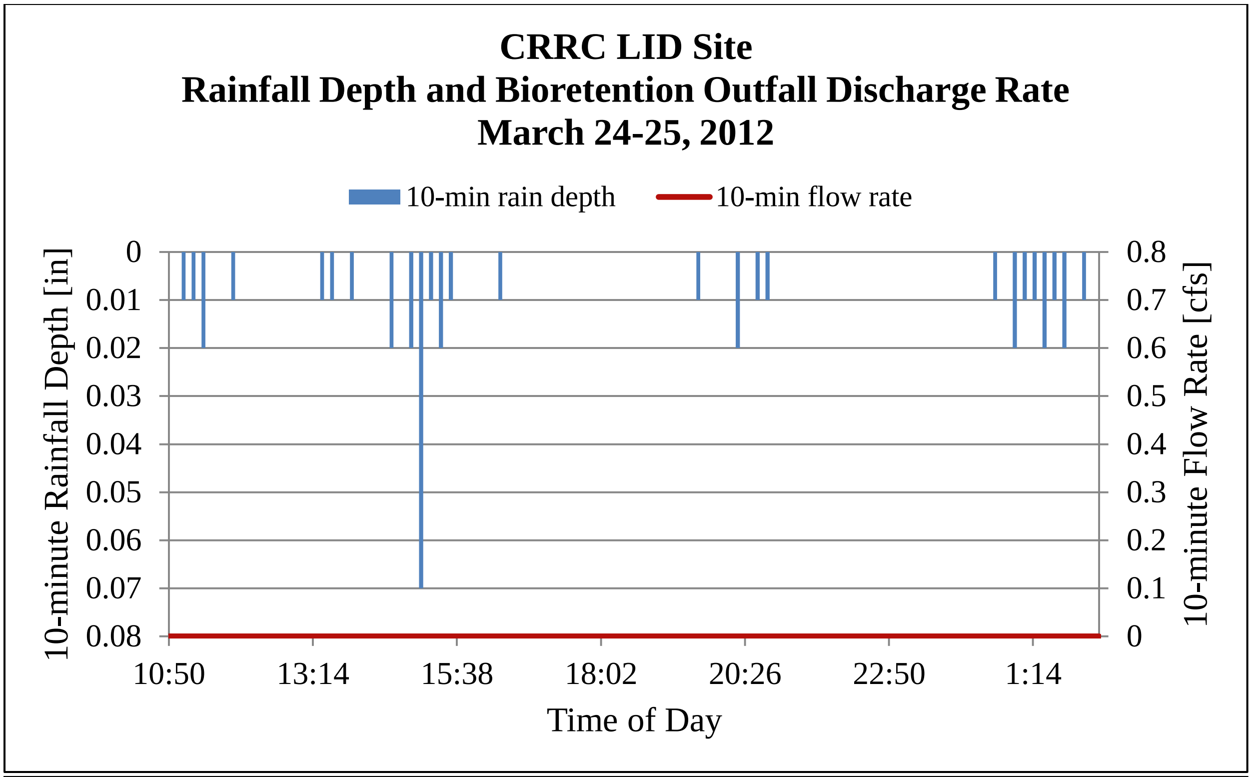


Figure A-30. Hydrograph and hyetograph of Feb 29–Mar 3, 2012 event.
Dry time = 110.8 hrs.



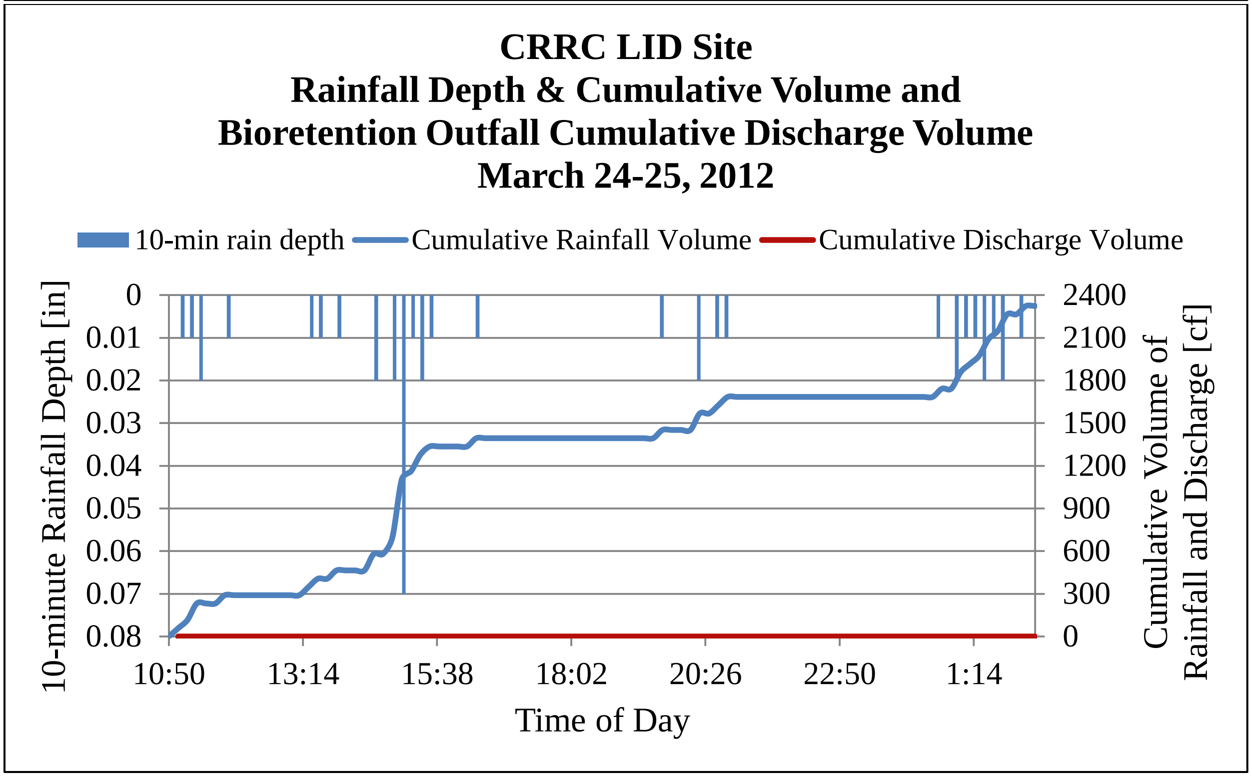
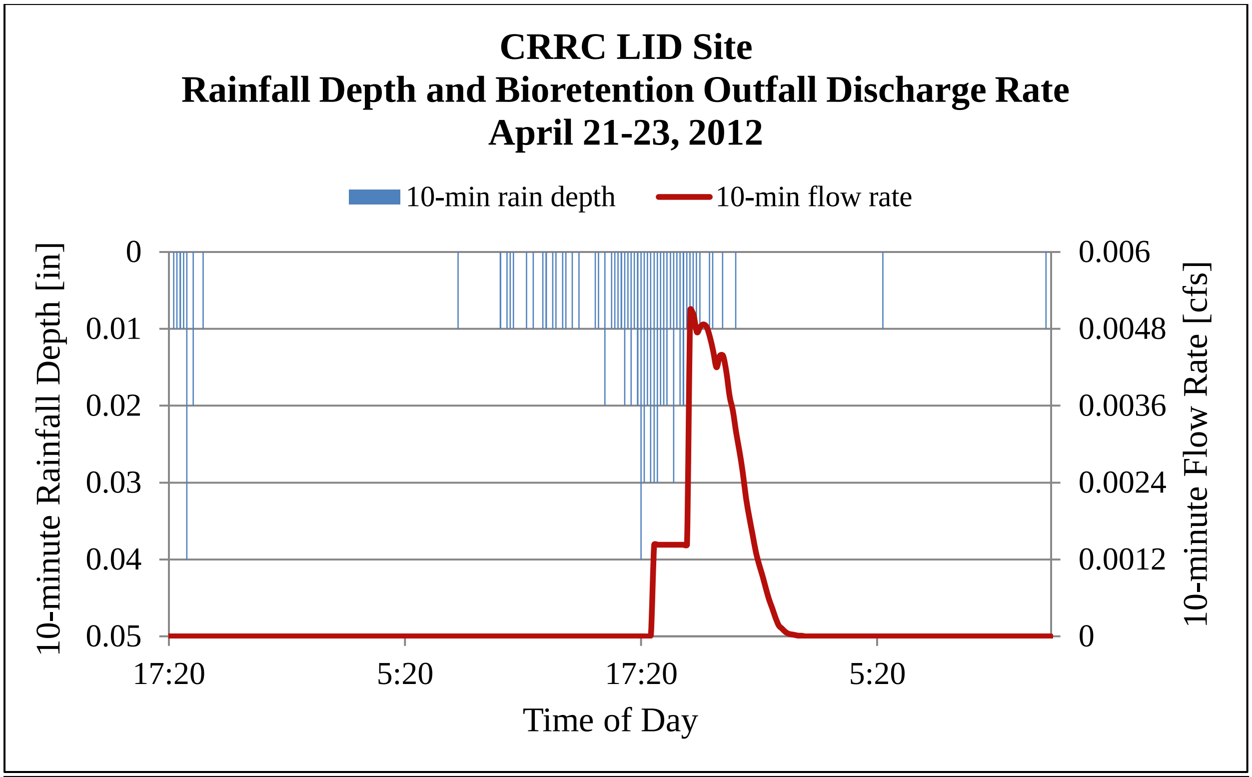


Figure A-31. Hydrograph and hyetograph of Mar 24-25, 2012 storm event.
Dry time = 508.3 hrs.



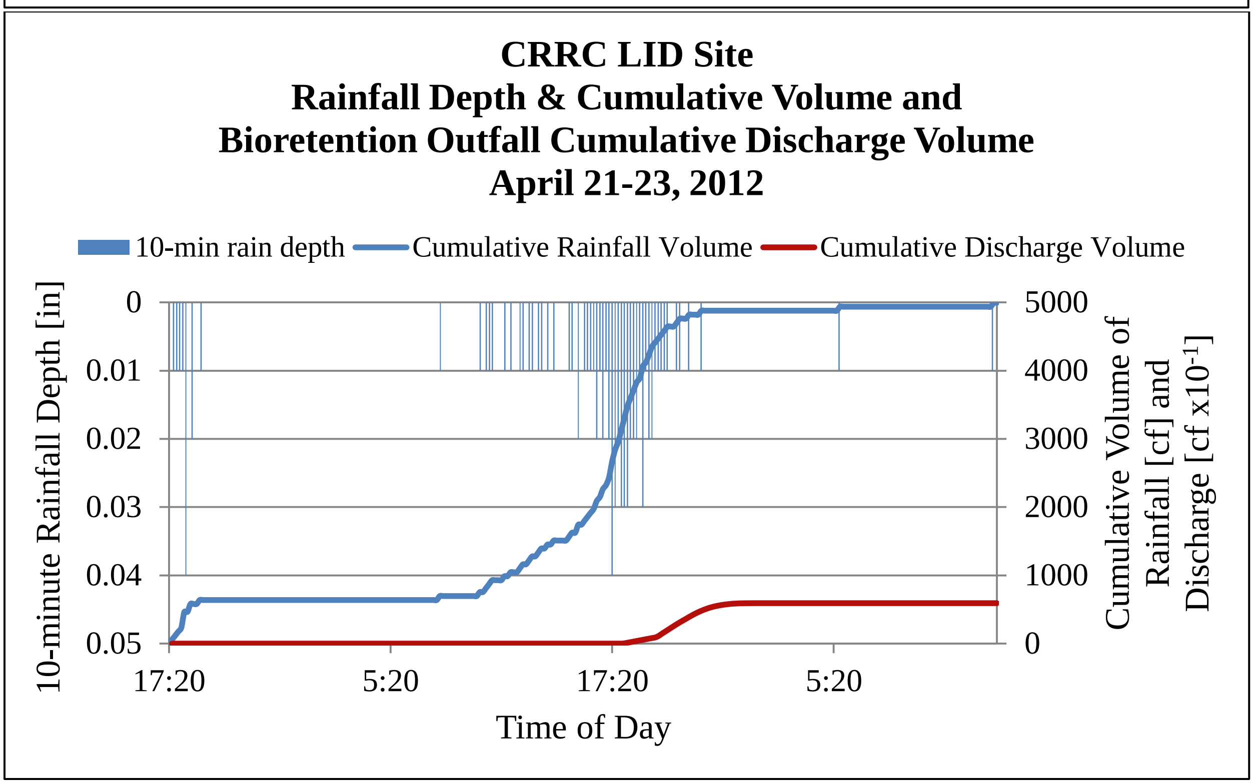


Figure A-32. Hydrograph and hyetograph of Apr 21-23, 2012 storm event.
Dry time = 65.8 hrs.

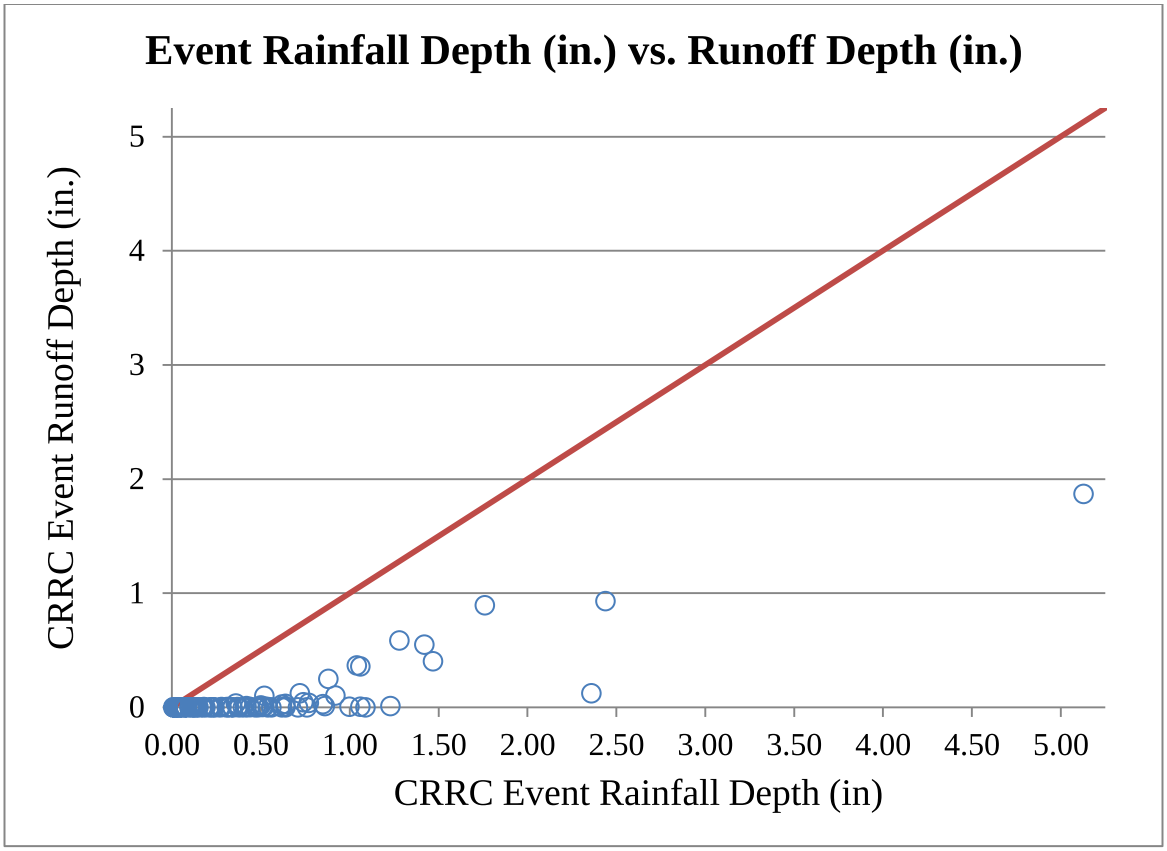


Figure A-33. Event rainfall depth vs. runoff depth at the Cub Run Recreation Center for all storm events.

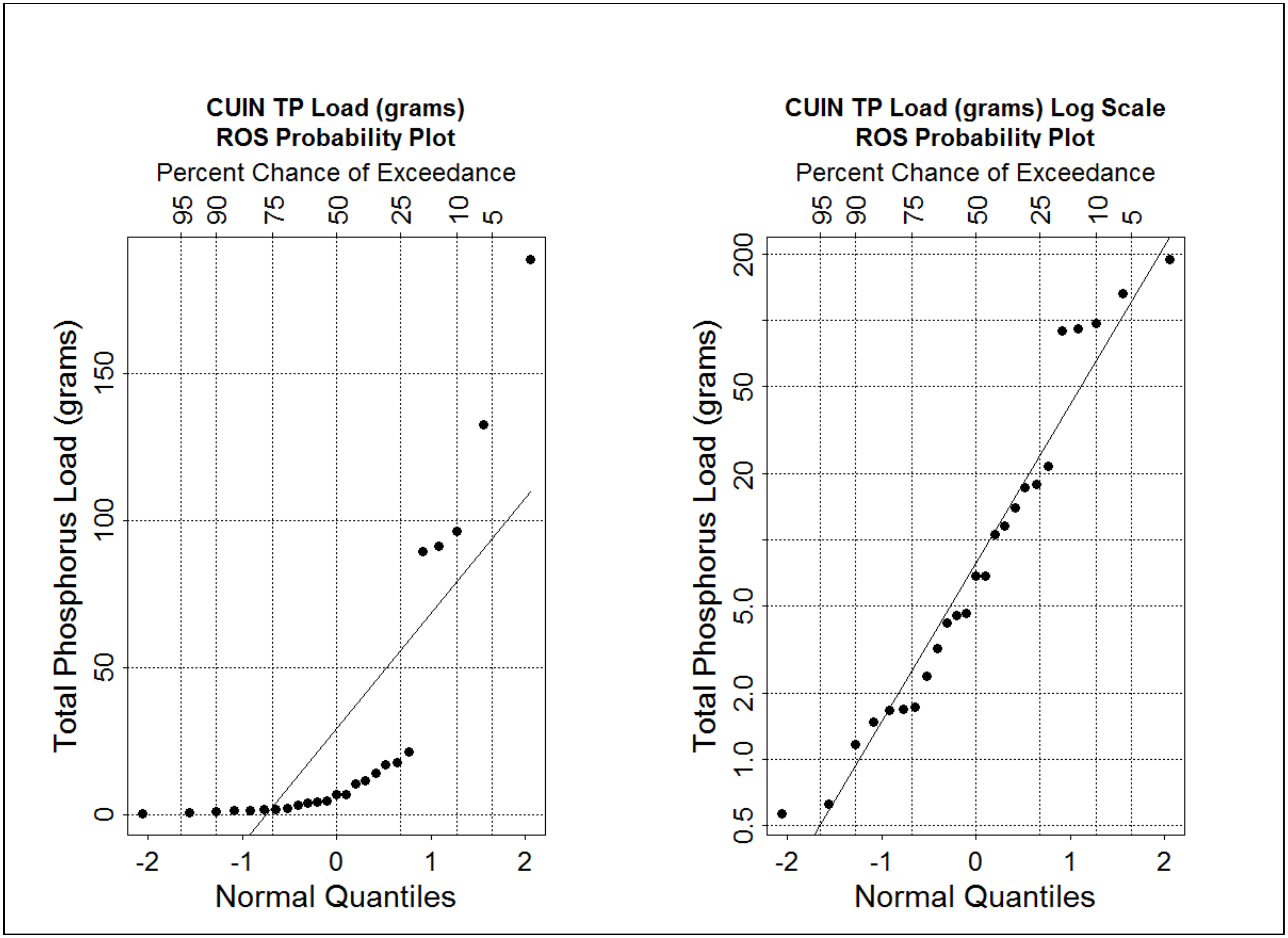


Figure A-34a. Q-Q Plots of CUIN load dataset for total phosphorus.

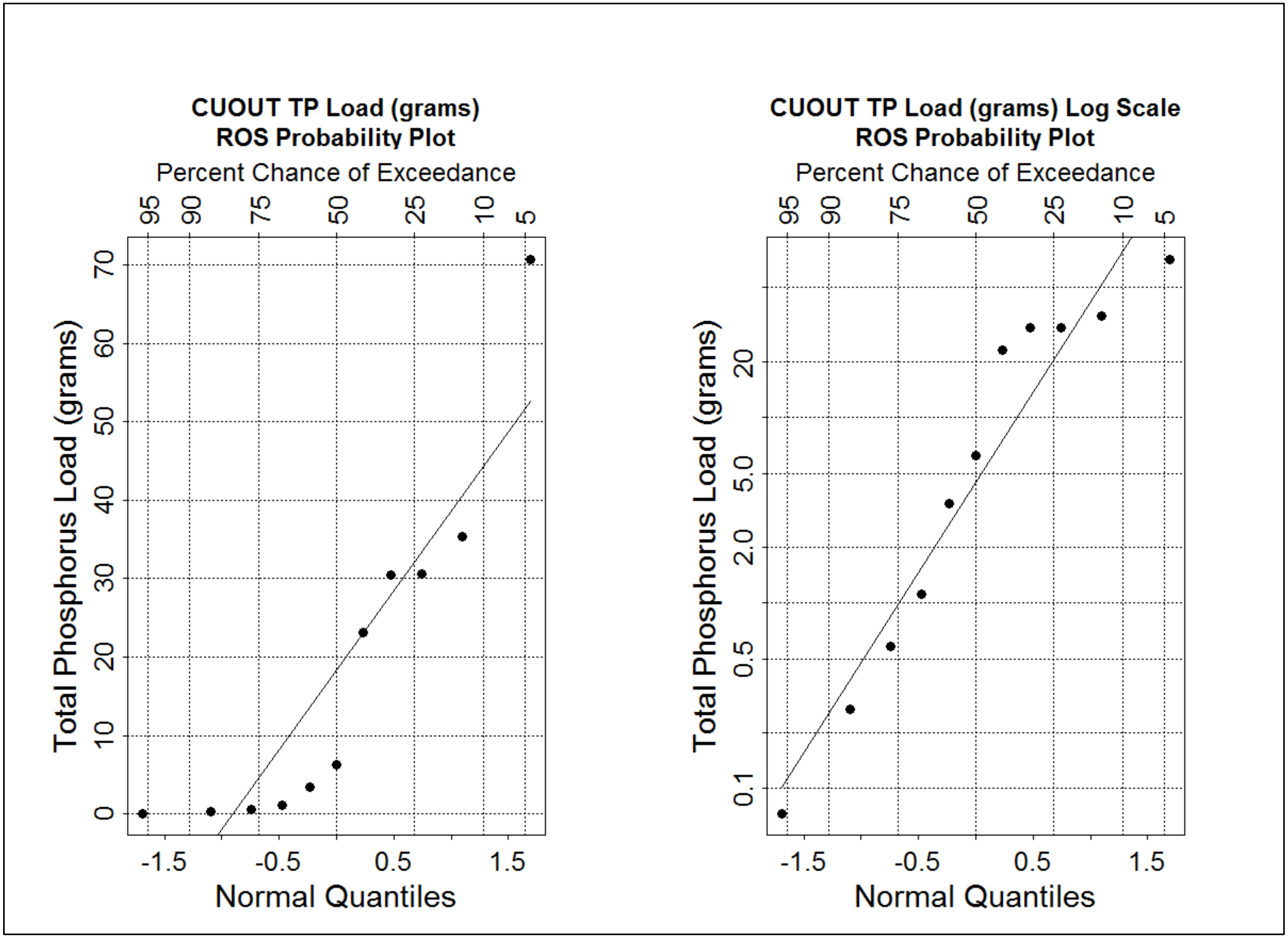


Figure A-34b. Q-Q Plots of CUOUT load dataset for total phosphorus.

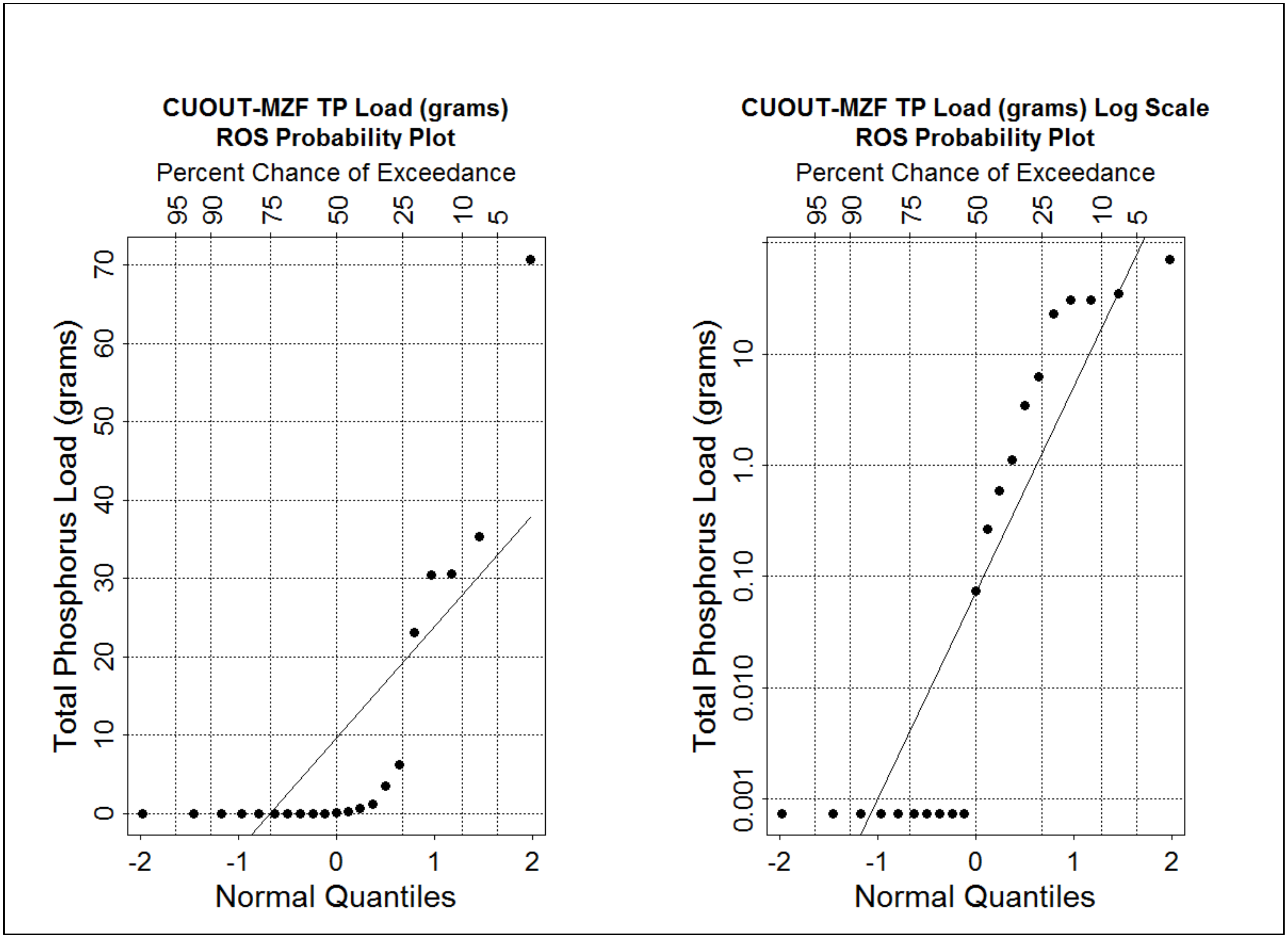


Figure A-34c. Q-Q Plots of CUOUT-MZF load dataset for total phosphorus.

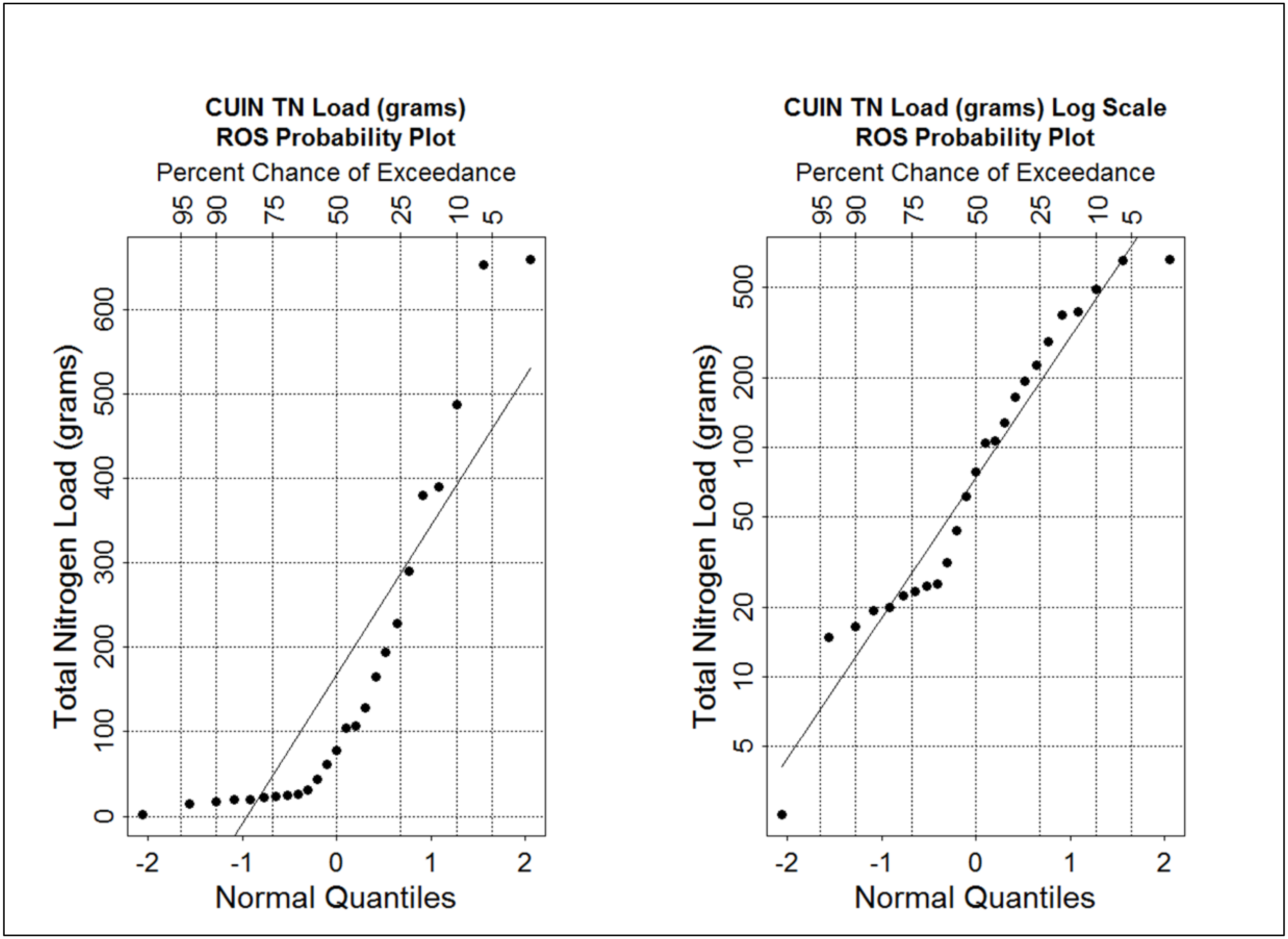


Figure A-35a. Q-Q Plots of CUIN load dataset for total nitrogen.

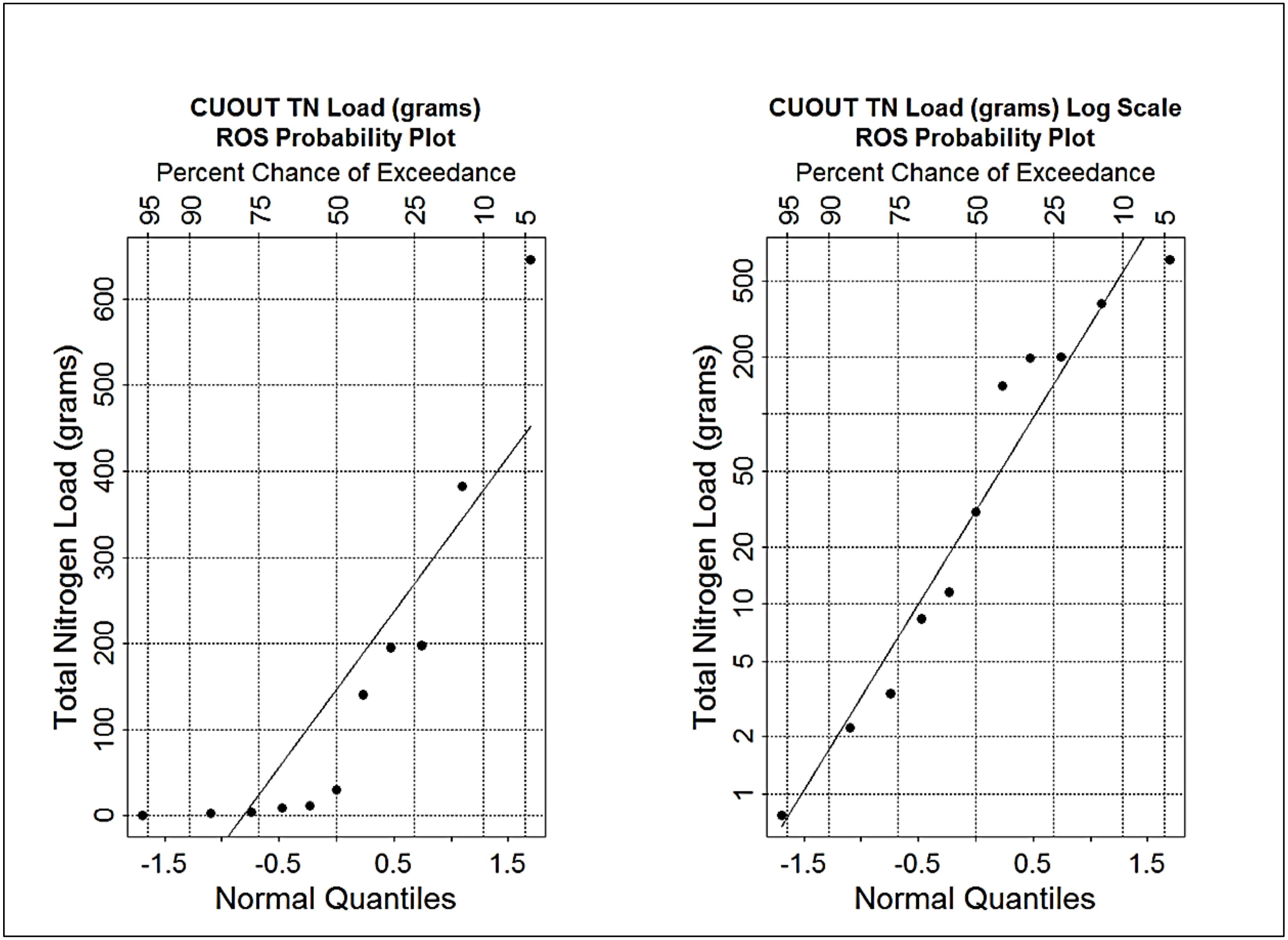


Figure A-35b. Q-Q Plots of CUOUT load dataset for total nitrogen.

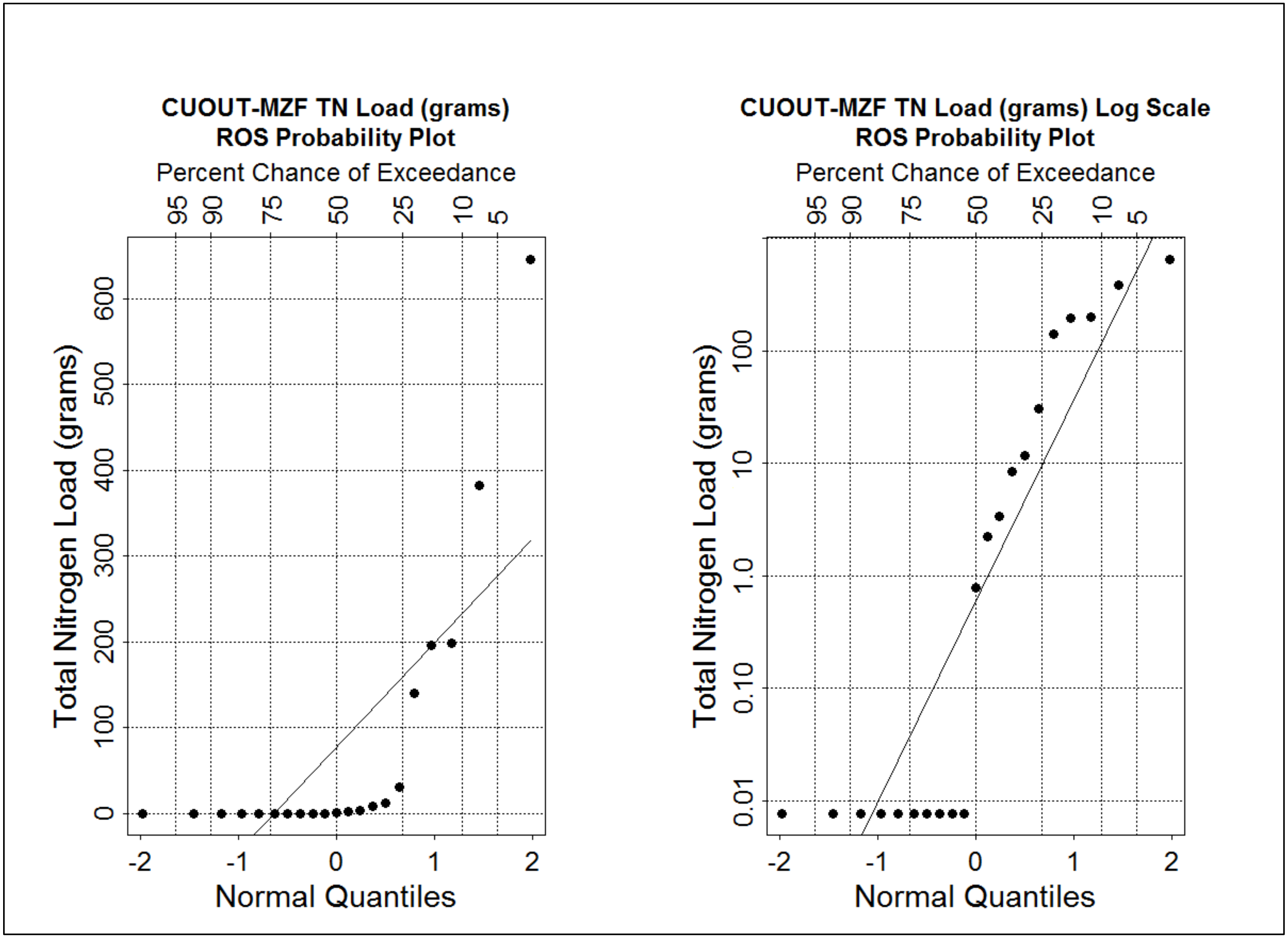


Figure A-35c. Q-Q Plots of CUOUT-MZF load dataset for total nitrogen.

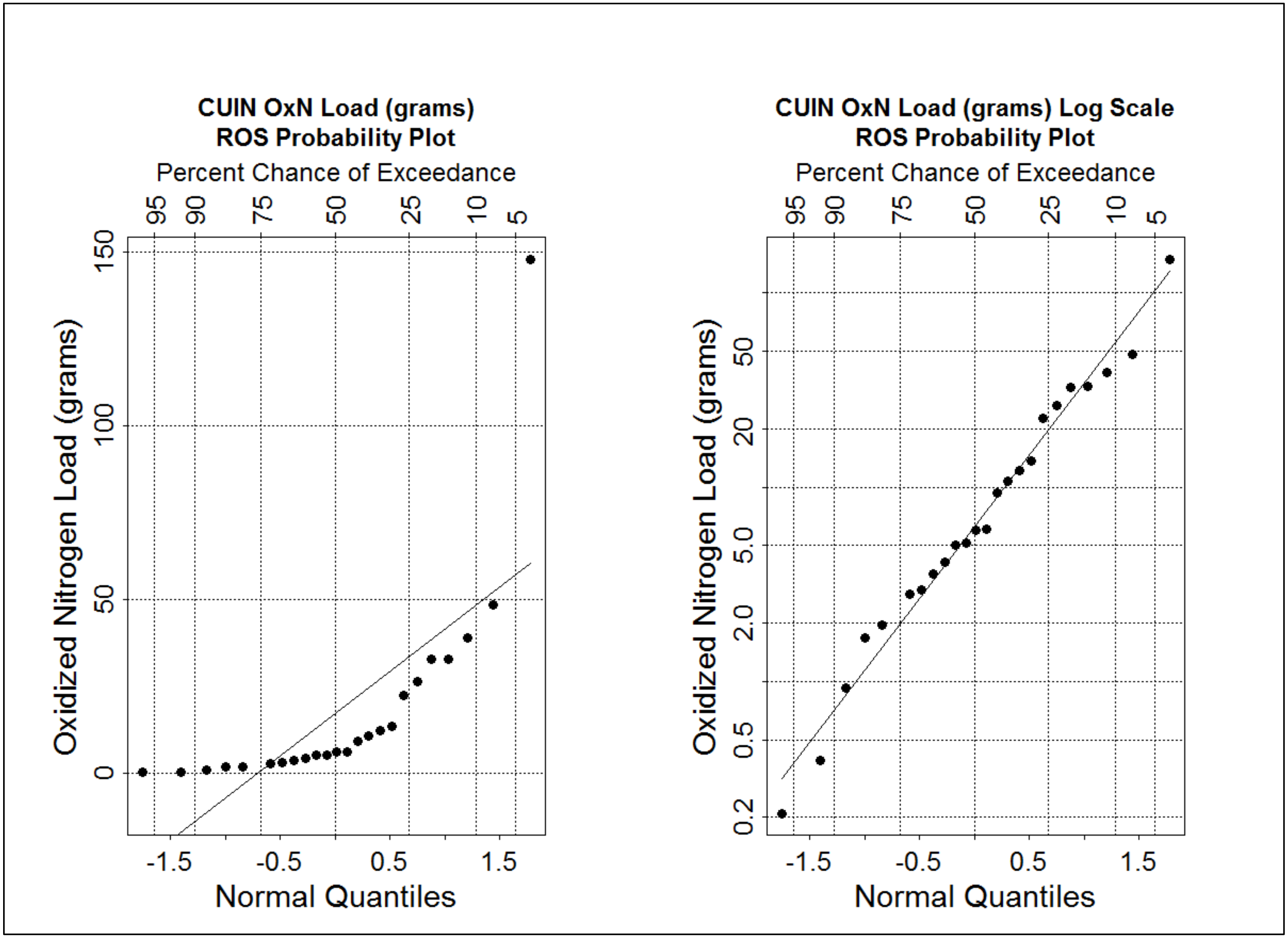


Figure A-36a. Q-Q Plots of CUIN load dataset for oxidized nitrogen.

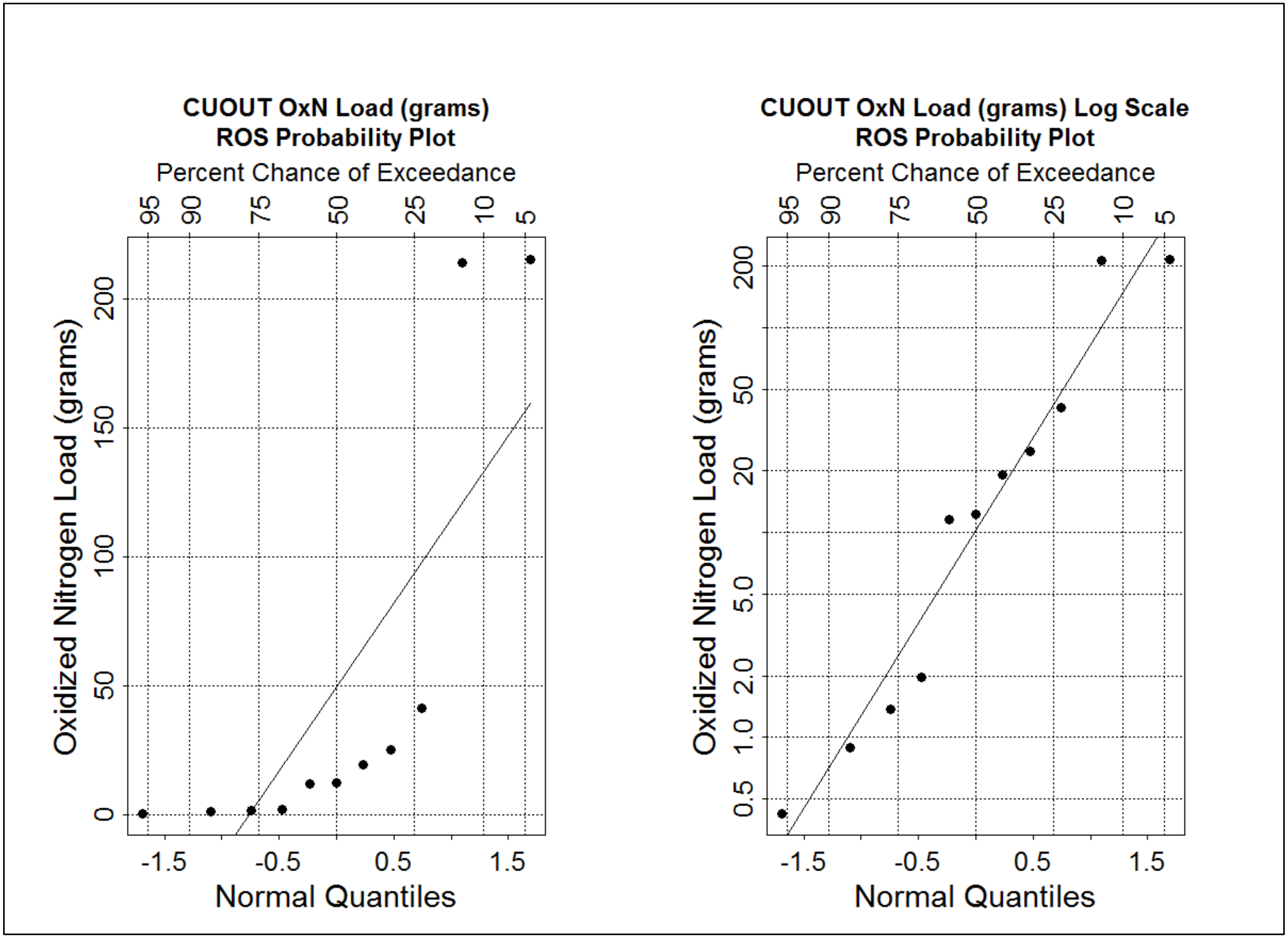


Figure A-36b. Q-Q Plots of CUOUT load dataset for oxidized nitrogen.

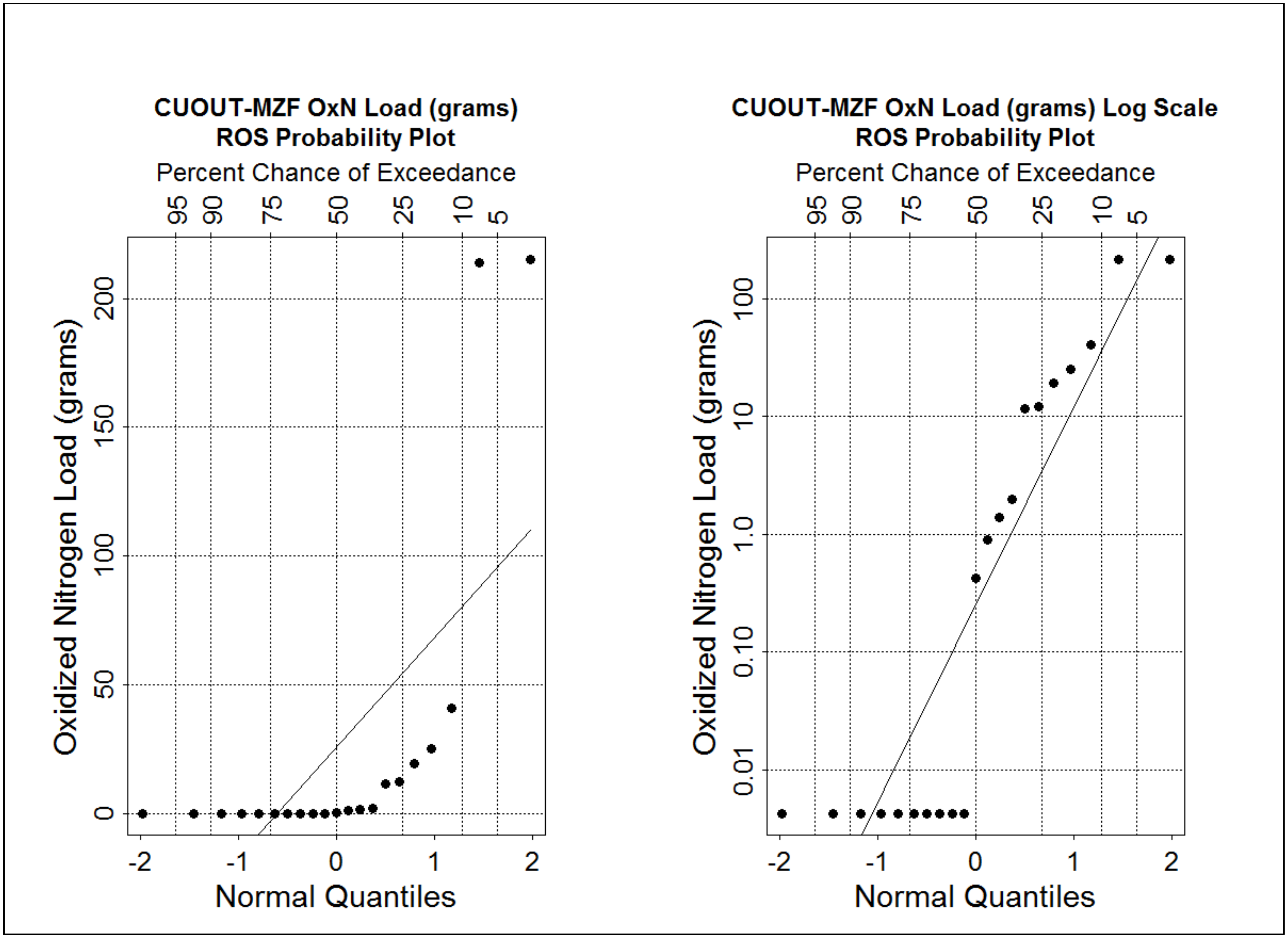


Figure A-36c. Q-Q Plots of CUOUT-MZF load dataset for oxidized nitrogen.

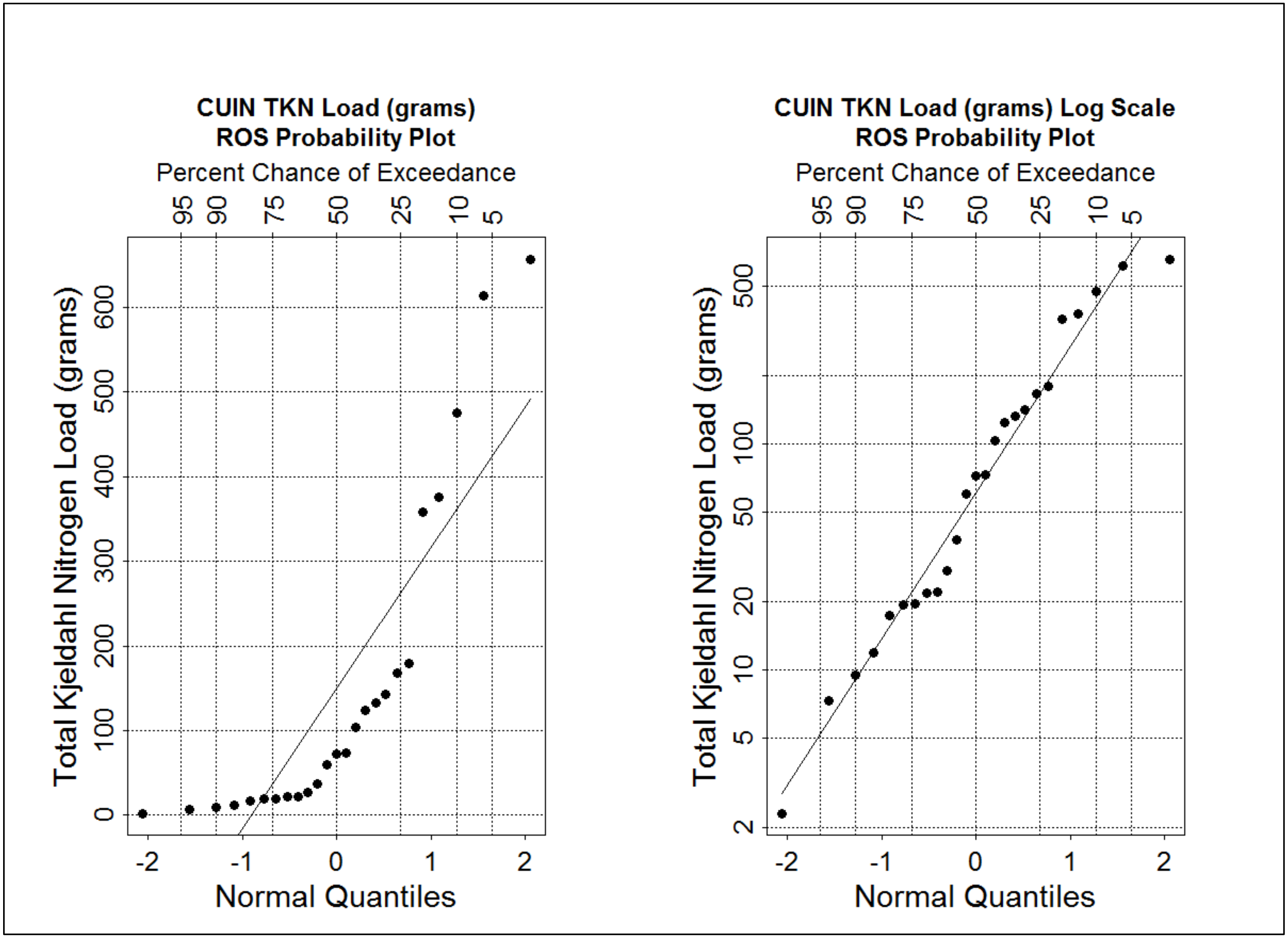


Figure A-37a. Q-Q Plots of CUIN load dataset for total Kjeldahl nitrogen.

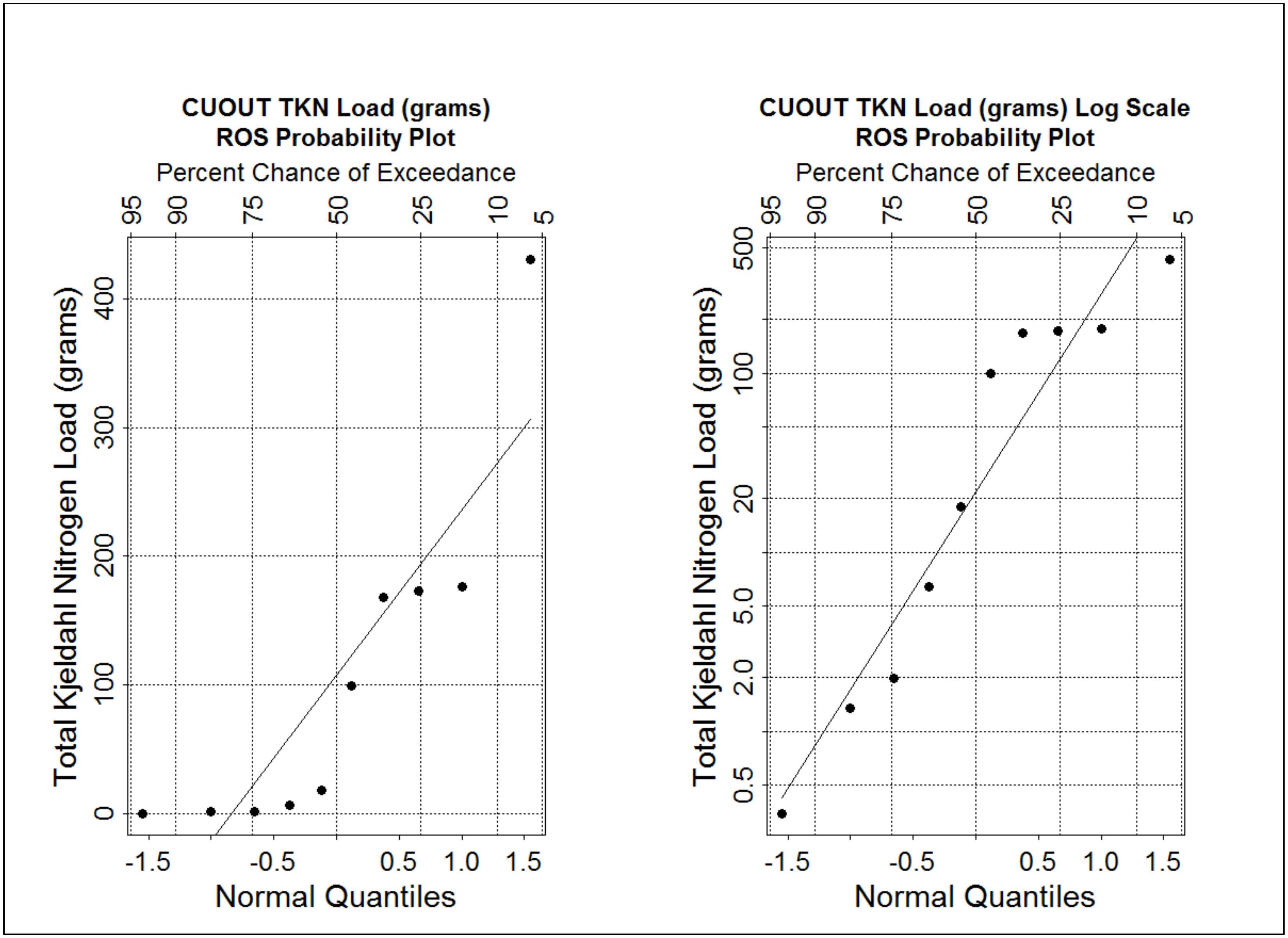


Figure A-37b. Q-Q Plots of CUOUT load dataset for total Kjeldahl nitrogen.

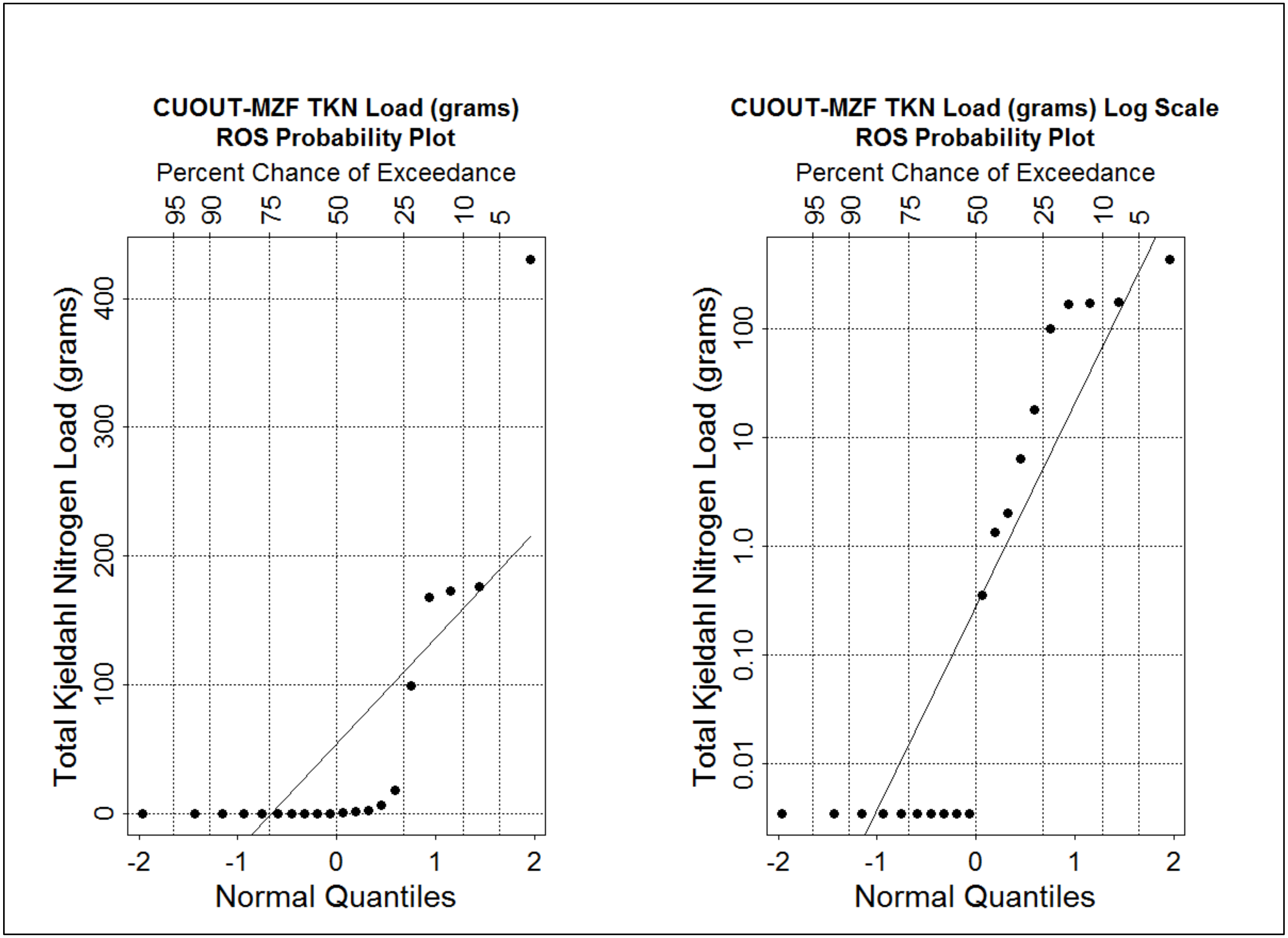


Figure A-37c. Q-Q Plots of CUOUT-MZF load dataset for total Kjeldahl nitrogen.

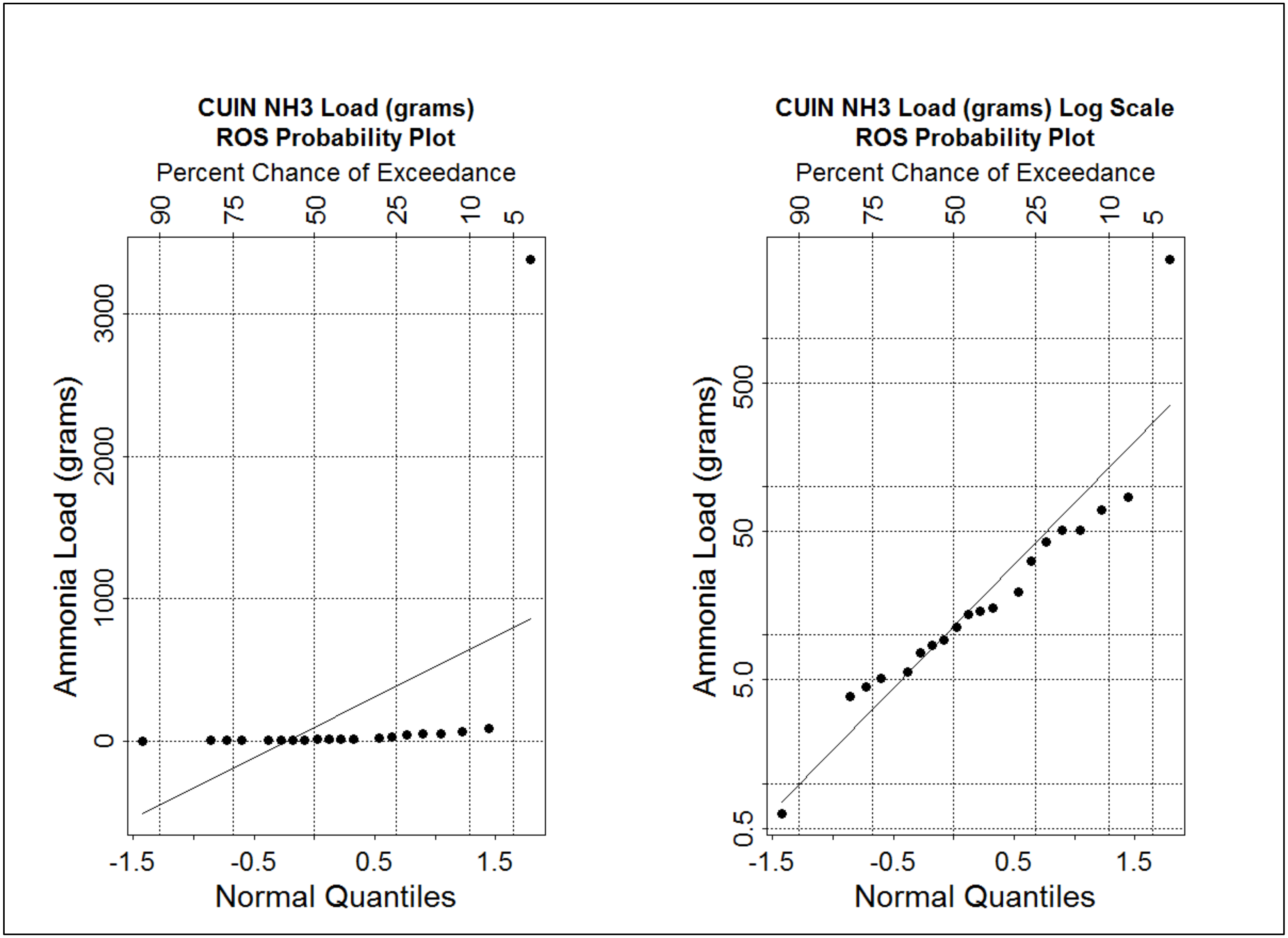


Figure A-38a. Q-Q Plots of CUIN load dataset for ammonia nitrogen.

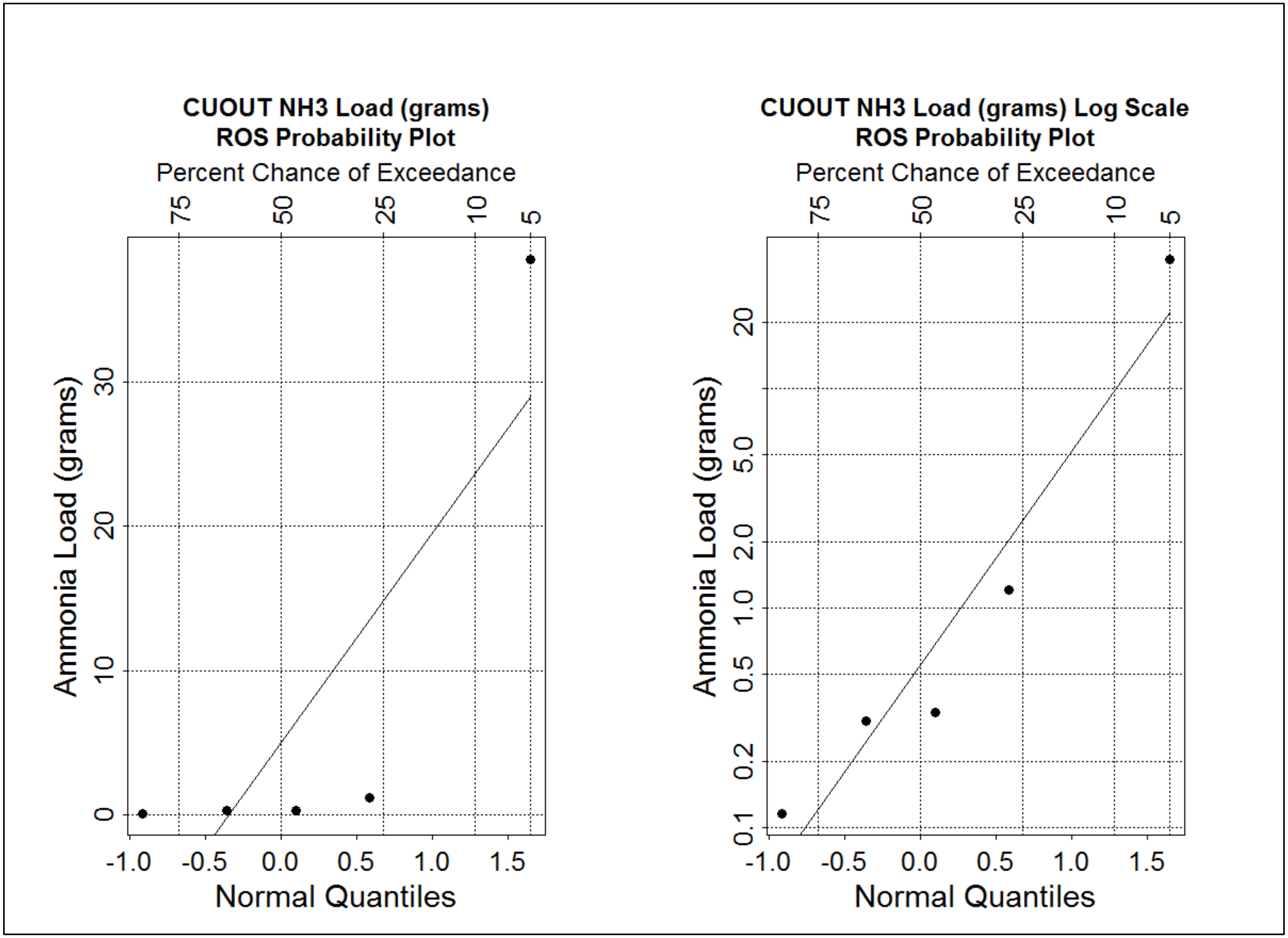


Figure A-38b. Q-Q Plots of CUOUT load dataset for ammonia nitrogen.

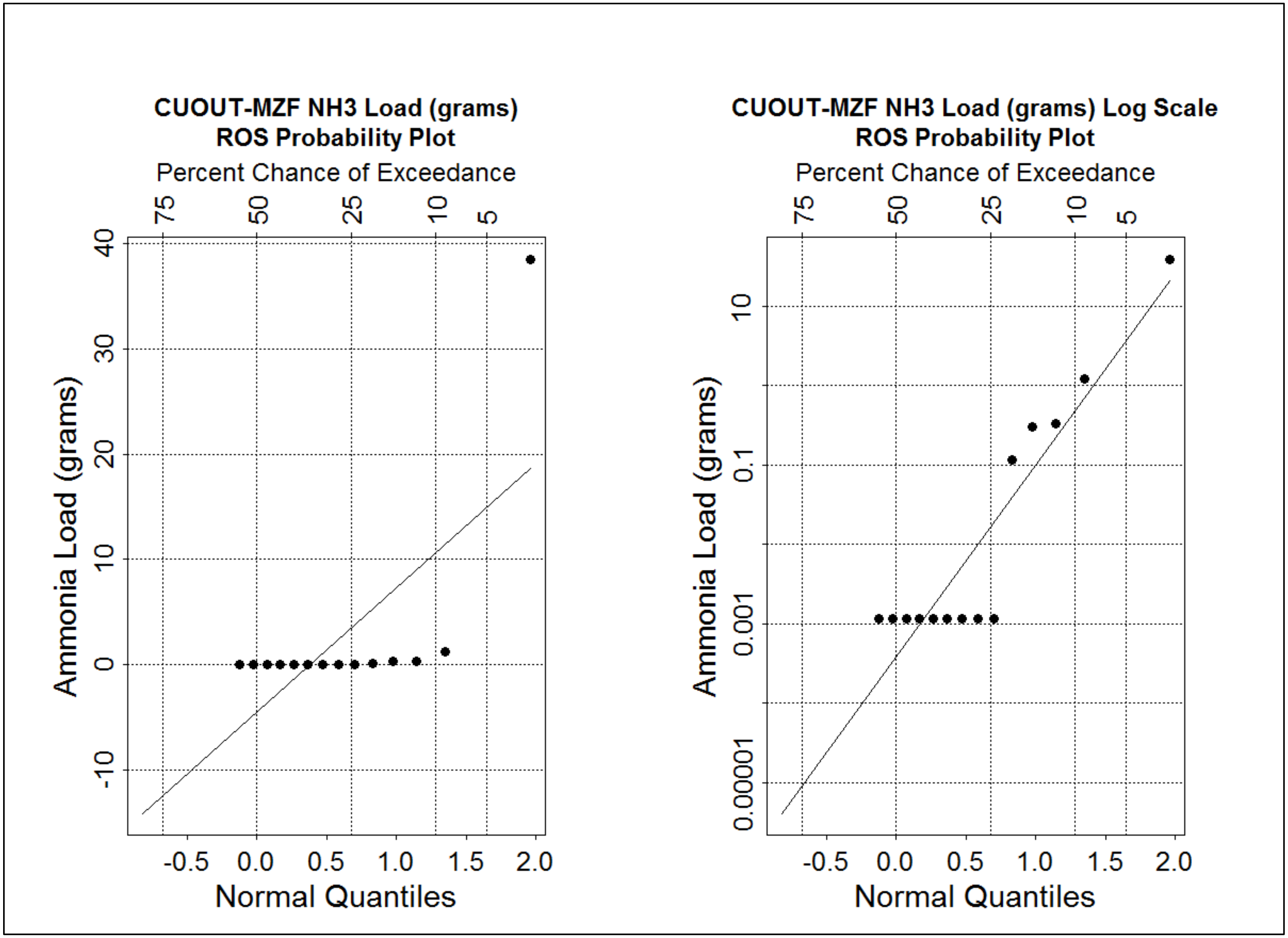


Figure A-38c. Q-Q Plots of CUOUT-MZF load dataset for ammonia nitrogen.

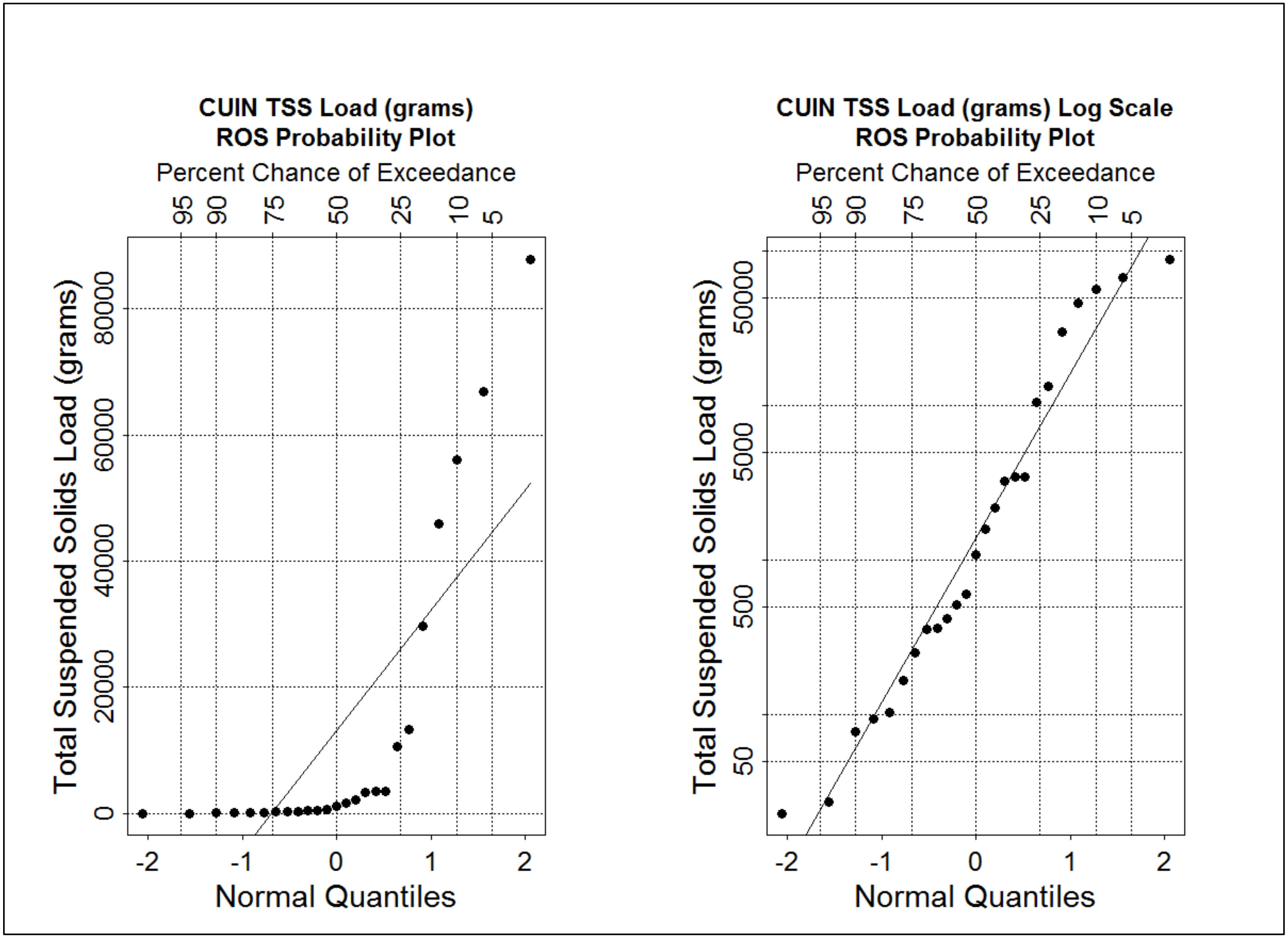


Figure A-39a. Q-Q Plots of CUIN load dataset for total suspended solids.

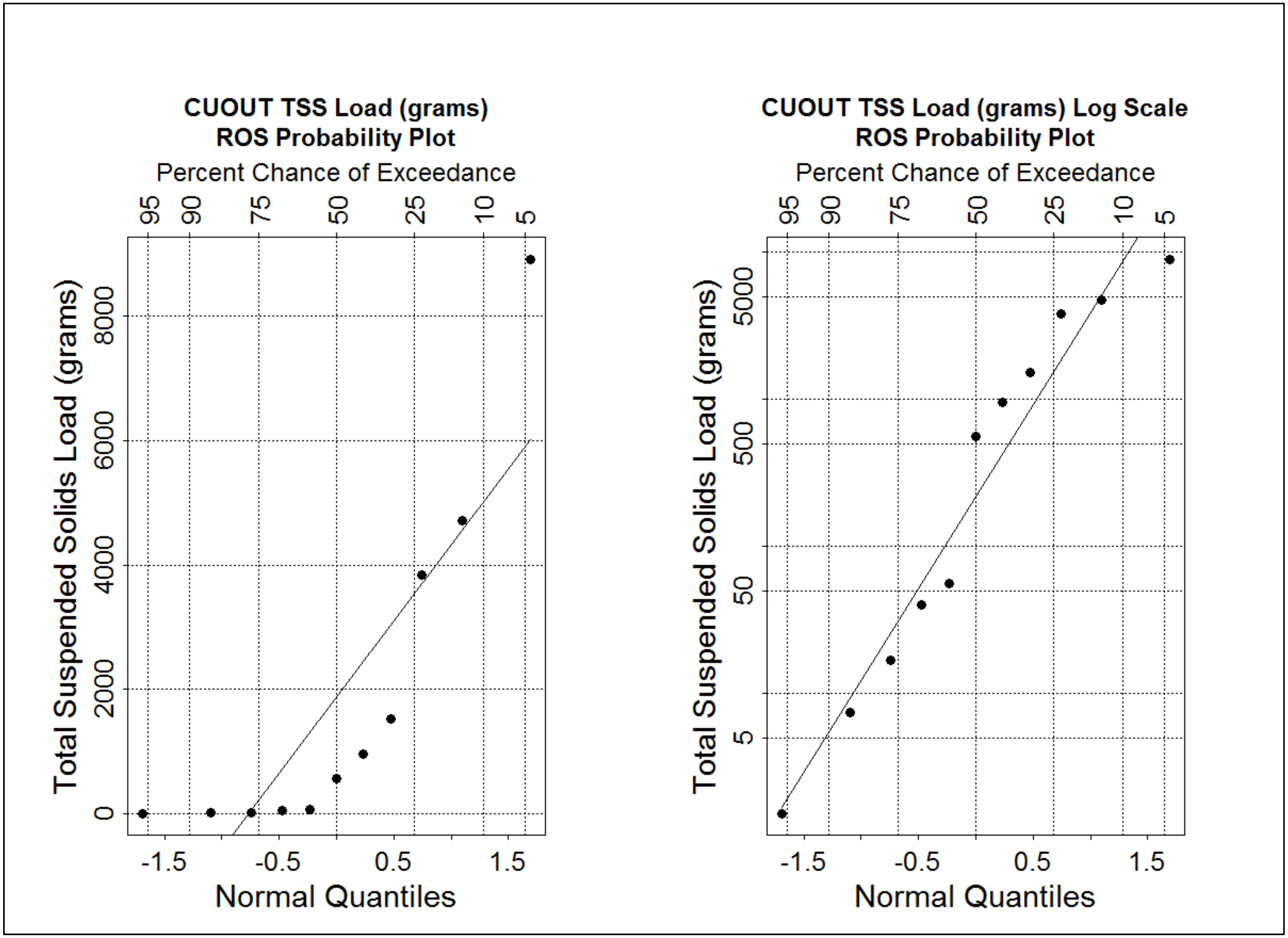


Figure A-39b. Q-Q Plots of CUOUT load dataset for total suspended solids.

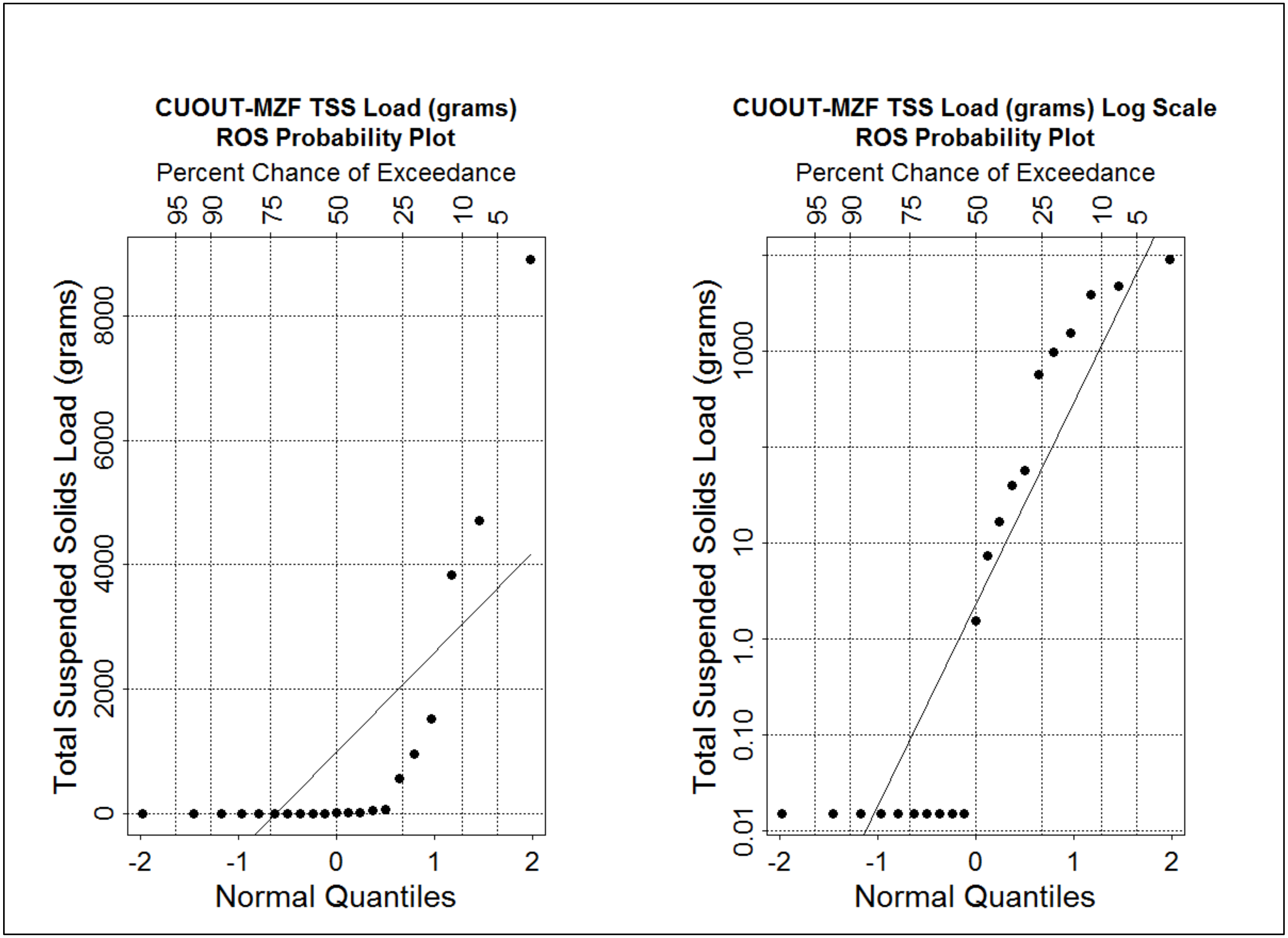


Figure A-39c. Q-Q Plots of CUOUT-MZF load dataset for total suspended solids.

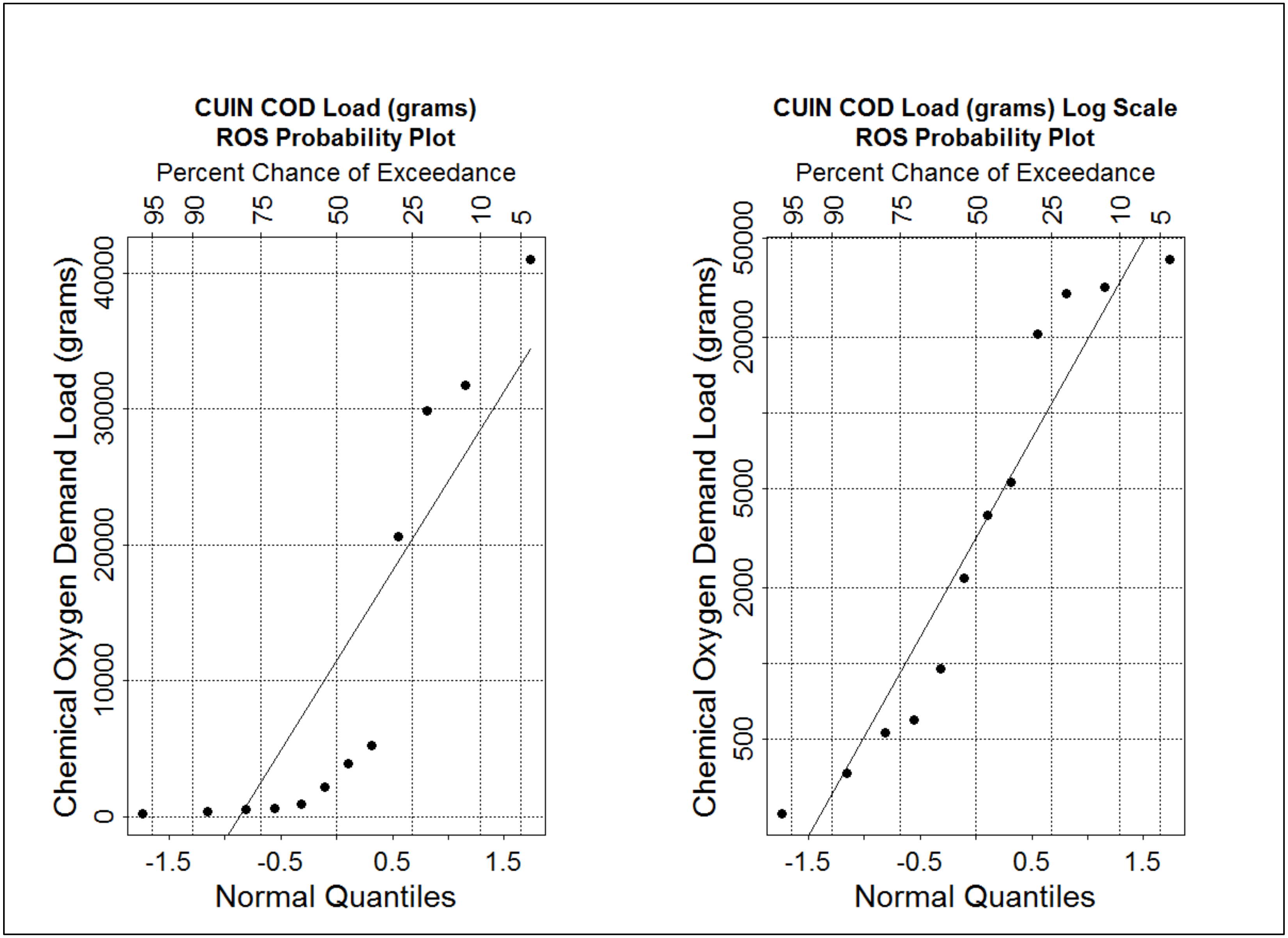


Figure A-40a. Q-Q Plots of CUIN load dataset for chemical oxygen demand.

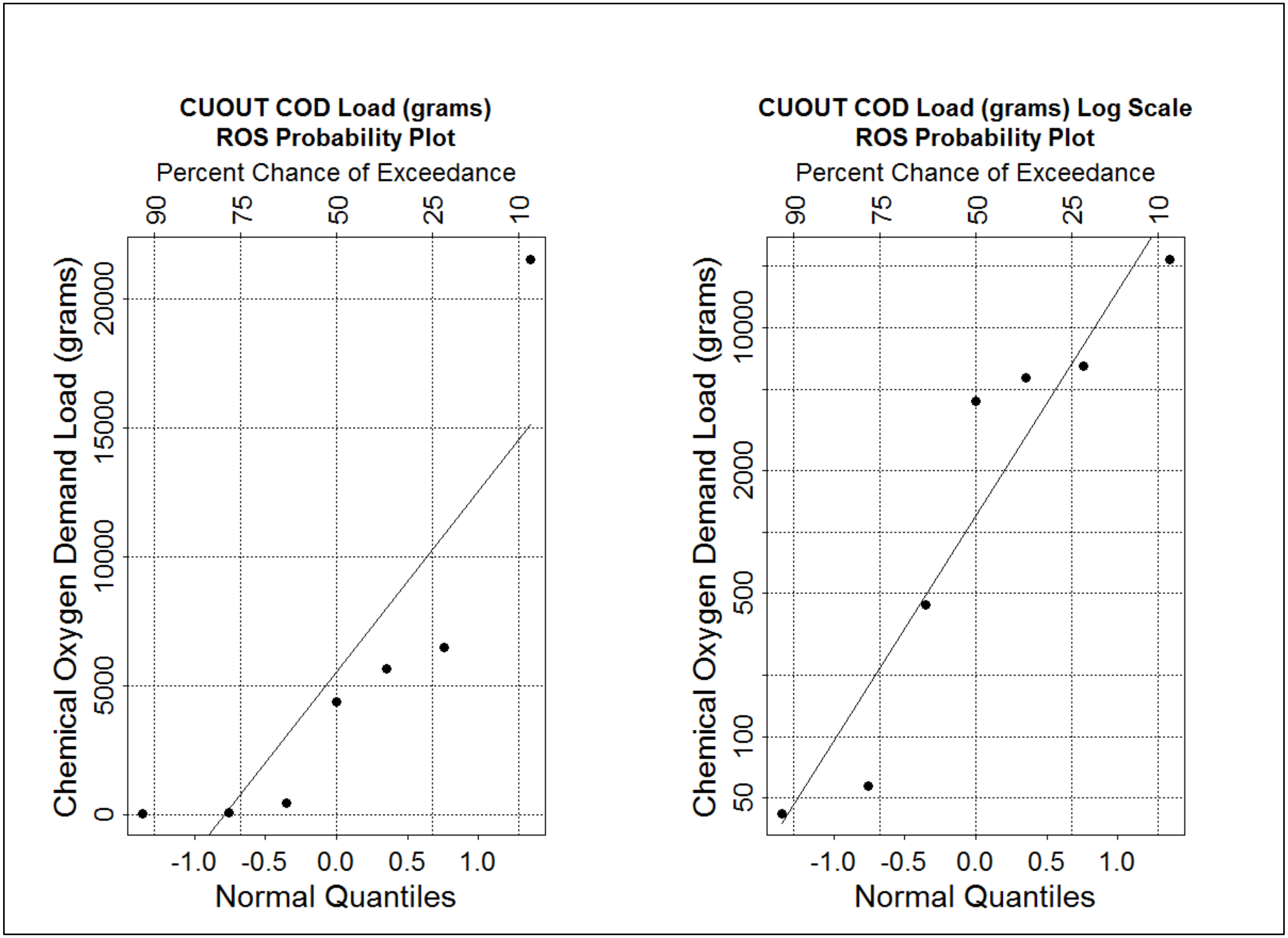


Figure A-40b. Q-Q Plots of CUOUT load dataset for chemical oxygen demand.

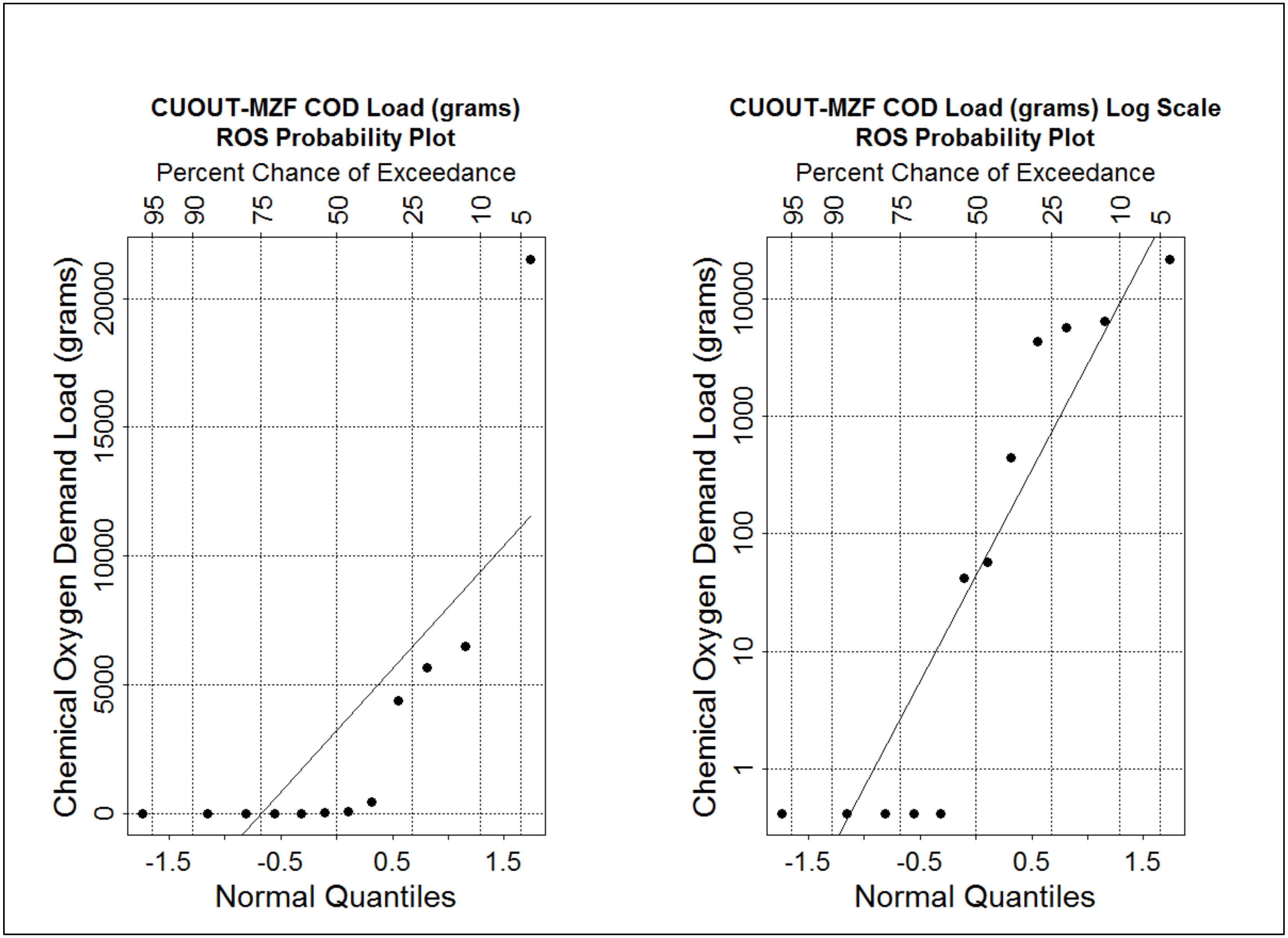


Figure A-40c. Q-Q Plots of CUOUT-MZF load dataset for chemical oxygen demand.

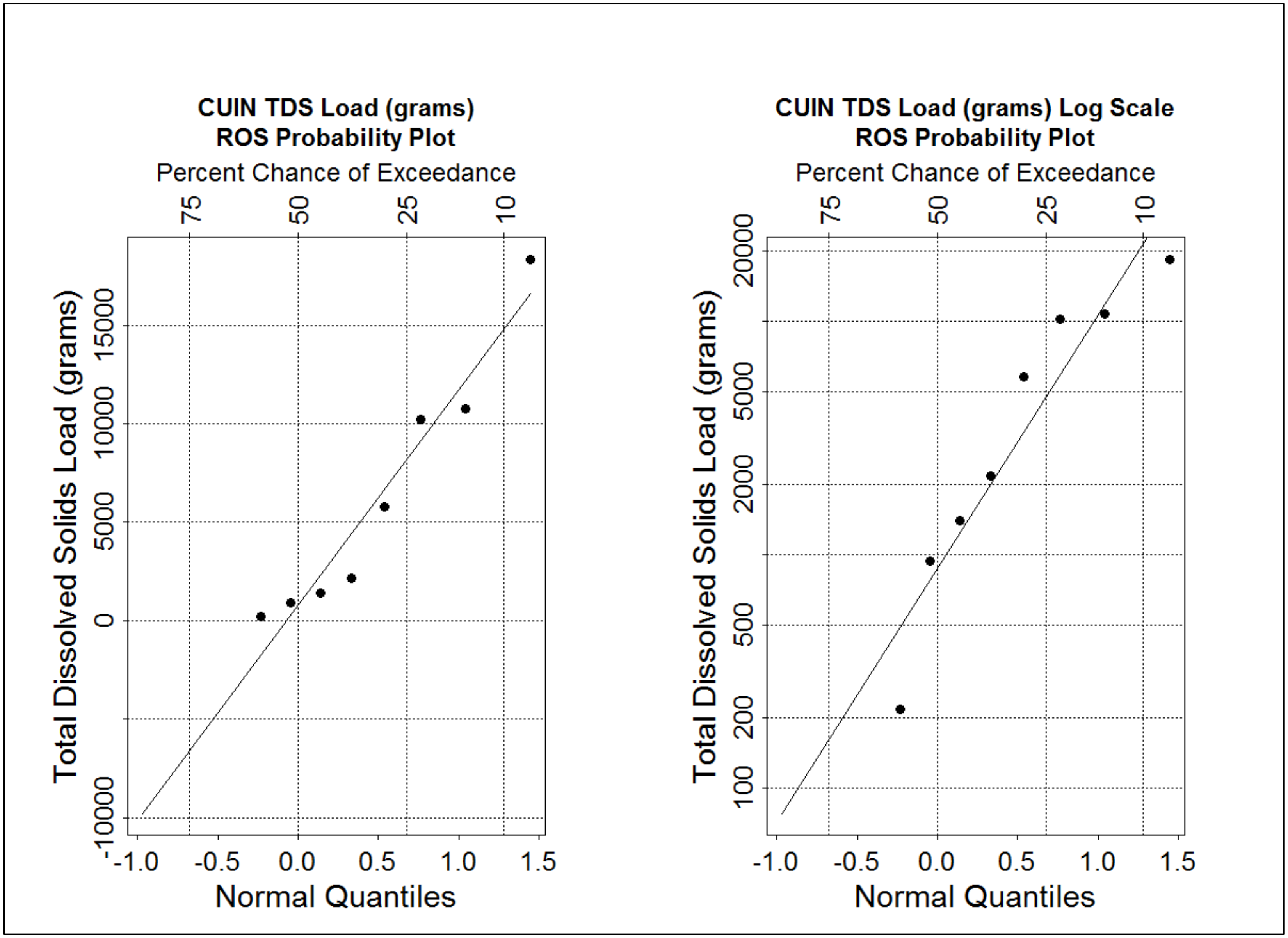


Figure A-41a. Q-Q Plots of CUIN load dataset for total dissolved solids.

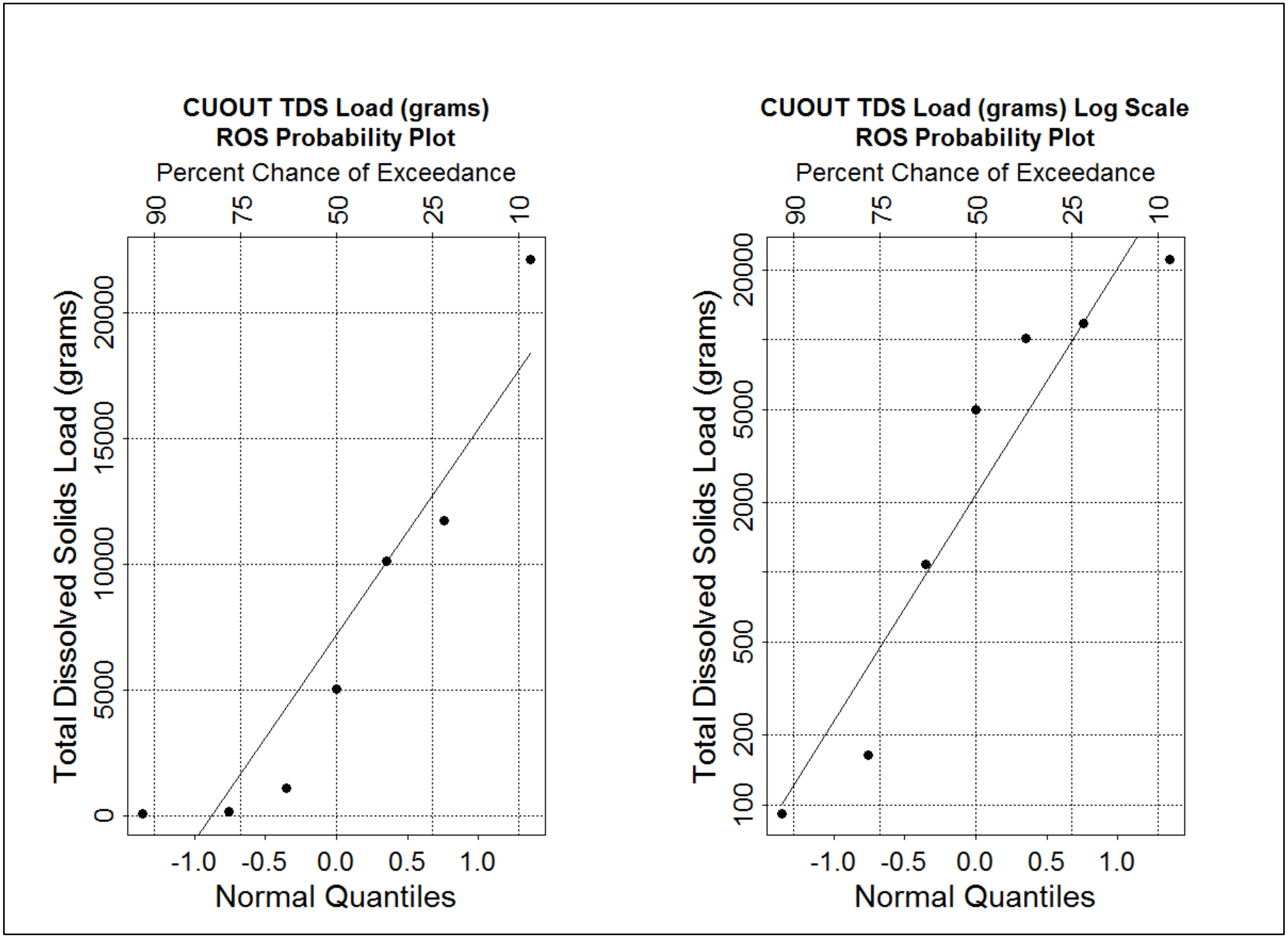


Figure A-41b. Q-Q Plots of CUOUT load dataset for total dissolved solids.

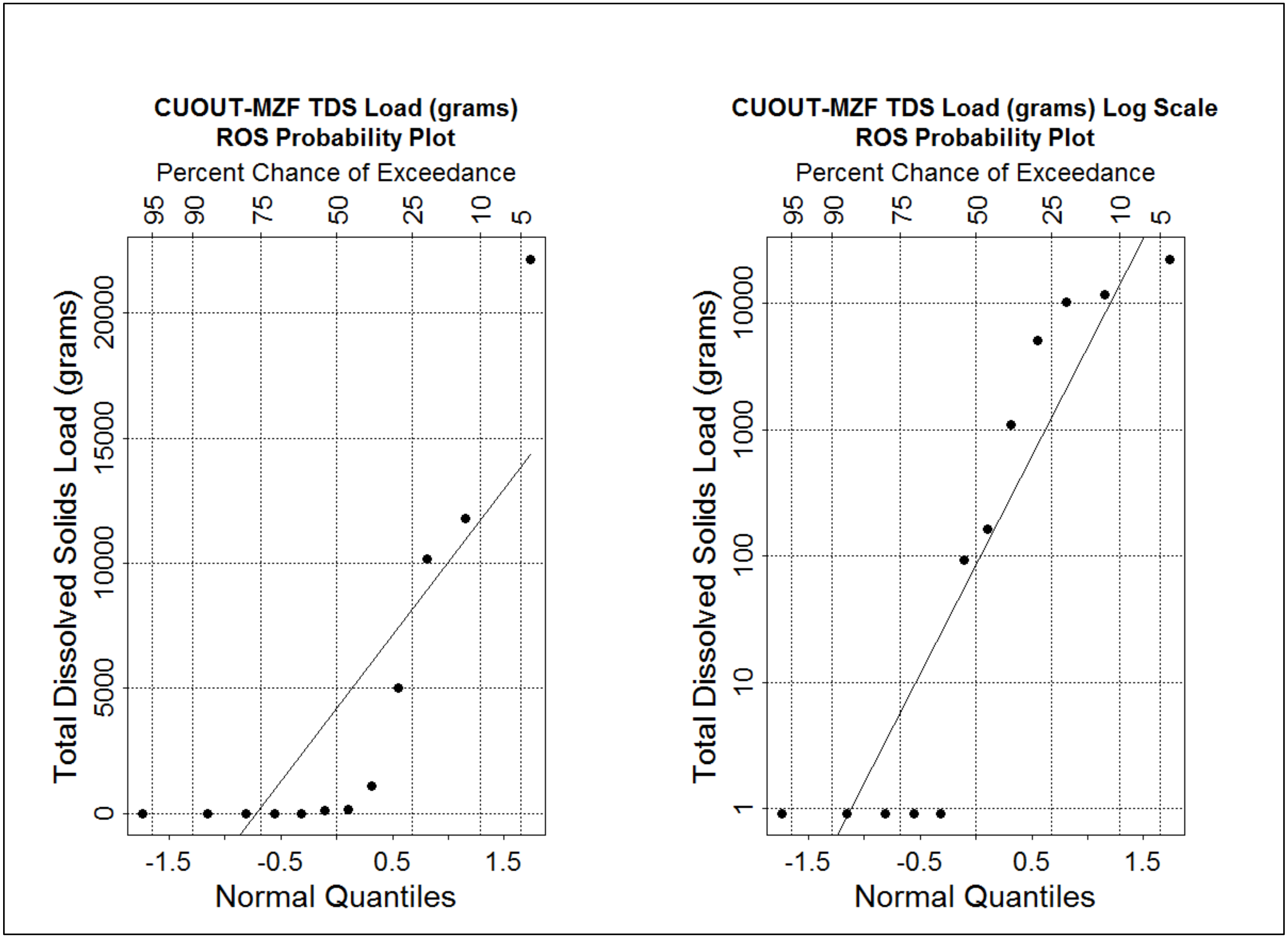


Figure A-41c. Q-Q Plots of CUOUT-MZF load dataset for total dissolved solids.

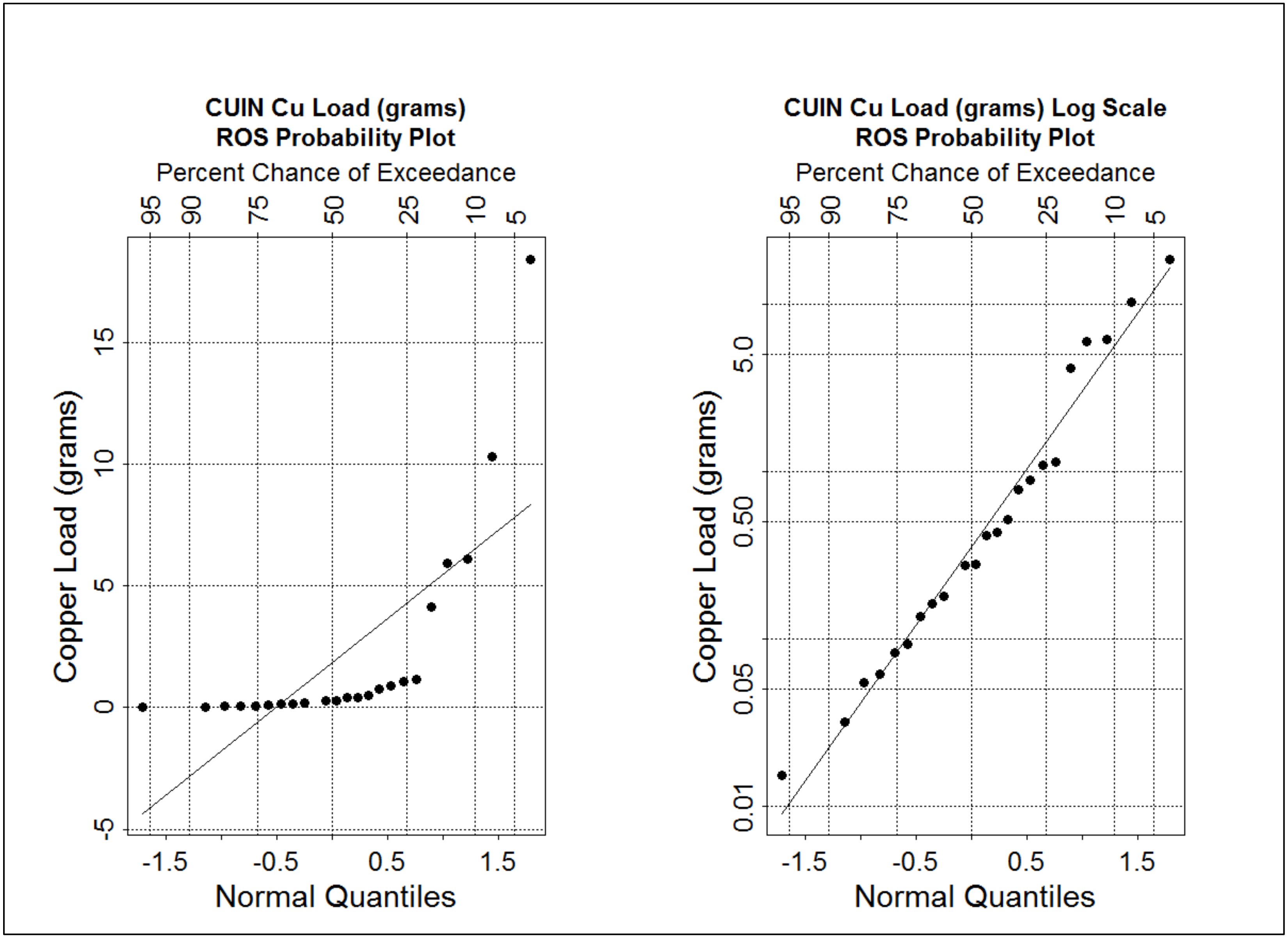


Figure A-42a. Q-Q Plots of CUIN load dataset for copper.

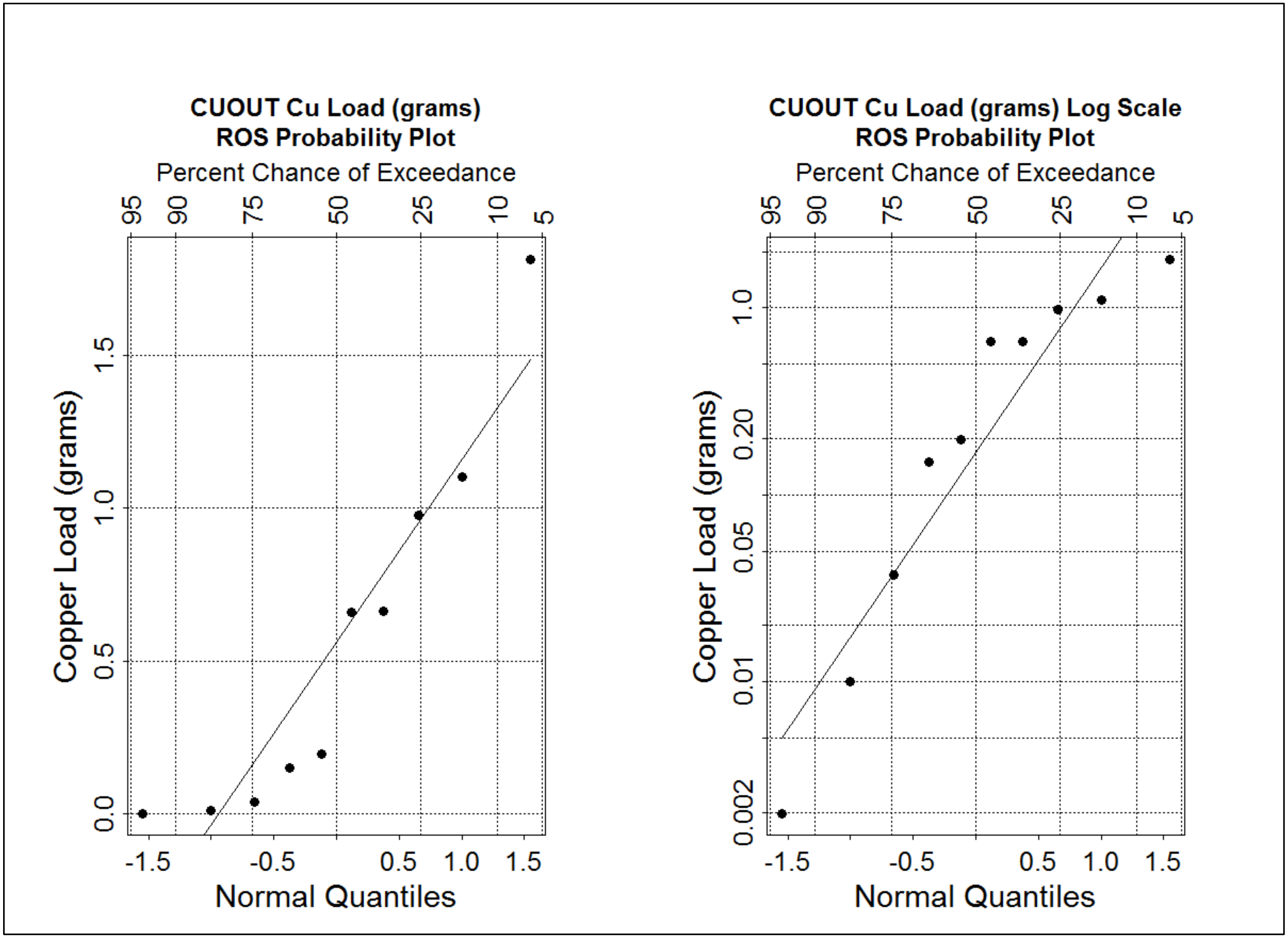


Figure A-42b. Q-Q Plots of CUOUT load dataset for copper.

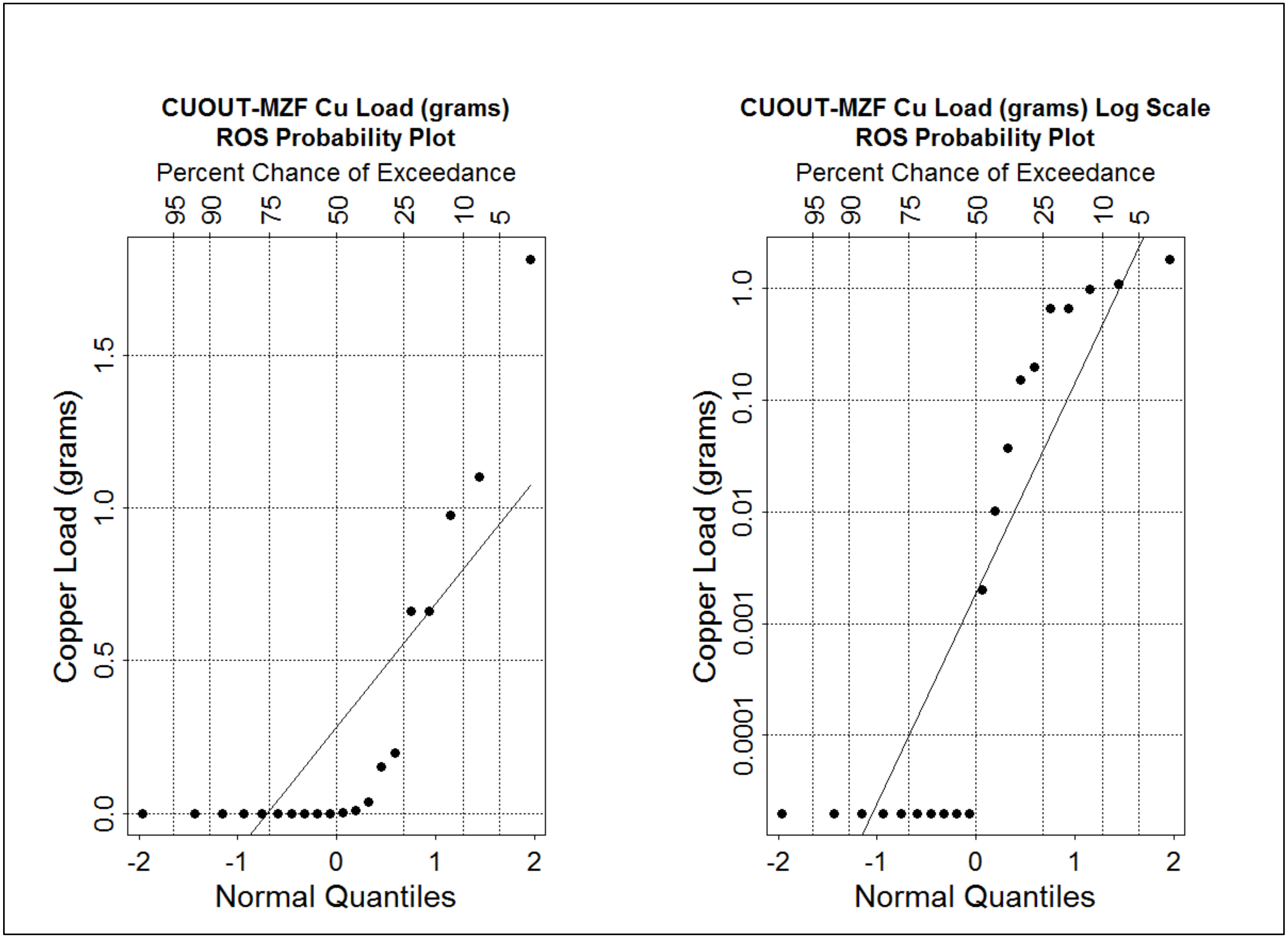


Figure A-42c. Q-Q Plots of CUOUT-MZF load dataset for copper.

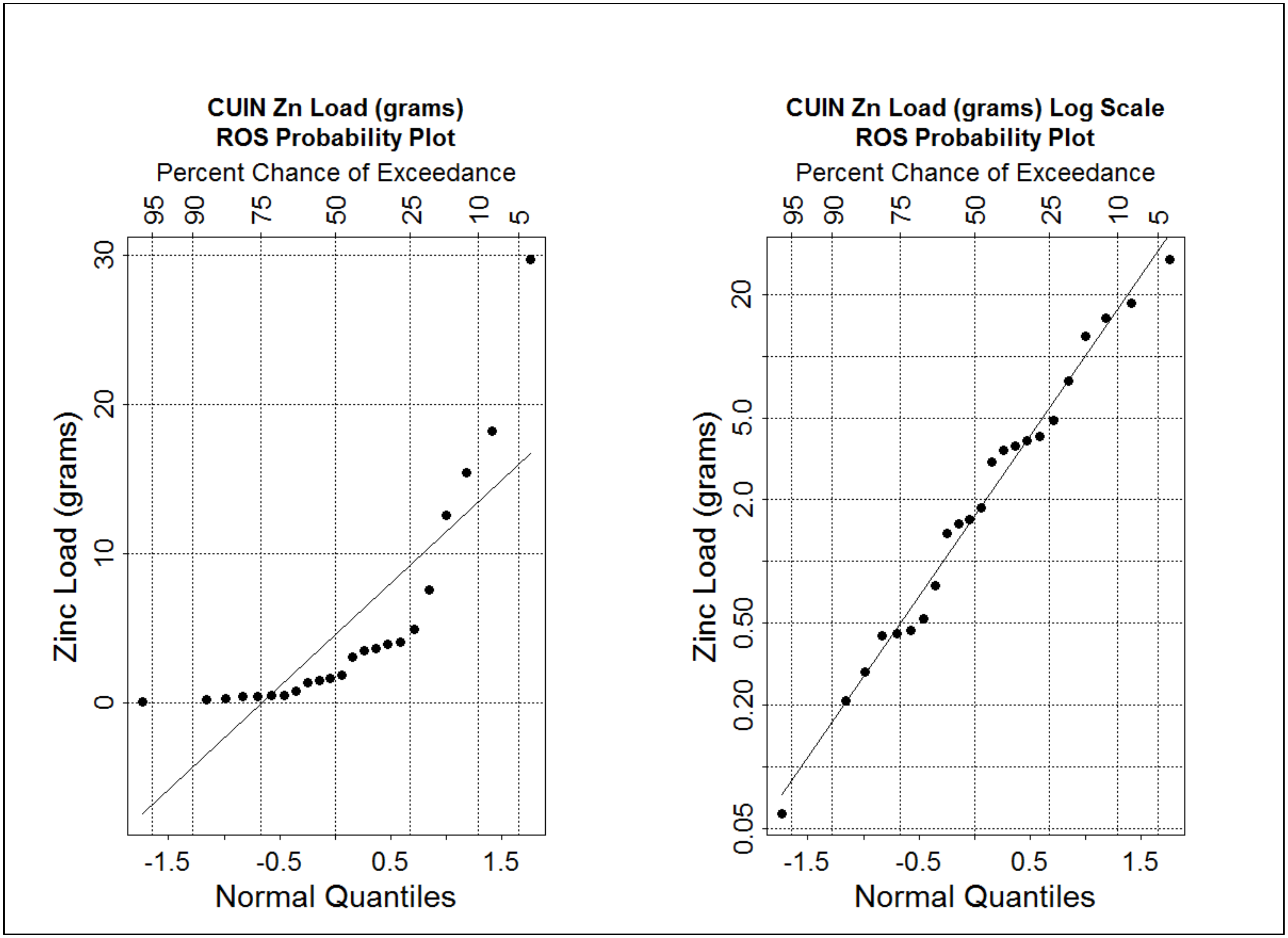


Figure A-43a. Q-Q Plots of CUIN load dataset for zinc.

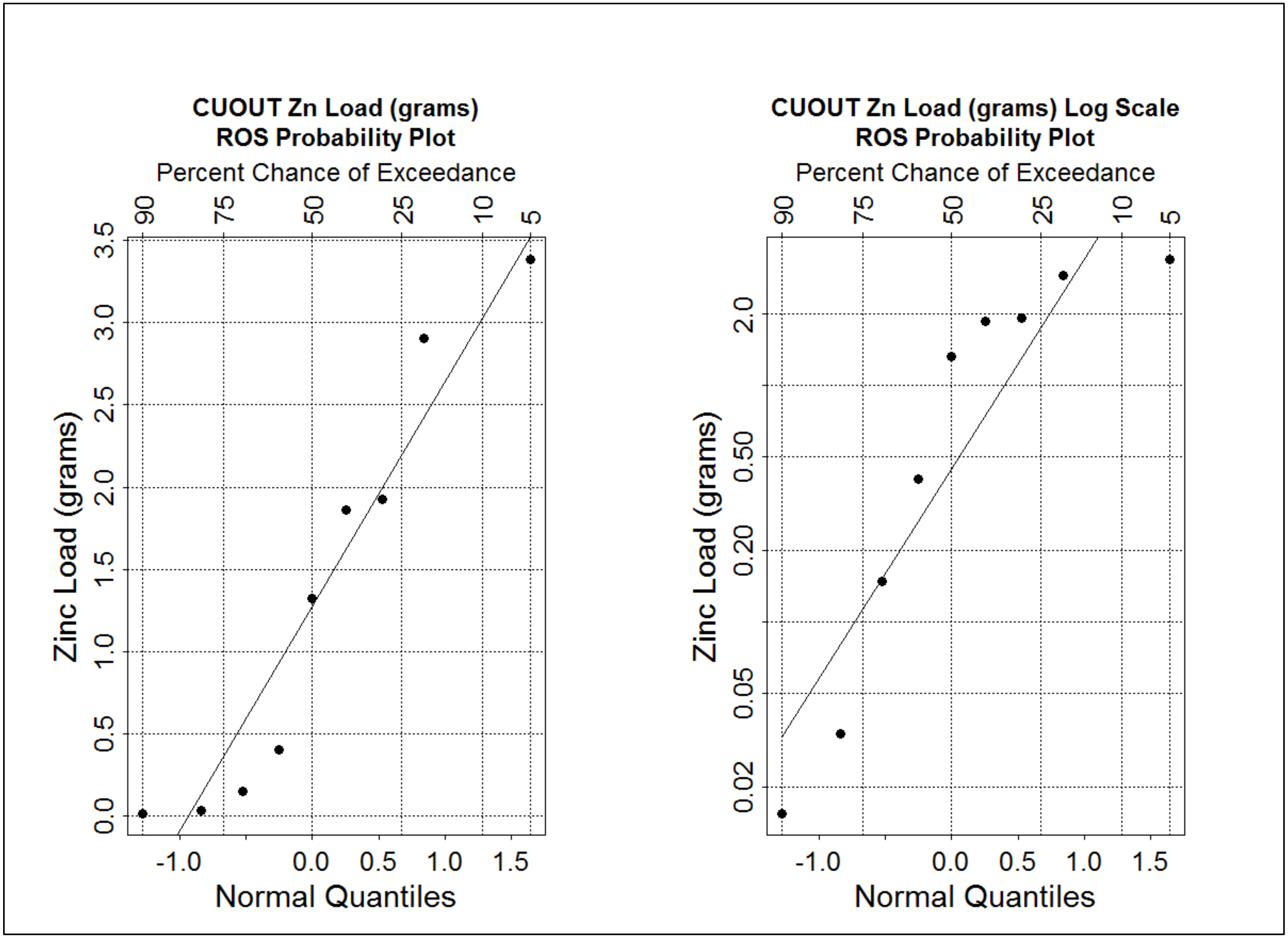


Figure A-43b. Q-Q Plots of CUOUT load dataset for zinc.

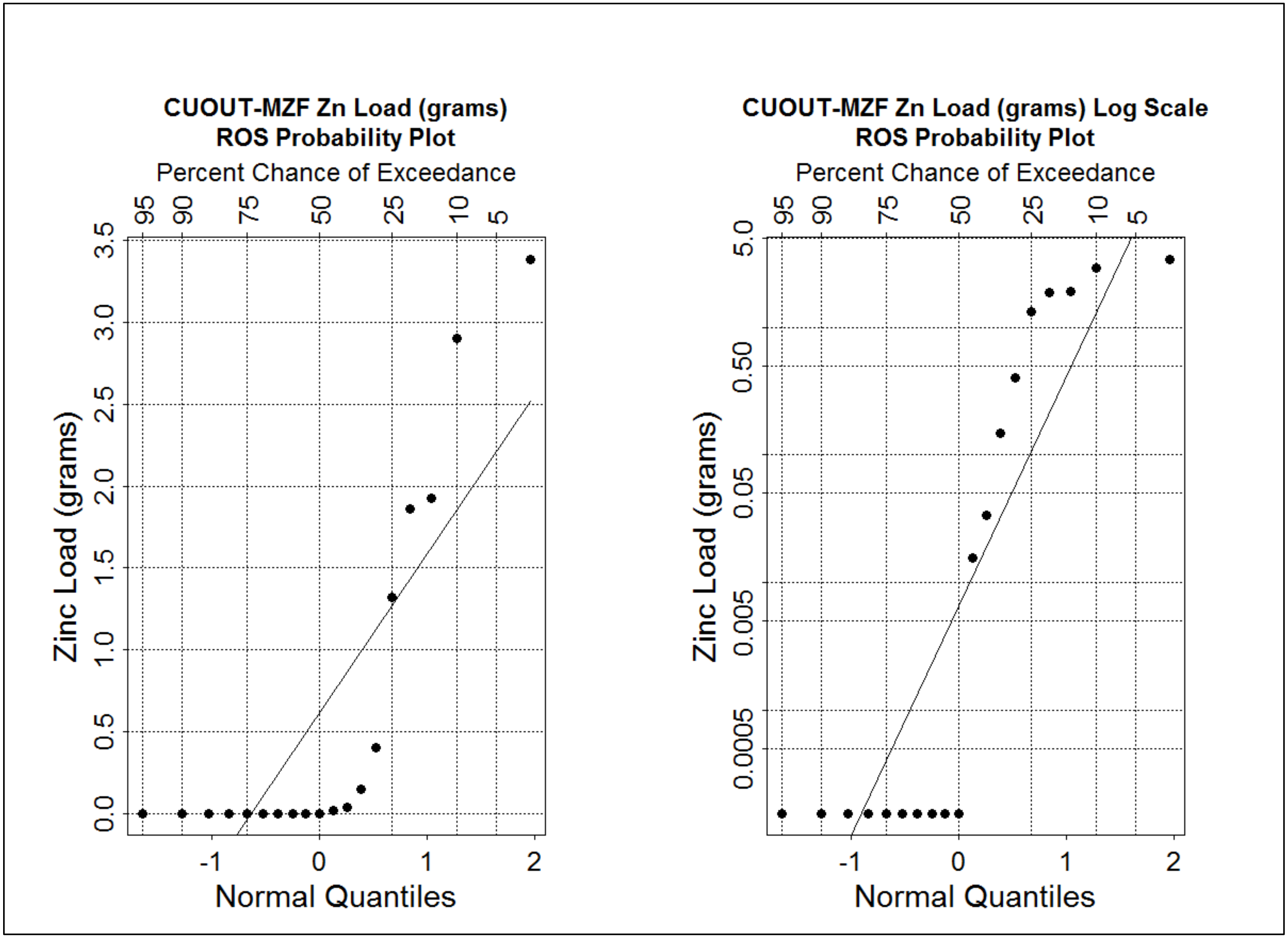


Figure A-43c. Q-Q Plots of CUOUT-MZF load dataset for zinc.

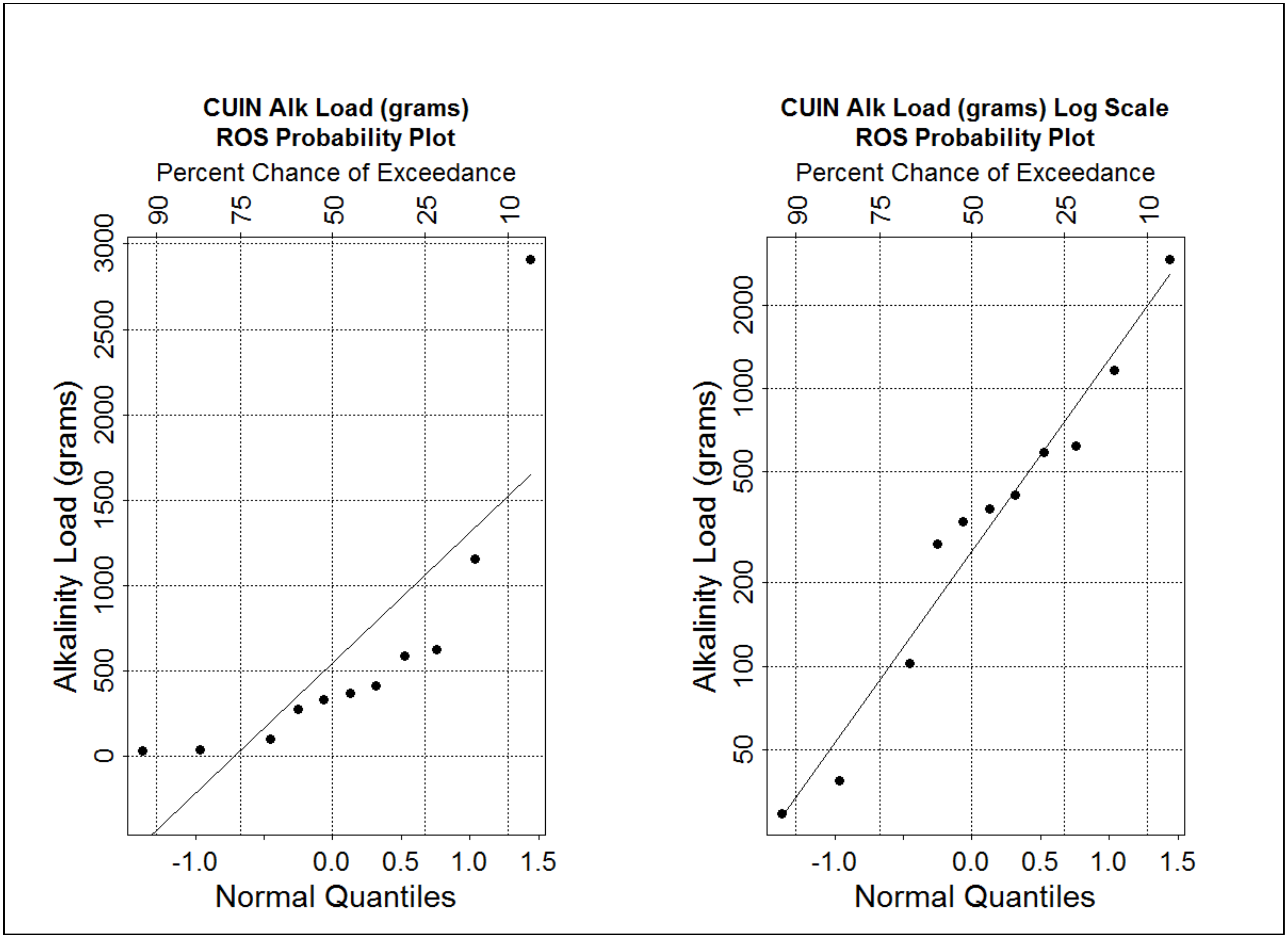


Figure A-44a. Q-Q Plots of CUIN load dataset for alkalinity.

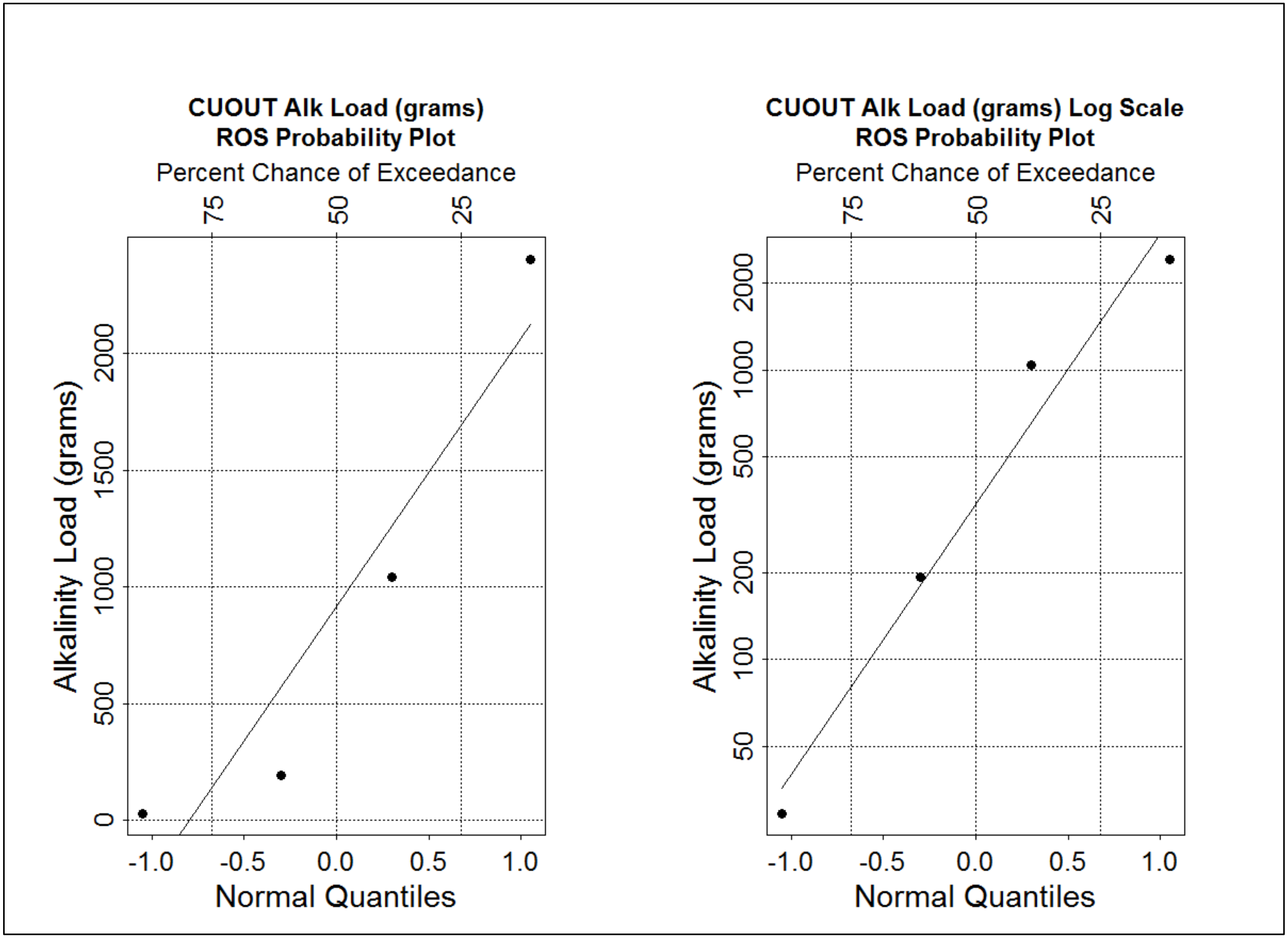


Figure A-44b. Q-Q Plots of CUOUT load dataset for alkalinity.

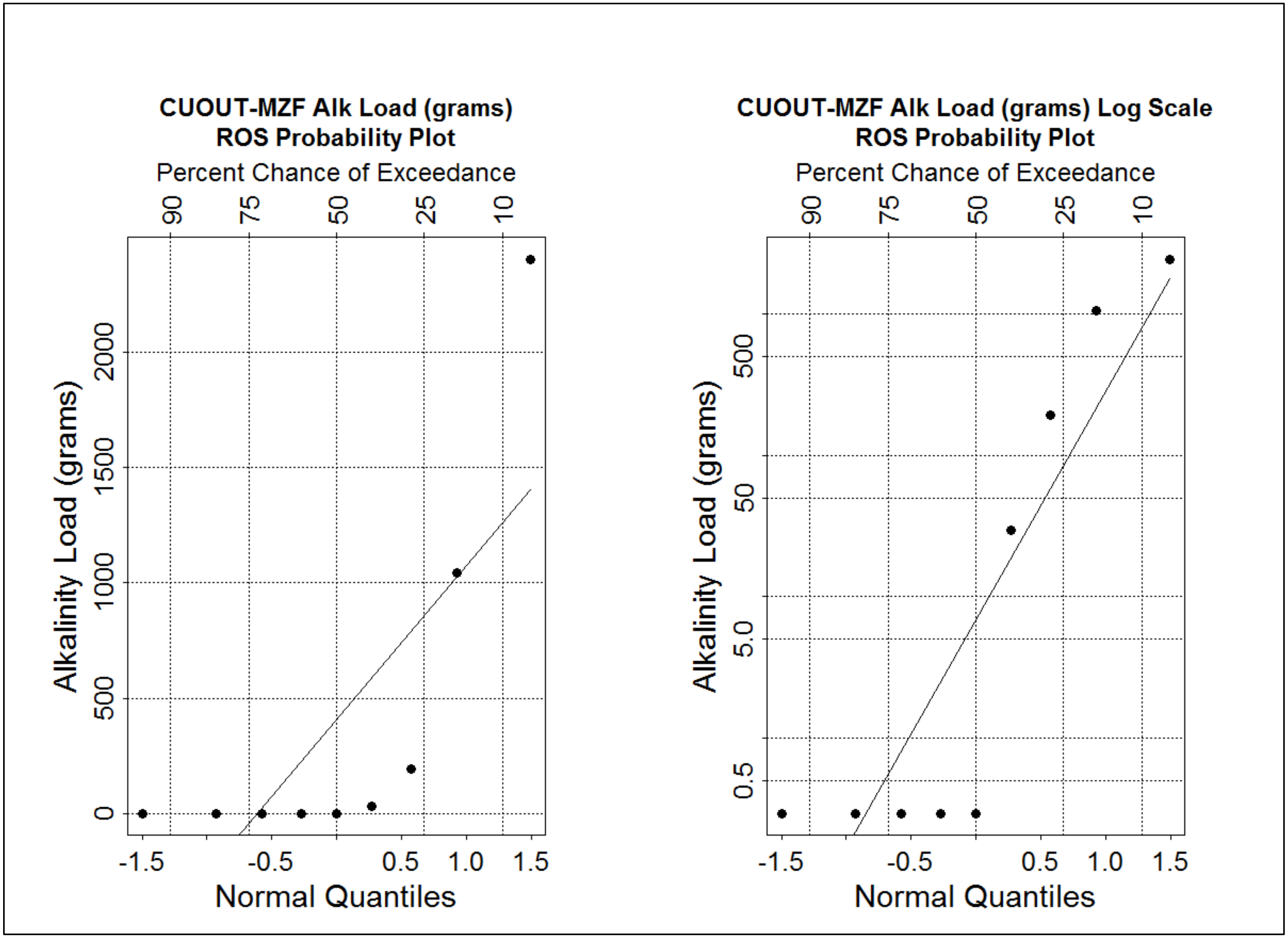


Figure A-44c. Q-Q Plots of CUOUT-MZF load dataset for alkalinity.

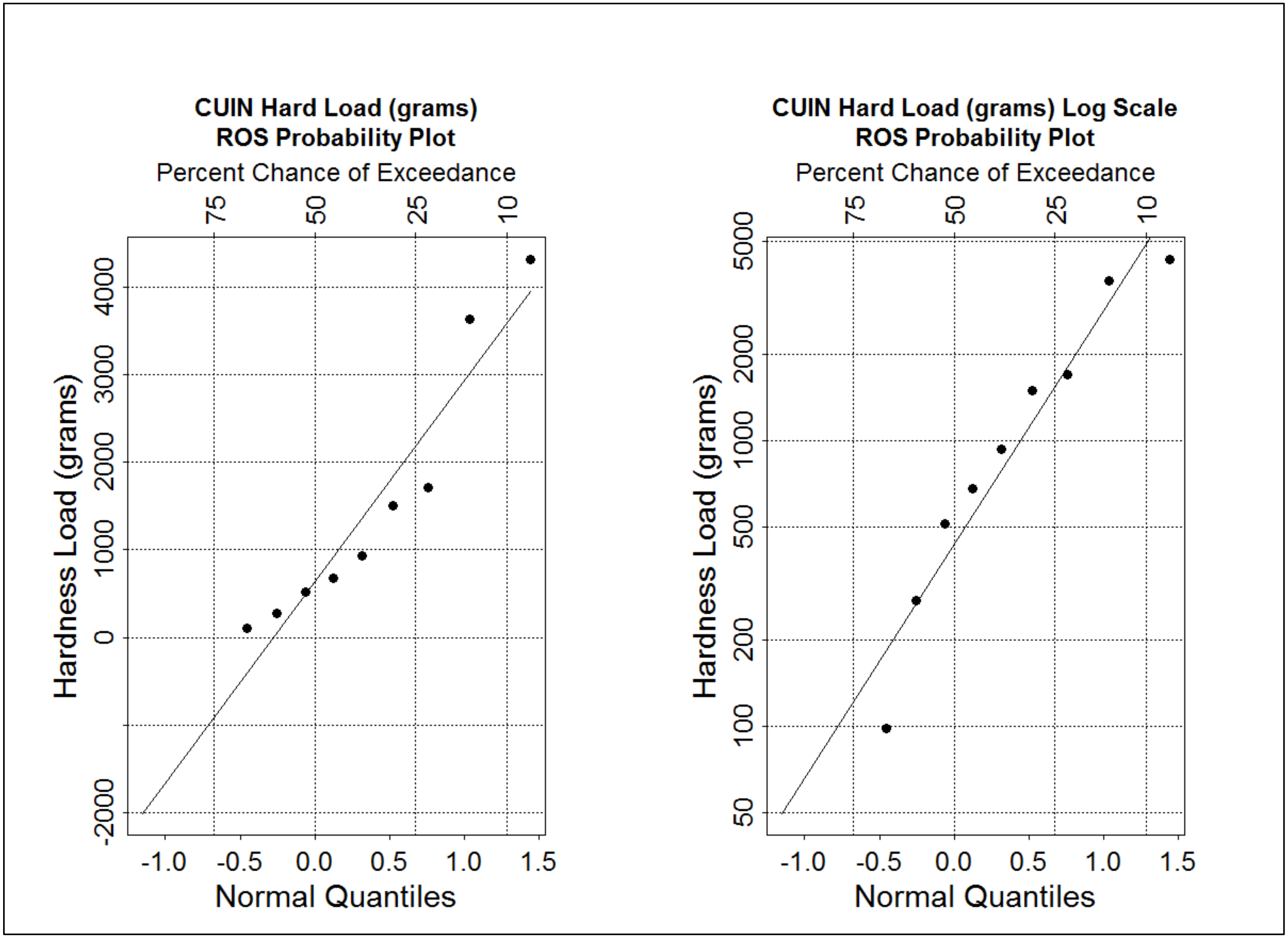


Figure A-45a. Q-Q Plots of CUIN load dataset for hardness.

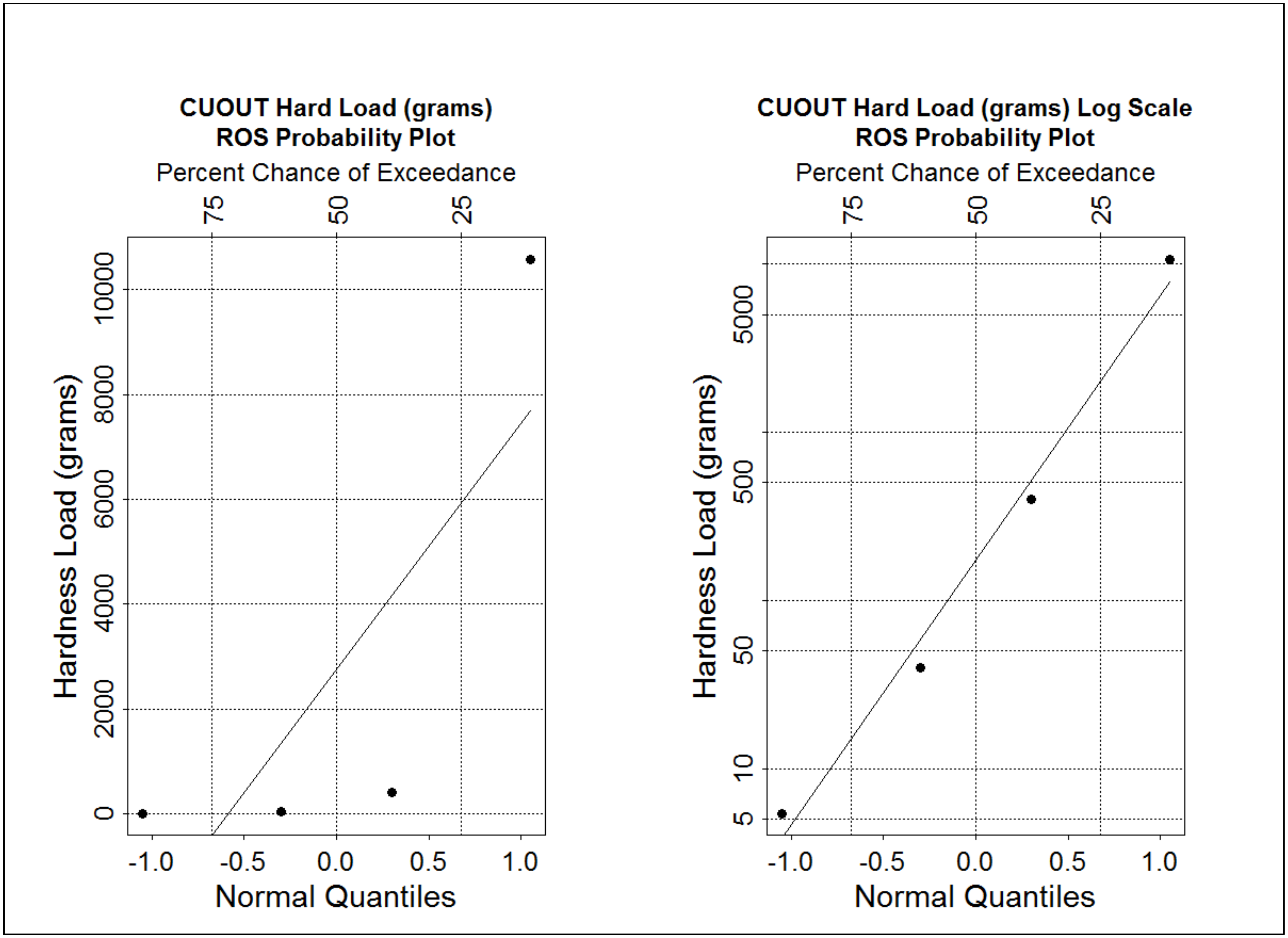


Figure A-45b. Q-Q Plots of CUOUT load dataset for hardness.

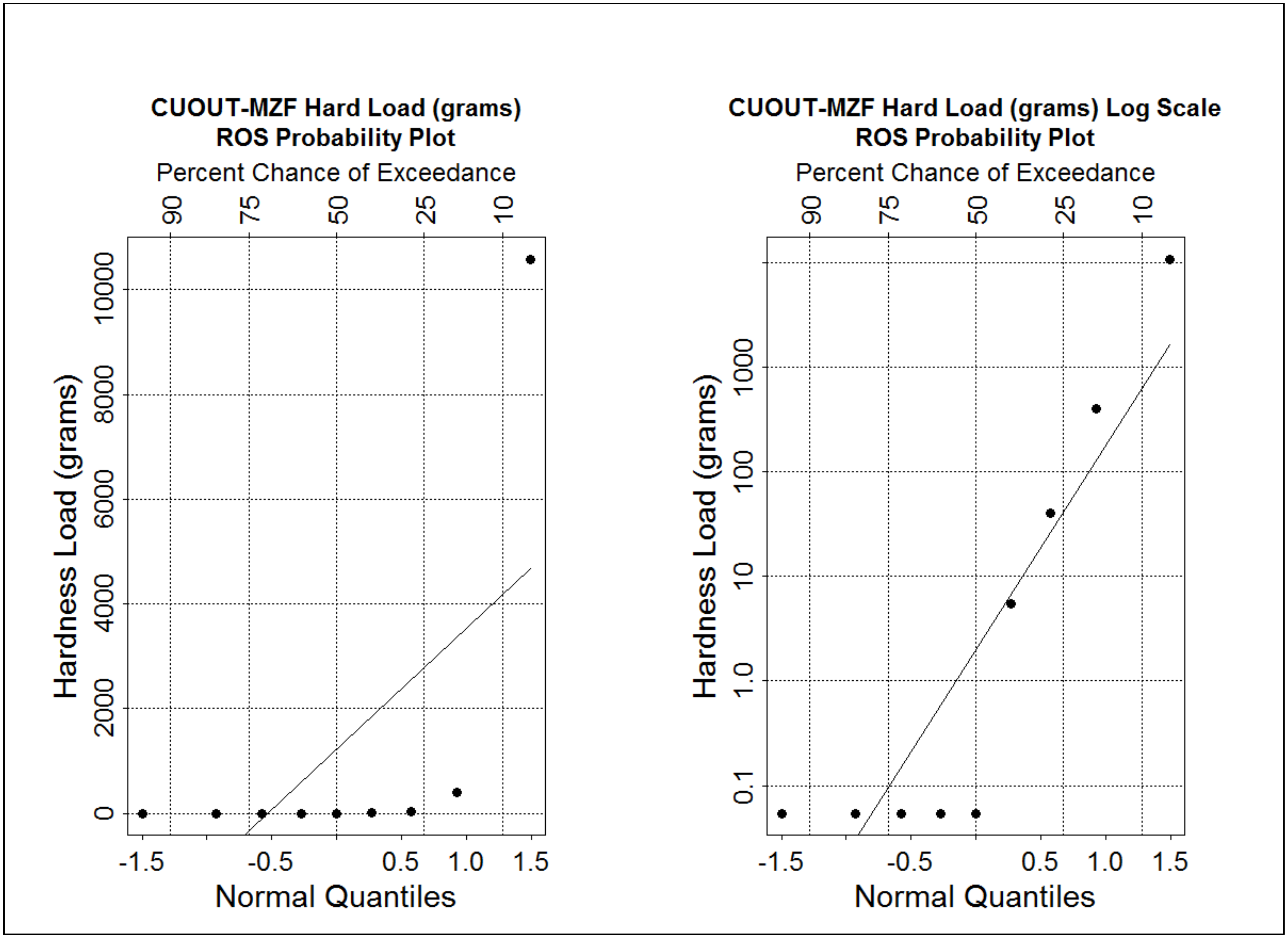


Figure A-45c. Q-Q Plots of CUOUT-MZF load dataset for hardness.

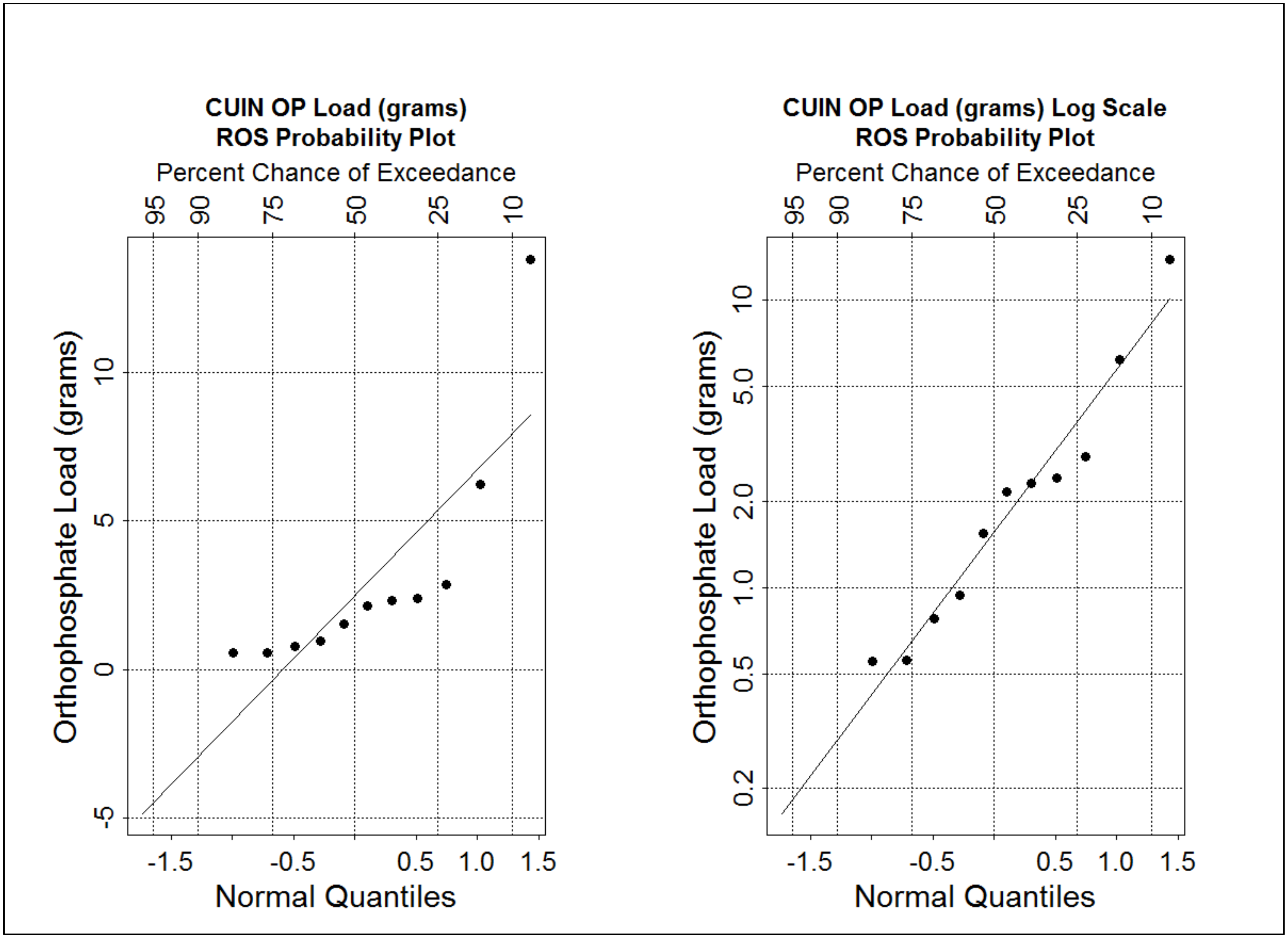


Figure A-46a. Q-Q Plots of CUIN load dataset for orthophosphate phosphorus.

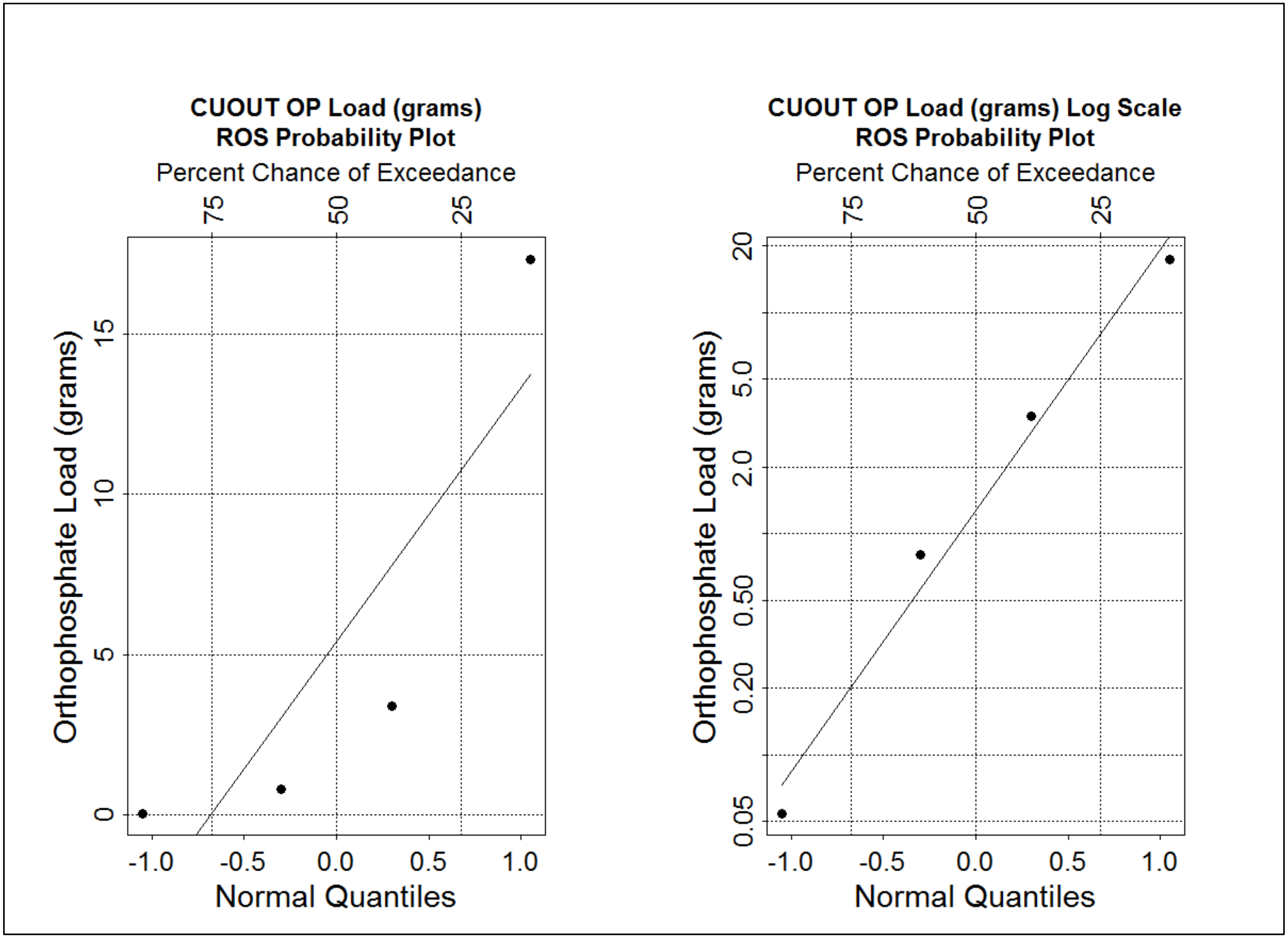


Figure A-46b. Q-Q Plots of CUOUT load dataset for orthophosphate phosphorus.

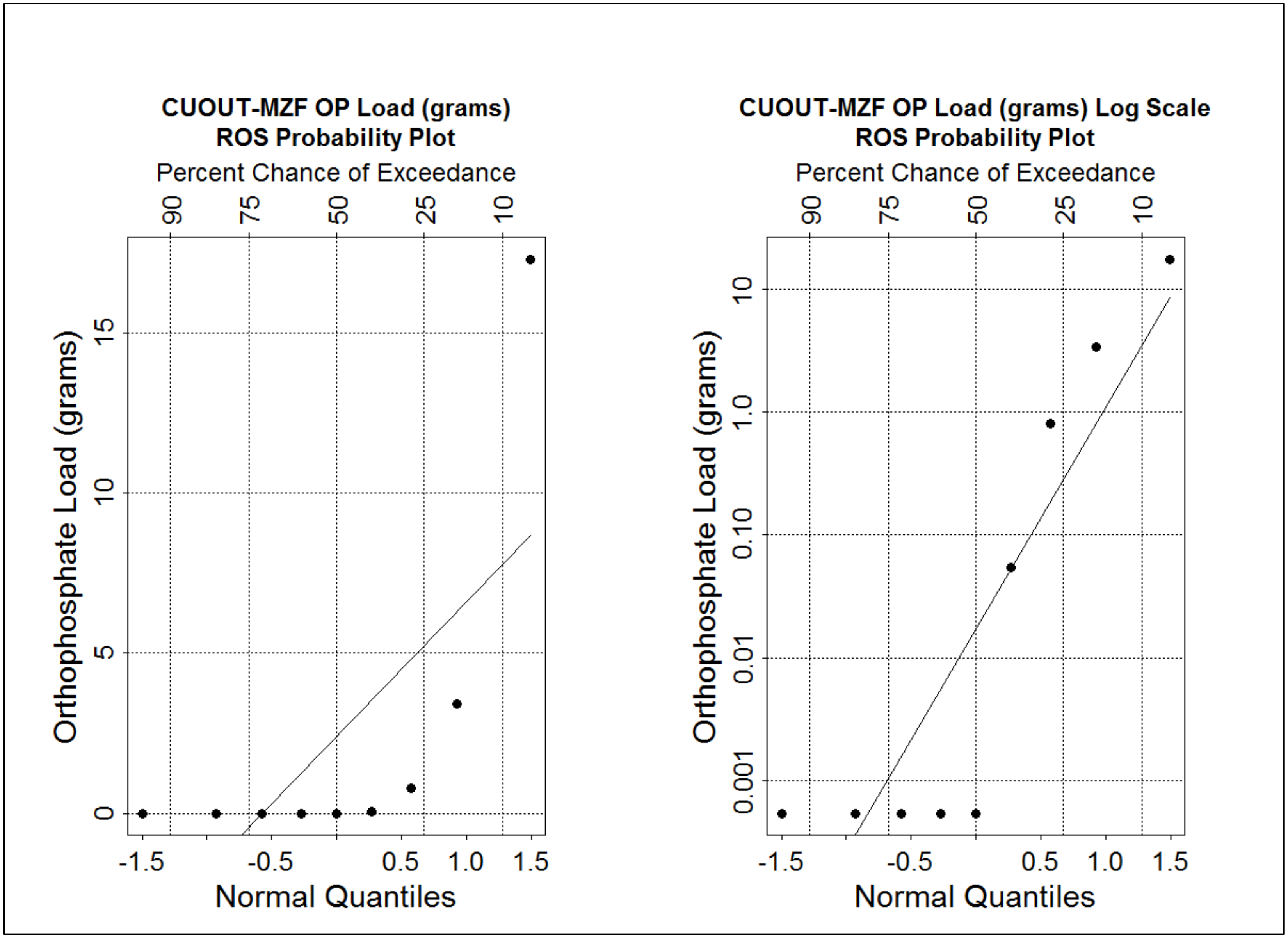


Figure A-46c. Q-Q Plots of CUOUT-MZF load dataset for orthophosphate phosphorus.

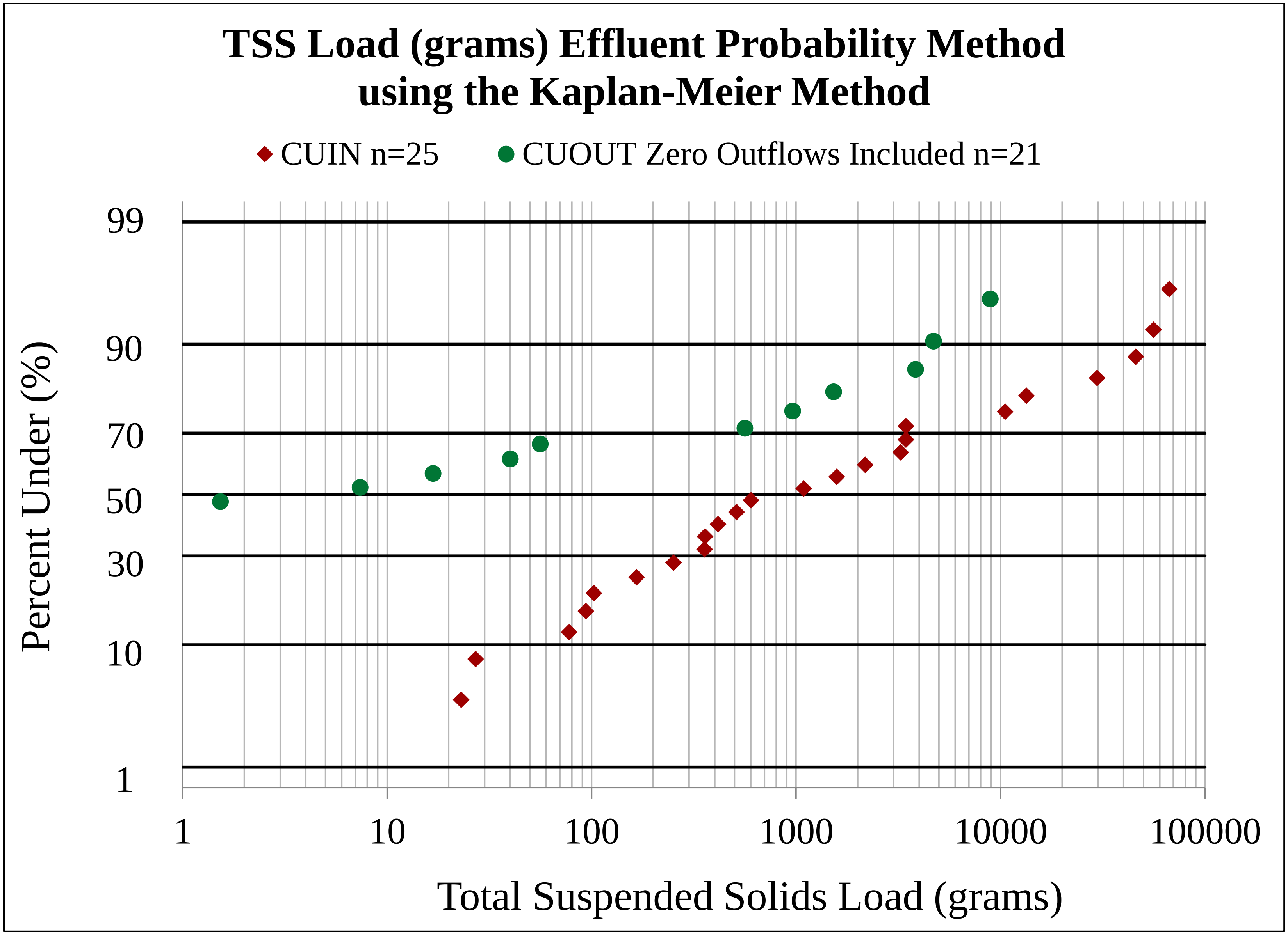


Figure A-47. Effluent Probability Method plot of CUIN & CUOUT-ZF load datasets for total suspended solids.

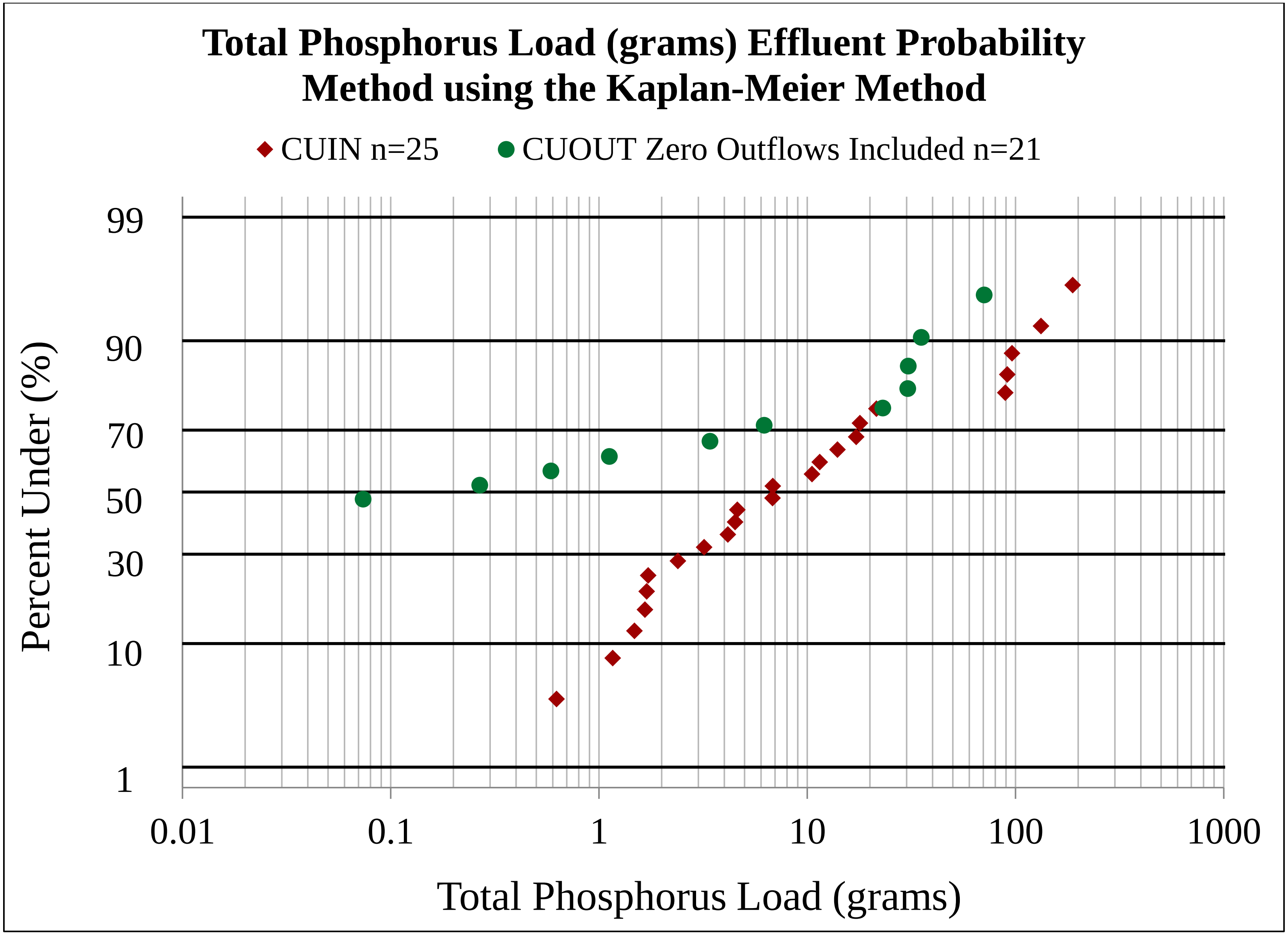


Figure A-48. Effluent Probability Method plot of CUIN & CUOUT-ZF load datasets for total phosphorus.

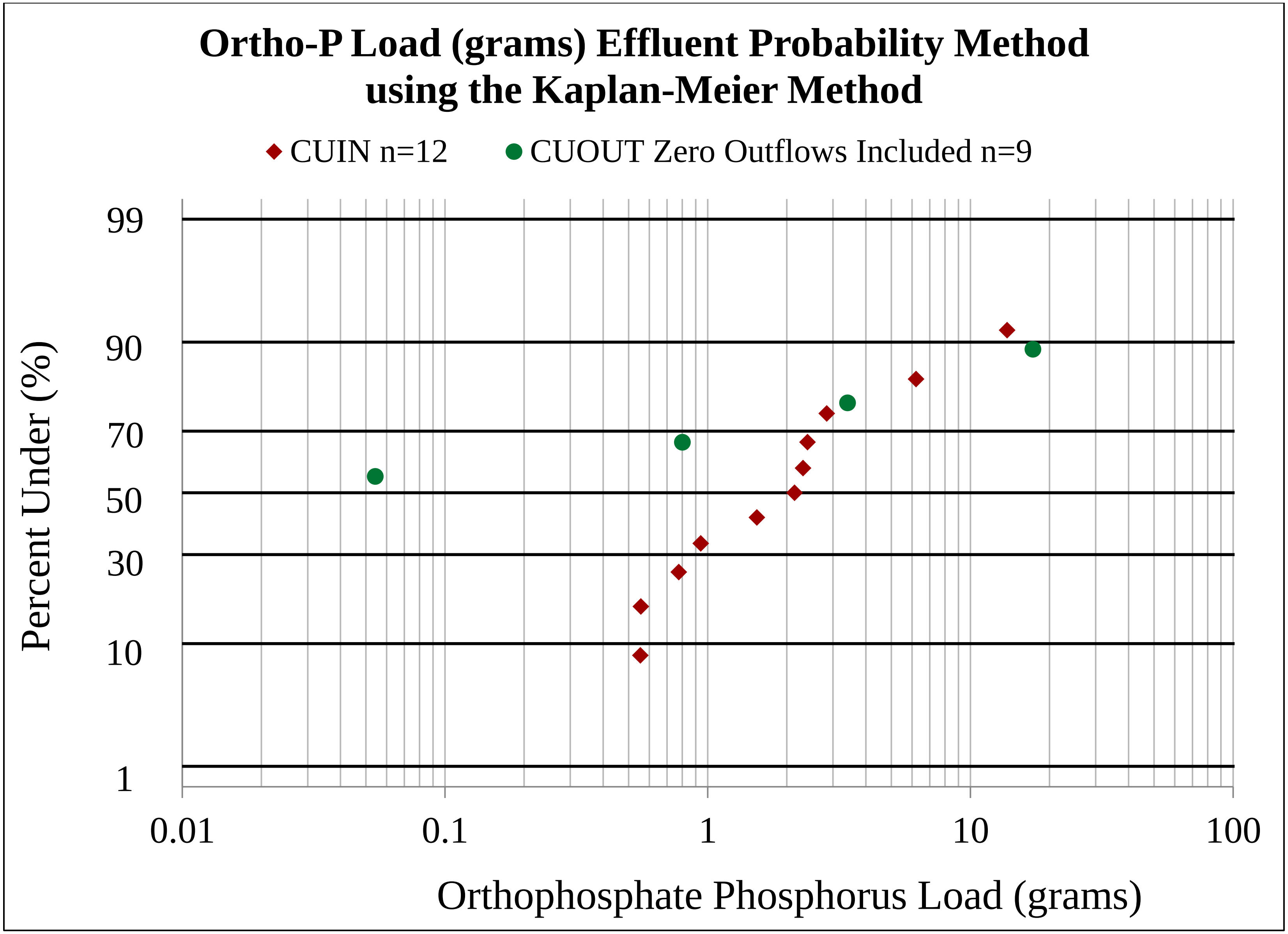


Figure A-49. Effluent Probability Method plot of CUIN & CUOUT-ZF load datasets for orthophosphate phosphorus.

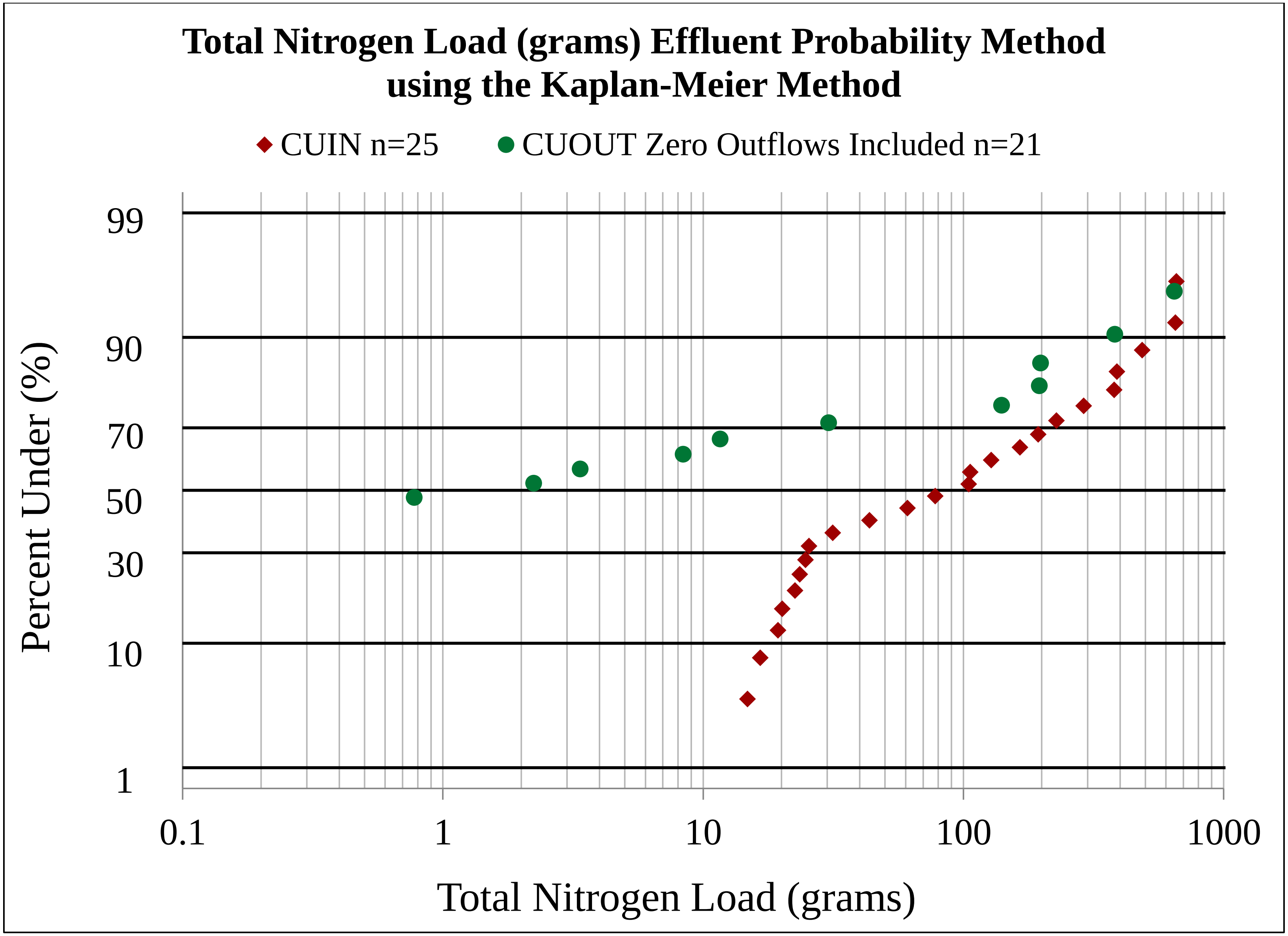


Figure A-50. Effluent Probability Method plot of CUIN & CUOUT-ZF load datasets for total nitrogen.

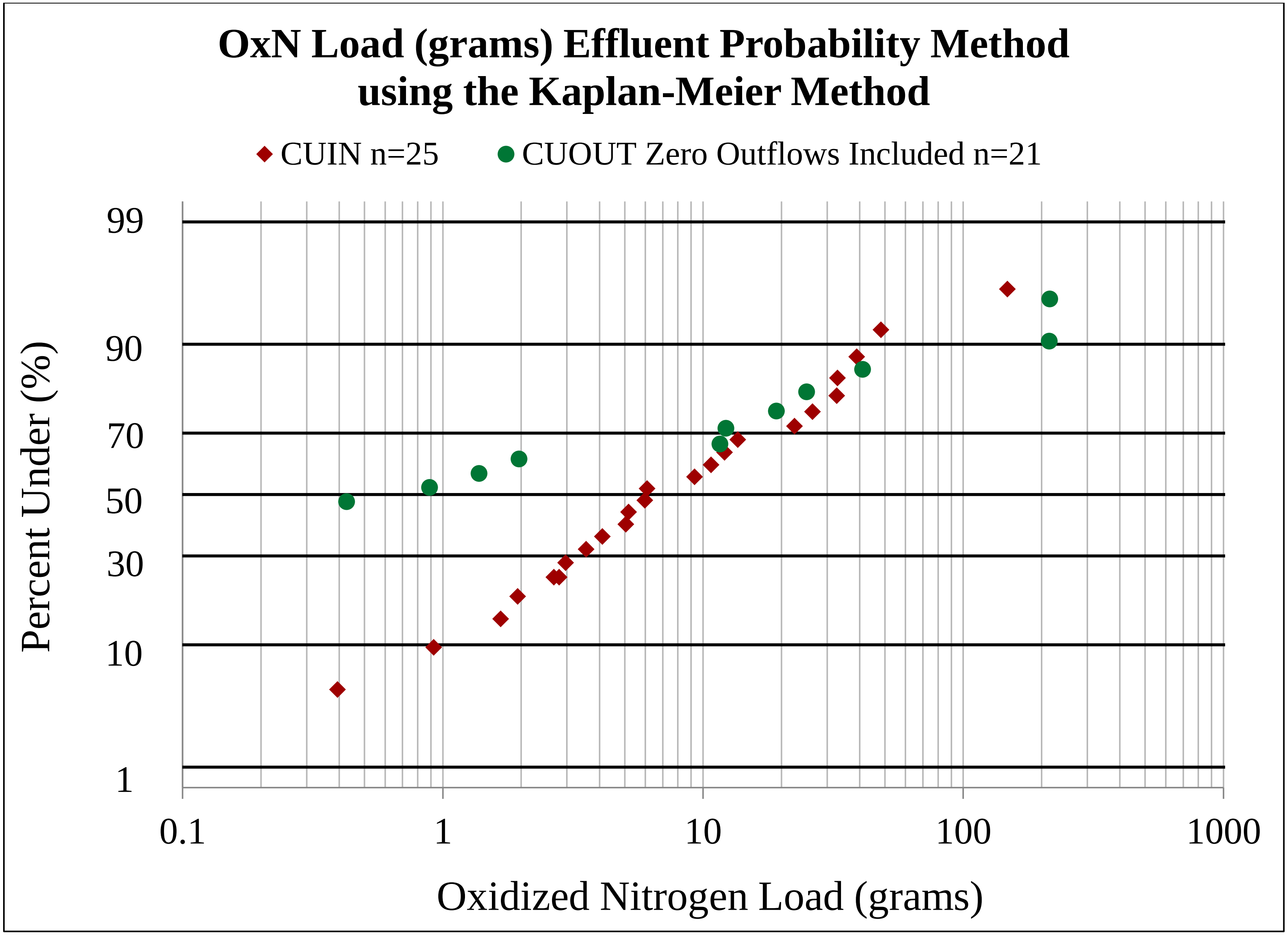


Figure A-51. Effluent Probability Method plot of CUIN & CUOUT-ZF load datasets for oxidized nitrogen.

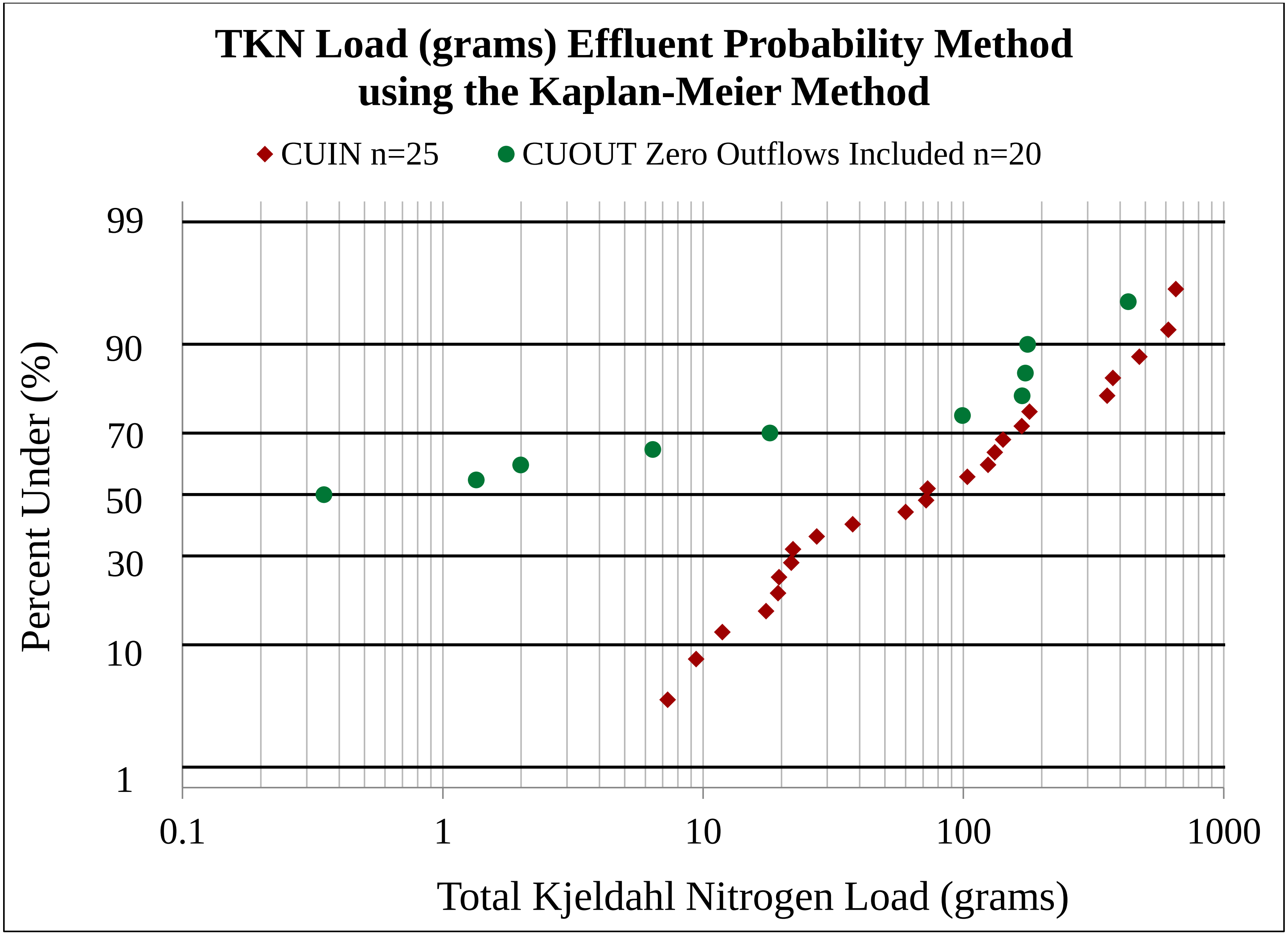


Figure A-52. Effluent Probability Method plot of CUIN & CUOUT-ZF load datasets for total Kjeldahl nitrogen.

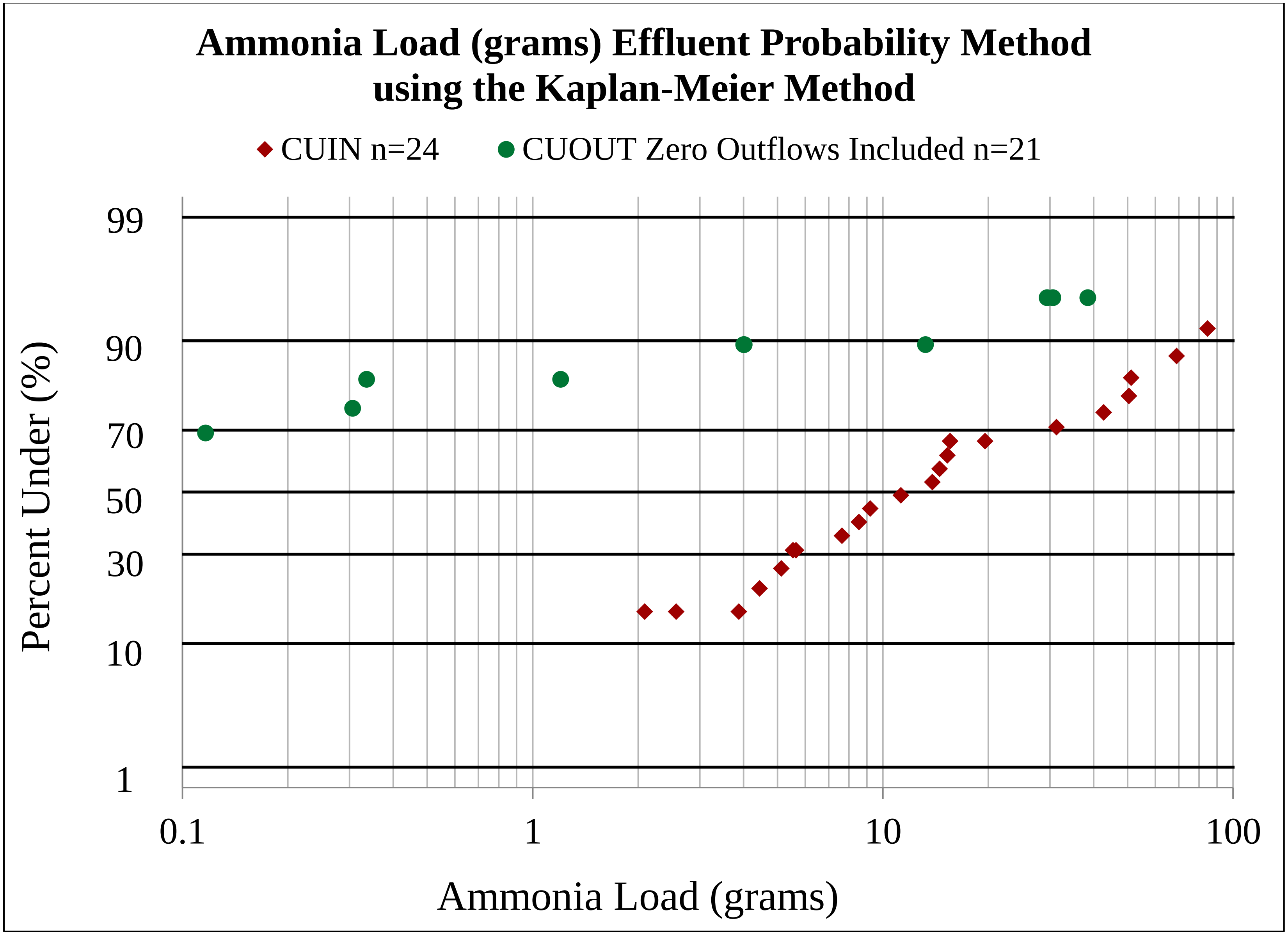


Figure A-53. Effluent Probability Method plot of CUIN & CUOUT-ZF load datasets for ammonia nitrogen.

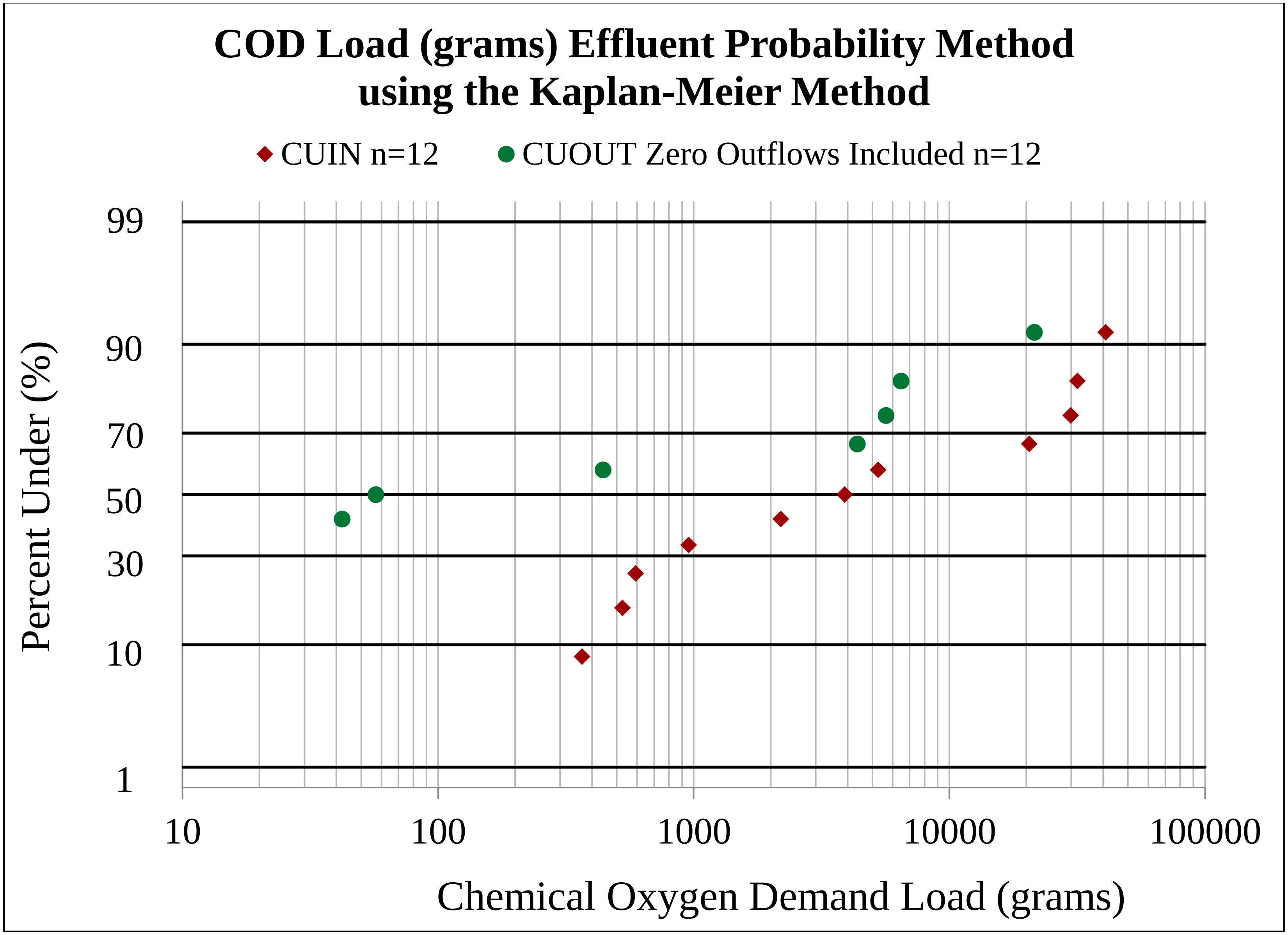


Figure A-54. Effluent Probability Method plot of CUIN & CUOUT-ZF load datasets for chemical oxygen demand.

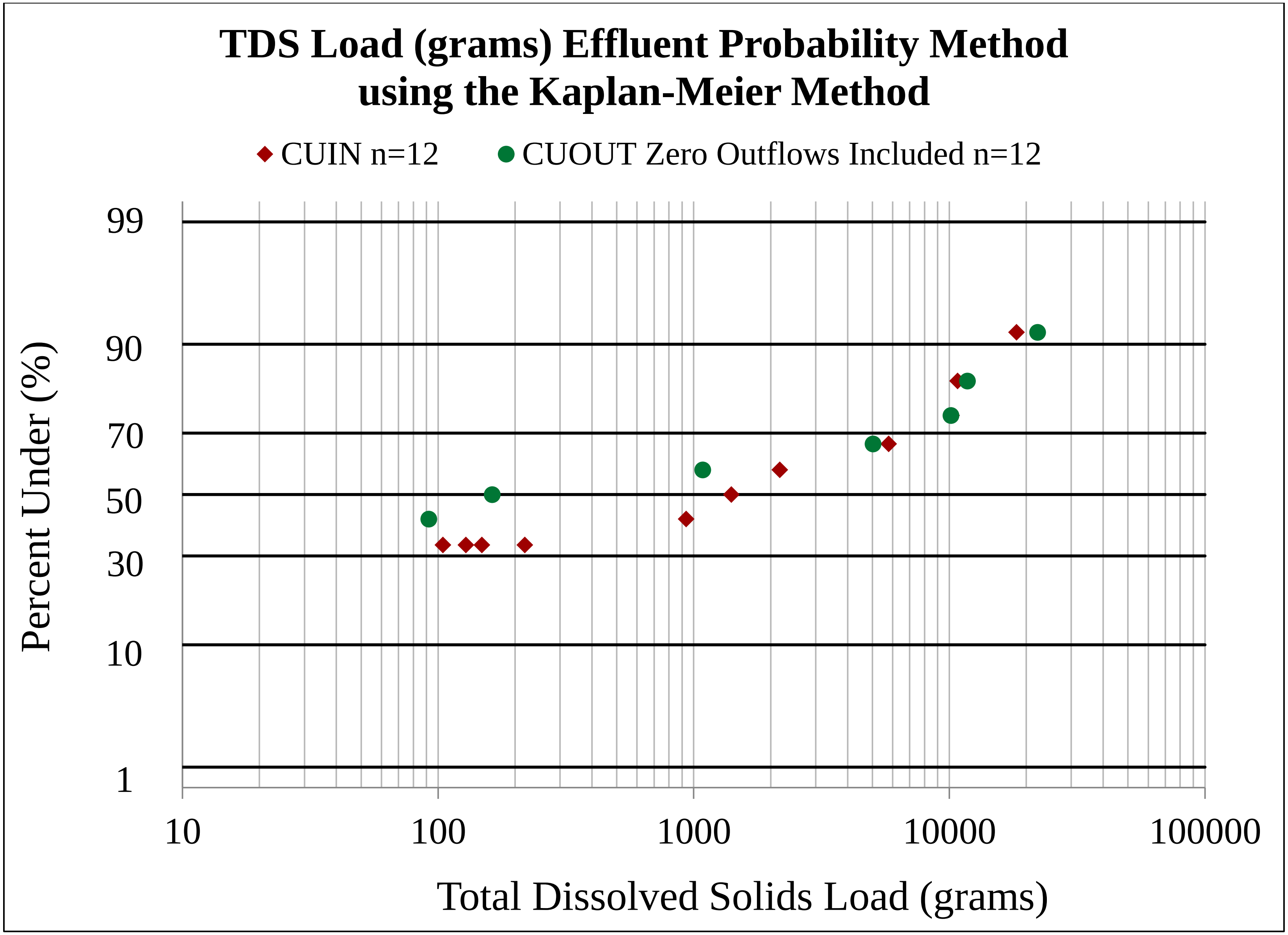


Figure A-55. Effluent Probability Method plot of CUIN & CUOUT-ZF load datasets for total dissolved solids.

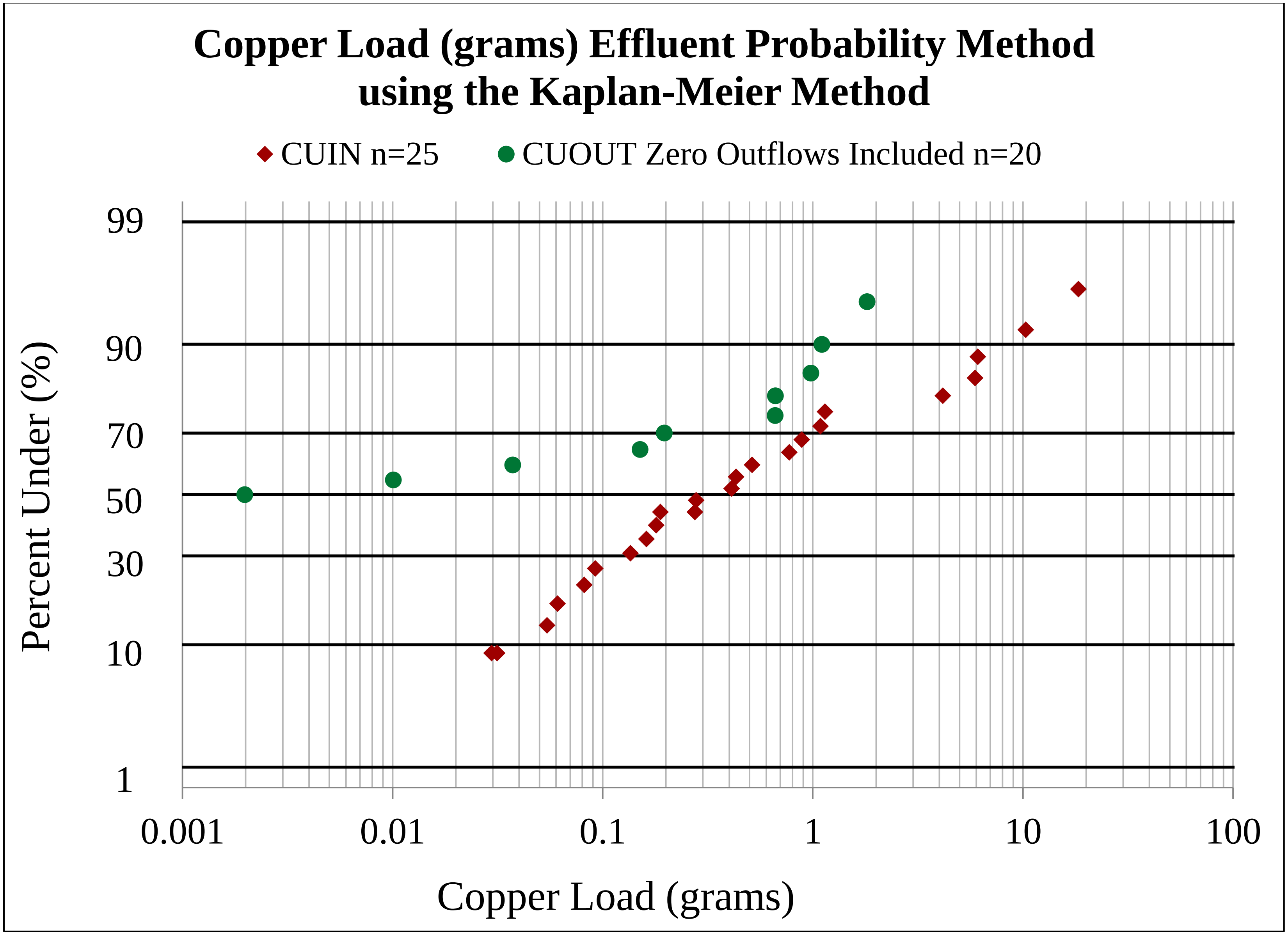


Figure A-56. Effluent Probability Method plot of CUIN & CUOUT-ZF load datasets for copper.

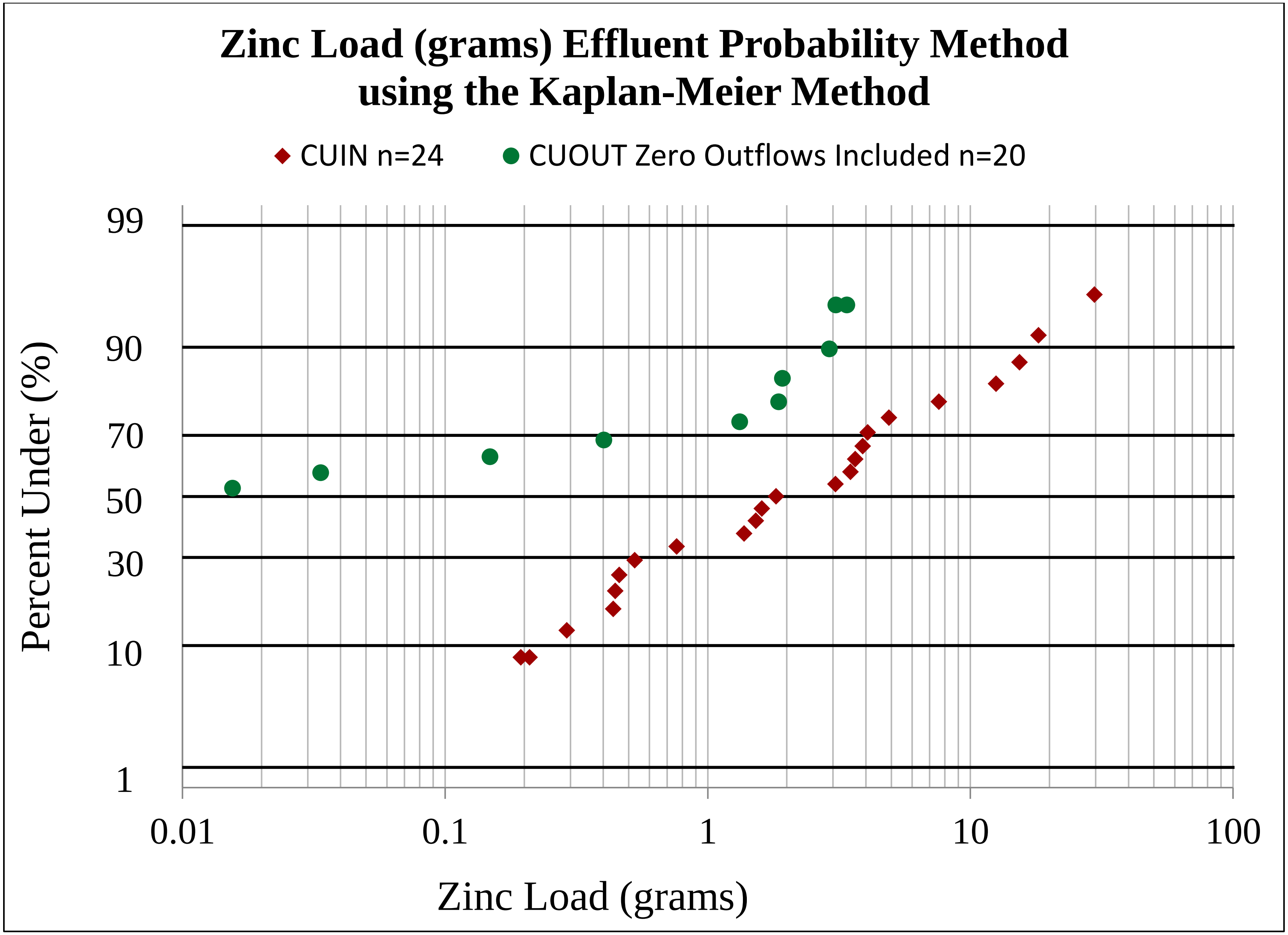


Figure A-57. Effluent Probability Method plot of CUIN & CUOUT-ZF load datasets for zinc.

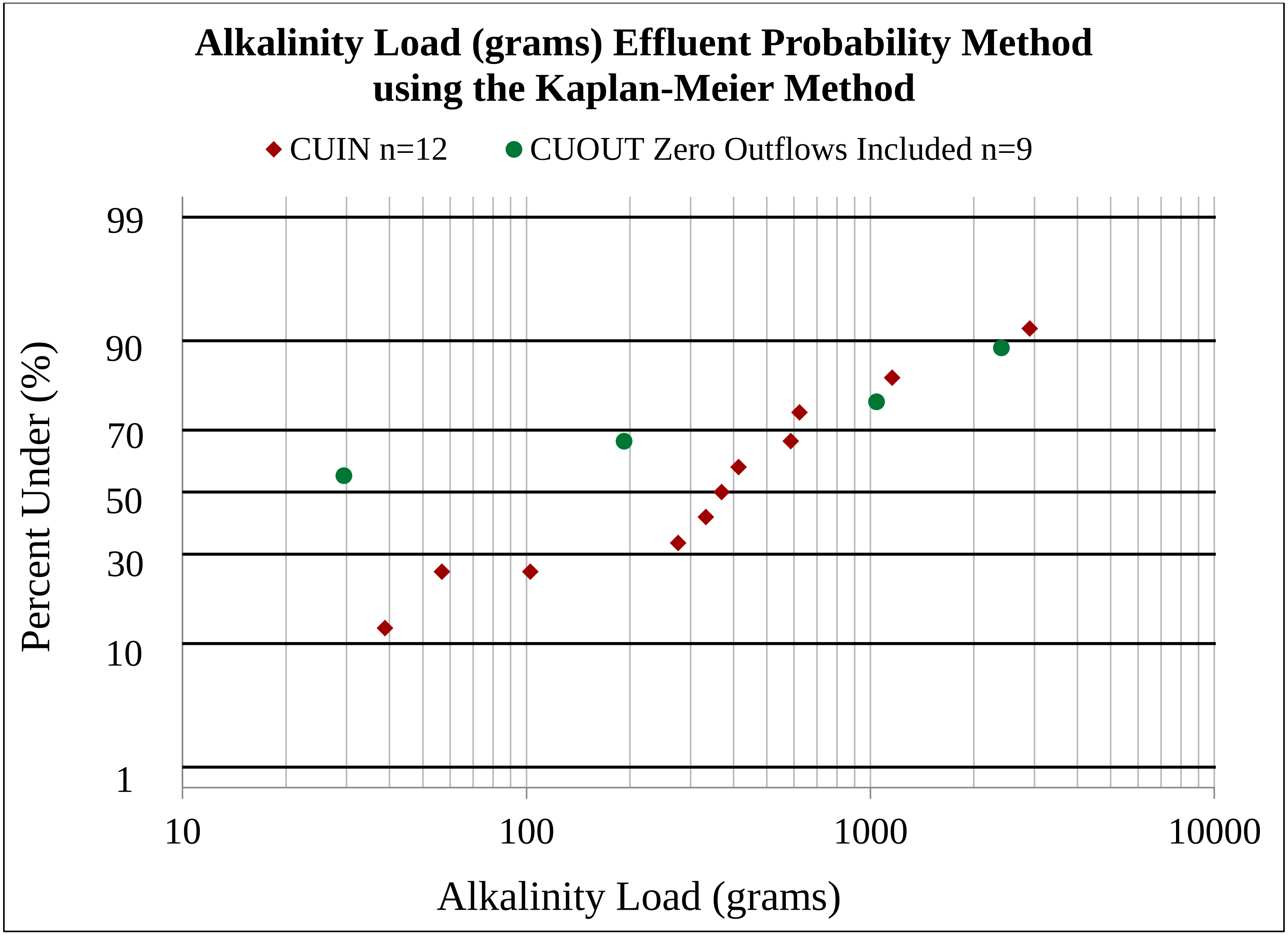


Figure A-58. Effluent Probability Method plot of CUIN & CUOUT-ZF load datasets for alkalinity.

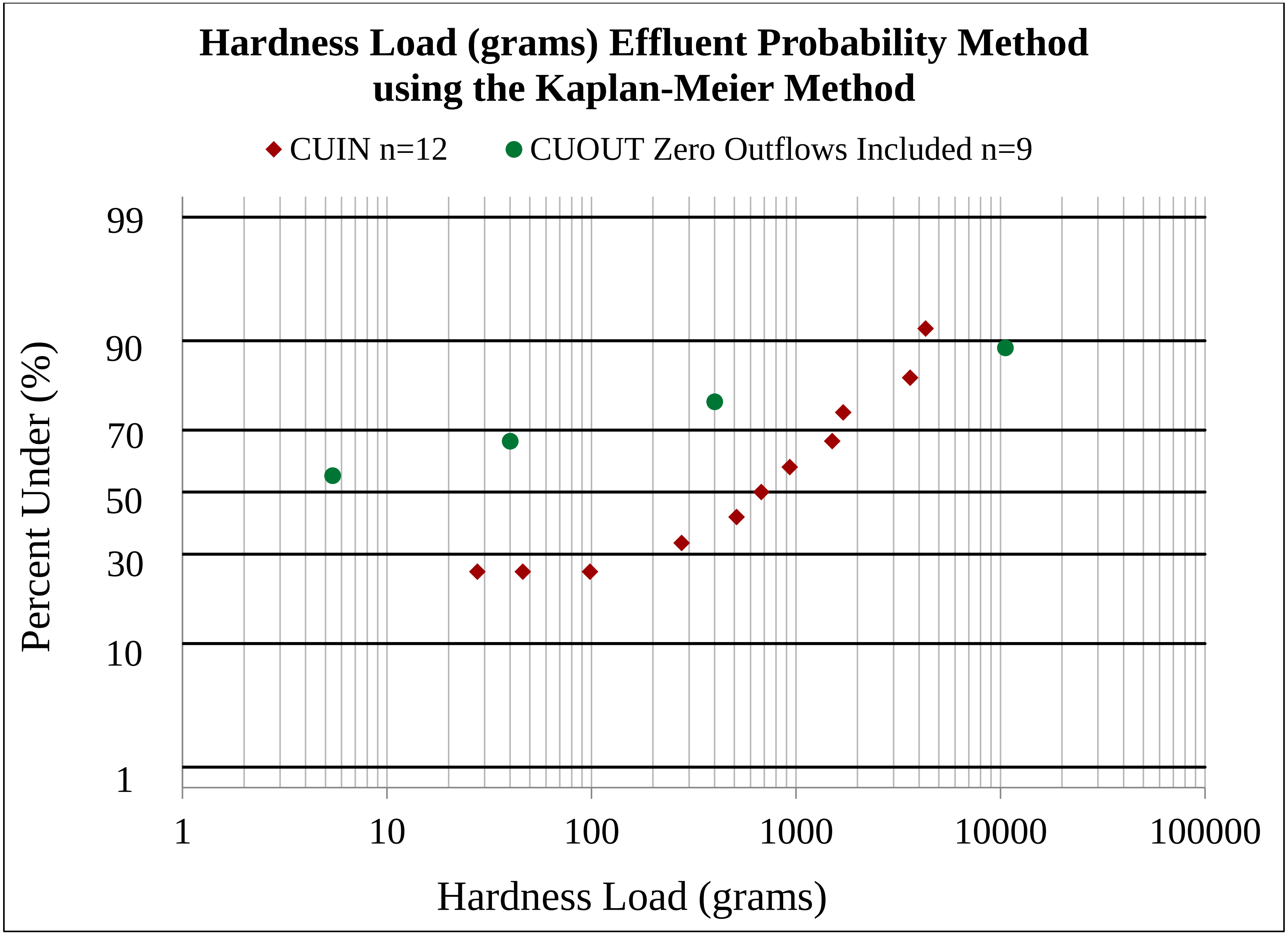


Figure A-59. Effluent Probability Method plot of CUIN & CUOUT-ZF load datasets for hardness.

APPENDIX B List of Tables

List of Tables

Table B-1. BMPs categorized by fundamental process category and unit operation and process.

Fundamental Process Category	Unit Operation or Process	Examples of BMPs capable of providing UOP
Hydrological Operations	Flow Attenuation	Extended detention basins Retention/detention ponds Wetlands Tanks/Vaults Rain Barrels/Cisterns
	Volume Reduction	Infiltration/exfiltration trenches and basins Porous pavement Permeable Pavers Bioretention systems Dry well Extended detention basins Partial Exfiltration Reactor (PER) Volumetric Clarifying Filter (VCF) Bioswales Hydrodynamic Separator Green Roofs Tree Planters
Physical Treatment Operations	Density Separation	Extended detention basins Retention/detention ponds Wetlands Settling basins Tanks/Vaults Rain Barrels/Cisterns Swales with check dams Oil-water separators Vortex separators
	Size Separation and Exclusion	Screens/bars/trash racks Biofilters Bioretention systems Porous pavement Permeable Pavers Infiltration/exfiltration trenches and basins Manufactured bioretention systems Media/sand/compost filters Hydrodynamic separators Catch basin inserts

Table B-1. BMPs categorized by fundamental process category and unit operation and process (Continued).

Fundamental Process Category	**Unit Operation or Process**	**Examples of BMPs capable of providing UOP**
		Partial Exfiltration Reactor (PER) Volumetric Clarifying Filter (VCF) Bioswales Hydrodynamic Separator Tree Planters
	Absorption	Biofilters Bioretention systems Media/sand/compost filters Catch basin inserts Infiltration/exfiltration trenches and basins Partial Exfiltration Reactor (PER) Volumetric Clarifying Filter (VCF) Bioswales Hydrodynamic Separator Green Roofs
Biological Processes	Nutrient Assimilation	Wetlands/Wetland channels Bioretention systems Biofilters Retention ponds Bioswales Green Roofs Tree Planters
	Uptake and Storage	Wetlands/wetland channels Bioretention systems Biofilters Retention ponds Bioswales
	Microbially Mediated Transformation	Wetlands/Wetland channels Bioretention systems Biofilters Retention ponds Bioswales Green Roofs Tree Planters

Table B-1. BMPs categorized by fundamental process category and unit operation and process (Continued).

Fundamental Process Category	Unit Operation or Process	Examples of BMPs capable of providing UOP
Chemical Processes	Flocculation/Precipitation	Detention/Retention ponds
	Adsorption and Ion Exchange	Subsurface wetlands Media/Sand/Compost filters Infiltration/exfiltration trenches and basins Bioretention with an internal water storage layer or zone. Partial Exfiltration Reactor (PER) Volumetric Clarifying Filter (VCF) Bioswales Hydrodynamic Separator
	Ultra-Violet Disinfection	Shallow retention ponds Advanced treatment systems
	Chemical Disinfection	Custom devices for mixing chlorine or aerating with ozone Advanced treatment systems

Adapted from (Quigley et al., 2005) and expanded from other literature sources including (Barber et al., 2003; Sansalone and Teng, 2004; Minton, 2005; Quigley et al., 2005; Davis, 2007; Pitt et al., 2007; Traver et al., 2008; Cates et al., 2009; Geosyntec Consultants and Wright Water Engineers, 2009; Roseen et al., 2009; Palhegyi, 2010b; Sansalone et al., 2010; She and Pang, 2010; Brown and Hunt III, 2011b).

Table B-2. Performance Removals for Bioretention Studies as found in the Literature.

Site Name	Type of Performance Analysis	Percent Removal (Conc.)	Percent Removal (Mass)	Reference
Summary of TP Removal from Bioretention Studies				
Greenbelt, Maryland	Change in Mean Conc.	65%		Davis et al. (2006)
Largo, Maryland	Change in Mean Conc.	87%		Davis et al. (2006)
Durham, New Hampshire	Efficiency Ratio (ER)	27%		Roseen et al. (2009)
Durham, New Hampshire	Efficiency Ratio (ER)	-38%		Roseen et al. (2009)
College Park, Maryland	Efficiency Ratio (ER)	74%		Davis (2007)
College Park, Maryland	Efficiency Ratio (ER)	68%		Davis (2007)
Charlotte, North Carolina	Efficiency Ratio (ER)	31%		Hunt et al. (2008)
Rocky Mount, North Carolina	Efficiency Ratio (ER)	-10%		Brown and Hunt III (2011b)
College Park, Maryland	Median Removal	-200%		Li and Davis (2009)
Silver Spring, Maryland	Median Removal	0%		Li and Davis (2009)
Greensboro, North Carolina	Summation of Loads (SOL)		-240%	Hunt et al. (2006)
Chapel Hill, North Carolina	Summation of Loads (SOL)		65%	Hunt et al. (2006)
Nashville, North Carolina	Summation of Loads (SOL)		5%	Brown and Hunt III (2011a)
Nashville, North Carolina	Summation of Loads (SOL)		44%	Brown and Hunt III (2011a)
College Park, Maryland	Summation of Loads (SOL)		80%	Li and Davis (2009)
Silver Spring, Maryland	Summation of Loads (SOL)		58%	Li and Davis (2009)
Summary of Orthophosphate Phosphorus (OP) Removal from Bioretention Studies				
Rocky Mount, North Carolina	Efficiency Ratio (ER)	64%		Brown and Hunt III (2011b)
Greensboro, North Carolina	Summation of Loads (SOL)		-9%	Hunt et al. (2006)
Chapel Hill, North Carolina	Summation of Loads (SOL)		69%	Hunt et al. (2006)
Nashville, North Carolina	Summation of Loads (SOL)		-37%	Brown and Hunt III (2011a)
Nashville, North Carolina	Summation of Loads (SOL)		-5%	Brown and Hunt III (2011a)
Summary of TN Removal from Bioretention Studies				
Greenbelt, Maryland	Change in Mean Conc.	49%		Davis et al. (2006)
Largo, Maryland	Change in Mean Conc.	59%		Davis et al. (2006)
Charlotte, North Carolina	Efficiency Ratio (ER)	32%		Hunt et al. (2008)

Table B-2. Performance Removals for Bioretention Studies as found in the Literature (Continued).

Site Name	Type of Performance Analysis	Percent Removal (Conc.)	Percent Removal (Mass)	Reference
Rocky Mount, North Carolina	Efficiency Ratio (ER)	58%		Brown and Hunt III (2011b)
College Park, Maryland	Median Removal	-53%		Li and Davis (2009)
Silver Spring, Maryland	Median Removal	-10%		Li and Davis (2009)
Greensboro, North Carolina	Summation of Loads (SOL)		40%	Hunt et al. (2006)
Chapel Hill, North Carolina	Summation of Loads (SOL)		40%	Hunt et al. (2006)
Nashville, North Carolina	Summation of Loads (SOL)		12%	Brown and Hunt III (2011a)
Nashville, North Carolina	Summation of Loads (SOL)		13%	Brown and Hunt III (2011a)
College Park, Maryland	Summation of Loads (SOL)		73%	Li and Davis (2009)
Silver Spring, Maryland	Summation of Loads (SOL)		63%	Li and Davis (2009)
Summary of OxN Removal from Bioretention Studies				
Charlotte, North Carolina	Efficiency Ratio (ER)	-5%		Hunt et al. (2008)
Rocky Mount, North Carolina	Efficiency Ratio (ER)	58%		Brown and Hunt III (2011b)
Nashville, North Carolina	Summation of Loads (SOL)		-81%	Brown and Hunt III (2011a)
Nashville, North Carolina	Summation of Loads (SOL)		-142%	Brown and Hunt III (2011a)
Summary of Nitrate Nitrogen (NO_3^--N) Removal from Bioretention Studies				
Greenbelt, Maryland	Change in Mean Conc.	16%		Davis et al. (2006)
Largo, Maryland	Change in Mean Conc.	15%		Davis et al. (2006)
College Park, Maryland	Efficiency Ratio (ER)	79%		Davis (2007)
College Park, Maryland	Efficiency Ratio (ER)	86%		Davis (2007)
College Park, Maryland	Median Removal	-170%		Li and Davis (2009)
Silver Spring, Maryland	Median Removal	86%		Li and Davis (2009)
Greensboro, North Carolina	Summation of Loads (SOL)		75%	Hunt et al. (2006)
Chapel Hill, North Carolina	Summation of Loads (SOL)		13%	Hunt et al. (2006)
College Park, Maryland	Summation of Loads (SOL)		79%	Li and Davis (2009)
Silver Spring, Maryland	Summation of Loads (SOL)		95%	Li and Davis (2009)
Summary of Nitrite Nitrogen (NO_2^--N) Removal from Bioretention Studies				
College Park, Maryland	Median Removal	0%		Li and Davis (2009)

Table B-2. Performance Removals for Bioretention Studies as found in the Literature (Continued).

Site Name	Type of Performance Analysis	Percent Removal (Conc.)	Percent Removal (Mass)	Reference
Silver Spring, Maryland	Median Removal	0%		Li and Davis (2009)
College Park, Maryland	Summation of Loads (SOL)		85%	Li and Davis (2009)
Silver Spring, Maryland	Summation of Loads (SOL)		70%	Li and Davis (2009)
Summary of Total Kjeldahl Nitrogen (TKN) Removal from Bioretention Studies				
Greenbelt, Maryland	Change in Mean Conc.	52%		Davis et al. (2006)
Largo, Maryland	Change in Mean Conc.	67%		Davis et al. (2006)
Charlotte, North Carolina	Efficiency Ratio (ER)	44%		Hunt et al. (2008)
Rocky Mount, North Carolina	Efficiency Ratio (ER)	58%		Brown and Hunt III (2011b)
College Park, Maryland	Median Removal	-11%		Li and Davis (2009)
Silver Spring, Maryland	Median Removal	-30%		Li and Davis (2009)
Greensboro, North Carolina	Summation of Loads (SOL)		-5%	Hunt et al. (2006)
Chapel Hill, North Carolina	Summation of Loads (SOL)		45%	Hunt et al. (2006)
Nashville, North Carolina	Summation of Loads (SOL)		39%	Brown and Hunt III (2011a)
Nashville, North Carolina	Summation of Loads (SOL)		58%	Brown and Hunt III (2011a)
College Park, Maryland	Summation of Loads (SOL)		73%	Li and Davis (2009)
Silver Spring, Maryland	Summation of Loads (SOL)		40%	Li and Davis (2009)
Summary of Ammonia Nitrogen (NH_3 -N) Removal from Bioretention Studies				
Greensboro, North Carolina	Summation of Loads (SOL)		-1%	Hunt et al. (2006)
Chapel Hill, North Carolina	Summation of Loads (SOL)		86%	Hunt et al. (2006)
Nashville, North Carolina	Summation of Loads (SOL)		78%	Brown and Hunt III (2011a)
Nashville, North Carolina	Summation of Loads (SOL)		79%	Brown and Hunt III (2011a)
Summary of Ammonium Nitrogen (NH_4^+ -N) Removal from Bioretention Studies				
Charlotte, North Carolina	Efficiency Ratio (ER)	73%		Hunt et al. (2008)
Summary of Organic Nitrogen (org-N) Removal from Bioretention Studies				
Rocky Mount, North Carolina	Efficiency Ratio (ER)	50%		Brown and Hunt III (2011b)
Nashville, North Carolina	Summation of Loads (SOL)		13%	Brown and Hunt III (2011a)
Nashville, North Carolina	Summation of Loads (SOL)		43%	Brown and Hunt III (2011a)

Table B-2. Performance Removals for Bioretention Studies as found in the Literature (Continued).

Site Name	Type of Performance Analysis	Percent Removal (Conc.)	Percent Removal (Mass)	Reference
Summary of Dissolved Inorganic Nitrogen (DIN) Removal from Bioretention Studies				
Durham, New Hampshire	Efficiency Ratio (ER)	75%		Roseen et al. (2009)
Durham, New Hampshire	Efficiency Ratio (ER)	41%		Roseen et al. (2009)
Durham, New Hampshire	Efficiency Ratio (ER)	65%		Roseen et al. (2009)
Summary of Total Suspended Solids (TSS) Removal from Bioretention Studies				
Durham, New Hampshire	Efficiency Ratio (ER)	86%		Roseen et al. (2009)
Durham, New Hampshire	Efficiency Ratio (ER)	86%		Roseen et al. (2009)
Durham, New Hampshire	Efficiency Ratio (ER)	52%		Roseen et al. (2009)
College Park, Maryland	Efficiency Ratio (ER)	22%		Davis (2007)
College Park, Maryland	Efficiency Ratio (ER)	41%		Davis (2007)
Charlotte, North Carolina	Efficiency Ratio (ER)	60%		Hunt et al. (2008)
Rocky Mount, North Carolina	Efficiency Ratio (ER)	58%		Brown and Hunt III (2011b)
College Park, Maryland	Median Removal	88%		Li and Davis (2009)
Silver Spring, Maryland	Median Removal	88%		Li and Davis (2009)
Greensboro, North Carolina	Summation of Loads (SOL)		-170%	Hunt et al. (2006)
Nashville, North Carolina	Summation of Loads (SOL)		71%	Brown and Hunt III (2011a)
Nashville, North Carolina	Summation of Loads (SOL)		84%	Brown and Hunt III (2011a)
College Park, Maryland	Summation of Loads (SOL)		97%	Li and Davis (2009)
Silver Spring, Maryland	Summation of Loads (SOL)		93%	Li and Davis (2009)
Summary of Copper (Cu) Removal from Bioretention Studies				
Largo, Maryland	Change in Mean Conc.	43%		Davis et al. (2006)
Greenbelt, Maryland	Change in Mean Conc.	97%		Davis et al. (2006)
College Park, Maryland	Efficiency Ratio (ER)	51%		Davis (2007)
College Park, Maryland	Efficiency Ratio (ER)	57%		Davis (2007)
Charlotte, North Carolina	Efficiency Ratio (ER)	54%		Hunt et al. (2008)
College Park, Maryland	Median Removal	31%		Li and Davis (2009)
Silver Spring, Maryland	Median Removal	0%		Li and Davis (2009)

Table B-2. Performance Removals for Bioretention Studies as found in the Literature (Continued).

Site Name	Type of Performance Analysis	Percent Removal (Conc.)	Percent Removal (Mass)	Reference
Greensboro, North Carolina	Summation of Loads (SOL)		99%	Hunt et al. (2006)
College Park, Maryland	Summation of Loads (SOL)		72%	Li and Davis (2009)
Silver Spring, Maryland	Summation of Loads (SOL)		63%	Li and Davis (2009)
Summary of Iron (Fe) Removal from Bioretention Studies				
Charlotte, North Carolina	Efficiency Ratio (ER)	-330%		Hunt et al. (2008)
Greensboro, North Carolina	Summation of Loads (SOL)		-13000%	Hunt et al. (2006)
Summary of Zinc (Zn) Removal from Bioretention Studies				
Largo, Maryland	Change in Mean Conc.	64%		Davis et al. (2003)
Greenbelt, Maryland	Change in Mean Conc.	>95%		Davis et al. (2003)
Durham, New Hampshire	Efficiency Ratio (ER)	95%		Roseen et al. (2009)
Durham, New Hampshire	Efficiency Ratio (ER)	80%		Roseen et al. (2009)
Durham, New Hampshire	Efficiency Ratio (ER)	72%		Roseen et al. (2009)
College Park, Maryland	Efficiency Ratio (ER)	57%		Davis (2007)
College Park, Maryland	Efficiency Ratio (ER)	63%		Davis (2007)
Charlotte, North Carolina	Efficiency Ratio (ER)	77%		Hunt et al. (2008)
College Park, Maryland	Median Removal	78%		Li and Davis (2009)
Silver Spring, Maryland	Median Removal	80%		Li and Davis (2009)
Greensboro, North Carolina	Summation of Loads (SOL)		98%	Hunt et al. (2006)
College Park, Maryland	Summation of Loads (SOL)		94%	Li and Davis (2009)
Silver Spring, Maryland	Summation of Loads (SOL)		95%	Li and Davis (2009)
Summary of Lead (Pb) Removal from Bioretention Studies				
Largo, Maryland	Change in Mean Conc.	70%		Davis et al. (2003)
Greenbelt, Maryland	Change in Mean Conc.	>95%		Davis et al. (2003)
College Park, Maryland	Efficiency Ratio (ER)	79%		Davis (2007)
College Park, Maryland	Efficiency Ratio (ER)	86%		Davis (2007)
Charlotte, North Carolina	Efficiency Ratio (ER)	31%		Hunt et al. (2008)
College Park, Maryland	Median Removal	55%		Li and Davis (2009)

Table B-2. Performance Removals for Bioretention Studies as found in the Literature (Continued).

Site Name	**Type of Performance Analysis**	**Percent Removal (Conc.)**	**Percent Removal (Mass)**	**Reference**
Silver Spring, Maryland	Median Removal	0%		Li and Davis (2009)
Greensboro, North Carolina	Summation of Loads (SOL)		81%	Hunt et al. (2006)
College Park, Maryland	Summation of Loads (SOL)		86%	Li and Davis (2009)
Silver Spring, Maryland	Summation of Loads (SOL)		83%	Li and Davis (2009)
Summary of Total Petroleum Hydrocarbons-Diesel (TPH-D) Removal from Bioretention Studies				
Durham, New Hampshire	Efficiency Ratio (ER)	99%		Roseen et al. (2009)
Durham, New Hampshire	Efficiency Ratio (ER)	84%		Roseen et al. (2009)
Durham, New Hampshire	Efficiency Ratio (ER)	53%		Roseen et al. (2009)

Table B-3. Performance Removals for Green Roof Studies as found in the Literature.

Site Name	Type of Performance Analysis	% (Conc)	% (Mass)	Reference
Summary of TP Removal from Green Roof Studies				
Southfield, MI	Mean Mass Removal[1]		28%	Carpenter and Kaluvakolanu (2011)
Southfield, MI	Mean Mass Removal[2]		-1160%	Carpenter and Kaluvakolanu (2011)
Toronto, Ontario	Unit Area Load Removal[3]		-248%	Van Seters et al. (2009)
Waterloo, Ontario	Mean Conc. Removal [4]	-548%		Linden and Stone (2009)
Waterloo, Ontario	Mean Conc. Removal [5]	-491%		Linden and Stone (2009)
Estonia	Mean Conc. Removal [6]	-2630%		Teemusk and Mander (2011)
Estonia	Mean Conc. Removal [7]	-1200%		Teemusk and Mander (2011)
Summary of TN Removal from Green Roof Studies				
Estonia	Mean Conc. Removal [6]	-55%		Teemusk and Mander (2011)
Estonia	Mean Conc. Removal [7]	-183%		Teemusk and Mander (2011)
Summary of $NO3^-$-N Removal from Green Roof Studies				
Southfield, MI	Mean Mass Removal[1]		21%	Carpenter and Kaluvakolanu (2011)
Southfield, MI	Mean Mass Removal[2]		-123%	Carpenter and Kaluvakolanu (2011)
Toronto, Ontario	Percent Difference Unit Area Load [3]		91%	Van Seters et al. (2009)
Estonia	Mean Conc. Removal [6]	30%		Teemusk and Mander (2011)
Estonia	Mean Conc. Removal [7]	5%		Teemusk and Mander (2011)
Summary of $NO2^-$-N Removal from Green Roof Studies				
Toronto, Ontario	Percent Difference Unit Area Load [3]		76%	Van Seters et al. (2009)
Summary of TKN Removal from Green Roof Studies				
Toronto, Ontario	Percent Difference Unit Area Load [3]		15%	Van Seters et al. (2009)
Summary of NH_3 -N + NH_4^+ -N Removal from Green Roof Studies				
Toronto, Ontario	Percent Difference Unit Area Load [3]		98%	Van Seters et al. (2009)
Summary of NH_4^+ -N Removal from Green Roof Studies				
Estonia	Mean Conc. Removal [6]	69%		Teemusk and Mander (2011)
Estonia	Mean Conc. Removal [7]	33%		Teemusk and Mander (2011)
Summary of Total Solids Removal from Green Roof Studies				
Southfield, MI	Mean Mass Removal[1]		-88%	Carpenter and Kaluvakolanu (2011)
Southfield, MI	Mean Mass Removal[2]		-829%	Carpenter and Kaluvakolanu (2011)

Table B-3. Performance Removals for Green Roof Studies as found in the Literature (Continued).

Site Name	Type of Performance Analysis	% (Conc)	% (Mass)	Reference
Summary of Total Suspended Solids Removal from Green Roof Studies				
Toronto, Ontario	Percent Difference Unit Area Load [3]		89%	Van Seters et al. (2009)
Waterloo, Ontario	Mean Conc. Removal [4]	33%		Linden and Stone (2009)
Waterloo, Ontario	Mean Conc. Removal [5]	-143%		Linden and Stone (2009)
Summary of Total Dissolved Solids Removal from Green Roof Studies				
Waterloo, Ontario	Mean Conc. Removal [4]	-274%		Linden and Stone (2009)
Waterloo, Ontario	Mean Conc. Removal [5]	-908%		Linden and Stone (2009)
Summary of Chemical Oxygen Demand Solids Removal from Green Roof Studies				
Estonia	Mean Conc. Removal [6]	-140%		Teemusk and Mander (2011)
Estonia	Mean Conc. Removal [7]	-380%		Teemusk and Mander (2011)
Summary of Copper Removal from Green Roof Studies				
Toronto, Ontario	Percent Difference Unit Area Load [3]		86%	Van Seters et al. (2009)
Summary of Cadmium Removal from Green Roof Studies				
Toronto, Ontario	Percent Difference Unit Area Load [3]		52%	Van Seters et al. (2009)
Summary of Lead Removal from Green Roof Studies				
Toronto, Ontario	Percent Difference Unit Area Load [3]		53%	Van Seters et al. (2009)
Summary of Zinc Removal from Green Roof Studies				
Toronto, Ontario	Percent Difference Unit Area Load [3]		70%	Van Seters et al. (2009)
Summary of Hardness (as $CaCO_3$) Removal from Green Roof Studies				
Toronto, Ontario	Percent Difference Unit Area Load [3]		-121%	Van Seters et al. (2009)
Estonia	Mean Conc. Removal [6]	-2738%		Teemusk and Mander (2011)
Estonia	Mean Conc. Removal [7]	-2927%		Teemusk and Mander (2011)

[1] Green Roof vs. Asphalt Roof: The percent reduction between the green roof and asphalt roof was calculated using the mean value from each of the respective load datasets which were comprised of five storm events each (Carpenter and Kaluvakolanu, 2011).
[2] Green Roof vs. Stone-Ballasted Roof: The percent reduction between the green roof and stone-ballasted roof was calculated using the mean value from each of the respective load datasets which were comprised of five storm events each (Carpenter and Kaluvakolanu, 2011).
[3] Green Roof vs. Modified Bitumen Roof: Unit area loads from both roofs included sampled and unsampled events over the two year monitoring period. Sampled event loads were calculated by multiplying the sample concentration by the storm discharge volume. Unsampled events were estimated by multiplying the average concentration from the sampled events by the unsampled storm discharge volume. The overall unit area load was then calculated by summing the loads from the sampled and unsampled events for each roof. This method assumes that the mean concentration for the sampled and unsampled events is similar (Van Seters et al., 2009).
[4] Green Roof vs. Bitumen Roof: The percent reduction between the green and control roofs was calculated using the mean value from each of the respective

concentration datasets which were comprised of 18 storm events each (Linden and Stone, 2009).

[5] Green Roof vs. Rainfall: The percent reduction between the green roof and rainfall was calculated using the mean value from each of the respective concentration datasets which were comprised of 18 storm events each (Linden and Stone, 2009).

[6] Average of 8 Green Roofs vs. 1 Steel Roof: Discharge water quality was monitored from eight green roofs located across Estonia.
Each green roof was monitored during a single storm event which occurred between 2007 and 2009. The water quality results from all eight green roofs/events were averaged to arrive at an average value for the concentration of each water quality constituent (Teemusk and Mander, 2011). The average green roof concentrations were then compared to the discharge water quality results from a steel roof also monitored during a single event. A percent reduction value was assigned by comparing the average green roof concentration to the steel roof concentration for each water quality constituent.

[7] Average of 8 Green Roofs vs. 1 Rainfall Event: Discharge water quality was monitored from eight green roofs located across Estonia. Each green roof was monitored during a single storm event which occurred between 2007 and 2009. The water quality results from all eight green roofs/events were averaged to arrive at an average value for the concentration of each water quality constituent (Teemusk and Mander, 2011). The average green roof concentrations were then compared to rainfall concentrations also monitored during a single event. A percent reduction value was assigned by comparing the average green roof concentration to the rainfall concentration for each water quality constituent.

Table B-4. Performance Removals for Porous Asphalt Studies as found in the Literature.

Summary of TP Removal from Porous Asphalt Study				
Site Name	Type of Performance Analysis	% (Conc)	% (Mass)	Reference
Durham, New Hampshire	Efficiency Ratio (ER)	24%		Roseen et al. (2009)
Summary of Dissolved Inorganic Nitrogen (DIN) Removal from Porous Asphalt Study				
Durham, New Hampshire	Efficiency Ratio (ER)	-35%		Roseen et al. (2009)
Summary of Total Suspended Solids (TSS) Removal from Porous Asphalt Study				
Durham, New Hampshire	Efficiency Ratio (ER)	96%		Roseen et al. (2009)
Summary of Zinc (Zn) Removal from Porous Asphalt Study				
Durham, New Hampshire	Efficiency Ratio (ER)	79%		Roseen et al. (2009)
Summary of Total Petroleum Hydrocarbons-Diesel (TPH-D) Removal from Porous Asphalt Study				
Durham, New Hampshire	Efficiency Ratio (ER)	100%		Roseen et al. (2009)

Table B-5. Discrete water quality parameters monitored for targeted storm events.

Monitoring Period	September 2008 – June 2010		March 2011- May 2012	
Parameter	**Reportable Detection Limit (mg/L)**	**Method**	**Reportable Detection Limit (mg/L)**	**Method**
Total Phosphorus	0.01	SM 4500P-E	0.01	SM 4500P-E
Oxidized Nitrogen	0.02	SM 4500NO3-H	0.02	SM 4500NO3-H
Total Kjeldahl Nitrogen	0.5	SM 4500NH3-C	0.5	SM 4500NH3-C
Ammonia Nitrogen	0.2	SM 4500NH3-C	0.2	SM 4500NH3-C
Total Suspended Solids	1	SM 2540 D	1	SM 2540 D
Chemical Oxygen Demand[1]			10	EPA 410.4 & SM 5220-D
Total Dissolved Solids[1]			10	SM 2540C
Copper[3]	0.01	EPA 200.8	0.002	EPA 200.8
Cadmium	0.0005	EPA 200.8	0.0005	EPA 200.8
Zinc	0.01	EPA 200.8	0.01	EPA 200.8
Lead[3]	0.01 & 0.002	EPA 200.8	0.002	EPA 200.8
Oil and Grease	5	EPA 1664	5	EPA 1664
Total Petroleum Hydrocarbons[1]			5	EPA 1664
Alkalinity[2]	1	SM 2320 B		
Hardness[2]	1	SM 2340 B		
Orthophosphate Phosphorus[2]	0.01	SM 4500P-E		

[1] Chemical Oxygen Demand (COD), Total Dissolved Solids (TDS) and Total Petroleum Hydrocarbons (TPH) were not tested for during the first monitoring period September 2008 – June 2010. [2] Alkalinity, Hardness and Orthophosphate Phosphorus were not tested for during the most recent monitoring period March 2011- May 2012. [3] Copper and Lead had different reporting limits for the two monitoring periods.

Table B-6. Storm and runoff statistics for valid storms monitored at Cub Run Recreation Center LID facility.

	Measured Values		Calculated Values		Values Estimated by SCS Runoff CN Method				Measured and Calculated Values						
Event Date	**Total Rain (in.)**	**Outfall Volume (ft^3)**	**Outfall Equivalent Rain (in.)**	**Rain Retained (%)**	**Total Runoff Pavement (ft^3)**	**Runoff with CN Pavement (in.)**	**Total runoff Grassy/ Wooded (ft^3)**	**Runoff with CN Grassy/ Wooded (in.)**	**Dry Time (hr.)**	**Rainfall Duration (hr.)**	**Elevated Flow Duration (hr.)**	**Average Rainfall Rate (in./hr.)**	**Amount of Rain Before Flow (in.)**	**Time Before Flow (hr.)**	**Rainfall Rate Before Flow (in./hr.)**
9/25/08	0.47	0.00	0.00	100%	665	0.29	0	0.00	298.9[2]	18.42	N.R.	0.026	N.R.	N.R.	N.R.
4/20/09	1.80[1]	N.D.	N.D.	N.D.	3605	1.58	1279	0.00	98.8	25.67	N.D.	0.070	N.D.	N.D.	N.D.
6/3/09	1.28[1]	3394.73	0.58	54%	2433	1.06	513	0.00	85.9	1.50	4.00	0.853	0.43	0.33	1.303
8/21/09	2.36[1]	707.31	0.16	95%	4875	2.13	2326	0.22	368.5	15.50	6.17	0.152	1.62	7.67	0.211
9/11/09	0.15	0.00	0.00	100%	87	0.04	0	0.05	69.5	6.83	N.R.	0.022	N.R.	N.R.	N.R.
9/26/09	0.48	N.D.	N.D.	N.D.	686	0.30	0	0.10	30.1	31.17	N.R.	0.015	N.R.	N.R.	N.R.
10/15/09	0.62	0.00	0.00	100%	979	0.43	9	0.00	8.3	30.50	N.R.	0.020	N.R.	N.R.	N.R.
10/24/09	1.42	3178.18	0.73	61%	2747	1.20	695	0.00	151.7	5.83	3.00	0.243	0.21	2.67	0.079
10/27/09	0.92	602.35	0.14	89%	1632	0.71	155	0.00	10.7	13.00	3.00	0.071	0.55	7.83	0.070
11/11/09	1.09	0.00	0.00	100%	2009	0.88	303	0.09	230.1	35.50	N.R.	0.031	N.R.	N.R.	N.R.
12/2/09	0.44	4.20	0.001	100%	604	0.26	0	0.00	42.7	14.17	0.67	0.031	0.35	10.50	0.033
3/11/10	0.44	13.70	0.003	99%	604	0.26	0	0.15	217.3	9.33	4.83	0.047	0.43	6.83	0.063
3/28/10	0.62	141.49	0.03	96%	979	0.43	9	2.91	58.0	7.00	9.50	0.089	0.31	1.67	0.186
7/8/11	1.06	27.03	0.005	100%	1942	0.85	273	0.00	438.8	2.3	5.3	0.172	0.61	0.83	0.732
8/13/11	0.34	0.00	0.00	100%	407	0.18	0	0.80	140.5	33.5	N.R.	0.010	N.R.	N.R.	N.R.
8/27/11	1.23	67.79	0.01	99%	2321	1.01	454	0.39	44.0	19.7	15.8	0.056	0.46	6.00	0.077
9/5/11	5.13	10855.3	1.87	64%	11190	4.89	9097	0.01	51.2	93.2	89.5	0.054	0.37	6.00	0.062
9/23/11	0.32	0.00	0.00	100%	369	0.16	0	0.00	29.5	49.3	N.R.	0.006	N.R.	N.R.	N.R.
10/12/11	2.44	5395.19	0.93	62%	5057	2.21	2490	0.24	7.0	47.8	37.2	0.045	0.48	16.50	0.029
12/6/11	1.76	5195.13	0.89	49%	3514	1.54	1212	0.00	153.7	43.7	24.2	0.034	0.48	27.67	0.017
1/11/12	0.72	709.20	0.12	83%	1194	0.52	39	0.04	23.7	16.5	9.8	0.031	0.42	13.50	0.031
1/26/12	0.14	0.00	0.00	100%	74	0.03	0	0.00	58.8	29.7	N.R.	0.005	N.R.	N.R.	N.R.
2/29/12	1.47	2335.43	0.4	73%	2860	1.25	764	0.00	110.8	64.5	67.8	0.021	0.43	2.83	0.152
3/24/12	0.40	0.00	0.00	100%	524	0.23	0	0.00	508.3	15.5	N.R.	0.026	N.R.	N.R.	N.R.
4/21/12	0.86	59.28	0.01	99%	1500	0.66	113	0.22	65.8	44.8	7.7	0.019	0.51	24.50	0.021

N.R. = not applicable due to no runoff from the outfall pipe.
N.D. = data unavailable
[1] = Total rainfall determined from KVACHANT3 gauge located in Chantilly, VA.
[2] = Antecedent dry time determined from KIAD gauge located at Dulles International Airport.

Table B-7. Analytical results for monitored storm events.

Event Date	Pollutant Concentration (mg/L)																			
	Total Phosphorus					Total Nitrogen[2]					Oxidized Nitrogen					Total Kjeldahl Nitrogen				
	GKY	PVC	IN[1]	LYS[3]	OUT	GKY	PVC	IN[1]	LYS[3]	OUT	GKY	PVC	IN[1]	LYS[3]	OUT	GKY	PVC	IN[1]	LYS[3]	OUT
9/25/08	0.09		0.09			1.07		1.07			0.57		0.57			0.5		0.50		
4/20/09	1.3		0.96		0.28	3.72		2.75			0.22		0.16		0.25	3.5		2.58		2
6/3/09	0.04	0.12	0.05		0.24	2.18	3.02	2.32		2.06	0.38	<0.02	0.32		0.26	1.8	3	2.01		1.8
8/21/09	0.13		0.09		0.31	1.65		1.12		0.58	0.35		0.24		0.58	1.3		0.88		1.8
9/11/09	1.3		1.30			9.16		9.16			0.16		0.16			9		9.00		
9/26/09	0.06		0.06			1.00		1.00			0.1		0.10			0.9		0.90		
10/15/09	0.06		0.06			0.92		0.91			0.22		0.22			0.7		0.69		
10/24/09	0.18		0.14			2.12		1.69			0.42		0.34			1.7		1.36		
10/27/09	0.09		0.08			1.32		1.21			0.02		0.02			1.3		1.19		
11/11/09	0.12		0.10			5.10		4.43			2.6		2.26			2.5		2.17		
12/2/09	0.14	2.4	0.14			1.84		1.84			0.24	<0.02	0.24			1.6	11	1.60		
3/11/10	0.4	0.6	0.40		0.19	2.55		2.55		2.00	0.35	<0.02	0.35		1.1	2.2	3.7	2.20		0.9
3/28/10	0.77	0.63	0.77		0.28	3.80	4.11	3.80		2.09	0.1	0.11	0.10		0.49	3.7	4	3.70		1.6
7/8/11	0.04	1.2	0.18	0.74	0.35	1.16	5.30	1.67	28.40	4.40	0.26	2.40	0.52	20.00	1.80	0.90	2.90	1.15	8.40	2.60
8/13/11	0.15	4.7	0.15			2.15		2.15			0.45	5.70	0.45			1.70	17.00	1.70		
8/27/11		0.36	0.06	1.3			1.83	0.30	23.60			0.13	0.02	18.00			1.70	0.28	5.60	
9/5/11	0.23	0.45	0.33	0.32	0.23	0.85	1.49	1.14	1.92	2.10	0.05	0.09	0.07	0.52	0.70	0.80	1.40	1.07	1.40	1.40
9/23/11	0.06	0.72	0.06	0.72		1.59		1.59	5.10		0.89	6.90	0.89	1.70		0.70	3.50	0.70	3.40	
10/12/11	0.25	0.79	0.43	0.36	0.2	1.16	4.55	2.28	3.20	2.50	0.06	0.05	0.06	1.1	1.4	1.1	4.5	2.22	2.1	1.1
12/6/11	0.64	0.75	0.67	0.33	0.24	4.82	5.22	4.92	1.16	1.33	<0.02	<0.02	<0.02	0.16	0.13	4.8	5.2	4.90	1	1.2
1/11/12	0.48	0.91	0.49	0.35	0.17	3.60	5.66	3.66	2.90	1.51	0.1	0.16	0.10	1.3	0.61	3.5	5.5	3.56	1.6	0.9
1/26/12	0.27	1.4	0.27	0.64		1.20		1.20	2.60		0.1	0.06	0.10	0.6		1.1	4.4	1.10	2	
2/29/12	0.63	2.1	0.94	0.41	0.46	2.92	7.08	3.80	3.20	2.12	0.12	0.18	0.13	1.3	0.62	2.8	6.9	3.66	1.9	1.5
3/24/12	0.1	2	0.10	0.44		1.00		1.00	4.06		0.2	0.35	0.20	0.36		0.8	27	0.80	3.7	
4/21/12	0.21	0.51	0.23	0.37	0.35	1.58	3.42	1.71	3.50	1.33	0.08	0.52	0.11	1.3	0.53	1.5	2.9	1.60	2.2	0.8

[1]IN refers to the volume-weighted CUIN as discussed earlier in the report. [2]Total Nitrogen = (OxN_{Load} + TKN_{Load})/(Vol. of Runoff for Sampler's Drainage Area)
[3]Lysimeter samples were only taken for TP, OxN and TKN. Lysimeter samples were only taken during the 2nd monitoring period.
Blank cells are indicative of a storm event which was sampled for water quality but not for that particular water quality constituent.

Table B-7. Analytical results for monitored storm events (Continued).

Event Date	Pollutant Concentration (mg/L)															
	Ammonia Nitrogen				Total Suspended Solids				Chemical Oxygen Demand[4]				Total Dissolved Solids[4]			
	GKY	PVC	IN[1]	OUT	GKY	PVC	IN[1]	OUT	GKY	PVC	IN[1]	OUT	GKY	PVC	IN[1]	OUT
9/25/08	0.3		0.30		32		32									
4/20/09					450		332	74								
6/3/09	1.1	0.6	1.01	0.4	4	56	13	10								
8/21/09	0.5		0.34	<0.2	25		17	2								
9/11/09	5.9		5.90		11		11									
9/26/09	0.2		0.20		4		4									
10/15/09	<0.2		<0.20		6		6									
10/24/09	<0.2		<0.16		28		22									
10/27/09	0.3		0.27		9		8									
11/11/09	0.9		0.78		9		8									
12/2/09	0.3	1	0.30		6	1600	6									
3/11/10	0.5	0.6	0.50	0.3	190	280	190	19								
3/28/10	0.4	0.7	0.40	0.3	480	290	478	14								
7/8/11	0.30	0.40	0.31	0.40	2	190	25	2	30	70	35	55	24	110	35	120
8/13/11	0.80	0.80	0.80		2		2		83		83		19		19	
8/27/11		<0.2	<0.03			28	5			41	7			<10	<1.7	
9/5/11	<0.2	13.00	5.88	<0.2	8	250	117	29	48	100	71	70	<10	65	32	72
9/23/11	<0.2	0.70	<0.2		9		9		35	50	35		<10		<10	
10/12/11	0.2	0.2	0.20	<0.2	150	490	262	10	110	200	140	37	28	88	48	77
12/6/11	0.3	0.6	0.38	<0.2	610	790	656	32	250	200	237	44	51	21	43	69
1/11/12	0.2	0.8	0.22	<0.2	290	680	302	28	150	180	151	22	39	78	40	54
1/26/12	0.3	0.4	0.30		170	580	170		120	170	120		<10	130	<10	
2/29/12	0.2	0.7	0.31	0.2	180	700	290	58	190	240	201	66	85	180	105	76
3/24/12	0.3	1.4	0.30		17	1300	17		40	310	40		<10	<10	<10	
4/21/12	0.3	0.8	0.33	<0.2	74	95	75	10	85	91	85	34	17	67	20	97

[1]IN refers to the volume-weighted EMC referred to as CUIN and discussed in previous sections.
[4]COD and TDS were not tested for during 1st monitoring period.
Blank cells are indicative of a storm event which was sampled for water quality but not for that particular water quality constituent.

Table B-7. Analytical results for monitored storm events (Continued).

Event Date	Pollutant Concentration (mg/L)											
	Copper				Cadmium				Zinc			
	GKY	PVC	IN[1]	OUT	GKY	PVC	IN[1]	OUT	GKY	PVC	IN[1]	OUT
9/25/08	<0.01		<0.01		<0.0005		<0.0005		0.073		0.07	
4/20/09	0.058		0.0428	<0.01	<0.0005		<0.0004	<0.0005	1.8			0.064
6/3/09	0.0033	0.014	0.0052	0.0069	<0.0005	<0.0005	<0.0005	<0.0005	0.044	0.032	0.04	0.02
8/21/09	0.0056		0.0038	0.0098	<0.0005		<0.0003	<0.0005	0.055		0.04	0.093
9/11/09	0.0062		0.0062		<0.0005		<0.0005		0.024		0.02	
9/26/09	0.0028		0.0028		<0.0005		<0.0005		<0.01		<0.01	
10/15/09	0.0022		0.0022		<0.0005		<0.0005		0.019		0.019	
10/24/09	0.014		0.0112		<0.0005		<0.0004		0.05		0.040	
10/27/09	0.0035		0.0032		<0.0005		<0.0005		0.033		0.030	
11/11/09	0.0049		0.0043		<0.0005		<0.0004		0.032		0.028	
12/2/09	0.0054	0.125	0.0054		<0.0005	0.0015	<0.0005		0.017	0.17	0.017	
3/11/10	0.024	0.018	0.0240	0.0051	0.002	<0.0005	0.0020	<0.0005	0.094	0.041	0.094	0.04
3/28/10	0.041	0.024	0.0408	0.0093	0.0028	<0.0005	0.0028	0.00055	0.13	0.15	0.130	0.037
7/8/11	0.005		0.0044		<0.0005		<0.0004		0.074		0.065	
8/13/11	0.0071	0.104	0.0071		<0.0005	0.0019	<0.0005		0.04	0.15	0.040	
8/27/11		0.014	0.0023			0.001	0.0002			0.034	0.006	
9/5/11	0.00692	0.063	0.0321	0.0059	<0.0005	<0.0005	<0.0005	<0.0005	0.02	0.046	0.032	<0.01
9/23/11	0.013	0.035	0.0130		0.00065	0.00083	0.0007		0.073	0.089	0.073	
10/12/11	0.023	0.04	0.0286	0.0064	<0.0005	<0.0005	<0.0005	<0.0005	0.073	0.07	0.072	0.019
12/6/11	0.08	0.069	0.0772	0.0075	0.00065	<0.0005	0.0005	<0.0005	0.25	0.14	0.222	0.023
1/11/12	0.024	0.069	0.0254	0.0075	<0.0005	<0.0005	<0.0005	<0.0005	0.14	0.15	0.140	0.02
1/26/12	0.015	0.034	0.0150		<0.0005	<0.0005	<0.0005		0.1	0.07	0.100	
2/29/12	0.03	0.08	0.0405	0.01	<0.0005	<0.0005	<0.0005	<0.0005	0.12	0.13	0.122	0.02
3/24/12	<0.002		<0.002		0.001		0.0010		0.03	0	0.030	
4/21/12	0.011	0.015	0.0113	0.006	<0.0005	<0.0005	<0.0005	<0.0005	0.07	0.03	0.067	0.02

[1]IN refers to the volume-weighted EMC referred to as CUIN and discussed in previous sections.
Blank cells are indicative of a storm event which was sampled for water quality but not for that particular water quality constituent.

Table B-7. Analytical results for monitored storm events (Continued).

Event Date	Pollutant Concentration (mg/L)											
	Lead				Oil and Grease				Total Petroleum Hydrocarbons			
	GKY	PVC	IN[1]	OUT	GKY	PVC	IN[1]	OUT	GKY	PVC	IN[1]	OUT
9/25/08	<0.01		<0.01									
4/20/09	0.032		0.024	<0.01	42		31.0					
6/3/09	<0.002	<0.002	<0.002	<0.002	5.7	10	6.4					
8/21/09	<0.002		<0.001	<0.002	<5		<3.38					
9/11/09	<0.002		<0.002		<5		<5					
9/26/09	<0.002		<0.002		<5		<5					
10/15/09	<0.002		<0.002		<5		<4.96					
10/24/09	0.0021		0.002		<5		<3.99					
10/27/09	<0.002		<0.002		<5		<4.57					
11/11/09	<0.002		<0.002		<5		<4.35					
12/2/09	<0.002	0.022	<0.002		<5		<5					
3/11/10	0.014	0.0057	0.014	<0.002	<5		<5					
3/28/10	0.02	0.009	0.0199	<0.002	<5		<4.96					
7/8/11	<0.002		<0.002		<5		<4.38					
8/13/11	<0.002	0.016	<0.002		<5		<5					
8/27/11		<0.002	<0.0003			<5	<0.82					
9/5/11	<0.002	0.0081	0.004184	<0.002	<5	<5	<5	5.8				
9/23/11	0.012	0.004	0.012		<5		<5					
10/12/11	0.0054	0.0077	0.006	<0.002	<5	<5	<5	14				
12/6/11	0.024	0.0084	0.020	<0.002					<5	<5	<5	<5
1/11/12	0.016	0.011	0.016	<0.002					<5	<5	<5	<5
1/26/12	0.021	0.013	0.021						<5	<5	<5	
2/29/12	0.016	0.014	0.016	<0.002					<5	<5	<5	<5
3/24/12	<0.002	0	<0.002						<5		<5	
4/21/12	0.007	0.002	0.007	<0.002					<5	<5	<5	<5

[1]IN refers to the volume-weighted EMC referred to as CUIN and discussed in previous sections.
Blank cells are indicative of a storm event which was sampled for water quality but not for that particular water quality constituent.

Table B-7. Analytical results for monitored storm events (Continued).

Event Date	Pollutant Concentration (mg/L)											
	Alkalinity[5]				Hardness[5]				Orthophosphate[5]			
	GKY	PVC	IN[1]	OUT	GKY	PVC	IN[1]	OUT	GKY	PVC	IN[1]	OUT
9/25/08	22		22		36		36		0.05		0.05	
4/20/09												
6/3/09	2	70	14	25	16	220	52	110	0.02	0.07	0.03	0.18
8/21/09	2		1	52	2		1	2	0.10		0.07	0.17
9/11/09	12		12		40		40		0.87		0.87	
9/26/09	2		2		<1			68	0.04		0.04	
10/15/09	12		12		<1		<0.99		0.02		0.02	
10/24/09	8		6		12		10		0.08		0.06	
10/27/09	8		7		<1		<0.91		0.05		0.05	
11/11/09	<1		<0.87		30		26		0.05		0.04	
12/2/09	6	140	6		88	220	88		0.09	0.15	0.09	
3/11/10	170	16	170	76	30	60	30	14	<0.01	<0.01	<0.01	0.14
3/28/10	20	130	21	48	130	80	130	100	0.02	<0.01	0.02	0.20
7/8/11												
8/13/11												
8/27/11												
9/5/11												
9/23/11												
10/12/11												
12/6/11												
1/11/12												
1/26/12												
2/29/12												
3/24/12												
4/21/12												

[1]IN refers to the volume-weighted EMC referred to as CUIN and discussed in previous sections.
[5]Alkalinity, Hardness and Orthophosphate were not sampled for during the 2nd monitoring period.
Blank cells are indicative of a storm event which was sampled for water quality but not for that particular water quality constituent.

Table B-8. Load results for CUIN & CUOUT with BDL = 0.

Event Date	Pollutant Load (g)											
	TP		TN		OxN		TKN		NH_3		TSS	
	CUIN	CUOUT	CUIN	CUOUT	CUIN	CUOUT	CUIN	CUOUT	CUIN	CUOUT	CUIN	CUOUT
9/25/08	1.70	0	20.15	0	10.74	0	9.42	0	5.65	0	603	0
4/20/09	132.70		379.74		22.46		357.28				45936	
6/3/09	4.50	23.07	193.80	198.03	26.18	24.99	167.62	173.03	84.51	38.45	1089	961
8/21/09	17.95	6.21	227.76	47.67	48.31	11.62	179.45	36.05	69.02	0.00	3451	40
9/11/09	3.20	0	22.57	0	0.39	0	22.18	0	14.54	0	27	0
9/26/09	1.17		19.42		1.94		17.48		3.88		78	
10/15/09	1.66	0	25.52	0	6.10	0	19.41	0	0.00	0	166	0
10/24/09	14.00		164.94		32.68		132.26		0.00		2178	
10/27/09	4.16		60.99		0.92		60.07		13.86		416	
11/11/09	6.83	0	290.08	0	147.89	0	142.20	0	51.19	0	512	0
12/2/09	2.39	0	31.47	0	4.11	0	27.37	0	5.13	0	103	0
3/11/10	6.84	0.07	43.62	0.78	5.99	0.43	37.63	0.35	8.55	0.12	3250	7
3/28/10	21.51	1.12	106.42	8.37	2.80	1.96	103.62	6.41	11.27	1.20	13385	56
7/8/11	11.49	0.27	104.83	3.37	32.88	1.38	71.95	1.99	19.59	0.31	1581	2
8/13/11	1.73	0	24.76	0	5.18	0	19.58	0	9.21	0	23	0
8/27/11	4.62	0	23.50	0	1.67	0	21.84	0	0.00	0	360	0
9/5/11	188.79	70.70	653.14	645.52	39.03	215.17	614.11	430.35	3348.64	0.00	66932	8914
9/23/11	0.63	0	16.61	0	9.30	0	7.31	0	0.00	0	94	0
10/12/11	91.49	30.56	486.86	381.94	12.12	213.89	474.75	168.05	42.74	0.00	56022	1528
12/6/11	89.43	35.31	656.14	195.66	0.00	19.12	656.14	176.53	50.45	0.00	87818	4708
1/11/12	17.24	3.41	127.99	30.32	3.56	12.25	124.43	18.07	7.65	0.00	10557	562
1/26/12	0.57	0	2.52	0	0.21	0	2.31	0	0.63	0	357	0
2/29/12	96.47	30.42	389.71	140.20	13.61	41.00	376.09	99.20	31.35	13.23	29727	3836
3/24/12	1.48	0	14.83	0	2.97	0	11.87	0	4.45	0	252	0
4/21/12	10.55	0.59	78.01	2.23	5.06	0.89	72.96	1.34	15.29	0.00	3446	17

Blank cells are indicative of a storm event which was sampled for water quality but not for that particular water quality constituent.

Table B-8. Load results for CUIN & CUOUT with BDL = 0 (Continued).

	Pollutant Load (g)											
Event	COD		TDS		Cu		Cd		Zn		Pb	
Date	CUIN	CUOUT	CUIN	CUOUT	CUIN	CUOUT	CUIN	CUOUT	CUIN	CUOUT	CUIN	CUOUT
9/25/08					0.000	0	0.000	0	1.375	0	0.000	0
4/20/09					5.921		0.000		183.743		3.267	
6/3/09					0.431	0.663	0.000	0.000	3.497	1.923	0.000	0.000
8/21/09					0.773	0.196	0.000	0.000	7.592	1.863	0.000	0.000
9/11/09					0.015	0	0.000	0	0.059	0	0.000	0
9/26/09					0.054		0.000		0.000		0.000	
10/15/09					0.061	0	0.000	0	0.527	0	0.000	0
10/24/09					1.089		0.000		3.890		0.163	
10/27/09					0.162		0.000		1.525		0.000	
11/11/09					0.279	0	0.000	0	1.820	0	0.000	0
12/2/09					0.092	0	0.000	0	0.291	0	0.000	0
3/11/10					0.411	0.002	0.034	0.000	1.608	0.016	0.239	0.000
3/28/10					1.143	0.037	0.078	0.002	3.643	0.148	0.557	0.000
7/8/11	2192	42	2172	92	0.275		0.000		4.069		0.000	
8/13/11	956	0	219	0	0.082	0	0.000	0	0.461	0	0.000	0
8/27/11	527	0	0	0	0.180	0	0.013	0	0.437	0	0.000	0
9/5/11	40968	21517	16743	22132	18.421	1.814	0.000	0.000	18.186	0.000	2.086	0.000
9/23/11	366	0	0	0	0.136	0	0.007	0	0.762	0	0.125	0
10/12/11	29850	5653	10213	11764	6.113	0.978	0.000	0.000	15.388	2.903	1.316	0.000
12/6/11	31743	6473	5796	10151	10.329	1.103	0.065	0.000	29.684	3.384	2.677	0.000
1/11/12	5271	442	1405	1084	0.888	0.151	0.000	0.000	4.900	0.402	0.553	0.000
1/26/12	252	0	0	0	0.032	0	0.000	0	0.210	0	0.044	0
2/29/12	20582	4365	10779	5026	4.161	0.661	0.000	0.000	12.532	1.323	1.599	0.000
3/24/12	593	0	0	0	0.000	0	0.015	0	0.445	0	0.000	0
4/21/12	3900	57	936	163	0.515	0.010	0.000	0.000	3.069	0.034	0.304	0.000

Blank cells are indicative of a storm event which was sampled for water quality but not for that particular water quality constituent.

Table B-8. Load results for CUIN & CUOUT with BDL = 0 (Continued).

Event Date	Pollutant Load (g)									
	O&G		TPH		Alk		Hard		OP	
	CUIN	CUOUT	CUIN	CUOUT	CUIN	CUOUT	CUIN	CUOUT	CUIN	CUOUT
9/25/08					414	0	678	0	0.942	0
4/20/09	4287									
6/3/09	538	0			1155	2403	4300	10574	2.395	17.303
8/21/09	0	0			276	1042	276	40	13.804	3.405
9/11/09	0	0			30	0	99	0	2.144	0
9/26/09	0				39		0		0.777	
10/15/09	0	0			333	0	0	0	0.555	0
10/24/09	0				622		934		6.224	
10/27/09	0				370		0		2.310	
11/11/09	0	0			0	0	1706	0	2.844	0
12/2/09	0	0			103	0	1505	0	1.539	0
3/11/10	0	0			2908	29	513	5	0.000	0.054
3/28/10	0	0			587	192	3626	401	0.555	0.801
7/8/11	0	0								
8/13/11	0	0								
8/27/11	0	0								
9/5/11	0	1783								
9/23/11	0	0								
10/12/11	0	2139								
12/6/11			0	0						
1/11/12			0	0						
1/26/12			0	0						
2/29/12			0	0						
3/24/12			0	0						
4/21/12			0	0						

Blank cells are indicative of a storm event which was sampled for water quality but not for that particular water quality constituent.

Table B-9. Load results for CUIN & CUOUT with BDL = ½ detection limit.

Event Date	Pollutant Load (g)											
	TP		TN		OxN		TKN		NH_3		TSS	
	CUIN	CUOUT	CUIN	CUOUT	CUIN	CUOUT	CUIN	CUOUT	CUIN	CUOUT	CUIN	CUOUT
9/25/08	1.70	0	20.15	0	10.74	0	9.42	0	5.65	0	603	0
4/20/09	132.70		379.74		22.46		357.28				45936	
6/3/09	4.50	23.07	193.95	198.03	26.33	24.99	167.62	173.03	84.51	38.45	1089	961
8/21/09	17.95	6.21	227.76	47.67	48.31	11.62	179.45	36.05	69.02	2.00	3451	40
9/11/09	3.20	0	22.57	0	0.39	0	22.18	0	14.54	0	27	0
9/26/09	1.17		19.42		1.94		17.48		3.88		78	
10/15/09	1.66	0	25.52	0	6.10	0	19.41	0	2.77	0	166	0
10/24/09	14.00		164.94		32.68		132.26		7.78		2178	
10/27/09	4.16		60.99		0.92		60.07		13.86		416	
11/11/09	6.83	0	290.08	0	147.89	0	142.20	0	51.19	0	512	0
12/2/09	2.39	0	31.47	0	4.11	0	27.37	0	5.13	0	103	0
3/11/10	6.84	0.07	43.62	0.78	5.99	0.43	37.63	0.35	8.55	0.12	3250	7
3/28/10	21.51	1.12	106.42	8.37	2.80	1.96	103.62	6.41	11.27	1.20	13385	56
7/8/11	11.49	0.27	104.83	3.37	32.88	1.38	71.95	1.99	19.59	0.31	1581	2
8/13/11	1.73	0	24.76	0	5.18	0	19.58	0	9.21	0	23	0
8/27/11	4.62	0	23.50	0	1.67	0	21.84	0	1.28	0	360	0
9/5/11	188.79	70.70	653.14	645.52	39.03	215.17	614.11	430.35	3380.33	30.74	66932	8914
9/23/11	0.63	0	16.61	0	9.30	0	7.31	0	1.04	0	94	0
10/12/11	91.49	30.56	486.86	381.94	12.12	213.89	474.75	168.05	42.74	15.28	56022	1528
12/6/11	89.43	35.31	657.48	195.66	1.34	19.12	656.14	176.53	50.45	14.71	87818	4708
1/11/12	17.24	3.41	127.99	30.32	3.56	12.25	124.43	18.07	7.65	2.01	10557	562
1/26/12	0.57	0	2.52	0	0.21	0	2.31	0	0.63	0	357	0
2/29/12	96.47	30.42	389.71	140.20	13.61	41.00	376.09	99.20	31.35	13.23	29727	3836
3/24/12	1.48	0	14.83	0	2.97	0	11.87	0	4.45	0	252	0
4/21/12	10.55	0.59	78.01	2.23	5.06	0.89	72.96	1.34	15.29	0.17	3446	17

Blank cells are indicative of a storm event which was sampled for water quality but not for that particular water quality constituent.

Table B-9. Load results for CUIN & CUOUT with BDL = ½ detection limit (Continued).

	Pollutant Load (g)											
Event	COD		TDS		Cu		Cd		Zn		Pb	
Date	CUIN	CUOUT	CUIN	CUOUT	CUIN	CUOUT	CUIN	CUOUT	CUIN	CUOUT	CUIN	CUOUT
9/25/08					0.094	0	0.0047	0	1.375	0	0.0942	0
4/20/09					5.921		0.0255		183.743		3.2665	
6/3/09					0.431	0.663	0.0209	0.0240	3.497	1.923	0.0834	0.0961
8/21/09					0.773	0.196	0.0345	0.0050	7.592	1.863	0.1380	0.0200
9/11/09					0.015	0	0.0006	0	0.059	0	0.0025	0
9/26/09					0.054		0.0049		0.097		0.0194	
10/15/09					0.061	0	0.0069	0	0.527	0	0.0277	0
10/24/09					1.089		0.0195		3.890		0.1634	
10/27/09					0.162		0.0116		1.525		0.0462	
11/11/09					0.279	0	0.0142	0	1.820	0	0.0569	0
12/2/09					0.092	0	0.0043	0	0.291	0	0.0171	0
3/11/10					0.411	0.002	0.0342	0.0001	1.608	0.016	0.2395	0.0004
3/28/10					1.143	0.037	0.0777	0.0022	3.643	0.148	0.5569	0.0040
7/8/11	2192	42	2172	92	0.275		0.0137		4.069		0.0550	
8/13/11	956	0	219	0	0.082	0	0.0029	0	0.461	0	0.0115	0
8/27/11	527	0	64	0	0.180	0	0.0128	0	0.437	0	0.0128	0
9/5/11	40968	21517	18327	22132	18.421	1.814	0.1436	0.0768	18.186	1.537	2.4033	0.3074
9/23/11	366	0	52	0	0.136	0	0.0068	0	0.762	0	0.1253	0
10/12/11	29850	5653	10213	11764	6.113	0.978	0.0534	0.0382	15.388	2.903	1.3160	0.1528
12/6/11	31743	6473	5796	10151	10.329	1.103	0.0733	0.0368	29.684	3.384	2.6767	0.1471
1/11/12	5271	442	1405	1084	0.888	0.151	0.0087	0.0050	4.900	0.402	0.5532	0.0201
1/26/12	252	0	11	0	0.032	0	0.0005	0	0.210	0	0.0441	0
2/29/12	20582	4365	10779	5026	4.161	0.661	0.0257	0.0165	12.532	1.323	1.5988	0.0661
3/24/12	593	0	74	0	0.015	0	0.0148	0	0.445	0	0.0148	0
4/21/12	3900	57	936	163	0.515	0.010	0.0114	0.0004	3.069	0.034	0.3037	0.0017

Blank cells are indicative of a storm event which was sampled for water quality but not for that particular water quality constituent.

Table B-9. Load results for CUIN & CUOUT with BDL = ½ detection limit (Continued).

Event Date	Pollutant Load (g)									
	O&G		TPH		Alk		Hard		OP	
	CUIN	CUOUT	CUIN	CUOUT	CUIN	CUOUT	CUIN	CUOUT	CUIN	CUOUT
9/25/08					414	0	678	0	0.942	0
4/20/09	4287									
6/3/09	538	0			1155	2403	4300	10574	2.395	17.303
8/21/09	345	0			276	1042	276	40	13.804	3.405
9/11/09	6	0			30	0	99	0	2.144	0
9/26/09	49				39		10		0.777	
10/15/09	69	0			333	0	14	0	0.555	0
10/24/09	195				622		934		6.224	
10/27/09	116				370		23		2.310	
11/11/09	142	0			28	0	1706	0	2.844	0
12/2/09	43	0			103	0	1505	0	1.539	0
3/11/10	43	0			2908	29	513	5	0.086	0.054
3/28/10	69	0			587	192	3626	401	0.556	0.801
7/8/11	137	0								
8/13/11	29	0								
8/27/11	32	0								
9/5/11	1436	1783								
9/23/11	26	0								
10/12/11	534	2139								
12/6/11			335	368						
1/11/12			87	50						
1/26/12			5	0						
2/29/12			257	165						
3/24/12			37	0						
4/21/12			114	4						

Blank cells are indicative of a storm event which was sampled for water quality but not for that particular water quality constituent.

Table B-10. Load results for CUIN & CUOUT with BDL = detection limit.

Event Date	Pollutant Load (g)											
	TP		TN		OxN		TKN		NH_3		TSS	
	CUIN	CUOUT	CUIN	CUOUT	CUIN	CUOUT	CUIN	CUOUT	CUIN	CUOUT	CUIN	CUOUT
9/25/08	1.70	0	20.15	0	10.74	0	9.42	0	5.65	0	603	0
4/20/09	132.70		379.74		22.46		357.28				45936	
6/3/09	4.50	23.07	194.09	198.03	26.47	24.99	167.62	173.03	84.51	38.45	1089	961
8/21/09	17.95	6.21	227.76	47.67	48.31	11.62	179.45	36.05	69.02	4.01	3451	40
9/11/09	3.20	0	22.57	0	0.39	0	22.18	0	14.54	0	27	0
9/26/09	1.17		19.42		1.94		17.48		3.88		78	
10/15/09	1.66	0	25.52	0	6.10	0	19.41	0	5.55	0	166	0
10/24/09	14.00		164.94		32.68		132.26		15.56		2178	
10/27/09	4.16		60.99		0.92		60.07		13.86		416	
11/11/09	6.83	0	290.08	0	147.89	0	142.20	0	51.19	0	512	0
12/2/09	2.39	0	31.47	0	4.11	0	27.37	0	5.13	0	103	0
3/11/10	6.84	0.07	43.62	0.78	5.99	0.43	37.63	0.35	8.55	0.12	3250	7
3/28/10	21.51	1.12	106.42	8.37	2.80	1.96	103.62	6.41	11.27	1.20	13385	56
7/8/11	11.49	0.27	104.83	3.37	32.88	1.38	71.95	1.99	19.59	0.31	1581	2
8/13/11	1.73	0	24.76	0	5.18	0	19.58	0	9.21	0	23	0
8/27/11	4.62	0	23.50	0	1.67	0	21.84	0	2.57	0	360	0
9/5/11	188.79	70.70	653.14	645.52	39.03	215.17	614.11	430.35	3412.01	61.48	66932	8914
9/23/11	0.63	0	16.61	0	9.30	0	7.31	0	2.09	0	94	0
10/12/11	91.49	30.56	486.86	381.94	12.12	213.89	474.75	168.05	42.74	30.56	56022	1528
12/6/11	89.43	35.31	658.82	195.66	2.68	19.12	656.14	176.53	50.45	29.42	87818	4708
1/11/12	17.24	3.41	127.99	30.32	3.56	12.25	124.43	18.07	7.65	4.02	10557	562
1/26/12	0.57	0	2.52	0	0.21	0	2.31	0	0.63	0	357	0
2/29/12	96.47	30.42	389.71	140.20	13.61	41.00	376.09	99.20	31.35	13.23	29727	3836
3/24/12	1.48	0	14.83	0	2.97	0	11.87	0	4.45	0	252	0
4/21/12	10.55	0.59	78.01	2.23	5.06	0.89	72.96	1.34	15.29	0.34	3446	17

Blank cells are indicative of a storm event which was sampled for water quality but not for that particular water quality constituent.

Table B-10. Load results for CUIN & CUOUT with BDL = detection limit (Continued).

	Pollutant Load (g)											
Event	COD		TDS		Cu		Cd		Zn		Pb	
Date	CUIN	CUOUT	CUIN	CUOUT	CUIN	CUOUT	CUIN	CUOUT	CUIN	CUOUT	CUIN	CUOUT
9/25/08					0.188	0	0.0094	0	1.375	0	0.1884	0
4/20/09					5.921		0.0510		183.743		3.2665	
6/3/09					0.431	0.663	0.0417	0.0481	3.497	1.923	0.1669	0.1923
8/21/09					0.773	0.196	0.0690	0.0100	7.592	1.863	0.2761	0.0401
9/11/09					0.015	0	0.0012	0	0.059	0	0.0049	0
9/26/09					0.054		0.0097		0.194		0.0388	
10/15/09					0.061	0	0.0139	0	0.527	0	0.0555	0
10/24/09					1.089		0.0389		3.890		0.1634	
10/27/09					0.162		0.0231		1.525		0.0924	
11/11/09					0.279	0	0.0284	0	1.820	0	0.1138	0
12/2/09					0.092	0	0.0086	0	0.291	0	0.0342	0
3/11/10					0.411	0.002	0.0342	0.0002	1.608	0.016	0.2395	0.0008
3/28/10					1.143	0.037	0.0778	0.0022	3.643	0.148	0.5569	0.0080
7/8/11	2192	42	2172	92	0.275		0.0275		4.069		0.1100	
8/13/11	956	0	219	0	0.082	0	0.0058	0	0.461	0	0.0230	0
8/27/11	527	0	128	0	0.180	0	0.0128	0	0.437	0	0.0257	0
9/5/11	40968	21517	19912	22132	18.421	1.814	0.2872	0.1537	18.186	3.074	2.7202	0.6148
9/23/11	366	0	104	0	0.136	0	0.0068	0	0.762	0	0.1253	0
10/12/11	29850	5653	10213	11764	6.113	0.978	0.1068	0.0764	15.388	2.903	1.3160	0.3056
12/6/11	31743	6473	5796	10151	10.329	1.103	0.0818	0.0736	29.684	3.384	2.6767	0.2942
1/11/12	5271	442	1405	1084	0.888	0.151	0.0175	0.0100	4.900	0.402	0.5532	0.0402
1/26/12	252	0	21	0	0.032	0	0.0011	0	0.210	0	0.0441	0
2/29/12	20582	4365	10779	5026	4.161	0.661	0.0513	0.0331	12.532	1.323	1.5988	0.1323
3/24/12	593	0	148	0	0.030	0	0.0148	0	0.445	0	0.0297	0
4/21/12	3900	57	936	163	0.515	0.010	0.0228	0.0008	3.069	0.034	0.3037	0.0034

Blank cells are indicative of a storm event which was sampled for water quality but not for that particular water quality constituent.

Table B-10. Load results for CUIN & CUOUT with BDL = detection limit (Continued).

Event Date	Pollutant Load (g)									
	O&G		TPH		Alk		Hard		OP	
	CUIN	CUOUT	CUIN	CUOUT	CUIN	CUOUT	CUIN	CUOUT	CUIN	CUOUT
9/25/08		0			414	0	678	0	0.942	0
4/20/09	4287									
6/3/09	538	0			1155	2403	4300	10574	2.395	17.303
8/21/09	690	0			276	1042	276	40	13.804	3.405
9/11/09	12	0			30	0	99	0	2.144	0
9/26/09	97				39		19		0.777	
10/15/09	139	0			333	0	28	0	0.555	0
10/24/09	389				622		934		6.224	
10/27/09	231				370		46		2.310	
11/11/09	284	0			57	0	1706	0	2.844	0
12/2/09	86	0			103	0	1505	0	1.539	0
3/11/10	86	0			2908	29	513	5	0.171	0.054
3/28/10	139	0			587	192	3626	401	0.557	0.801
7/8/11	275	0								
8/13/11	58	0								
8/27/11	64	0								
9/5/11	2872	1783								
9/23/11	52	0								
10/12/11	1068	2139								
12/6/11			669	736						
1/11/12			175	100						
1/26/12			11	0						
2/29/12			513	331						
3/24/12			74	0						
4/21/12			228	8						

Blank cells are indicative of a storm event which was sampled for water quality but not for that particular water quality constituent.

Table B-11. Sample number and percent censoring for loads at influent and effluent sampler locations.

CUIN																	
	TP	TN	OxN	TKN	NH_3	TSS	COD	TDS	Cu	Cd	Zn	Lead	O&G	TPH	Alk	Hard	OP
Censored Observations	0	0	1	0	4	0	0	4	2	19	1	13	16	6	1	3	1
Total Observations	25	25	25	25	24	25	12	12	25	25	24	25	18	6	12	12	12
Percent Censored	0%	0%	4%	0%	17%	0%	0%	33%	8%	76%	4%	52%	89%	100%	8%	25%	8%
CUOUT																	
	TP	TN	OxN	TKN	NH_3	TSS	COD	TDS	Cu	Cd	Zn	Lead	O&G	TPH	Alk	Hard	OP
Censored Observations	0	0	0	0	6	0	0	0	0	9	1	10	0	4	0	0	0
Total Observations	11	11	11	10	11	11	7	7	10	10	10	10	2	4	4	4	4
Percent Censored	0%	0%	0%	0%	55%	0%	0%	0%	0%	90%	10%	100%	0%	100%	0%	0%	0%
CUOUT-ZF (CUOUT Loads including events with no discharge at the outfall and therefore no effluent loads)																	
	TP	TN	OxN	TKN	NH_3	TSS	COD	TDS	Cu	Cd	Zn	Lead	O&G	TPH	Alk	Hard	OP
Censored Observations	0	0	0	0	6	0	0	0	0	9	1	10	0	4	0	0	0
Total Observations	21	21	21	20	21	21	12	12	20	20	20	20	7	9	9	9	9
Percent Censored	0%	0%	0%	0%	29%	0%	0%	0%	0%	45%	5%	50%	0%	44%	0%	0%	0%

Table B-12. Rainfall depths, rates and durations that did and did not produce outfall discharge.

Events Producing Discharge at LID facility outfall				
	Minimum	Maximum	Average	Median
Rainfall Depths (in.)	0.12	5.13	0.86	0.59
Rainfall Rates (in./hr.)	0.02	0.23	0.07	0.05
Storm Event Durations (hr.)	2.0	95.5	19.1	12.9
Events Without Discharge at LID facility outfall				
	Minimum	Maximum	Average	Median
Rainfall Depths (in.)	0.01	1.09	0.14	0.07
Rainfall Rates (in./hr.)	0.004	0.60	0.05	0.03
Storm Event Durations (hr.)	0.17	49.3	5.8	2.4

Table B-13. Cub Run LID facility pollutant removal efficiencies for Summation of Loads Method and percent censoring.

	TP	TN	OxN	TKN	NH_3	TSS	COD	TDS	Cu	Cd	Zn	Pb	O&G	TPH	Alk	Hard	OP
Below Detection Limit Observations set as 0 (BDL = 0)																	
Summation of Loads	65%	53%	-44%	65%	99%	93%	72%	-4%	87%	99%	89%	100%	-629%	n/a[1]	37%	13%	13%
Below Detection Limit Observations set as one-half the detection limit (BDL = ½ DL)																	
Summation of Loads	65%	53%	-43%	65%	97%	93%	72%	-1%	87%	64%	88%	92%	-14%	30%	37%	13%	13%
Below Detection Limit Observations set as the detection limit (BDL = DL)																	
Summation of Loads	65%	53%	-42%	65%	95%	93%	72%	3%	87%	56%	86%	85%	38%	30%	37%	13%	14%
Percent Censoring of CUIN and CUOUT Loads (from Table 4-9**).**																	
CUIN	0%	0%	4%	0%	17%	0%	0%	33%	8%	76%	4%	52%	89%	100%	8%	25%	8%
CUOUT	0%	0%	0%	0%	29%	0%	0%	0%	0%	45%	5%	50%	0%	44%	0%	0%	0%

Table B-14. Reported TP, TN, TSS, Cu, Zn, and Pb removals in bioretention BMPs by Summation of Loads Method.

Location	Percent TP Removal mass basis	Reference
Total Phosphorus		
Greensboro, North Carolina	-240%	Hunt et al. (2006)
Chapel Hill, North Carolina	65%	Hunt et al. (2006)
Nashville, North Carolina	5%	Brown and Hunt III (2011a)
Nashville, North Carolina	44%	Brown and Hunt III (2011a)
College Park, Maryland	80%	Li and Davis (2009)
Silver Spring, Maryland	58%	Li and Davis (2009)
CRRC LID facility, Virginia	65%	This report
Total Nitrogen		
Greensboro, North Carolina	40%	Hunt et al. (2006)
Chapel Hill, North Carolina	40%	Hunt et al. (2006)
Nashville, North Carolina	12%	Brown and Hunt III (2011a)
Nashville, North Carolina	13%	Brown and Hunt III (2011a)
College Park, Maryland	73%	Li and Davis (2009)
Silver Spring, Maryland	63%	Li and Davis (2009)
CRRC LID facility, Virginia	53%	This report
Total Suspended Solids		
Greensboro, North Carolina	-170%	Hunt et al. (2006)
Nashville, North Carolina	71%	Brown and Hunt III (2011a)
Nashville, North Carolina	84%	Brown and Hunt III (2011a)
College Park, Maryland	97%	Li and Davis (2009)
Silver Spring, Maryland	93%	Li and Davis (2009)
CRRC LID facility, Virginia	93%	This report
Copper		
Greensboro, North Carolina	99%	Hunt et al. (2006)
College Park, Maryland	72%	Li and Davis (2009)
Silver Spring, Maryland	63%	Li and Davis (2009)
CRRC LID facility, Virginia	87%	This report
Zinc		
Greensboro, North Carolina	98%	Hunt et al. (2006)
College Park, Maryland	94%	Li and Davis (2009)
Silver Spring, Maryland	95%	Li and Davis (2009)
CRRC LID facility, Virginia	86%[1]	This report
Lead		
Greensboro, North Carolina	81%	Hunt et al. (2006)

Table B-14. Reported TP, TN, TSS, Cu, Zn, and Pb removals in bioretention BMPs by Summation of Loads Method (Continued).

Location	Percent TP Removal mass basis	Reference
College Park, Maryland	86%	Li and Davis (2009)
Silver Spring, Maryland	83%	Li and Davis (2009)
CRRC LID facility, Virginia	85%[1]	This report

[1]The SOL method results reported for Zn and Pb are based on substituting the detection limit for below detection limit observations, which in this case provided a more conservative estimate of performance.

Table B-15. Generalized Wilcoxon two-sided test for CUIN & CUOUT-ZF loads.

Water Quality Constituent	Sample	No. Samples	Statistically Different at 95% confidence level?	p-value
Total Phosphorus	CUIN	25	Yes	0.002
	CUOUT-ZF	21		
Total Nitrogen	CUIN	25	Yes	<0.001
	CUOUT-ZF	21		
Oxidized Nitrogen	CUIN	25	Yes	0.023
	CUOUT-ZF	21		
Total Kjeldahl Nitrogen	CUIN	25	Yes	<0.001
	CUOUT-ZF	20		
Ammonia	CUIN	24	Yes	<0.001
	CUOUT-ZF	21		
Total Suspended Solids	CUIN	25	Yes	<0.001
	CUOUT-ZF	21		
Chemical Oxygen Demand	CUIN	12	Yes	0.025
	CUOUT-ZF	12		
Total Dissolved Solids	CUIN	12	No	0.582
	CUOUT-ZF	12		
Copper	CUIN	25	Yes	0.003
	CUOUT-ZF	20		
Zinc	CUIN	24	Yes	<0.001
	CUOUT-ZF	20		
Alkalinity	CUIN	12	Yes	0.053
	CUOUT-ZF	9		
Hardness	CUIN	12	No[2]	0.061
	CUOUT-ZF	9		
Orthophosphate Phosphorus	CUIN	12	No[2]	0.071
	CUOUT-ZF	9		

[2]While the Generalized Wilcoxon Two-Sided Test did not find a significant difference between CUIN and CUOUT-ZF for Hardness and Orthophosphate Phosphorus at the 95% confidence level, their p-values are very close to being significant at p = 0.061 and 0.071, respectively.

Table B-16. CRRC Load reduction quantiles from Effluent Probability Method with empirical distribution functions calculated from the Kaplan-Meier method.

Percentile	TSS		TP		TN		COD		Cu		Zn	
	Grams Removed	Percent Reduction	Grams Removed	Percent Reduction	Grams Removed	Percent Reduction	Grams Removed	Percent Reduction	Grams Removed	Percent Reduction	Grams Removed	Percent Reduction
Minimum	23	100%	0.57	100%	2.52	100%	252	100%	0.02	100%	0.06	100%
25th	278	100%	1.86	98%	23.4	98%	568	96%	0.09	99%	0.45	98%
50th	1,330	100%	6.66	98%	89.9	98%	3,840	99%	0.34	99%	1.81	99%
75th	11,820	93%	1.77	9%	162	59%	24,200	81%	0.47	41%	3.46	71%
Maximum	78,900	90%	118	63%	13.3	2%	19,450	47%	16.6	90%	26.3	89%

Table B-17. Percentage of water quality observations below the detection limit (BDL).

CUIN Load				
	Cadmium	**Lead**	**Oil & Grease**	**Total Petroleum Hydrocarbons**
Censored Observations	19	13	16	6
Total Observations	25	25	18	6
Percent BDL	76%	52%	**89%**	**100%**
CUOUT Load				
	Cadmium	**Lead**	**Oil & Grease**	**Total Petroleum Hydrocarbons**
Censored Observations	9	10	0	4
Total Observations	10	10	2	4
Percent BDL	**90%**	**100%**	0%	**100%**
CUOUT-ZF Load				
	Cadmium	**Lead**	**Oil & Grease**	**Total Petroleum Hydrocarbons**
Censored Observations	9	10	0	4
Total Observations	20	20	7	9
Percent BDL	45%	50%	0%	44%

APPENDIX C Fair Use Checklist for Images
Fair Use Checklist for Images

Image Credits: Credited images are reproduced and used under “fair use”. All other images, figures and illustrations are by the author, Paul D. Le Bel.

Figures 1-1, 3-1, 4-1, 5-1 and A-1 Used under fair use, 2013
Google Maps (2013). “Cub Run Rec Center Satellite Image Google Maps, Used under fair use, 2013.”. Retrieved 2/15/2013, from http://goo.gl/maps/LzirW, Fair use determination attached.

Draft 09/01/2009

(Questions? Concerns? Contact Gail McMillan, Director of the Digital Library and Archives at Virginia Tech's University Libraries: gailmac@vt.edu)

(Please ensure that Javascript is enabled on your browser before using this tool.)

Virginia Tech ETD Fair Use Analysis Results

This is not a replacement for professional legal advice but an effort to assist you in making a sound decision.

Name: Paul Le Bel

Description of item under review for fair use: Google Maps (2013). "Cub Run Rec Center Satellite Image Google Maps, Used under fair use, 2013.". Retrieved 2/15/2013, from http://goo.gl/maps/LzirW, Fair use determination attached.

Report generated on: 04-11-2013 at : 16:18:38

Based on the information you provided:

Factor 1

Your consideration of the purpose and character of your use of the copyright work weighs: ***in favor of fair use***

Factor 2

Your consideration of the nature of the copyrighted work you used weighs: ***in favor of fair use***

Factor 3

Your consideration of the amount and substantiality of your use of the copyrighted work weighs: ***in favor of fair use***

Factor 4

Your consideration of the effect or potential effect on the market after your use of the copyrighted work weighs: ***in favor of fair use***

Based on the information you provided, your use of the copyrighted work weighs: *in favor of fair use*