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Underground Stormwater Treatment Performance in Urban Coastal Catchments: Case Study of Baffle Boxes in the City of Tampa

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Underground Stormwater Treatment Performance in Urban Coastal Catchments:

Case Study of Baffle Boxes in the City of Tampa

by

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ABSTRACT

In coastal urban regions, underground stormwater treatment units are suitable infrastructure options because they take less space where premium land is expensive. Even then, they should be accessible and ideally small enough to fit into existing stormwater networks. Since 2003, the City of Tampa and Florida's Department of Transportation (FDOT) have installed 47 baffle boxes into the city's stormwater pipe networks. Baffle boxes are underground stormwater treatment structures designed to capture sediments and floating debris. Since their deployment, many challenges regarding their practical sediment capturing performance was raised by the city.

The objective of this research was to evaluate the effects of rainfall, land use, and maintenance on the sediment trapping efficiency of the baffle boxes and identify solutions to enhance their performance. This was addressed through site visits, sediment accumulation measurements and analysis of historical and field data. The results of these measurements and analysis were then compared to rainfall intensity, catchment characteristics, size and type of the units. During the preliminary site visits and sediment measurements it was observed that most of the units located in the south of Tampa were inundated by backflows from Tampa Bay. Survey information collected from inspection crew members also showed that resuspension of trapped sediments frequently occurs in these units. Concerning operation and maintenance (O&M), it was indicated that units mounted with screens are costly and difficult to clean-out. Additionally, it was found that 80% of the units have very small trap inlets and lack the baffle structures needed to slow down and settle sediments.

Historical sediment measurements and O&M practices were analyzed to calculate the overall performance of the units. The analysis of the data determined the sediments captured, the resuspension rate, and yearly cost of maintenance for different types of baffle boxes. Rainfall intensity and land use and land cover (LULC) data for each catchment of the units was correlated to the performance of the units. The LULC data used impervious fraction and tree canopy area of the catchments to project sediment and leaf matter accumulation within the units.

This research study found that total daily rainfall intensity is a good predictor of sediment accumulation. Cleanout crews can use this relationship to conduct their work efficiently and to promptly react to occurring rainfall events. Thus, the prediction of sediments accumulated from rainfall events and the coordination of clean-out trucks can optimize O&M practices. It was also determined that large-sized (24-40 in) units and those with three chambers (baffles) perform better at trapping sediments. Thus, installing baffles in units within the large-sized ones can enhance their performance. The study also found that baffle boxes mounted with screens can individually take up to eight hours to cleanup which makes them costly and difficult. This can be detrimental for municipalities to follow up on their O&M practices effectively. Therefore, to alleviate the clean out complexity and reduce maintenance expenditures complementary practices such as bag filters need to be explored and implemented for trials

CHAPTER 1: INTRODUCTION

It is projected that by 2050 70% of the world's population will live in urban areas. In the United States, urbanization levels have already surpassed 80 % in 2008 (UN, 2008). Large infrastructure projects are implemented to accommodate and supply the augmenting urban population and provide living space. These include construction activities such as site clearing, surface leveling, and compaction, paving and concreting. These land use and land cover (LULC) changes reduce pervious areas and surface roughness, thus increase the amount and velocity of stormwater runoff. The replacement of tree and soil covers with roofs and pavements significantly lowers water infiltration and abstraction. This increase in the total surface area of impervious cover leads to higher surface runoff volume and velocity (Paul and Meyer, 2001; Yao et al., 2016). The generated runoff has higher scouring forces and releases pollutants that accumulate during the dry season.

The increased release of pollutants into the environment spawn problems in waterbody ecology, which may be disastrous to aquatic populations. Suspended sediments increase turbidity and can bury subaqueous plant species which provide food to benthic organisms and fish (Castro and Reckendorf, 1995; Chapman et al., 2014). They also limit plants access to sunlight and therefore their ability to conduct photosynthesis. Reduced levels of dissolved oxygen cause biological effects on aquatic organisms. Physiological and behavioral effects on fishes from sublethal effects, reduced hatching to migration and mortality have been observed (Kjelland et al., 2015). Nutrients - primary nitrogen and phosphorus loads - proportionally increase with suspended sediment load (Moran et al., 2005). Excessive nutrients are known to cause eutrophication which depletes dissolved oxygen and increases toxicity from algal blooms. This can be detrimental to fish population in the receiving waters and to humans that depend on the fishes for food (Callisto et al., 2014).

In order to reduce pollutants like sediments, leaf matter and trash to Hillsborough River and Tampa Bay, the City of Tampa and FDOT installed 47 baffle boxes in their stormwater pipe networks since 2003. The majority are installed at stormwater outfalls but several of them are also deployed within the pipe network. The boxes made from precast concrete and plastic materials are divided by baffles to create sediment settling chambers. In urbanized areas of Florida, baffle boxes are a commonly used best management practice (BMP) to improve water quality of stormwater with high sediment loads (FDOT, 2016). They can be retrofitted into existing stormwater pipe networks which is an advantage to more expensive new large-scale BMP structures that need large land area (US EPA, 2001). However, stormwater ponds are by far the most common type of BMP in the Tampa Bay region.

The deployment of the baffle box units presented a set of challenges in operating and maintaining them to achieve sediment removal performance. This challenge can be attributed to different factors that affect sediment fluxes and the units' maintenance and operation (O&M). As it has been suggested by previous research elsewhere, those include rainfall and catchment characteristics, O&M procedures and the overall size and configuration of the units (Liu et al., 2015, 2013). Therefore, this research studied these factors in comparison to other stormwater treatment structures and provided recommendations to improve the baffle boxes performance.

A number of the aforementioned weather and catchment characteristics including rainfall duration and intensity, LULC, and population income/education statistics for the City of Tampa are available to the public. This data can be linked and spatially correlated to sediment accumulation measurements conducted within the units. Evidently, by studying the above-mentioned factors that may affect the performance of baffle boxes, the City of Tampa could improve the quality of its receiving waters and save vast resources in the O&M of these units.

The objective of this research is to improve functionality and performance of underground stormwater treatment units. The primary factors considered for evaluating the treatment unit performance were rainfall intensity, catchment characteristics and maintenance practices. These factors are tested based on quantitative and spatial data collected on 39 baffle boxes and two hydrodynamic separators installed by City of Tampa. The quantitative data include more than ten years of rainfall intensity and sediment measurement reports, which was used to calculate sediment trapping and resuspension rates and their corresponding rainfall intensities. The data also include maintenance schedule, staff hours and total maintenance expenses incurred throughout the unit's implementation. Spatial data of impervious area, tree canopy cover and grass cover was retrieved for the unit's catchments. Based on these factors the research study gives recommendations maintenance schedules and predictions mechanisms to improve performance. Additionally, the results indicate practices and improvements that should be followed to improve the performance of underground stormwater treatment units.

CHAPTER 2: BACKGROUND AND LITERATURE REVIEW

In the United States, the USEPA (United States Environmental Protection Agency) regulates municipalities and states to protect their receiving waters by reducing the amount of runoff and pollutants produced in cities (US Congress, 2007). USEPA gives permits known as MS4's to small municipals with separate stormwater systems to reduce their pollutant runoffs to maximum extent possible (USEPA, 2016). These permits have led to the inception of different programs known as stormwater BMPs, which are structural retrofits and non-structural programs that are implemented to reduce flooding and pollutant runoff into natural water bodies. BMPs operation principles imitate nature's processes to control flooding and improve water quality (FDOT, 2015). For example, the hydrology of retention and detention ponds is based on natural lake or wetland systems (Hogan and Walbridge, 2007). Both BMPs temporarily detain peak discharges to prevent flooding of urban areas.

In urban settings the choice of BMP implemented to mitigate pollutant loads highly depends on the affordability of premium land areas (Weiss et al., 2007). This limitation forces cities to look for small footprint treatment designs that occupy less space and are cheaper to construct. BMP structures are thus selected by comparing their affordability and performance to mitigate floods and pollutants. Their affordability is measured by their total construction, land and annual maintenance costs. Their performance is assessed through comparisons to the water quality standard regulations set to protect the receiving water bodies.

Early BMPs used to focus only on preventing floods and damages to property. Eventually, pollutant reduction initiatives by impacted communities led to the development of BMPs that address the negative impacts of uncontrolled urban stormwater runoff on receiving water's bank stability, quality and aquatic organisms (Watershed Management Plan, 2005). In the United States alone, urban stormwater runoff was responsible for 38,114 miles of impaired rivers and streams and 2742 square miles of impaired bays and estuaries (Greenway, 2008). Nowadays, a variety of structural BMPs or sustainable drainage systems is commonly employed to mitigate the negative effects of urban development and presence of humans (FDOT, 2015).

Stormwater runoff is characterized by highly varying flow rates and water quality. Thus, BMPs need to be robust enough to handle the varying flows and pollutant loads. BMPs can use physical (infiltration), chemical (adsorption) and biological (decomposition) processes to remove and degrade contaminants from stormwater (Scholes et al., 2005). For example a legacy study on wet detention ponds in Florida found that sediment loads were reduced by 94% and total phosphorus by 91% in Brevard county and Orlando respectively (Harper, 1995). Depending on their proper design and annual maintenance schedules, BMPs can effectively mitigate floods and remove pollutants.

Baffle boxes are structural BMPs designed to reduce sediment loads from stormwater. Their size is typically 10-15 feet long, 4 feet wide and 6- 8 feet high (US EPA, 2001). They have settling chambers that are separated by raised baffles to block particle movement and slow down concentrated flows from pipe networks (Figure 2-1). The horizontal flow reduction causes suspended particles with higher density than water to settle down in the chambers. Baffle boxes are suitable for retrofit into existing pipe networks in precast form and can be installed in-line or near outfalls (US EPA, 2001). Their primary function is to remove sediments and suspended particles, but they can also be mounted with trash screens or skimmers to capture plastics, leaves and oils in their chambers (Figure 2-2). Baffle boxes are installed below ground which makes them cheaper to install in urban areas where premium land can be scarce and expensive.

Overall, the main challenge of this treatment technology is the requirement of frequent clean-up maintenance. The performance of baffle boxes significantly reduces as they fill up and trapped sediments resuspend during subsequent storms. In states with humid climates like Florida, the recommended clean up and maintenance frequency is annually eight times which can be costly to stormwater utilities (US EPA, 2001).

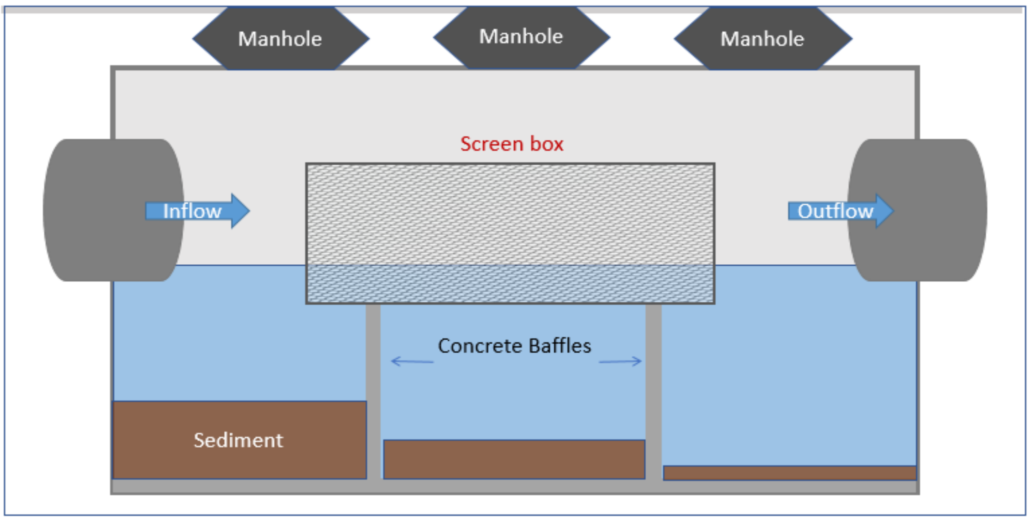


Figure 2-1: Schematic of a typical baffle box

Figure 2-2: Baffle box retrofitted with screens
(From www.suntree.com)

Besides clean-up frequency, rainfall and catchment characteristics are other factors that mainly affect pollutant-trapping efficiencies of most BMP structures. These factors are used in different models for the analysis of stormwater treatment designs. Specifically, this includes variables such as precipitation intensity, duration, flow velocity, LULC, and land formation (slope) (Liu et al., 2015, 2013). Population demographics such as density and income can also affect both sediment and trash generated to baffle boxes (Keep America Beautiful, Inc., 2009). All these parameters drive sediment and trash generation from small watersheds that make their way to the baffle boxes. Therefore, they are directly linked to sediment accumulation in the baffle box units.

2.1. Hydrological Impacts on Sediment Loading

Urban runoff generates when rainfall reaches the land and starts moving as sheet flow along the surface. The volume of stormwater runoff produced depends significantly on the quantity, intensity and duration of rainfall. The generated runoff accumulates kinetic energy to erode the surface and move soil particles and pollutants along the catchment (Shaver et al., 2007). Also pollutants in the atmosphere can be captured by rainfall and transported by surface runoff (Murphy et al., 2015). The wash off and transport of pollutants by surface runoff depends on land cover type and associated urbanization. Thus, an understanding of the engineering principles and models that relate rainfall to runoff and solids pollutant wash off is important.

One of the basic methods used to calculate runoff discharge is the rational method:

$$Q = C \times i \times A \qquad \text{Equation (1)}$$

where Q = Flood peak, C = runoff coefficient, i = storm rainfall intensity, and A = catchment area. The method assumes that surface runoff is directly proportional to a constant rainfall intensity during the time of concentration. It also assumes that the maximum runoff occurs when the duration of rainfall equals the time of concentration. The time of concentration is the time a runoff takes to equilibrate its volumetric discharge at an outfall (Parak and Pegram, 2007). This method has several limitations because it does not consider parameters like non-linear rainfall intensity, abstraction, evaporation, infiltration, impervious and pervious fractions (Akan and Houghtalen, 2003).

To overcome the rational method's oversimplification, several models relate the rainfall-runoff relationship using different empirical formulas. For example, EPA's Stormwater Management Model (SWMM) uses the runoff curve number method in its discharge routing calculations (Rossman, 2015). The curve number method is commonly used because it uses effective rainfall to calculate stormwater discharge (Hernandez et al., 2003). The curve number also gives an empirical runoff-catchment relationship by considering soil type characteristics and impervious fraction. This method was developed by the US Soil Conservation Service in 1986 (Akan and Houghtalen, 2003). Runoff or rainfall excess *R* is calculated through:

$$R = \frac{(P - Ia)^2}{(P - Ia) + S} \qquad \text{Equation (2)}$$

where: $S = (1000 - 10\,CN)/CN$; P = precipitation, Ia = initial abstraction, S = soil moisture storage deficit at the time of runoff, CN = curve number, $P - Ia$ = Effective rainfall (Hernandez et al., 2003).

Solid pollutant wash-off in impervious areas is governed by the average runoff and duration of the rainfall event. Therefore, Akan and Houghtalen, (2003) estimate it by:

$$\Delta Pt = P°(\,1 - e^{-kR}\,) \qquad \text{Equation (3)}$$

where: ΔPt= total suspended solids washed off, P^o = initial suspended solids built up, R = total runoff volume, k =wash off coefficient. According to Equation (3) , the total suspended sediments (TSS) washout increases as the total depth of runoff and a wash off coefficient increase; it follows a logistical growth pattern and is limited by the total amount of suspended solids available (here

P^o). As discussed earlier, the total volume of runoff is correlated to rainfall intensity, while the wash off coefficient is also dependent on rainfall intensity, as well as on sediment particle diameter and catchment area (Akan and Houghtalen, 2003). Rainfall intensity consequently plays a major factor in determining the runoff volume and TSS wash off characteristics.

Stormwater quality is highly influenced by the capacity of a rainfall event to remove sediments from the surface. This capacity depends on the rainfall characteristics such as intensity, duration and antecedent dry days strongly; the magnitudes of rainfall intensity and duration lead to varying stormwater quality concentrations in terms of suspended sediments concentrations from watersheds (Liu et al., 2013). High intensity rainfall events coupled with long antecedent dry days can produce high pollutant event mean concentrations (EMC) in a phenomenon known as first flush. Long rainfall durations however tend to dilute the EMC and first flush during this period (Gnecco et al., 2005).

In the case of low intensity rainfall only a fraction of the pollutant is removed and the rest is accumulated in the environment; runoff with high kinetic energy is produced by rainfall intensity values greater than 5mm/h and can lift and remove pollutants during washout periods (Egodawatta et al., 2007). During a rainfall event, intensity is considered the most important parameter in the overall pollutant wash off compared to antecedent dry days. This is because pollutant build up will equilibrate after long-lasting frequent rain events, for example during rainy season (Liu et al., 2012).

The state of the art knowledge on sediment transport in urban watersheds retrieved from the literature indicates the need to focus on rainfall intensity as a primary driver. It also specifies that rainfall types of high intensity and low duration will produce comparatively higher EMC concentrations and high scouring capability (Liu et al., 2013). This research project focuses on factors that affect sediment transport to the stormwater treatment units known as baffle boxes. It recognizes rainfall is one of the main factors that affect baffle box unit performances. The data used to analyze this relationship is City of Tampa's job inspection reports that measured sediment trappings of the units since their placement.

2.2. Catchment Characteristic Impact on Sediment Loading

Continuous housing and infrastructure development in urban areas intended to meet the fast-growing population growth and economic demands creates unique catchment characteristics (Paule-Mercado et al., 2017). Construction activities include compaction, levelling, concreting and asphalt roadworks. The corresponding LULC changes cause a substitution of natural landscapes with human-made surfaces, which increase the percentage of impervious area as well as reduce soil cover and canopy fraction. Consequently, the rate and volume of runoff in urban areas increase because the soil's texture, structure, permeability, thickness, moisture content and canopy abstraction is reduced (Shaver et al., 2007). A high percentage of impervious areas are found in residential, commercial, industrial, and transportation (roads) areas. An important parameter looking at impervious areas is the impervious area connectivity. Connected impervious areas do not have stormwater practices or natural/man made water bodies designed to recharge or reduce discharge (EPA, 2014). Impervious surfaces that are interrupted by permeable surfaces distribute their runoff to soils and vegetation can reduce surface runoff (Shaver et al., 2007).

In urban areas, watersheds that contribute to stormwater runoff do not simply follow the land gradient. This is because of land modifications and conversions that are implemented during certain infrastructure developments such as roadworks follow certain drainage paths (Lambin et al., 2001). There are few cost and labor intensive fieldwork studies that demarcated surface runoff based on contributing and non-contributing watersheds (e.g., Lyon et al., 2004). The use of a geospatial analysis can provide more accurate watershed delineation that improves sediment transport prediction to the baffle boxes units.

Urban areas produce higher pollutant concentrations in comparison to places of lesser human activities (Stovin et al., 2008; Wilson and Weng, 2010). Previous studies conducted within urban areas have demonstrated that certain types of human activities on land generate particular types and concentration of pollutants (e.g., Gan et al., 2008). In order to determine the impact of LULC modifications and changes on the hydrology of urban watersheds, they can be delineated and their water quality parameters compared to land covers of different uses (residential, commercial, industrial, transportation, and developed/open space).

Different models are used to predict stormwater runoff and routing, yet their water quality parameters predictions are not specific to particular LULC types (Fraga et al., 2016). For example, the above-mentioned EPA-SWMM model uses the pollutant washout equations but does not account for variation in specific pollutants in different impermeable surfaces. The other parameter used to incorporate catchment characteristic into SWMM model is the curve number and wash off coefficient. These empirical parameters consider the impervious fraction, connectivity and suspended solids particle sizes. This research work examines impervious fraction as independent variable that drive suspended sediments transport to the baffle box units.

Tree canopy is also an important feature of catchment characteristics that plays a crucial role in the urban hydrological cycle because they counteract the effects of urbanization in regards to flooding and contamination to receiving waters. Trees intercept rainfall, filter pollutants in their leaves and adsorb pollutants in their root zones (Stovin et al., 2008). The level of interception depends on the type and density of vegetation and the rainfall amount. They reach their maximum interception quickly, thus they are only effective for shallow rainfall events. This makes them important in terms of water quality mitigation rather than runoff control (Akan and Houghtalen, 2003; Stovin et al., 2008); according to the modification of Horton's formula:

$$Li = c \times P_T{}^\wedge m \qquad \text{Equation (4)}$$

where: Li = abstraction, Pt = Total rainfall depth, c and m = are empirical fitting parameters (Akan and Houghtalen, 2003).

Trees can also contribute to nutrient loadings into receiving waters as they shed their leaves seasonally. Excessive export of nutrients such as phosphorus and nitrogen in stormwater is well known to accelerate eutrophication in receiving waters (Callisto et al., 2014). Depending on the type of tree species and seasonality a positive correlation was found between tree canopy and nutrient loads on the streets (Kalinosky et al., 2014). To address this issue, street sweeping (Figure 2-3) and bag filters (Figure 2-4) were found to significantly reduce the amount of leaves entering to stormwater pipe networks (Kalinosky et al., 2014; Stack et al., 2013). However, according to a study conducted by Allison et al. (1998) removing leaf matters from stormwater do little to reduce the total nutrient loads. The study found that the nutrient contribution from leaf litter is two orders of magnitude lower than nutrient loads in water samples in the stormwater. More recently, removal of leaves was found to reduce phosphorous loads by more than 80% and nitrogen loads up to 74 % in two residential catchments in Madison, Wisconsin (Selbig, 2016). From these findings, this research examines the relationship between tree canopy and organic matter capture in the baffle boxes units.

Figure 2-3: Sweeping truck in City of Edina, Minnesota
(from Kalinosky et al. (2014))

Figure 2-4: Bag filters installed in the Tred Avon Watershed Talbot County, MD
(from Stack et al. (2013))

The presence of litter in public spaces is also another stormwater management issue because it can cause flooding by blocking stormwater pipes and manholes. Demographic information such as age, educational level and income that constitute catchment's population can be indicators of trash generation (Keep America Beautiful, Inc., 2009). For instance, a study that investigated hot dog vendors in Philadelphia, St. Louis, and Richmond, found that young people are more likely to litter than elderly people (R.W. Beck, 2007). This study also found that people who live in urban areas and small households produce less litter compared to their counterparts.

Land use characteristics such as parking lots, commercial areas have higher litter production. The increased number and distinct coloring practices of trash bins in those places decreases littering rates (J. G., Huffman et al., 1993; Keep America Beautiful, Inc., 2009). This can help in understanding the disproportional clogging of some baffle boxes due to plastics and trash. Thus, the study of spatial and temporal production of litter from certain parts of urban catchments can provide us with insights into the baffle boxes that require screen retrofits to trap trash.

2.3. Maintenance and Cleanout Frequency

The main purpose for maintaining stormwater treatment units is to enhance the pollutant capturing capacity and control runoff rates (Erickson et al., 2010). US EPA, 2001 suggests monthly clean-ups during the wet season and bimonthly clean-ups in the dry season. This can account for the high seasonal variation in Florida rainfall events. But for several reasons, maintenance is often not frequently practiced. Primarily, the annual cost of adequate maintenance can be substantially deterring to cities and municipalities. According to Weiss et al., 2007, the annual maintenance cost of stormwater treatment structures can reach between 6-10% of their total construction costs. Depending on their drainage area, the average construction cost is around $22,000 and can range between $20,000-$30,000. For example, the installation cost in Brevard County, Florida for a baffle box project serving 134 acres was $33,925 and for another baffle box serving 1.8 acres was $14, 376 (Bateman et al., 1998).

Maintenance complexity, staff hours and number of treatment units are also some of the factors that can affect maintenance and cleanout practices (Erickson et al., 2010). In the city of Tampa, the overall average cleanout schedule for the baffle boxes is less than once per year (*City of Tampa work order report*, 2017). The cleanout involves inspection, truck vacuuming and general maintenance of the units. The annual maintenance cost for each baffle box is estimated at $450 with a vacuum truck cleaning of two baffle boxes a day (US EPA, 2001). However, this value widely fluctuates with the size of the units and complexity of the cleanouts. The maintenance crew reports that particularly the cleanout procedures for units retrofitted with screens is time consuming and difficult. For example, for type-2 units installed in Tampa, vacuuming can take up to eight hours (*City of Tampa work order report*, 2017).

The annual cleanout costs can reach up to $2400 for type-2 units and up to $1228 for type-1 units. Another challenge faced by maintenance crews is the inaccurate sediment accumulation prediction rates. These predictions are dependent on the inspection sediment probing done at earlier periods. This can incur substantial labor and equipment costs when cleanout activities turn up with zero sediments. These instances are caused by resuspension of sediments from the units after inspection is performed. All the above-mentioned challenges coupled with large numbers of baffle boxes can result in lower pollutant capturing performance.

2.4. Design of Baffle Boxes

Baffle boxes use the processes of sedimentation and trapping to collect sediments within their chambers. They are mostly designed to capture first flush runoffs and bypass greater flows (Aldheimer and Bennerstedt, 2003). The settling tank's first compartment (baffle) is used to trap this first flush while the remaining baffles serve to clarify the remaining runoff (Li et al., 2008). Conventional settling tanks use velocity of stormwater and settling particles to design their compartments (Crittenden and Montgomery Watson Harza (Firm), 2012). Thus, sediment treatment units are commonly designed using the estimated particle size distribution of suspended sediments and runoff discharge of the stormwater. The incoming flow velocity of stormwater is calculated from discharge routing equations (eg. curve number method) and geometry of the inlets pipes.

The diameter of suspended sediments in stormwater runoff typically ranges between 2µm and 500µm depending on the catchment characteristics (Selbig and Bannerman, 2011). Considering the flows in the stormwater pipes and particles size distribution, the settling velocity of the particles can be calculated from the buoyant, gravitational and drag forces acting on the particle (Equation (5)). For example, the critical settling velocity for the 500µm particles in laminar flows (Stoke's formula) is below 0.1m/s. Thus, the settling probability of the particles will considerably decrease for the smaller particles.

$$Vs = \frac{\left(g\, d_p^{\,2} \left[\rho_p - \rho_w\right]\right)}{(18\mu)} \qquad \text{Equation (5)}$$

where: *Vs* = settling or terminal velocity, g = gravitational acceleration, ρ_p and ρ_w = are densities of particles and water, d_p = diameter of particles ,μ = dynamic viscosity of water (Crittenden and Montgomery Watson Harza (Firm), 2012).

The volumetric discharge from a catchment can be estimated from the drainage area, catchment characteristics and basin development factors (*FDOT Drainage Design Guide*, 2018). For example, the 50-year peak discharge for baffle box catchments in the City of Tampa is estimated between 2.25 m^3/s to 4m^3/s. Depending on the geometry of the pipes, this can produce horizontal velocities of up to 20m/s. For a baffle box unit with a surface area of 9m^2 (a size commonly installed in Tampa), the overflow rate is around 0.3m/s, which is three times higher than the above mentioned settling velocity of sand particles under laminar flows. This significantly reduces the suspended sediments that need to be removed from the stormwater runoff.

CHAPTER 3: METHODOLOGY

Different types of data were collected to understand the factors that control the sediment trapping efficiency of baffle box units. A site visit was done to each of the 39 units to observe and record their current structural integrity and performances. Complementary to this on-site assessment, the operators that monitor the unit's functionality filled out questionnaires about the units O&M and performance. During these visits water quality measurements were taken to measure and estimate sediment depth, water depth, leaf matter volume, turbidity, conductivity and pH values. Information on the type, size and location of the units was collected as well. A report of these observations that included onsite performances, maintenance and structural issues was produced for the City of Tampa.

Following these visits historical cleanup and inspection records were gathered from the City of Tampa archives from which past sediment trappings, maintenance procedures, schedules and costs were determined. These historical records were compared to rainfall intensity and catchment characteristics data collected from different sources specified below. Those comparisons were analyzed by type of baffle boxes, size and yearly sediment measurements collected. The size and type of the units, their pipes and inlet structures were provided from the City of Tampa website (City of Tampa, 2018). A statistical analysis was conducted on correlations between the unit's structural size, sediment trapping performances, hydrological characteristics, impervious and tree canopy fraction.

3.1. Study Site

City of Tampa is largest municipality located in Hillsborough County bordering Tampa Bay from its south and southwest. Tampa is the third most populous city in Florida with 377,165 inhabitants in 2017. In the Tampa Bay region the highest population densities are associated with the cities of Tampa and St. Petersburg which is around 1800 people per square kilometer (Xian et al., 2007). The total impervious area for Tampa was around 31% while the total tree canopy and vegetation cover was around 64% in 2011. By planning district, USF institution ranks second with 37% tree canopy following New Tampa district with 45% (Landry et al., 2018). The average annual precipitation for the city is estimated around 46.31in ("U.S. Climate Data," 2018)

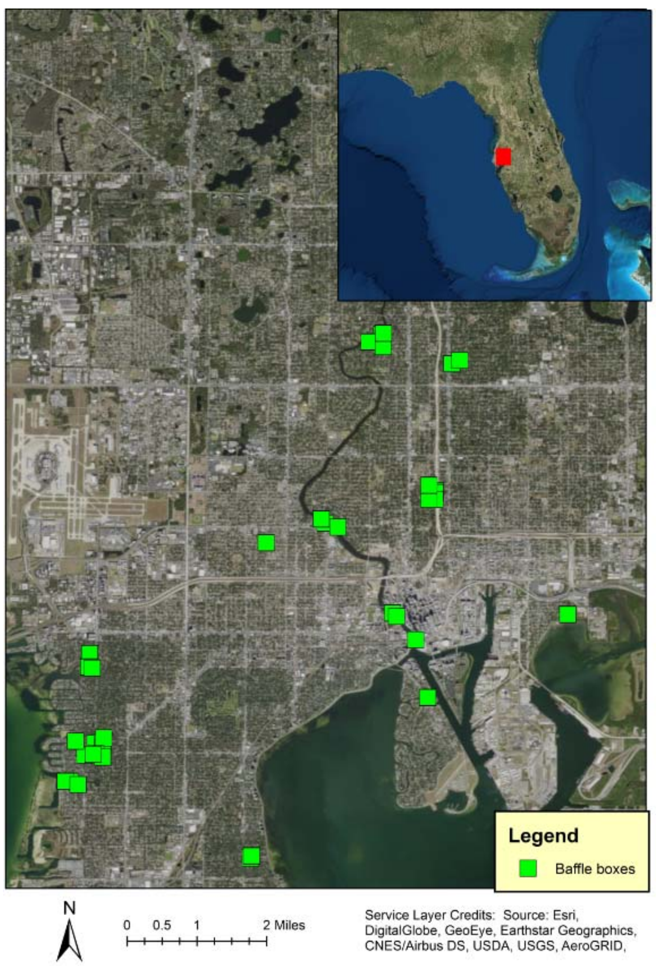


Figure 3-1: Overall map of the City of Tampa and baffle box locations

The study was conducted on 41 baffle boxes distributed in the north, central and south region of the City of Tampa (Figure 3-1). The baffle boxes installed can be divided into three types: type-1, three chambered and type-2 units. The majority 80 % are Type-1 units which do not have screens or baffles incorporated in their design. Around 12 % are type-2 units which are retrofitted with screens to trap leaves and trash. The rest of the units are three chambered units that have two built-in baffle structures.

3.2. Observational and Field Water Quality Data

During the fall of 2017 a four-day site visit was conducted to 41 baffle box units and hydrodynamic separators (HDS). The purpose of the visits was to collect preliminary data on the type of units, location, catchment categories and their current condition. This was done by preparing questionnaires to City of Tampa personnel that accompanied us during our visits. The personnel usually inspects these units by measuring the depth of sediments trapped in the units. Truck vacuum cleanout are then performed based on the sediment measurements. From the questionnaires, data was collected regarding the types of items that are usually trapped by the units. Information regarding the crew's maintenance routines that included baffle box performances and cleanout schedules was also collected.

Additionally, personnel experiences and water level measurements regarding the unit's flooding conditions were collected. The units are usually located on the outfalls to Hillsborough River, Tampa Bay and different parks thus backflows and flooding are frequently observed. The data collected as well as a preliminary evaluation study of the current conditions of the units can be found in Arias and Tsegay (2017). These observational and questionnaire data were used to understand the issues related to maintenance schedules, water backflows and material type collected in the units.

During the visits water quality measurements inside the baffle boxes were collected. Using YSI ProDSS water quality probe, different parameters were measured on-site. These included pH, specific conductance, dissolved oxygen, turbidity and total suspended solids (TDS). Additionally, measurements of settled sediments and organic matter were taken inside the units using a device known as sludge-judge that is used to measure settleable solids in wastewater (Figure 3-2). For this case, these measurements served to assess the functionality of the baffle box units based on their TSS pollutant reduction.

Figure 3-2: Sludge-judge in operation

3.3. Sediment Inspection and Maintenance Data

Yearly clean up and inspection reports (2005-2017) for sediment and trash capture were gathered from the City of Tampa. The data in the reports present sediment probing conducted prior to vacuum cleanout's and their dates. The data also displays the number of personnel and equipment deployed for probing, cleanout and maintenance activities. The measurements taken during these probing were usually used to plan vacuum cleanout trucks. These probing measurements were considered an accurate and reliable source for this research, as the expensive and time-consuming truck vacuuming cleanout orders depend on these reports. The reports were gathered starting from the installation of baffle boxes. This is a significant data collection for operational activities because it spans twelve years for some of the units. The data were used to calculate sediment trapping and resuspension rates of the baffle boxes by comparing sediment measurements and cleanout periods. The calculations were made by considering the differences of sediment measurements of individual probing.

A difference that resulted in a negative value is considered a resuspension and a positive value represents trapping (Equation (6)). The significance of these values was validated by comparing them to rainfall intensity measurements during this period. This was done by calculating the sum of rainfall intensities that occurred between corresponding measurements. The results of the calculations were then used to confirm the observations that were reported in the evaluation study (Arias and Tsegay, 2017). From these results, bar graphs were prepared for all the baffle boxes that represent sediment trapping and resuspension events (see APPENDIX B). Vacuum cleanout periods were excluded from the analysis to avoid exaggerating resuspension events.

$$\Delta\, SED\ depth = Sed_{initial} - Sed_{final} \qquad \text{Equation (6)}$$

$$\text{if} \ldots\ldots \begin{Bmatrix} \Delta SEDdepth \text{ is negative,} & \text{resuspension has occurred} \\ \Delta SEDdepth \text{ is positive,} & \text{trapping has occured} \end{Bmatrix}$$

where: ΔSED_{depth} = change in sediment (in), $Sed_{initial}$ = Sediment probing at initial date (in), and Sed_{final} = Sediment probing in the following date (in).

For example, resuspension occurring in the baffle boxes was calculated and linked to the corresponding rainfall. These calculations were performed for all the units and tabulated in the format showed for 100 S. Ashley Drive (Table 3.1).

Table 3.1: Sediment resuspension and trapping calculations for baffle box on S. Ashley Dr.

Date	**Probing (in)**	**# of rainy days Trap**	**Sediment inc.(in)**	**Sum rainfall (in)**	**# rainy days Resusp.**	**Resuspension (in)**	**Total rainfall (in)**
4/15/2010	1						
6/17/2010	22	19	21	4.69			
7/15/2010	30	18	8	10.25			
8/4/2010	10				13	-20	3.12
8/4/2010	0				1		0.03
9/23/2010	12	32	12	10.79			
10/26/2010	16	5	4	0.41			
11/22/2010	20	5	4	1.63			
12/23/2010	19				5	-1	0.65
1/26/2011	21	11	2	5.84			
2/23/2011	20				7	-1	2.21
8/25/2011	8				71	-12	33.62
2/28/2012	12	16	4	2.69			
5/1/2012	14	10	2	3.06			
7/24/2012	22	40	8	24.05			
10/24/2012	26	53	4	21.64			
1/8/2013	24				16	-2	2.71
1/30/2013	0				2		0.04
4/16/2013	16	16	16	4.56			
7/17/2013	15				60	-1	27.99
10/29/2013	8				71	-7	23.78
12/12/2013	0				10		1.78
1/15/2014	12	11	12	2.03			
7/23/2014	24	49	12	18.84			
10/22/2014	5				60	-19	18.75
12/23/2014	12	11	7	5.69			
1/27/2015	20	6	8	2.52			
4/16/2015	15				20	-5	8.53
10/5/2015	4				123	-11	55.64
10/13/2016	0				155	-4	61.74

Furthermore, the overall performance in sediment capture of all the units was calculated from the reports by averaging and normalizing the yearly sediment probing measurements by their maximum design performance. The maximum design performance of the units was collected from the manufacturer's information provided by City of Tampa (Table 3.2).

Table 3.2: Maximum design performances of baffle boxes by manufacturer

Sediment Control Structure Locations	**Facility ID**	**Max. Sed.**	**Sediment Control Structure Locations**	**Facility ID**	**Max. Sed.**
5001 South Shore Crest Drive	538702	10"	4807 West Sunset Blvd	538690	15"
4805 South Bayside Drive	538703	12"	4807 West Sunset Blvd	538704	15"
4900 West Neptune Way	538701	8"	97 Columbia Drive -	538717	6"
6404 North Otis Ave.	538693	12"	2505 North Habana	538716	24"
231 West Jean Street (S/E)	538695	15"	2826 Corrine Street	3062601	N/A
231 West Jean Street (N/E)	538696	15"	2519 North Riverside Drive	2861783	24"
223 West Fern Street	538694	15"	4601 Riverhills Drive	2811693	30"
229 West North Street	538691	10"	930 East Idlewild Ave.	2861789	30"
229 West North Street(N/E)	538692	10"	3202 North Rome Ave	1347610	24"
329 West Lambright Street (S)	538700	15"	3102 North Rome Ave	1347609	24"
329 West Lambright Street (N)	538697	8"	1208 East Park Circle	3062600	30"
East Clifton Street	538698	10"	100 South Ashley Drive (S/E)	2865620	40"
5015 West Spring Lake Drive	2870856	8"	4637 West Browning Ave	2863242	24"
5005 West Spring Lake Drive	2870853	12"	4634 West Sunset Blvd	2863303	24"
4901 West Spring Lake Drive	2870860	12"	4704 West San Jose Street	2863312	24"
4619 West Bay to Bay Ave	2870852	15"	3023 West Asbury Place	3062298	267 ft^3
2600 North Dundee Street	2870802	8"	2921 West Alline Ave	3062297	111 ft^3
2638 North Dundee Street	3065604	8"	East Emily Street	3090146	179 ft^3
2625 North Dundee Street	2870790	12"	East Adalee Street	3090142	450 ft^3

The calculation of these results determined the quartile, half and full sediment capture performances depending on the type of baffle boxes. The quartile - half - full sediment capture refers to the number of times a unit could capture 25%, 50%, and 100% of its maximum design features, respectively. These percentiles calculate the number of times a baffle box trapped sediments that are comparable to the design capacity forwarded by the manufacturers. For instance, the maximum sediment depth capacity for the facility located in 100 S. Ashley drive was 40 in, thus, its 25^{th} quartile performance should be 10 in and for the 50^{th} it is 20 in.

3.4. Rainfall and Catchment Characteristics Data

The rainfall intensity for the City of Tampa was retrieved from PRISM Climate Group (PRISM, 2018). It uses the Parameter-elevation Relationships on Independent Slopes Model (PRISM), which incorporates 13,000 surface stations across United States to analyze precipitation data (Daly et al., 2008). The rainfall data retrieved was geographically partitioned to represent the location of the units with respect to their regions. This allows to achieve greater accuracy by capturing rainfall event that best represent a unit. Sediment trapping and resuspension results that were calculated from the yearly maintenance reports were then compared to this rainfall data. This was done to identify the different rainfall characteristics such as the average, median, sum of rainfall intensities and number of rainy days that contribute to sediment capture.

Sediment data for the years 2009 and 2010 were chosen to be compared for rainfall and catchment characteristics data as those years provided the highest number of sediment measurements and cleanout schedules. These results were then statistically analyzed using Pearson's correlation and regression analysis. They were used to predict different rainfall intensity characteristics that drive sediment accumulation and resuspension. The results from the analysis gave the relationship between performance of the units and rainfall intensity. Understanding the effects of rainfall intensity on the different types and sizes of the units will help in implementing efficient maintenance schedules and replacement/retrofit options.

Regarding catchment characteristics, impervious and tree canopy fraction contributing to runoff to the baffle boxes were analyzed. Florida's specific terrain with very low elevation differences makes it generally challenging to use available watershed delineation tools. Furthermore, the available 3x3m digital elevation model (DEM) resolution (NRCS, FSA, RD, 2018) was not high enough to accurately delineate these small drainage areas using geospatial analysis tools (Figure 3-4). Thus, a combination of the stormwater pipe networks and their corresponding inlets were finally used to manually delineate the drainage areas (Figure 3-3). For some baffle boxes located near each other it is possible to have the same drainage areas and thus are assigned a single drainage area (Figure 3-4).

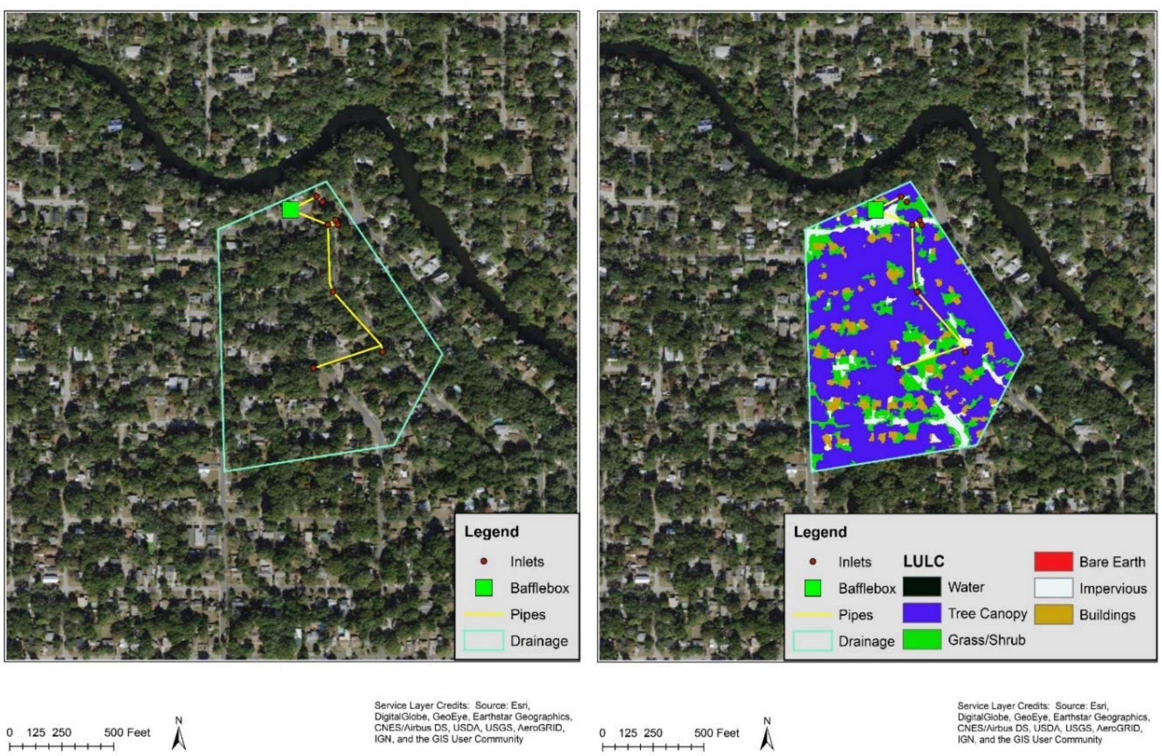


Figure 3-3: Water drainage delineation (left) and catchment characteristics (right)

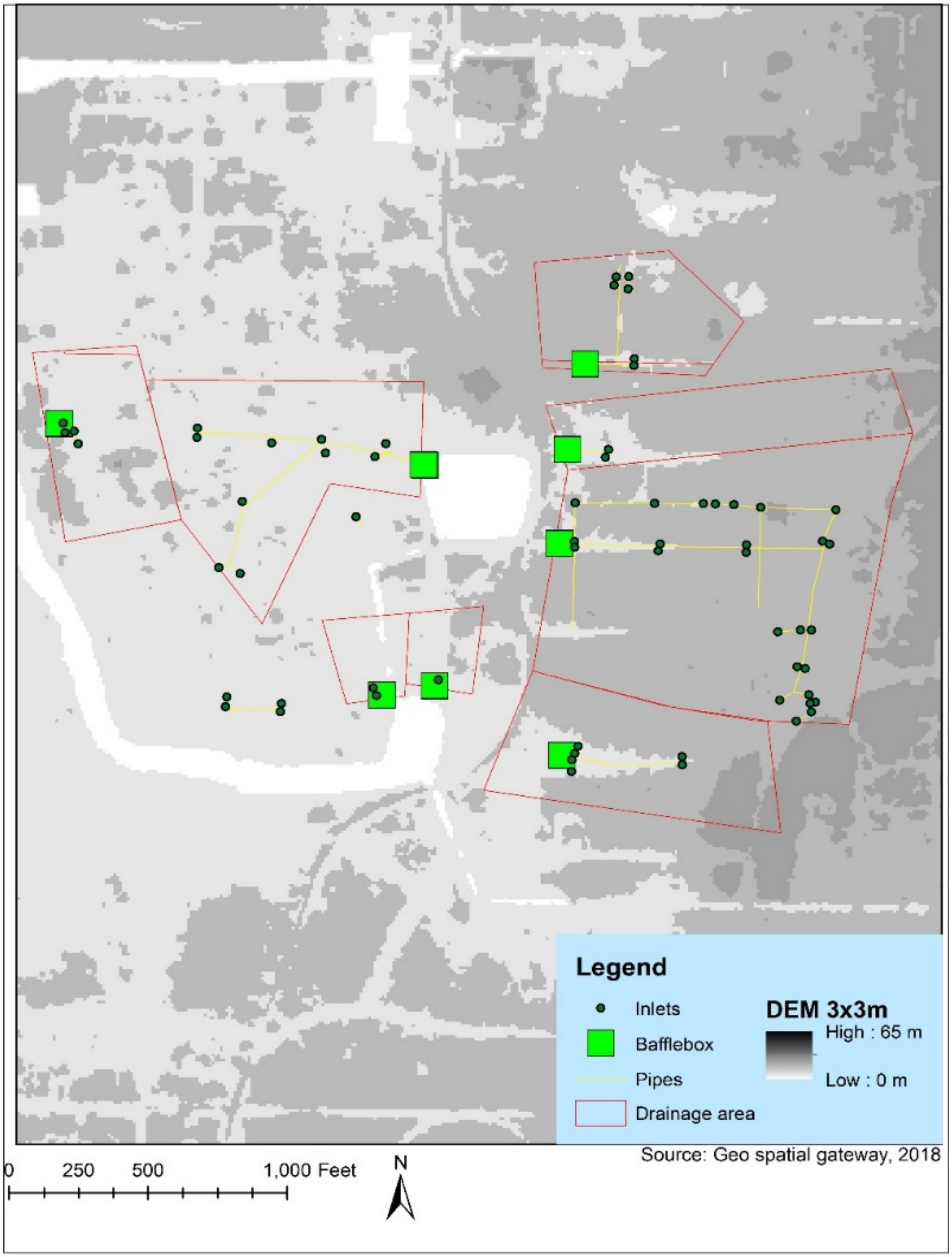
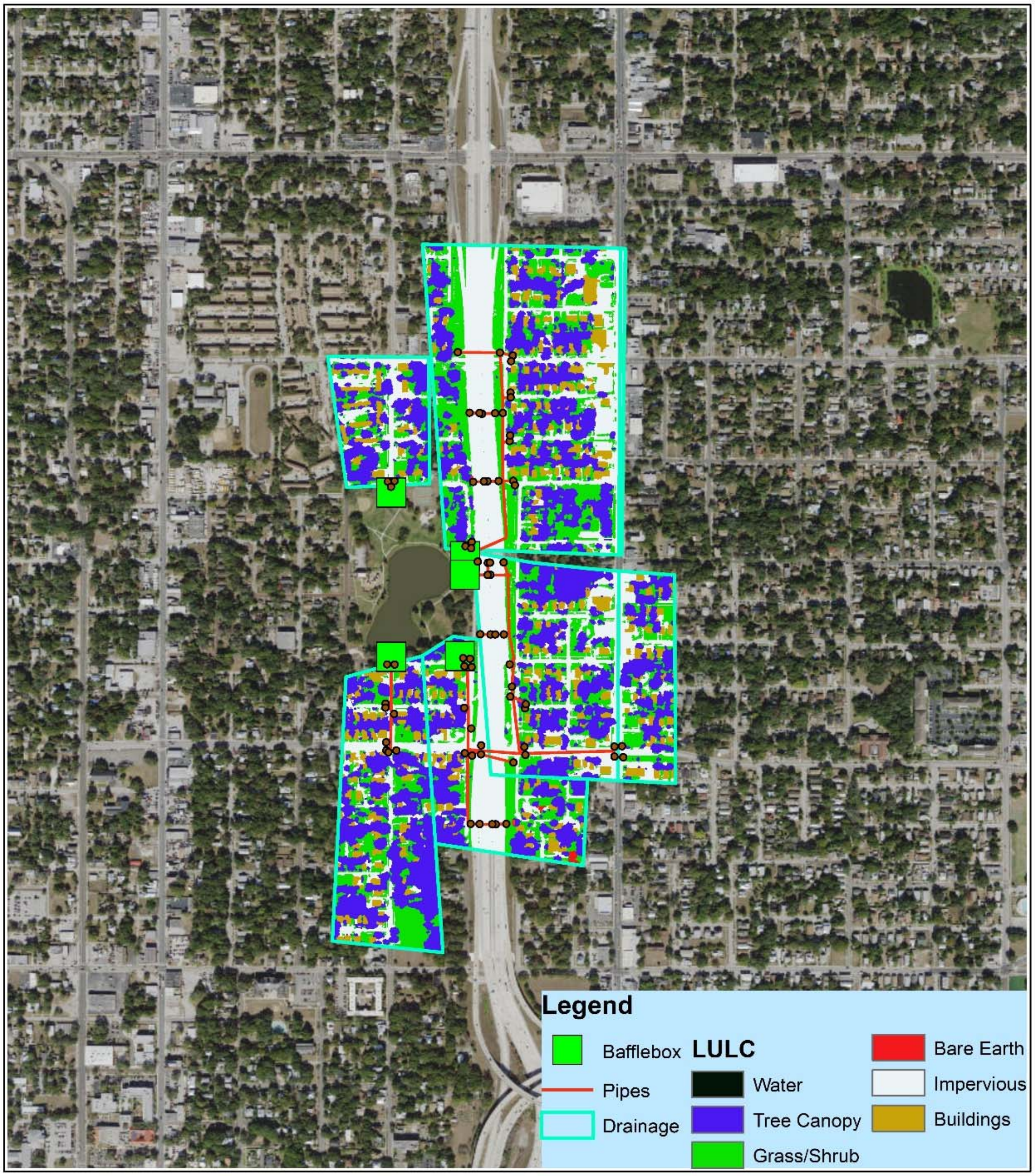


Figure 3-4: Subset of the digital elevation model (DEM) of the City of Tampa Horizontal grid resolution of 3x3m.DEM (Source: Geo Spatial gateway, 2018)

When the estimated catchment areas were delineated for the units, a single shape file was prepared to combine the data. A current geospatial raster file for the City of Tampa that included tree canopy and impervious area was collected (Landry et al., 2018). The corresponding percentages of impervious and tree canopy fraction for the delineated catchments were extracted using GIS's analyst tools. These extracted values were then tabulated and compared against unit performances that were calculated from yearly inspection and maintenance records.

A detailed yearly comparison was performed between rainfall intensity (total and/or maximum amount) as well as catchment characteristics and baffle box sediment capture efficiency (average and/or maximum sediment capture). As noted earlier, the years 2009 and 2010 were selected because they had the highest number of measurements available. Baffle box sizes were also separately considered to avoid normalizing their performances by their maximum capacity design.

Leaf matter data were indirectly collected for the baffle boxes located in the north region of Tampa. In this area the sludge-judge probing revealed null sediment measurements, yet a layer of leaf matter was present. The leave matter that settled inside the units was not sampled as the sludge-judge hole designed for sediment and sludge was not big enough to retrieve them. However, the presence of organic matter was an obvious resistance that influenced probing measurements. Overall, type-1 units were not designed to handle leaf matter volumes. The measurements of the organic matter were compared to tree canopy area from the raster files. This comparison was used to quantify the relationship between the area of tree canopy shedding their leaves and the loadings on the baffle boxes.



0 250 500 1,000 Feet

N

Service Layer Credits: Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure 3-5: Drainage area and catchment characteristics in Robles Park

CHAPTER 4: RESULTS AND DISCUSSION

4.1. Observational and Sediment Measurement Results

University of South Florida Department of Civil and Environmental Engineering in collaboration with Florida Centre for Community Design and Research visited the baffle boxes and evaluated their performance. Based on these observational and questionnaire enquiries a preliminary report of each unit was prepared. The report included water quality and sediment measurements and current condition of the individual units (a sample is presented in Figure 4-2). A geodatabase for the current year of 2017 was created that connected the data from the reports to the GIS files of pipes and outlet infrastructures that feed the baffle box units (Figure 4-1).

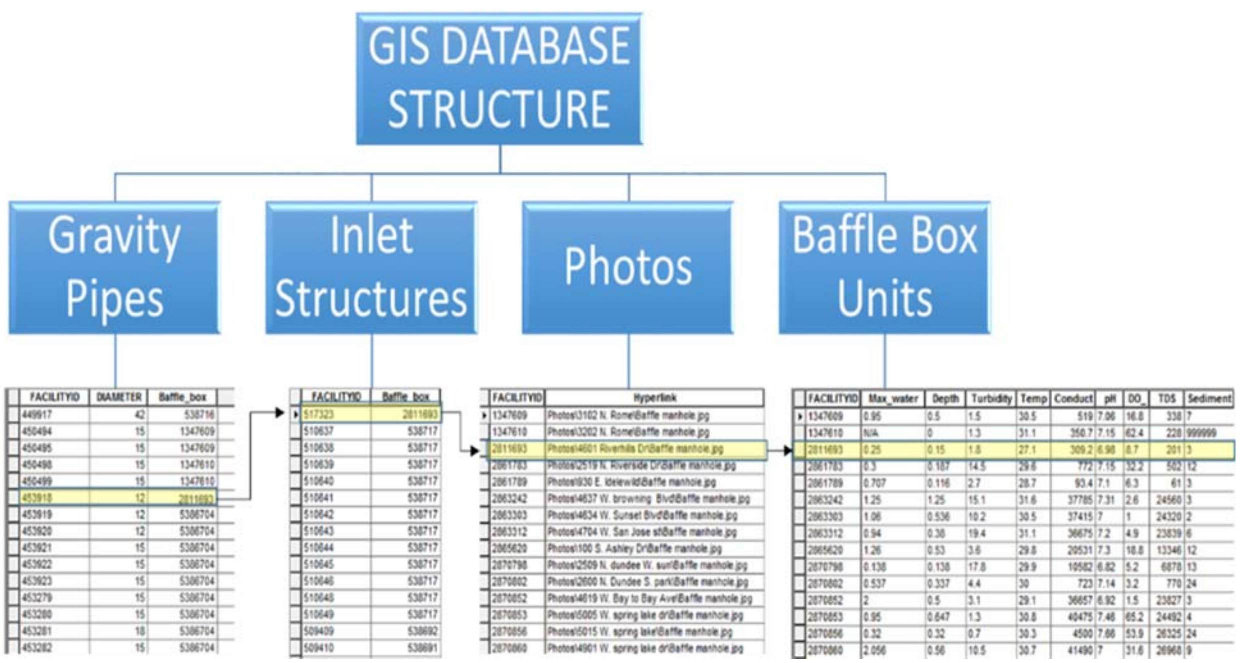
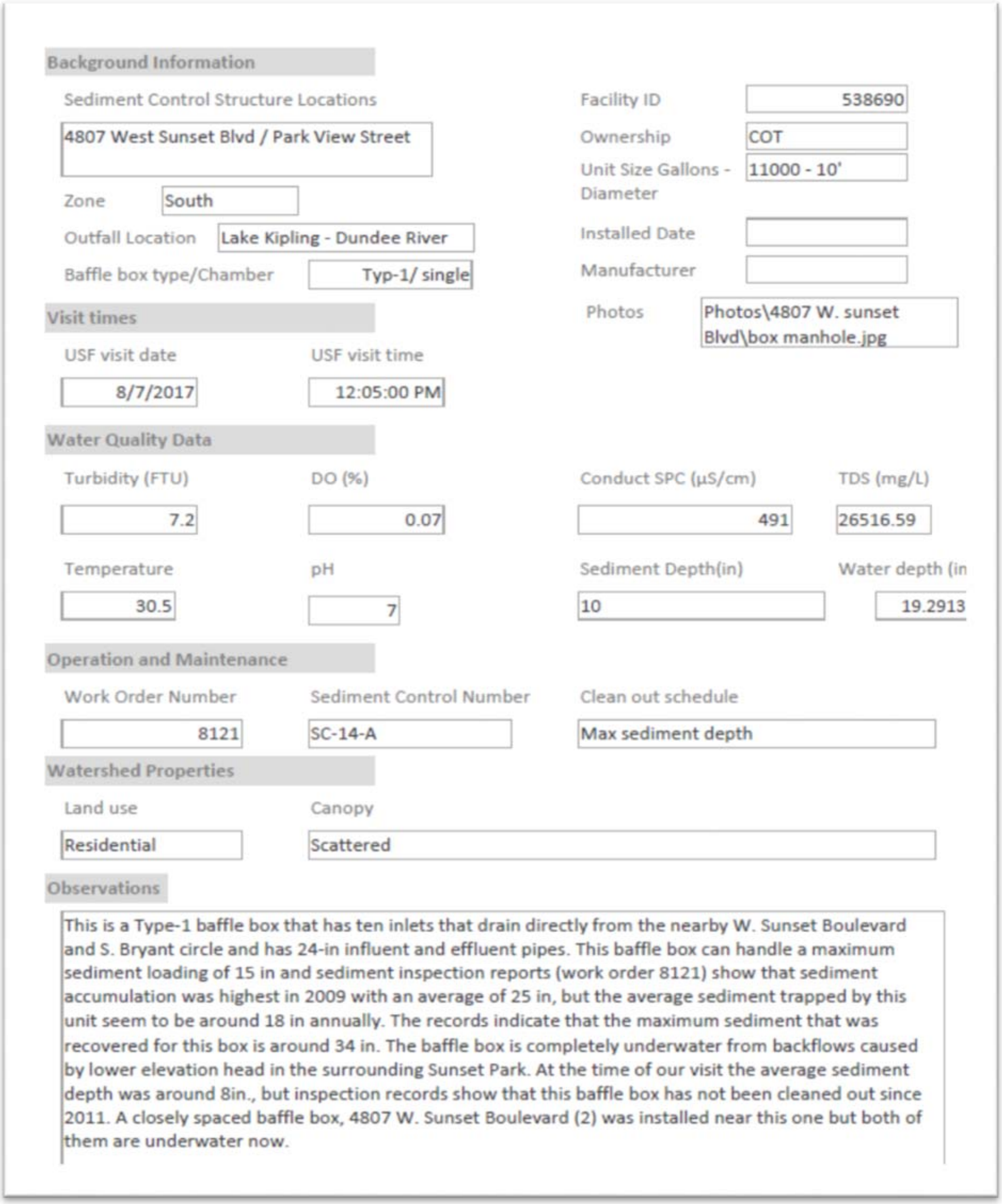


Figure 4-1: Structural geodatabase compiled from visits and City of Tampa



Background Information

Sediment Control Structure Locations: 4807 West Sunset Blvd / Park View Street

Zone: South

Outfall Location: Lake Kipling - Dundee River

Baffle box type/Chamber: Typ-1/ single

Facility ID: 538690

Ownership: COT

Unit Size Gallons - Diameter: 11000 - 10'

Installed Date:

Manufacturer:

Photos: Photos\4807 W. sunset Blvd\box manhole.jpg

Visit times

USF visit date: 8/7/2017

USF visit time: 12:05:00 PM

Water Quality Data

Turbidity (FTU)	DO (%)	Conduct SPC (µS/cm)	TDS (mg/L)
7.2	0.07	491	26516.59

Temperature	pH	Sediment Depth(in)	Water depth (in
30.5	7	10	19.2913

Operation and Maintenance

Work Order Number: 8121

Sediment Control Number: SC-14-A

Clean out schedule: Max sediment depth

Watershed Properties

Land use: Residential

Canopy: Scattered

Observations

This is a Type-1 baffle box that has ten inlets that drain directly from the nearby W. Sunset Boulevard and S. Bryant circle and has 24-in influent and effluent pipes. This baffle box can handle a maximum sediment loading of 15 in and sediment inspection reports (work order 8121) show that sediment accumulation was highest in 2009 with an average of 25 in, but the average sediment trapped by this unit seem to be around 18 in annually. The records indicate that the maximum sediment that was recovered for this box is around 34 in. The baffle box is completely underwater from backflows caused by lower elevation head in the surrounding Sunset Park. At the time of our visit the average sediment depth was around 8in., but inspection records show that this baffle box has not been cleaned out since 2011. A closely spaced baffle box, 4807 W. Sunset Boulevard (2) was installed near this one but both of them are underwater now.

Figure 4-2: Sample report format submitted to the City of Tampa

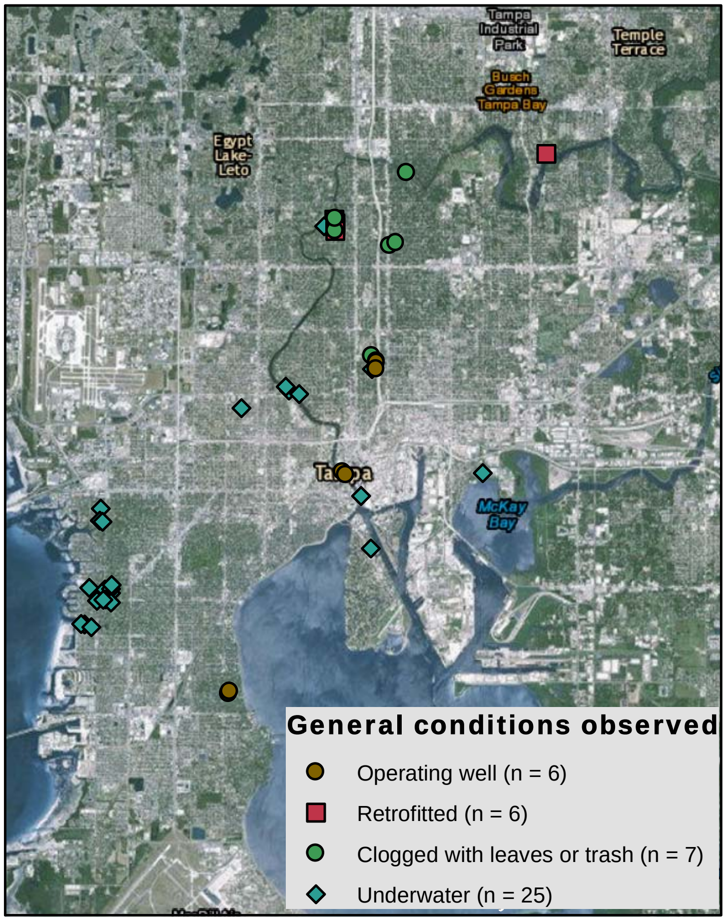


Figure 4-3: General conditions of baffle boxes observed during 2017 visits

From these evaluations it was found that half of the units that are primarily located in South Tampa were underwater from outfall backflows. For the units located in North and Central Tampa, the ones that were mounted with screens seemed to perform better at removing trash (Figure 4-3), while the ones that are large-sized and installed with three chambers were better at trapping sediments. It was also observed that the trapping capability of the units could be reduced due to baffle boxes' small inlet sizes (approximately 1 foot; Figure 4-5) But in units located in North Tampa the sediment measurements showed a lot of organic matter trapped inside the boxes. Prior to this, the maintenance crew recorded sediment depth in these units.

Figure 4-4: Stormwater units experiencing inundation (left) and tidal backflow (right)

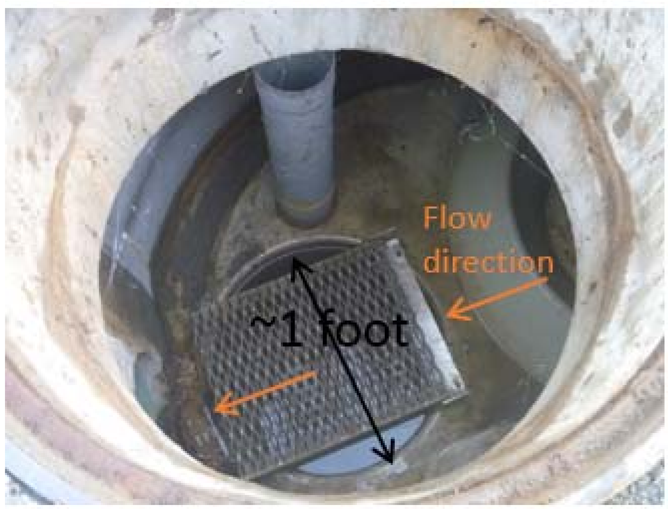


Figure 4-5: Example of a comparably very small inlet to a baffle box

The preliminary observations recorded during this period were helpful in understanding the general functioning, bulk performances and common maintenance issues related of the units. Additionally, most the issues raised during the visits directed the thesis research questions posed in this case study. For instance, maintenance operators consistently reported that trapped sediments are being resuspended during rainfall events. In order to confirm this phenomena, historical sediment depth data were analyzed. To understand the organic leaf matter that accumulated in north Tampa units, an analysis was again performed to see its correlation to tree canopy

4.2. Sediment Trapping and Resuspension

Equation (6) was used to calculate and tabulate the sediment trapping and resuspension values for all the units. These tabulations were then presented in bar graphs to observe visual relationships among baffle box sizes and type, exemplary shown for 100 S. Ashley Drive (Figure 4-6), 4704 San Jose street (Figure 4-7) and West spring lake drive (Figure 4-8). Detailed graphs for all units are presented in APPENDIX B. In these graphs, negative values on the x-axis indicate resuspension and positives values indicate sediment capture. These observations confirm that sediment resuspensions were occurring in all the unit types and sizes.

The resuspension rates occur in 8 % - 35 % of the rainfall events, with largest magnitudes occurring in the smaller units. For example, this can be seen by comparing the resuspension intensities for the 40in and 8in size baffle box bar graphs (Figure 4-6 and Figure 4-8). The small units are categorized from 6 in-8 in maximum sediment capture capacity while the large units are maximum size span from 24 in-40 in.

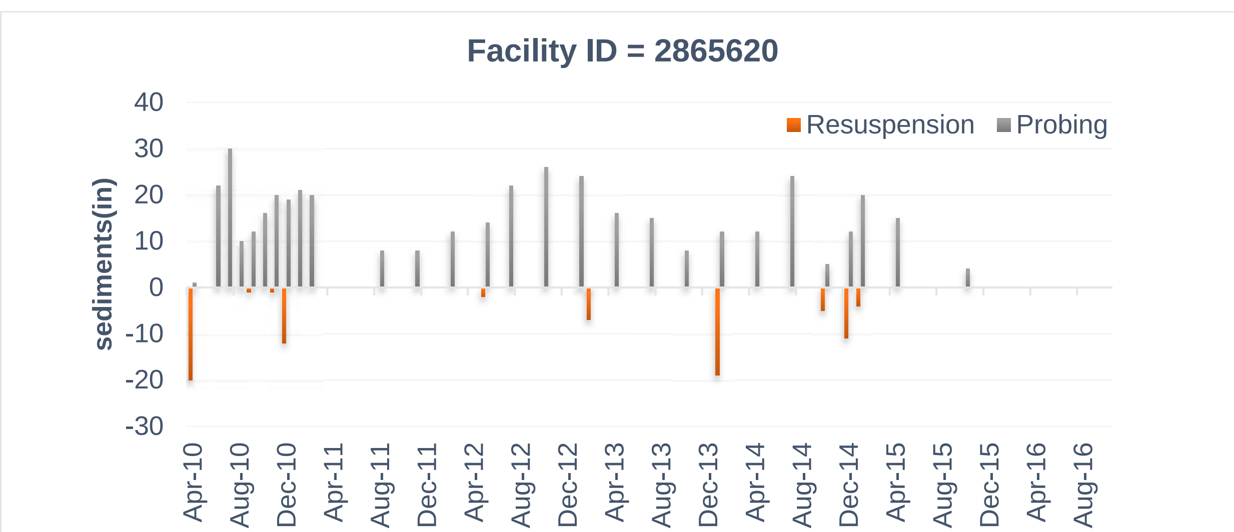


Figure 4-6: Sediment resuspension and trapping on 40in baffle box

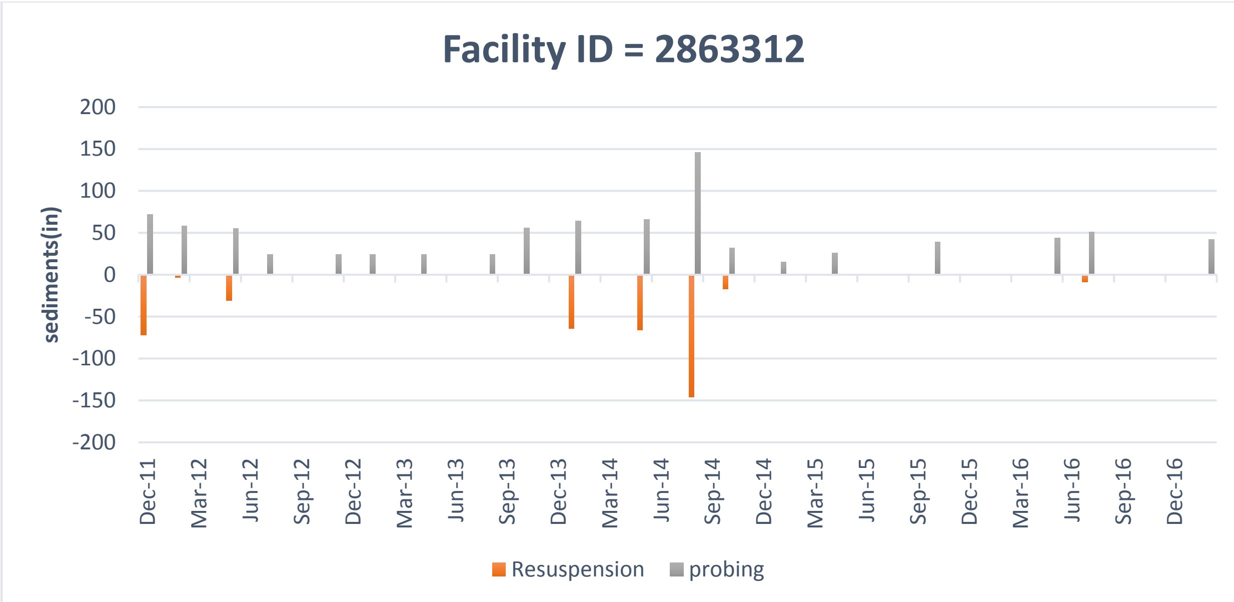


Figure 4-7: Sediment resuspension and trapping on 24in baffle box

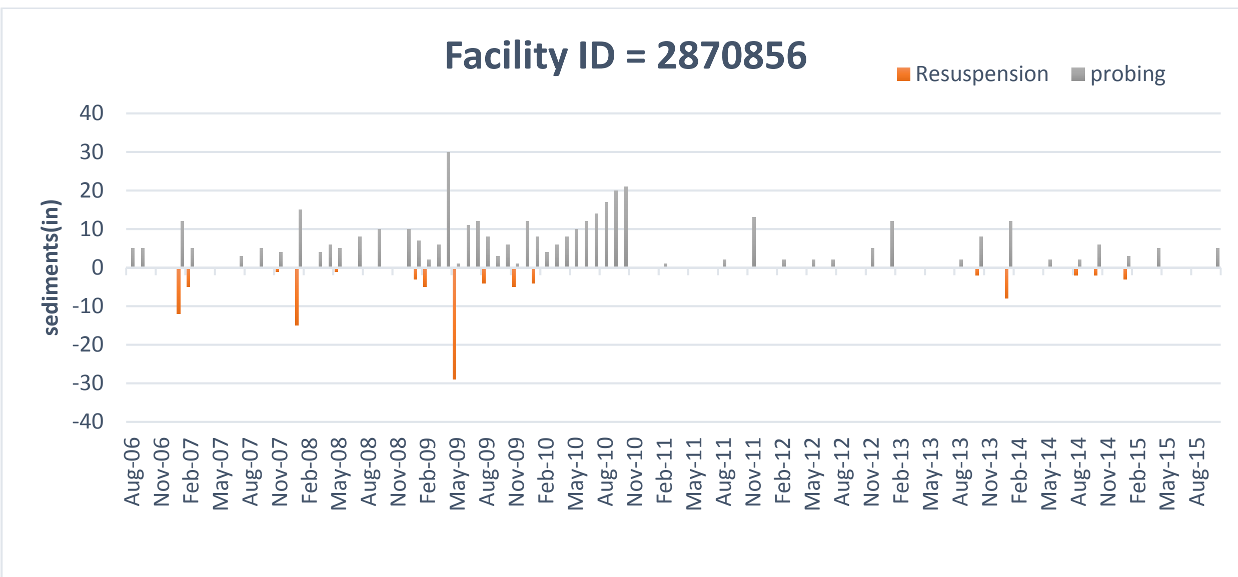


Figure 4-8: Sediment resuspension and trapping on 8in baffle box

Generally, resuspensions occur from surging inflow velocity, dried up permanent pool, and delayed maintenance schedules. This can be identified, when the EMC at the outlet of the treatment structure is greater than its inlet structure. For example, using a similar technique, a study conducted in Florida on hydrodynamic separators (HDS) showed the resuspension of trapped TSS that were not cleaned-out regularly (Arias et al., 2013). Another study in Queensland conducted for wetlands also showed consistent increase of TSS at the outlet of the structures (Greenway, 2008). Baffle boxes are very small compared to constructed wetlands or ponds but they are similarly designed to slow down flows and settle TSS.

The yearly inspection data, however, had limitations because parameters like first flush TSS values, leaves and trash capture efficiency could not be calculated. This is because the data was not collected at equal time intervals and frequency for all the units. Hence, it is difficult to accurately estimate seasonality and first flush events. For example, since measurements were taken randomly, it is not possible to relate a specific period of rainfall to a specific sediment capture. Accordingly, the sum of rainfalls that occurred between the sediment probing intervals were calculated to represent the sediment capture. Except for the few leaf matter measurements done in 2017 visits collected only sediment data.

4.3. Rainfall Effects

In this study, the total, average and median rainfall intensities were used to compare to sediment measurements inside the units. The total of rainfall intensities that occurred between successive sediment measurements showed statistically significant correlations with the sediment data. The analysis found positive correlations between sum of rainfalls and sediment trapping for all baffle box units (Figure 4-9).

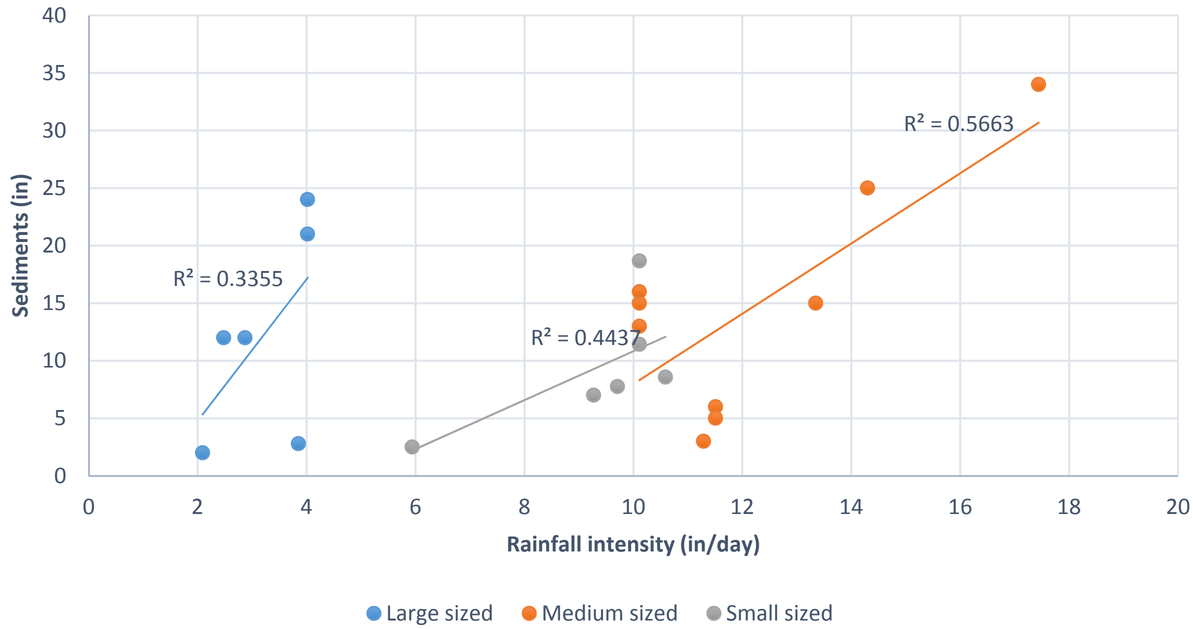


Figure 4-9: Effects of rainfall on sediment accumulation for the year of 2009

The sum of rainfall analysis for the year 2009 showed a maximum regression of 0.556 and p-value of 0.06 for the dependent variable sediment depth. This was the analysis that was performed for the mid-sized baffle boxes that range 10-15in maximum design depth. The overall R-square results for all the unit sizes range from 0.335, 0.443 and 0.566 with corresponding p-values of 0.06, 0.18 and 0.02 (Figure 4-9). In the analysis for the year 2010 similar results were found regarding the regression analysis. The R-square value for all unit sizes was around 0.41, 0.463 and 0.449 their corresponding p-value are 0.09, 0.06 and 0.15 (Figure 4-10).

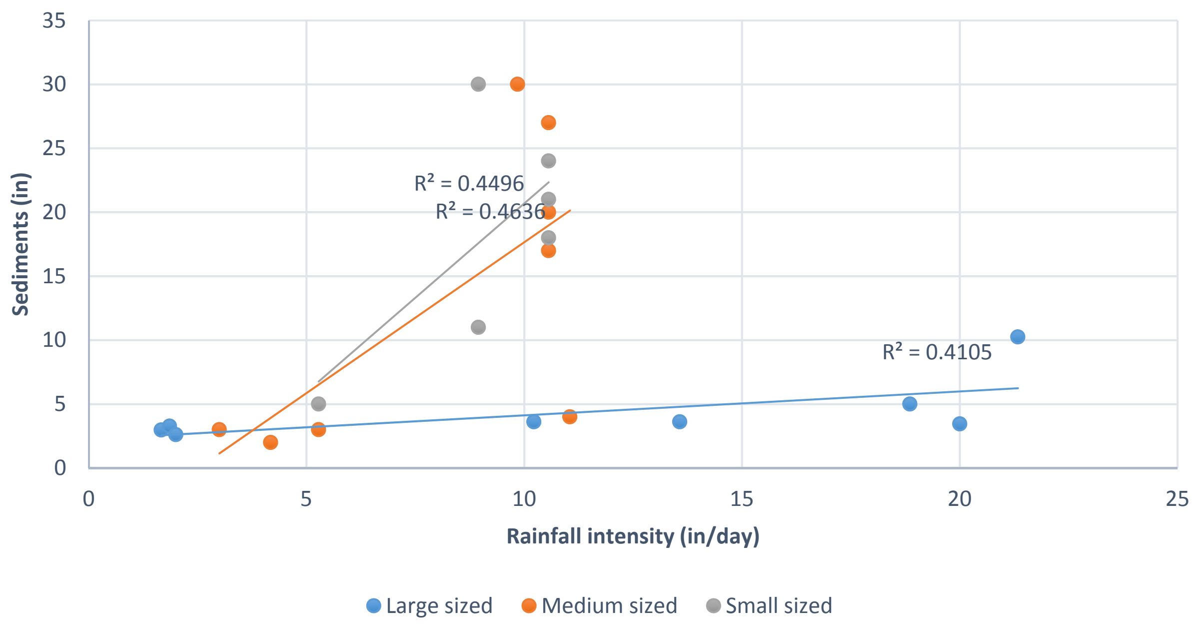


Figure 4-10: Effects of rainfall on sediment accumulation, year 2010

The literature suggests that rainfall intensity and duration are directly related to pollutant wash off to natural river systems. Based on that premise this study related the effects of rainfall to sediment accumulation in baffle box units. The results showed a positive correlation to the sum of rainfall characteristic between measurements. The units employ the same principles of other BMP's such as ponds and wetlands. They are designed to slow down concentrated discharges using their baffles to settle sediments (US EPA, 2001). However, the results could not be correlated to the size and trapping performance of the units. This may be because the units have very low residence times compared to ponds and wetlands because of their comparatively small size. This reduces their sediment capturing capability and complicates their prediction based on size.

Overall, the sum of rainfall intensity has shown to be a good indicator of sediment accumulation in the baffle boxes. Accordingly, the ability to predict the amount of sediments can be enhanced by counting the number of rainy days and summing up their intensity. This method can be used to schedule clean up before the practical performance of the units is exceeded.

Avoiding this exceedance is critical in preventing the resuspension of trapped sediments. This is because the decrease in the overall volume of the units causes concentrated flows from the pipes to scour trapped sediments.

4.4. Catchment Characteristics Effects

The delineation of the catchment areas that contribute to sediment loads was estimated based on the spatial configuration of the pipes and inlets network that feed them, in combination with other supporting layers like DEM and aerial imagery. The fraction of LULC of a 2016 Tampa raster file was extracted in GIS to give the domain that correspond to each of these drainage areas (Table 4.2). The baffle box units are designed to trap sediments but were additionally mounted with screens to capture leaves. Thus, for this study impervious fraction and tree canopy were considered for analysis. Then correlation results were obtained by comparing them with a dependent sediment accumulation variable.

The baffle box locations are categorized in three parts of the city: the north, the center and the south. The highest canopy area was observed on the units located in the north of Tampa with an average of 55.7%. The units located in central region have the highest area of impervious and building fraction with an average of 29.6 and 17.1% respectively.

Table 4.1: Average impervious fraction and tree canopy by region

	Impervious (%)	Buildings (%)	Tree canopy (%)
North Region	10.8	11.5	55.7
Central Region	29.6	17.1	33.4
South Region	13.2	13.7	49.7

Table 4.2: Catchment characteristics results tabulated from GIS

Baffle Box facility ID	% of tree canopy	% of imperv. area	% of buildings		Baffle Box facility ID	% of tree canopy	% of imperv. area	% of buildings
A_1347610	49.2	18.4	13.0		A_3090135	30.9	38.1	9.7
A_1347609	31.2	23.4	14.8		A_3090139	32.3	37.6	8.8
A_2861783	39.7	25.8	13.6		A_538695	56.1	11.6	11.4
A_2870856	40.9	17.4	24.6		A_538696	65.7	3.2	10.7
A_2870853	44.1	16.5	20.1		A_538694	38.3	15.1	18.9
A_2870860	41.3	22.7	16.1		A_538691	64.4	6.3	12.8
A_3065604	77.8	6.7	7.1		A_538692	54.7	8.8	16.6
A_2870802	68.6	8.2	10.9		A_538700	62.4	9.9	9.6
A_2863242	55.8	13.2	13.1		A_538697	65.9	7.2	11.9
A_2863303	64.4	6.4	16.2		A_3062600	56.9	11.4	9.3
A_2863312	53.7	13.9	13.7		A_538702	54.9	12.8	13.3
A_2870798	41.6	21.4	15.4		A_538703	50.6	14.8	14.1
A_538704	47.5	17.0	18.1		A_538701	1.0	1.3	0.2
A_2870852	58.8	12.3	8.3		A_538698	36.5	34.0	11.7
A_538717	33.4	33.1	20.4		A_2861789	41.2	5.1	7.2
A_2865620	6.9	57.2	26.4		A_3062298	52.3	10.1	17.4
A_3065912	4.8	51.9	5.2		A_2811693	71.1	6.4	6.8
A_3065911	1.3	25.9	41.5		A_3090146	40.6	27.7	13.4
A_538716	39.7	19.7	14.5		A_3090131	27.5	37.0	8.9
A_3090142	49.1	16.6	12.4					

4.4.1. Impervious Fraction

Large impervious areas accelerate surface runoffs which cause increased sediments wash-off to water bodies. Baffle boxes are designed to partially mitigate this problem by trapping sediments. Thus, depending on the fraction of impervious area baffle boxes are expected to receive different TSS loadings. To examine this relationship the mean sediment accumulation was compared to impervious fraction of contributing catchment areas. The years 2009 and 2010 were chosen for the analysis because sediment probing was particularly high in those years.

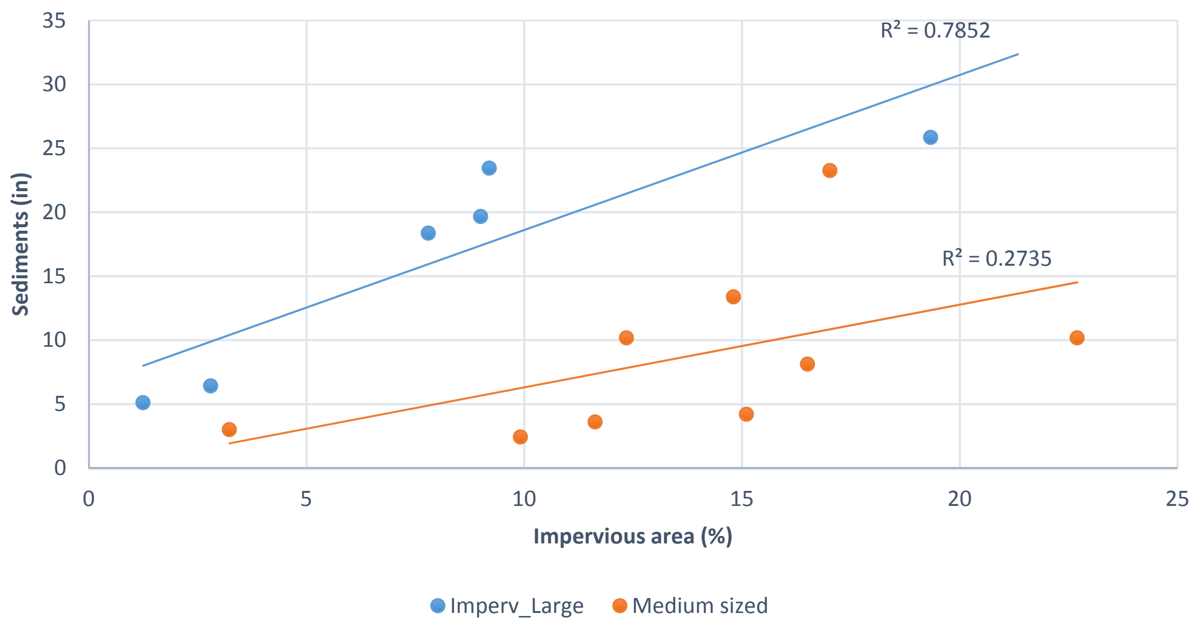


Figure 4-11: Effects of impervious area cover on sediment trapping, year 2009

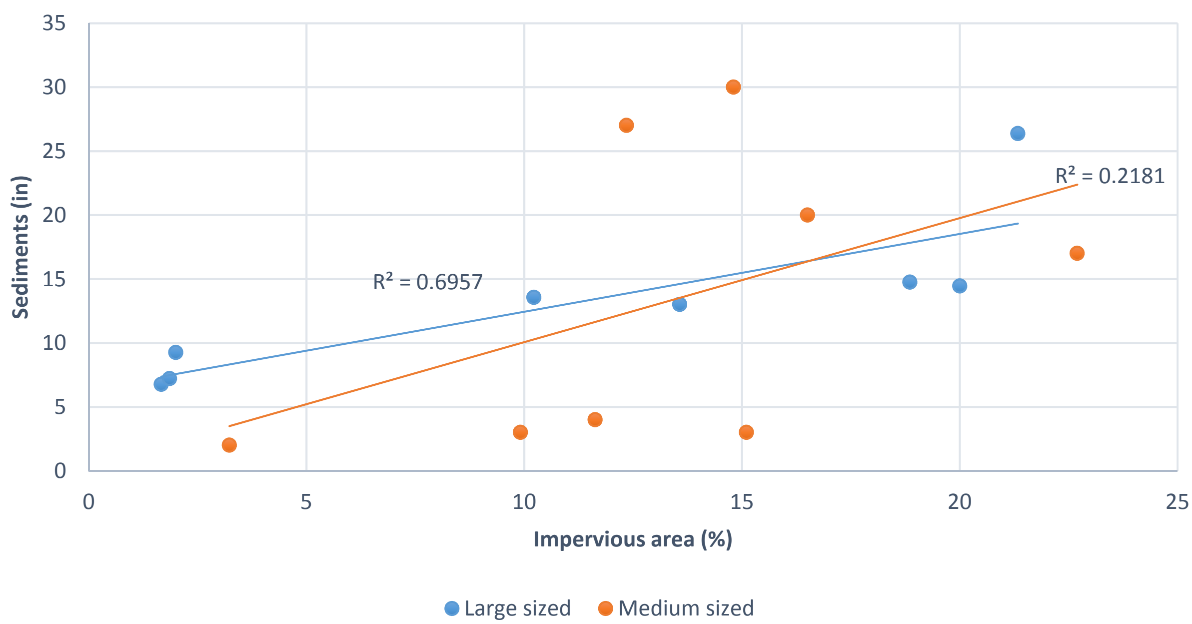


Figure 4-12: Effects of impervious cover on sediment trapping, year 2010

The regression analysis for these two years revealed similar results. For large-sized units the R-square was 0.785 and 0.695 for 2009 and 2010 respectively, with a p-value of 0.01 (Figure

4-11 and Figure 4-12). For the medium-sized units the R-square was around 0.24 and the p-value was around 0.02. The correlation significantly decreased with medium-sized units and there was no significant correlation for the small-sized units. Large impervious areas contribute to higher sediment loadings; thus, the above results indicate that the larger baffle boxes are better at trapping sediments. Thus, to increase the sediment trapping efficiency and at the same time prevent resuspension installing large-sized units sounds like a sensible strategy.

The results are consistent with the literature review that indicate higher impervious areas will generate more pollutants. This is due to the higher velocity of runoff created due to lower infiltration and abstraction. The flows will have higher erosivity to lift sediments and generate more suspended sediments (Egodawatta et al., 2007). Central region of Tampa has the highest impervious area fraction thus baffle boxes located in this region will receive more suspended sediments.

4.4.2. Tree Canopy Fraction

Leaf matter depth was collected for seven baffle boxes located in the north region of Tampa during the 2017 visits. These measurements were then compared to tree canopy fraction of their surroundings. A regression analysis of the measurements with tree canopy area show R-square of 0.55 and p-value of 0.05 (Figure 4-13). There is a large difference in the margin of tree canopy area for the catchments that range between 1.3% and 77.8% (Table 4.2). As, expected, the analysis confirmed that the baffle boxes located under higher canopy areas were receiving large volume of leaves.

The largest tree canopy area for the baffle boxes was comparatively in the northern region of Tampa. The units in this region can be receiving higher leaf matter loadings when the trees are shedding their leaves seasonally. Thus, the units surrounded by large tree canopy covers can be given priority for retrofitting them with screens or filter bags to ensure appropriate sediment trapping.

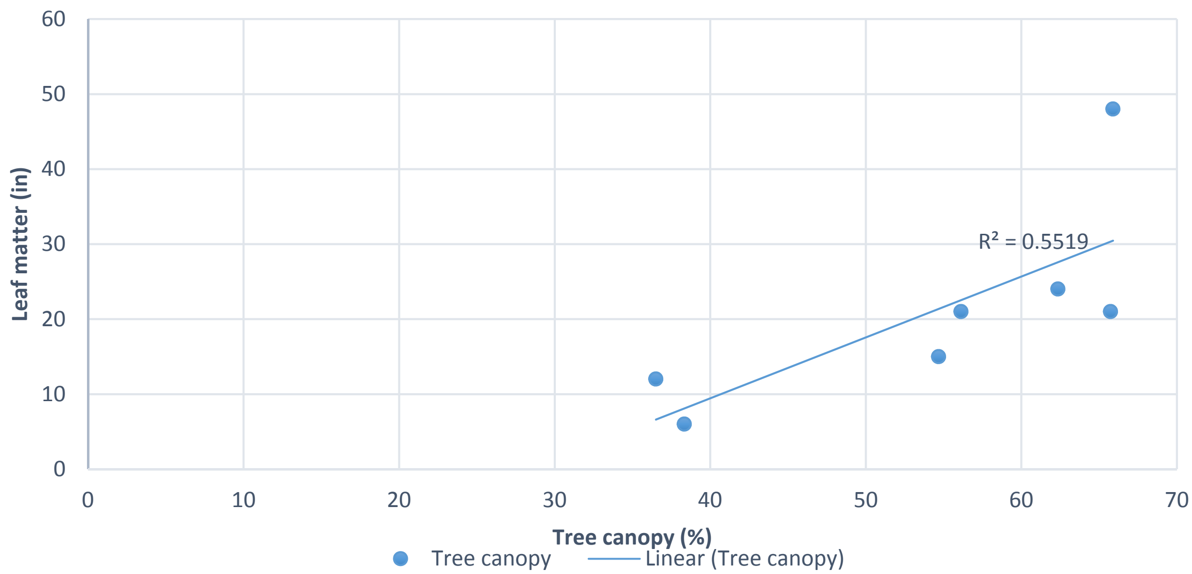


Figure 4-13: Effects of tree canopy on leaf matter generation, 2017.
Tree canopy data from Landry et al. (2018)

4.5. Baffle Box Type Performances

Baffle box performances that exceed the 25%, 50% and 100% of manufacturers' maximum design specification were analyzed (Table 4.3). The 50% performance was chosen for comparing efficiency of the units because the baffle boxes are performing considerably lower than their design claims. Figure 4-15 shows the overall performance of baffle boxes by type. It compares the median, max and min of 50% performances for the three types of baffle boxes. The results indicate that three chambered units are trapping sediments more effectively than type-1 and type-2 units. The three-chambered units capture more sediments with a median performance of 84% (Figure 4-15). This is because the baffles reduce concentrated flow speed and trap sediments.

While type-1 units are built without any baffles and have very small inlet openings (Figure 4-14). The type-2 baffle boxes occupy large portion of their volume with metallic screens that are designed to trap leaves and trash. This can reduce the sediment trapping capacity of the units and cause lower sediment trapping capacity. As noted earlier the units that are installed with screens (type-2) are also difficult and costly to clean up.

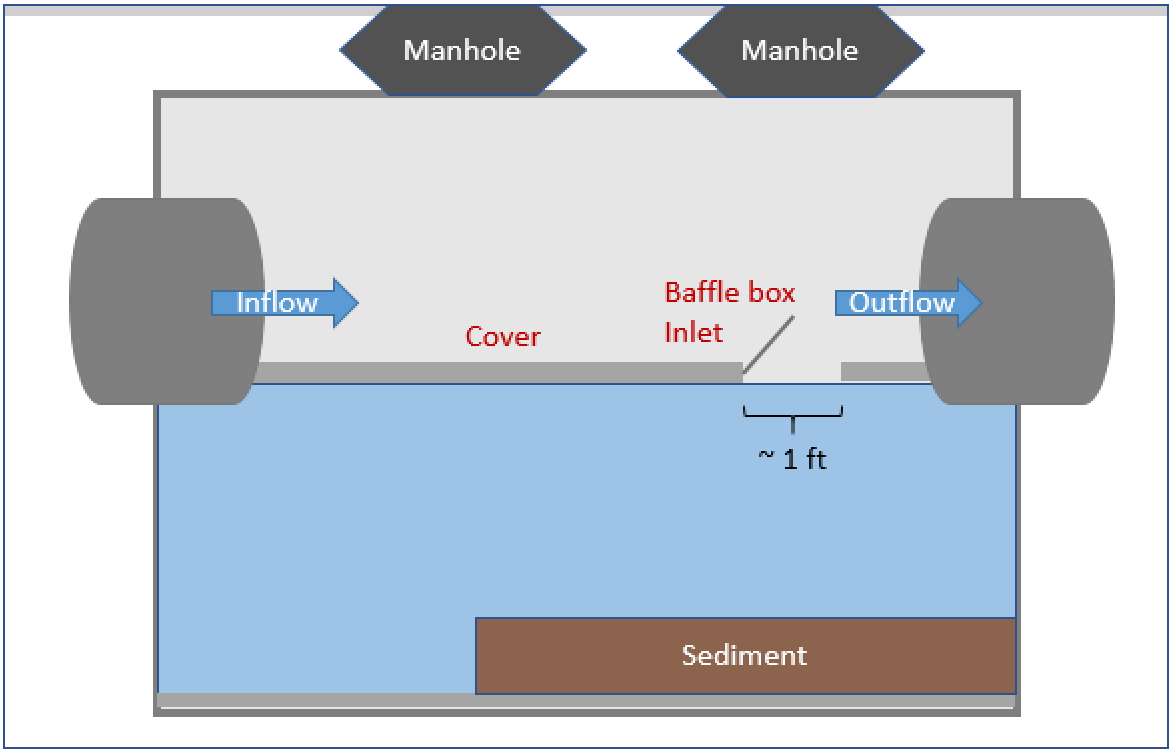


Figure 4-14: Schematics of small baffle box inlet with a cover and small inlet

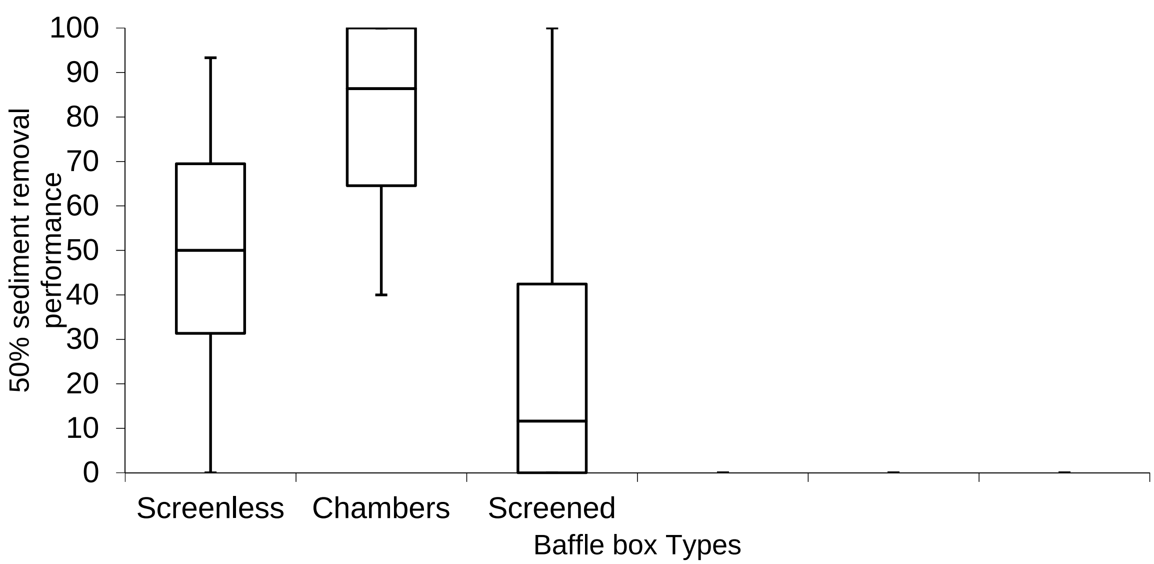


Figure 4-15: 50% Performance for the different types of baffle box units

Table 4.3: Overall performances of the units

Baffle Box ID	Max. Capacity	Unit Type/ chambers	25% performance	50% performance	100% performance
538691	10"	Type-1/single	62.9	37.1	14.3
538692	10"	Type-1/single	46.4	25.0	10.7
538694	15"	Type-1/single	15.0	17.2	0.0
538695	15"	Type-1/single	56.7	40.0	23.3
538696	15"	Type-1/single	55.2	27.6	13.8
538697	8"	Type-1/single	73.3	50.0	13.3
538698	10"	Type-2/single	48.8	23.3	7.0
538700	15"	Type-1/single	51.6	32.3	9.7
538701	8"	Type-1/single	77.5	65.0	32.5
538704	15"	Type-1/single	100.0	93.3	60.0
538716	24"	Type-1/single	56.0	28.0	0.0
538717	6"	Type-1/single	96.0	56.0	24.0
1347609	24"	Type-1/single	75.0	35.0	0.0
1347610	24"	Type-1/single	65.0	45.0	10.0
2811693	30"	Type-1/single	5.3	0.0	0.0
2861783	24"	Type-1/single	73.9	30.4	4.3
2861789	30"	Type-2/single	2.9	0.0	0.0
2863242	24"	Type1/ three	100.0	100.0	88.9
2863303	24"	Type1/ three	100.0	72.7	54.5
2863312	24"	Type1/ three	100.0	100.0	100.0
2865620	40"	Type2/ three	100.0	40.0	0.0
2870798	8"	Type-1/single	83.8	67.6	2.7
2870802	8"	Type-1/single	93.8	78.1	40.6
2870852	15"	Type-1/single	88.6	71.4	45.7
2870853	12"	Type-1/single	86.0	55.8	25.6
2870856	8"	Type-1/single	84.2	73.7	50.0
2870860	12"	Type-1/single	87.2	53.8	28.2
3062600	30"	Type2/single	0.0	0.0	0.0
3065604	8"	Type-1/single	94.9	79.5	59.0

A study on HDS found that the practical TSS removal efficiency to be 16.7% which was significantly lower than the designer's claim of 80% (Arias et al., 2013). This study was identified as a valid comparison to HDS studied in the above case because they had similar size, design characteristics and cleanout schedules to the baffle boxes in the City of Tampa. The baffle box units showed very low performance of meeting their design capacity (100%) requirements except for the three-chambered units. When present, the concrete baffle structures are setting and trapping sediments as per their design.

The use of baffle structures is known to significantly reduce recirculation zones and kinetic energy with in the chambers (Shahrokhi et al., 2012). Circulation zones and high storm velocities produce high turbulence and cause poor settling and/or resuspension of trapped sediments. The above study found that the positioning of baffles in a depth to length ratio of 0.125, 0.3 and 0.388 would significantly reduce circulation volume and kinetic energy. Additionally, reducing the overflow rate to match the settling velocity will also require increasing the surface area of the units. Thus, installing larger sized units will have higher sediment settling probability compared to the small sized units. However, this decision also needs to consider other tradeoffs such as site accessibility and construction cost compared to other types of treatment practices.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

Preliminary visits conducted by USF to observe the general conditions and operations provided some general understanding about the performance and issues of the baffle boxes. The visits revealed three main aspects that needed attention to improve the performance and functionality of the units. These were resuspension of trapped sediments, cleanout management, and installment of screens to trap leaves and trashes. To address the problems related to these aspects and to develop alternative solutions, different sets of data such as rainfall intensity, impervious and tree canopy fraction, O&M data were analyzed. This research identified three key results that can improve the performance of the baffle boxes.

1. Resuspension of trapped sediments: Results indicate that the total of daily rainfall intensities that sum up to 5 to 10 in between cleanouts can accumulate almost 5-10 in of sediments for the small and medium-sized units. This accumulation is satisfactory because the performance range for the units falls within the unit's 50 % practical operating performance. Thus, by considering the number of rainy days and sum of rainfall intensities inspection measurements can be performed. For example, 6.56in of rainfall was recorded in 27 rainy days to accumulate 6in of sediment in one of the units. Eventually the sum of rainfall intensity can be used as an indicator to predict a robust cleanout schedule for individual rainy days. This will increase the probability of inspection crews detecting sediment accumulations and therefore improve cost efficiency of the clean out effort.

O&M reports indicate that the vacuum trucks occasionally find no sediment when performing their routine cleanouts. The main reason for this is that resuspension of sediments would occur within the period between inspection and clean out. This is a costly practice while pollutants are released into the environment what contradicts the purpose of the baffle boxes. Furthermore, impervious and building area fraction showed a high positive correlation of sediment accumulation for large sized baffle boxes. This indicates that large sized units can capture more sediments from their catchment. Sediment resuspension occurs in small-sized units because their effective height reduces with sediment accumulations.

To reduce the resuspension of trapped sediments this study recommends the following: Regarding cleanout schedules, resuspension is caused due to long time periods between clean out call at inspection and actual cleanout. It can be avoided by primarily following the inspection crew measurements and responding quickly before subsequent rainfall events occur. The inspection measurements conducted closely before scheduling a clean out are necessary for vacuum trucks so that they will encounter sediments accumulation during their visits. Thus, optimizing cleanout schedules can partially prevent TSS resuspensions of existing units and save costs on vacuum trucks. For the installation of new baffle boxes, large-sized units should be preferred, as they can reduce resuspension and enhance sediment accumulations within their catchments.

2. Installation of screens into baffle boxes: To improve the trash and leaves trapping capacity of the baffle boxes, the City of Tampa plans to mount some of the units with screens. The results of this research indicate that tree canopy fraction is directly related to leaves trapped within the unit's and thus, nutrient discharge to water bodies. The units located in the northern region of Tampa have higher tree canopy by comparison.

Additionally, after analyzing O & M reports and observational results, the logistical and monetary expenses for baffle boxes with screens are disproportionately high. This is expected to deter the City of Tampa from cleaning the baffles boxes with metallic screens with the required frequency. The 50% overall sediment capture performance also stands third compared to three chambered units.

These findings lead to the following recommendations. The north region is most affected by leaf matter. Thus, priority should be given to equip baffle boxes located in catchments with high tree canopy fraction. However, in some cases, the provision of screens could be taking a large volume within the units that can decrease sediment trapping performances. As an alternative to screens, bag filters at the outlet pipes can be considered to trap leaves and trashes depending on the tree canopy area and site accessibility. The maintenance time of the bags is approximately 30 min and their design allows to automatically release the leaves if clogging in the units occurs (Stack et al., 2013).

3. Baffle box types: After comparing the three types of baffle boxes the units that are open and have three chambers (baffles) showed higher sediment capture performances. The low performance of the units for 80 % of the units is attributed to the small inlet size and no baffle structure presence. Thus, based on the performance of different baffle box types, it is recommended to install baffles structures and completely open baffle box covers. This would significantly improve the performance of those units. This can be particularly implemented in the large sized units because the results indicate higher probability sediment capture and comparable space.

This research project could not address first flush events and accurately measure the organic matter trapped in the units. This was because the historical sediment measurements were conducted randomly and did not include leaf depths. The findings for overall performance comparisons was similarly done from historical records. To address the data limitations of the present study, additional measurements should be conducted to measure first flush events and organic matter in the future. An alternative method could be the development of a physical model of the three-chambered unit on a laboratory scale to enhance it dimensions and configuration and specifically assess performance for different rain intensities and sediment loads.

The main objectives raised by this research were to compare the performance of the different types of baffle boxes and address their O&M challenges. To accomplish the needed results recorded daily rainfall data and catchment characteristic were compared against site visit measurements and historical data. The research has found that units installed with baffles (three-chambered) meet their design criteria while the others were found lacking in their performance (type 1 and 2). Concerning the units mounted with metallic screens this research recommends exploring other alternatives methods to improve maintenance complexity and cost. The O&M of the units can be enhanced by observing rainfall events to correlate sediment accumulation. This approach needs to be confirmed by onsite measurements to confirm and promptly order vacuum trucks.

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APPENDIX A: OBSERVATIONAL AND WATER QUALITY DATA

Table A.1: Observational field survey data

Facility ID	Land use	Canopy	Baffle conditions
538702	Residential	Scattered/along the roads	Underwater /backflow
538703	Residential	Scattered/along the roads	Underwater/backflow
538701	Residential	Scattered/hanging over the baffle	Underwater /backflow
538693	Recr./ Resid.	Dense/hanging over the baffle	under water/ hardly ever cleaned
538695	Residential	Scattered/along the roadway	retrofitted with inlet screens
538696	Residential	Scattered/along the roadway	lots of leaves/retrofitted with screens
538694	Residential	Scattered/along the roadway	retrofitted with inlet screens
538691	Residential	Scattered/along the roadway	retrofitted with inlet screens
538692	Residential	Scattered/along the roadway	retrofitted with inlet screens
538700	Recreational	Scattered/along the roadway	retrofitted with inlet screens
538697	Recreational	Scattered/along the roadway	full of leaves
538698	Residential	Scattered/hanging over the baffle	full of trash/backflow and blockage
2870856	Residential	Scattered/along the roadway	Underwater
2870853	Residential	Scattered/hanging over the baffle	Underwater
2870860	Residential	Scattered/along the roadway	Underwater
2870852	Residential	Scattered/along the roadway	Underwater
2870802	Residential	Scattered/hanging over the baffle	Underwater /backflow
3065604	Residential	Scattered/hanging over the baffle	Underwater /backflow
2870790	Residential	Scattered/hanging over the baffle	Underwater /backflow
2870798	Residential	Scattered/hanging over the baffle	water below screen
538690	Residential	Scattered	Underwater
538704	Residential	Scattered	Underwater

Table A.1 (Continued)

Facility ID	Land use	Canopy	Baffle conditions
538717	Residential	Scattered/hanging over the baffle	Oil and debris trapping
538716	Residential	Scattered/along the roadway	Side retrofits, different design
3062601	Recreational	Scattered	Underwater year around
2861783	Residential	Scattered/along the roadway	A retrofit of side metallic traps
2811693	Residential	Dense/hanging over the box	A retrofit of side metallic traps
2861789	Residential	Scattered/along the roadway	screen blockage from leaves
1347610	Residential	Scattered/along the roadway	Blocked by metallic object
1347609	Residential	Hanging over Baffle Box	A retrofit of side metallic traps
3062600	Recreational	Dense/hanging over the box	full of sediment/ trashes on screens
2865620	Commercial	Hanging over Baffle Box	Oil and debris trapping
2863242	Residential	Scattered/hanging over the baffle	Underwater
2863303	Residential	Scattered/along the roadway	Underwater
2863312	Residential	Scattered/along the roadway	Underwater
3062298	Residential	Scattered/along the roadway	Empty
3062297	Residential	Scattered/along the roadway	Empty
3065911	Recreational	Scattered/hanging over the baffle	low tide and shells, oil present
3065912	Recreational	Scattered	low tide, inaccessible, full of oil
3090146	Recr./ Resid.	Scattered/along the roadway	Dry/ full of trash/screens were open
3090142	Recr./ Resid.	Scattered/along the roadway	Underwater, clogged with trash

Table A.2: Water quality measurements taken using YSI

Facility ID	Water Depth (in)	Turbidity (NTU)	Temp. (C)	Conduct SPC	pH	DO (%)	Sediment Depth(in)	Organic matter(in)
538702	7.4	8.3	31.4	40261.0	7.4	0.8	14	
538703	16.0	10.5	31.1	40426.0	7.3	0.8	26	
538701	6.3	3.4	31.4	204.7	7.0	0.5	6	
538693	9.8	1.4	27.7	640.0	726.0	4.0	1	
538695	17.3	3.2	28.0	109.1	7.0	0.7	3	21
538696	17.3	5.6	28.6	319.1	6.7	0.6	3	21
538694	17.8	1.6	28.3	205.0	7.2	1.3	1	6
538691	22.0	2.8	28.0	59.5	6.8	0.4	4	
538692	20.6	1.7	28.0	76.4	6.6	0.4	2	15
538700	8.1	19.6	27.8	383.3	6.5	0.7	3	24
538697	22.2	8.2	27.3	81.1	6.7	0.6	1	48
538698	12.1	44.0	29.3	105.0	7.0	0.4	1	12
2870856	12.6	0.7	30.3	4500.0	7.7	3.5	24	
2870853	25.5	1.3	30.8	40475.0	7.5	4.2	4	
2870860	22.0	10.5	30.7	41490.0	7.0	2.0	9	
2870852	19.7	3.1	29.1	36657.0	6.9	0.1	3	
2870802	13.3	4.4	30.0	723.0	7.1	0.2	0	
3065604	4.6	9.9	31.6	38058.0	7.4	2.4	0	
2870790	6.1	3.7	30.5	33221.0	7.0	0.7	13	
2870798	5.4	17.8	29.9	10582.0	6.8	0.4	13	
538690	19.3	7.2	30.5	491.0	7.0	0.1	10	
538704	19.3	9.5	30.5	3934.0	6.8	0.2	11	
538717	16.2	9.0	29.4	16926.0	7.0	0.7	14	
538716	17.3	2.8	29.7	306.6	7.2	0.3	12	
3062601	19.3	4.9	29.9	26005.0	6.9	0.3	φ	
2861783	7.4	14.5	29.6	772.0	7.2	2.4	12	
2811693	5.9	1.8	27.1	309.2	7.0	0.7	3	
2861789	4.6	2.7	28.7	93.4	7.1	0.5	3	
1347610	0.0	1.3	31.1	350.7	7.2	4.6	NA	

Table A.2: (Continued)

Facility ID	Water Depth (in)	Turbidity (NTU)	Temp. (C)	Conduct SPC	pH	DO (%)	Sediment Depth(in)	Organic matter(in)
1347609	19.7	1.5	30.5	519.0	7.1	1.3	7	
3062600	4.8	3.5	29.2	645.0	7.2	3.8	3	
2865620	20.9	3.6	29.8	20531.0	7.3	1.3	12	
2863242	49.2	15.1	31.6	37785.0	7.3	0.2	3	
2863303	21.1	10.2	30.5	37415.0	7.0	0.1	2	
2863312	0.0	19.4	31.1	36675.0	7.2	0.3	6	
3062298	NA	NA	NA	NA	NA	NA	NA	
3062297	NA	NA	NA	NA	NA	NA	NA	
3065911	17.7	1.7	24.6	14821.0	7.5	4.9	NA	
3065912	NA	NA	NA	NA	NA	NA	NA	
3090146	NA	NA	NA	NA	NA	NA	NA	
3090142	0.0	4.9	31.2	169.3	7.1	0.8	NA	

APPENDIX B: SEDIMENT TRAPPING AND RESUSPENSION GRAPHS

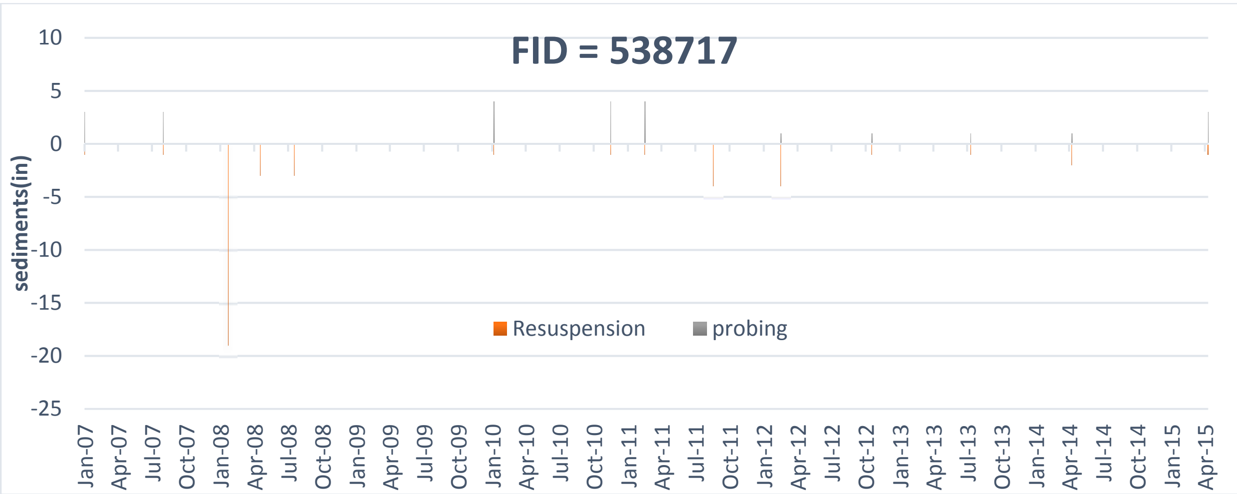

Figure B-1: 97 Columbia drive

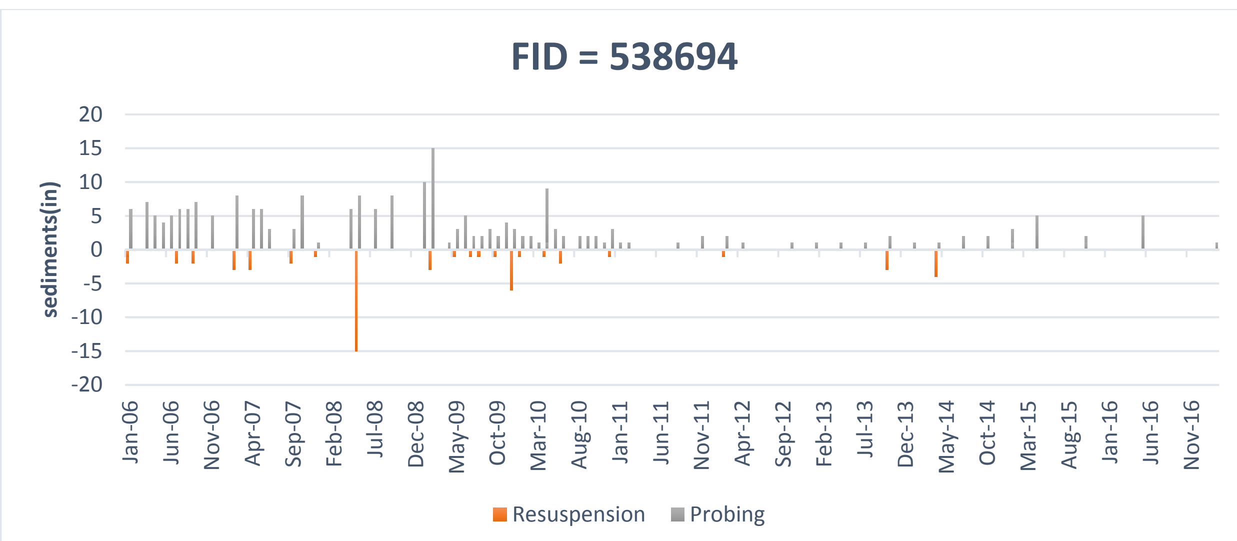

Figure B-2: 223 West Fern Street

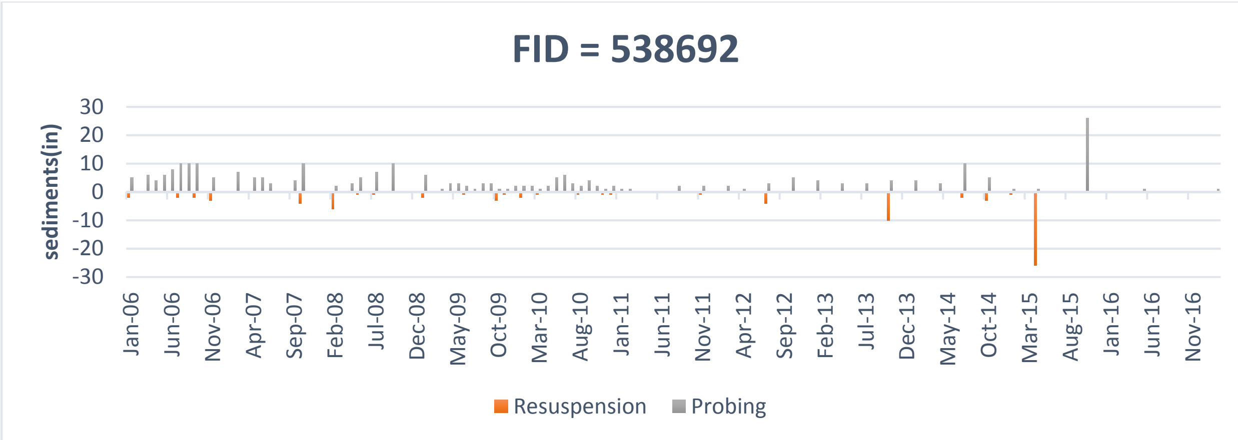

Figure B-3: 229 West North Street (NE Corner)

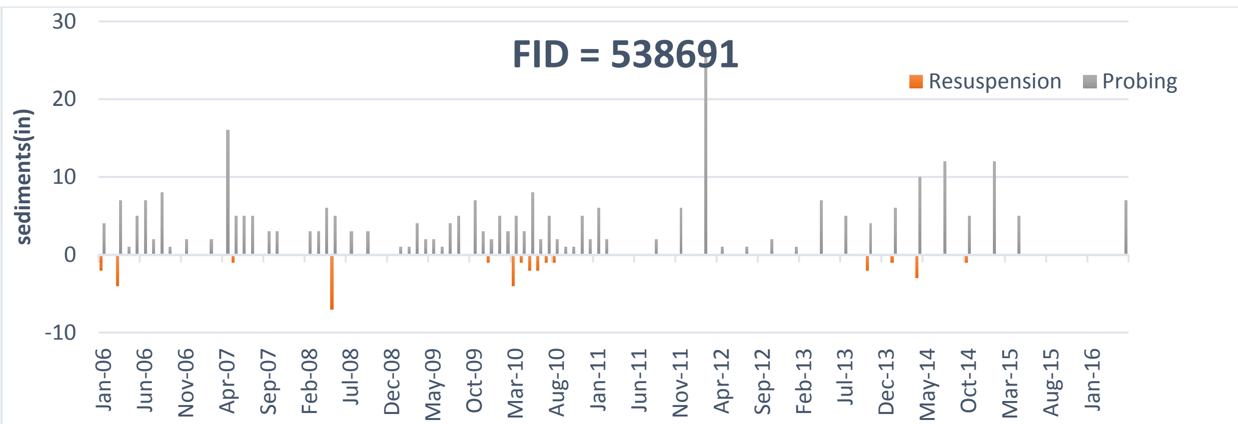

Figure B-4: 229 West North Street (SE Corner)

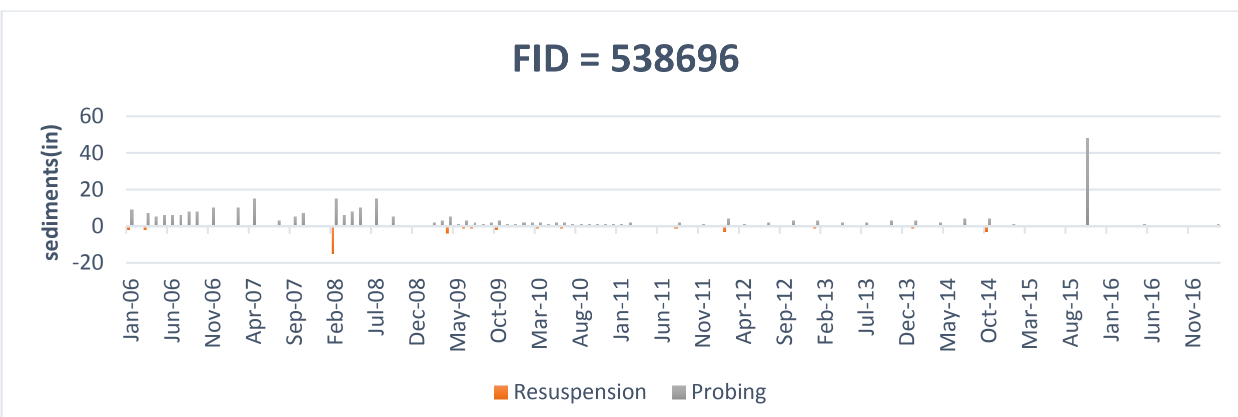

Figure B-5: 231 West Jean Street (NE Corner)

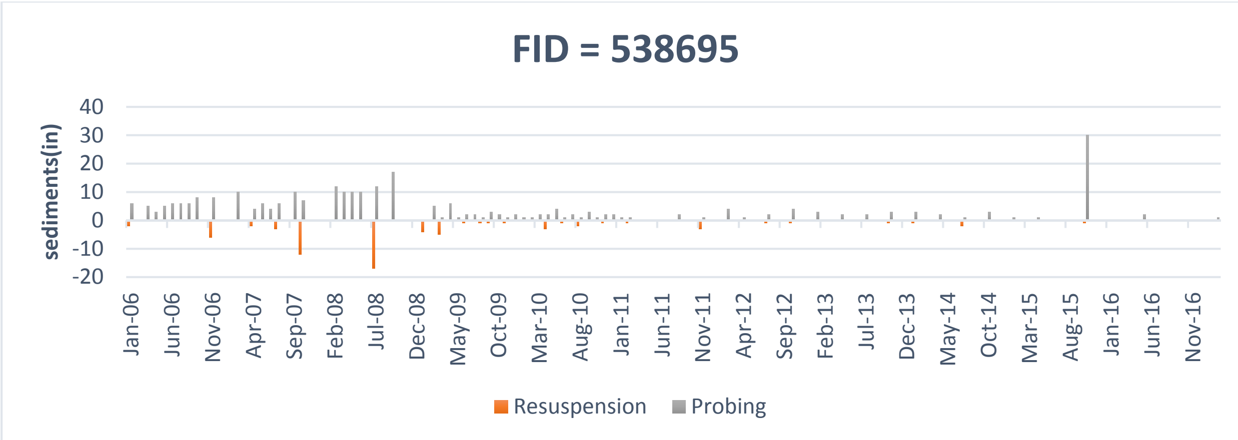

Figure B-6: 231 West Jean Street (SE Corner)

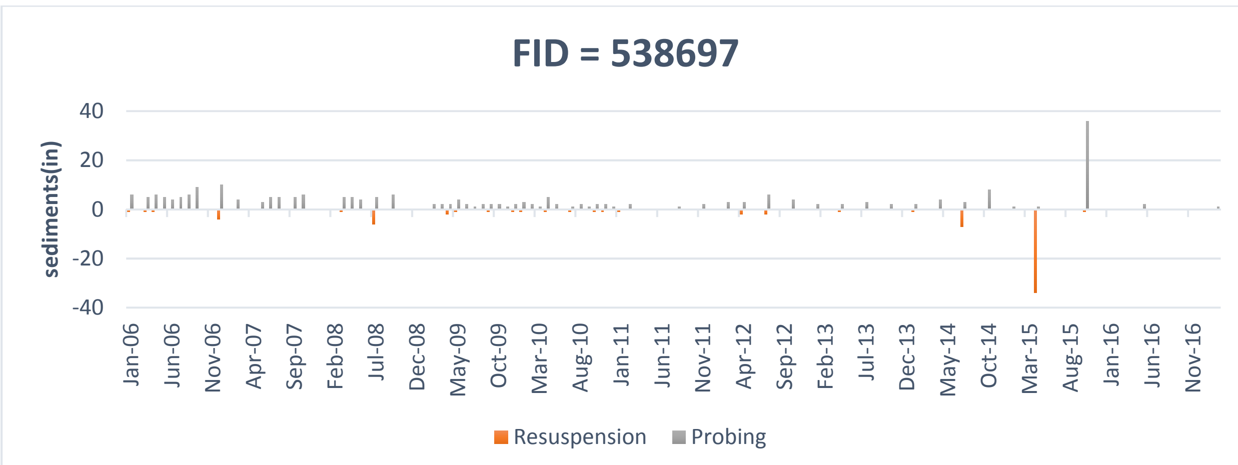

Figure B-7: 329 West Lambright Street (North End)

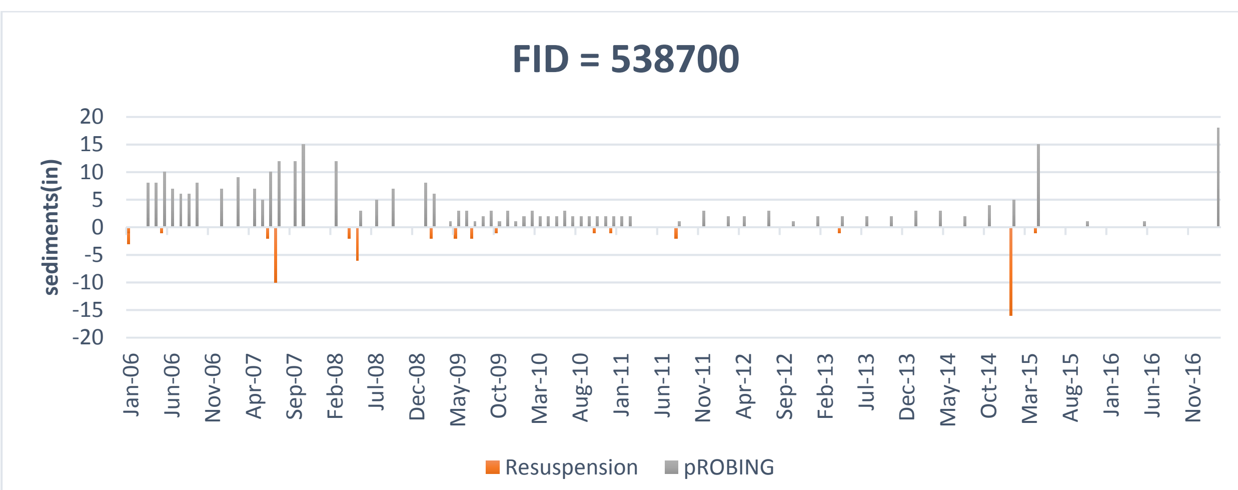

Figure B-8: 329 West Lambright Street (SE)

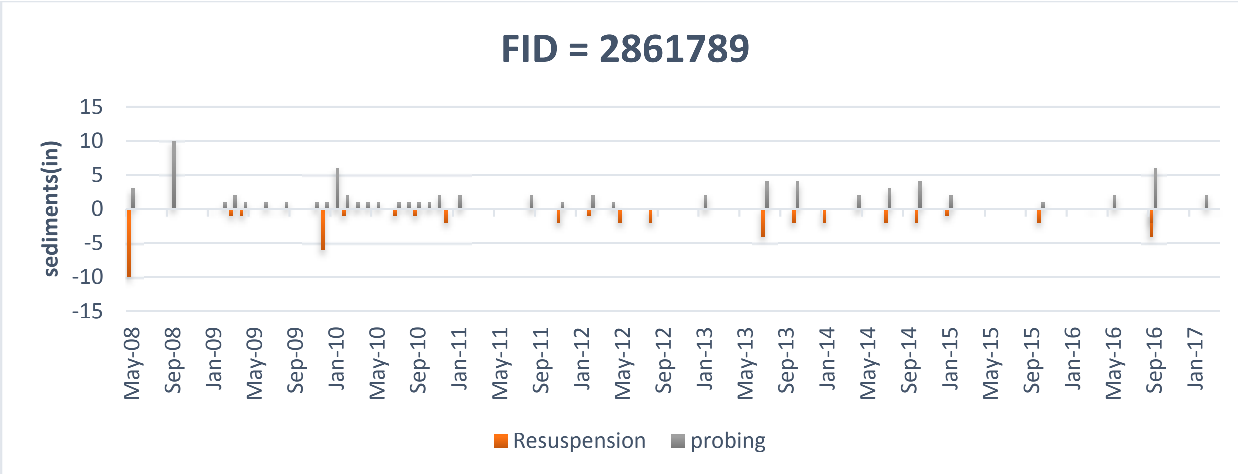

Figure B-9: 930 East Idlewild Ave.

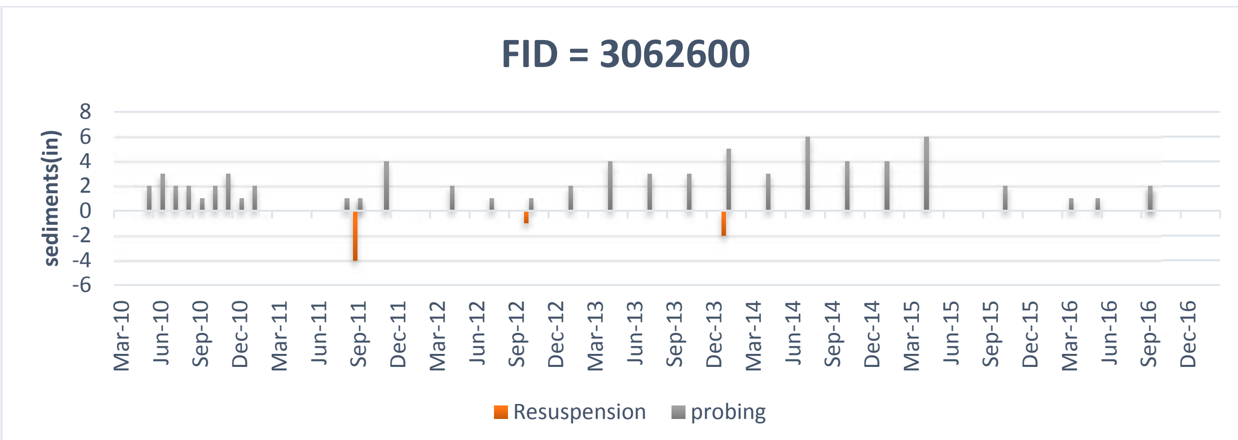

Figure B-10: 1208 East Park Circle

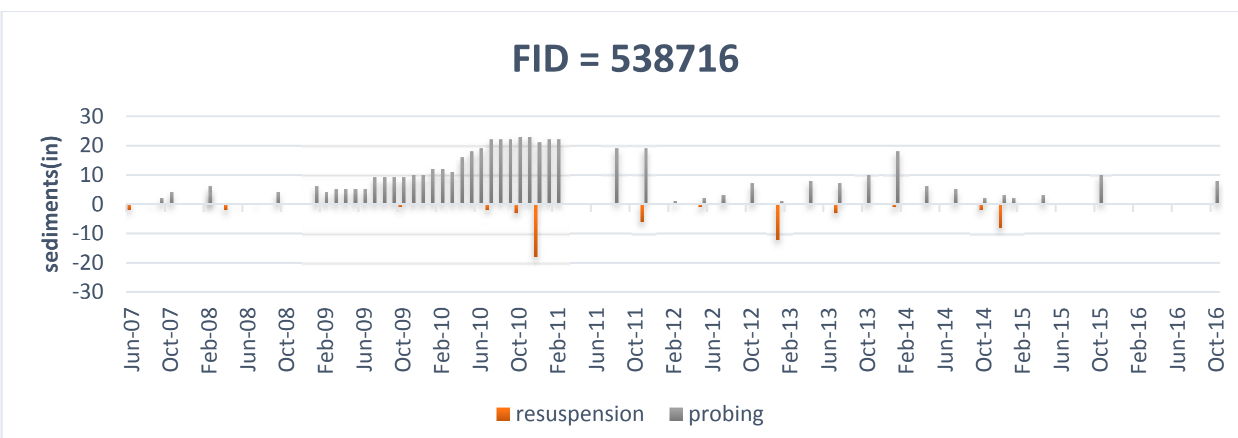

Figure B-11: 2505 North Habana

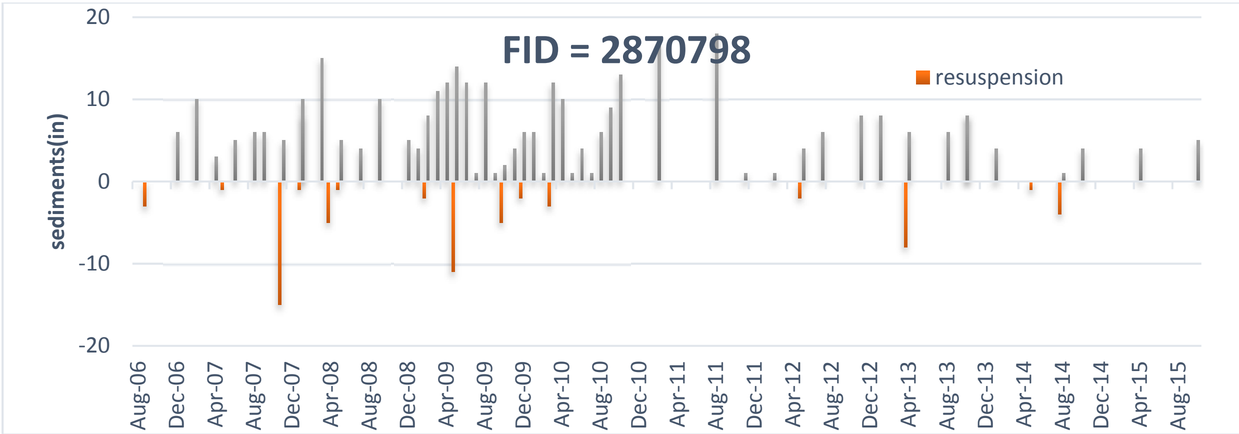

Figure B-12: 2508N. Dundee 2

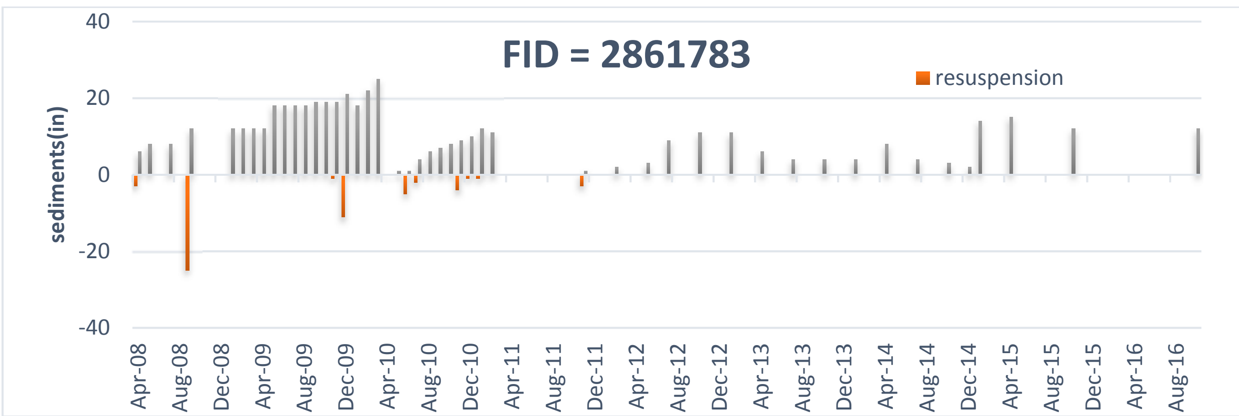

Figure B-13: 2519 North Riverside Drive

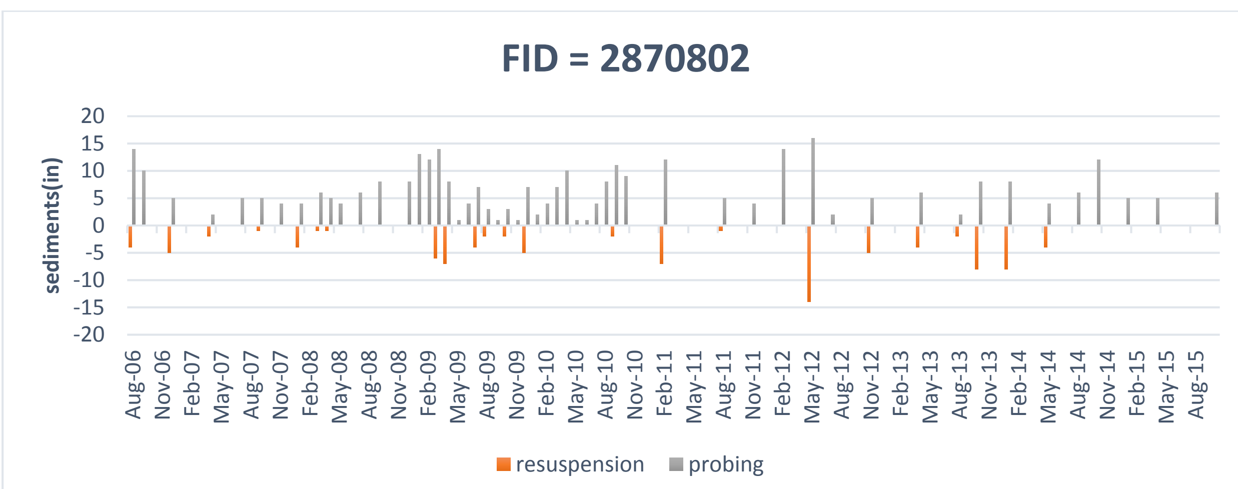

Figure B-14: 2600 North Dundee Street

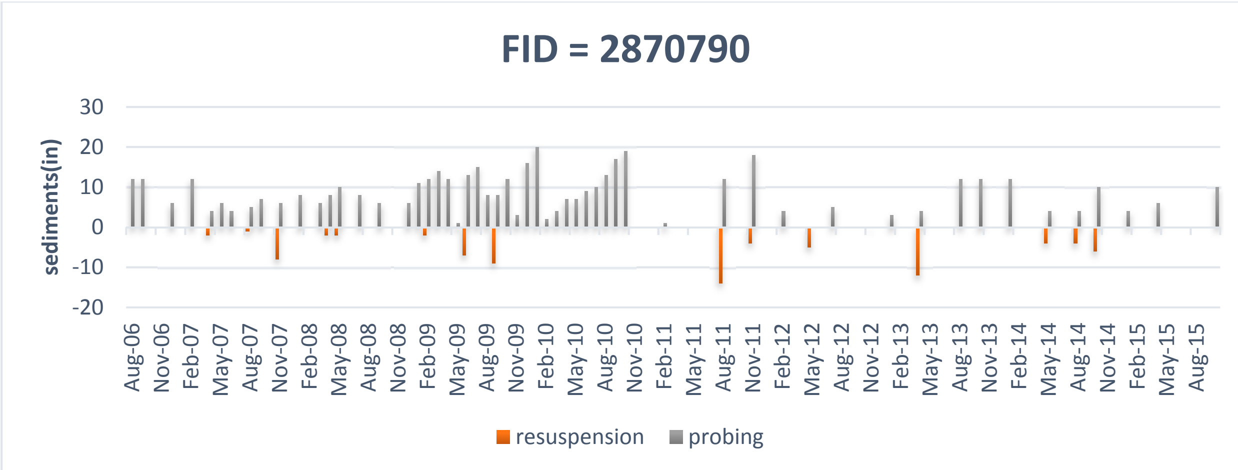

Figure B-15: 2625 North Dundee Street

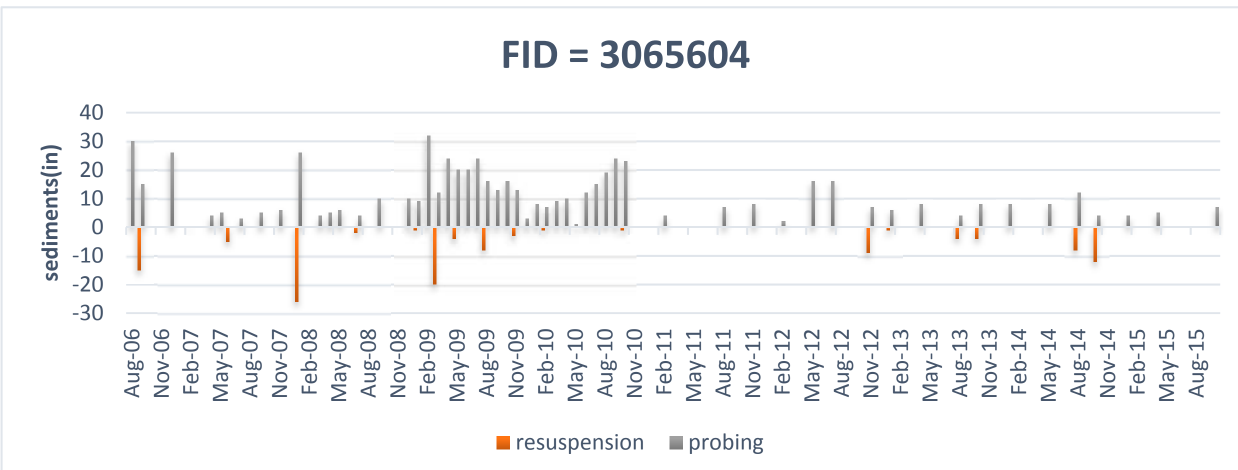

Figure B-16: 2638 North Dundee Street

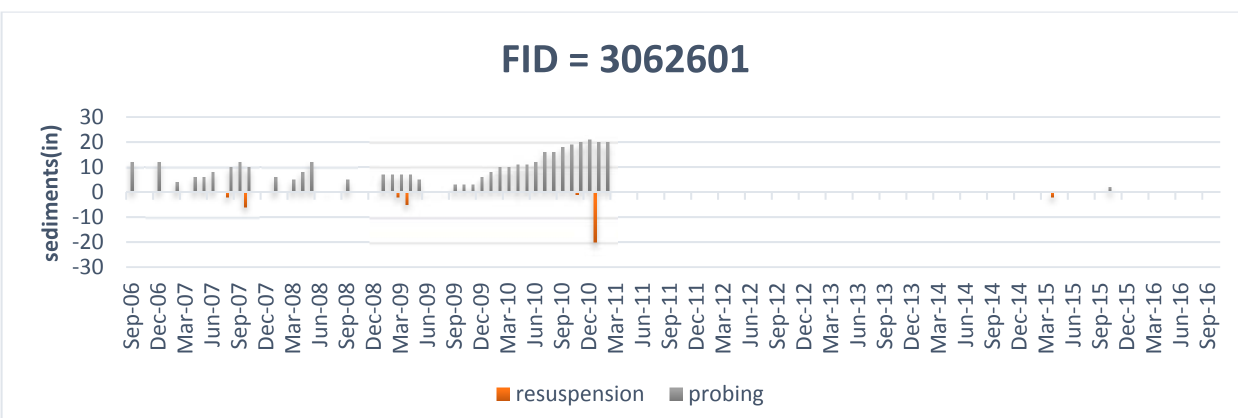

Figure B-17: 2826 Corrine Street

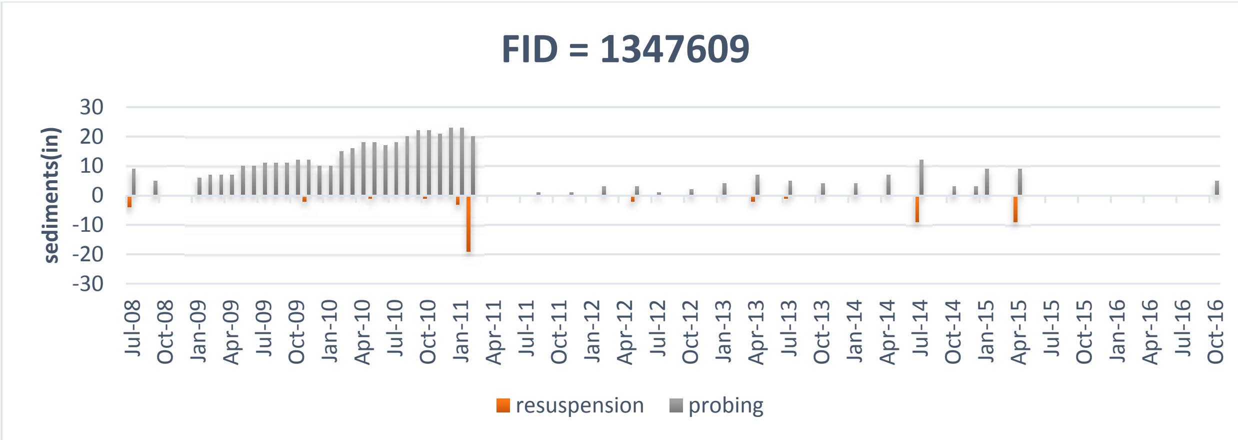

Figure B-18: 3102 North Rome Ave

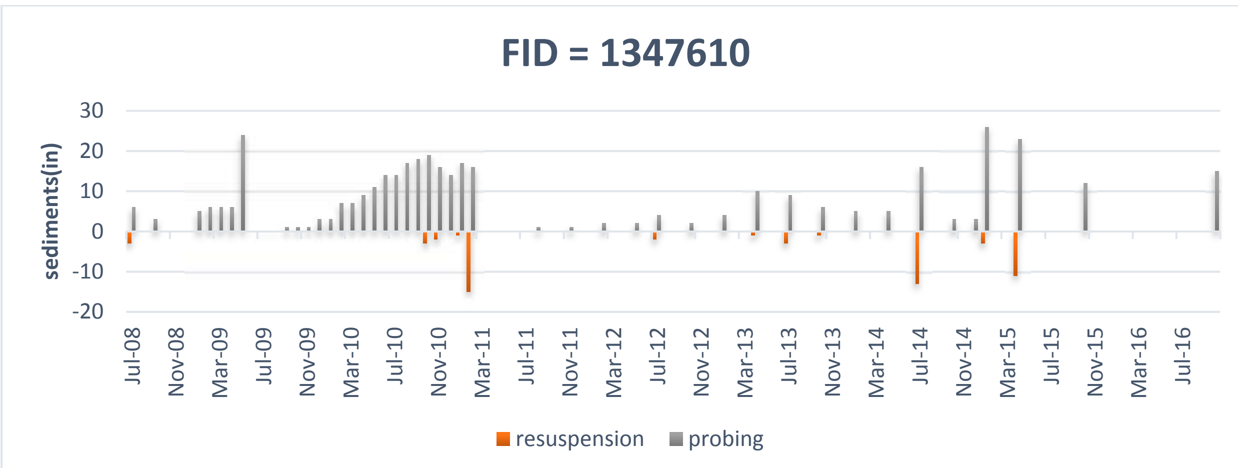

Figure B-19: 3202 North Rome Ave

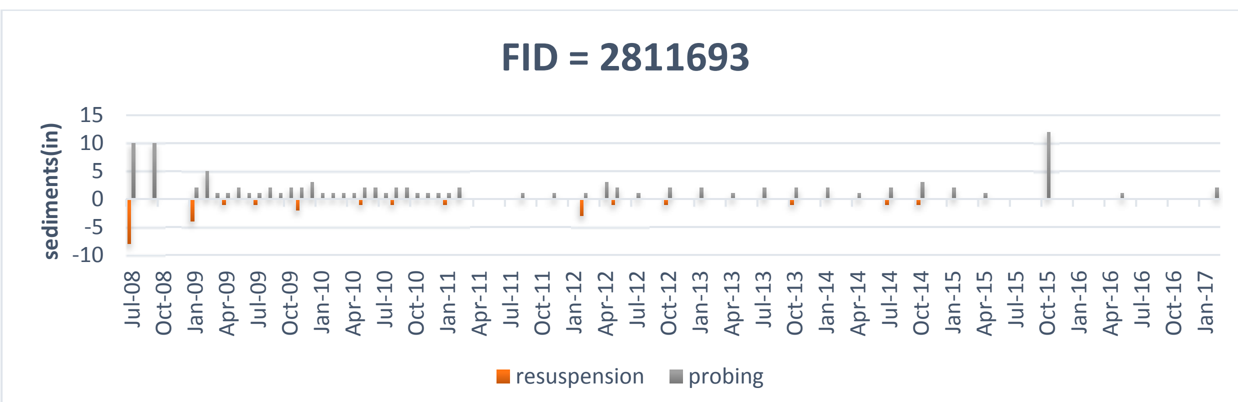

Figure B-20: 4601 Riverhills Drive

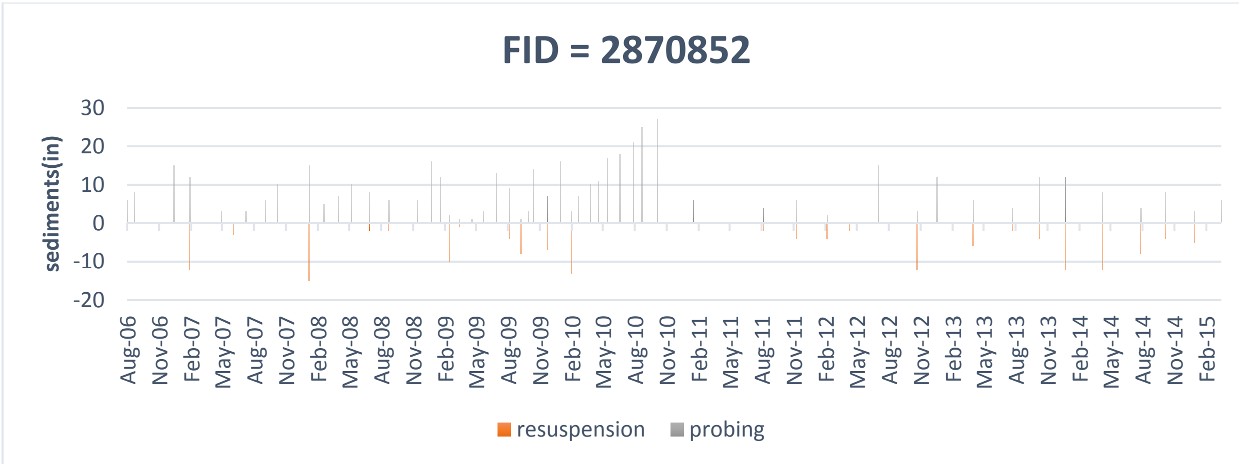

Figure B-21: 4619 West Bay to Bay Ave

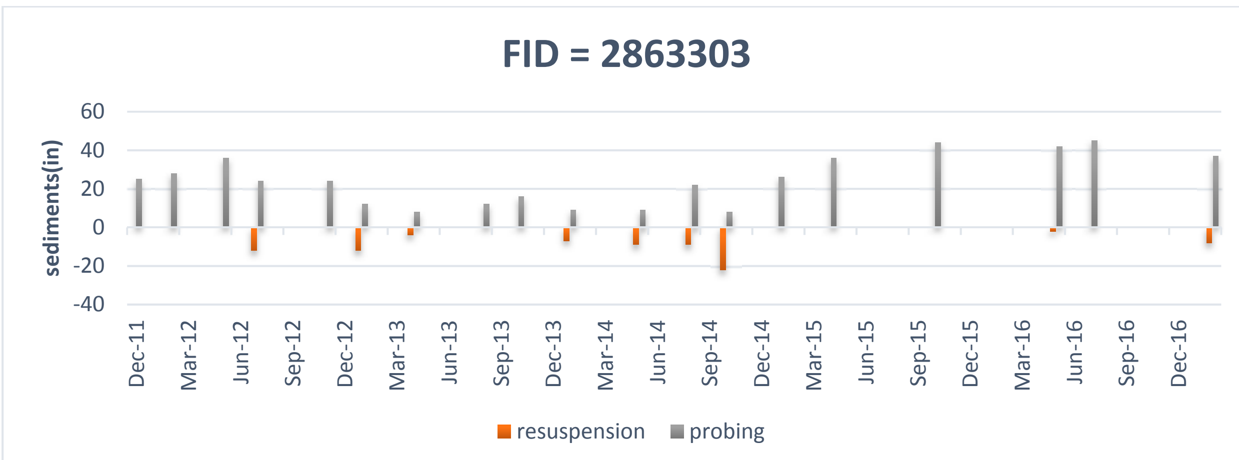

Figure B-22: 4634 West Sunset Blvd

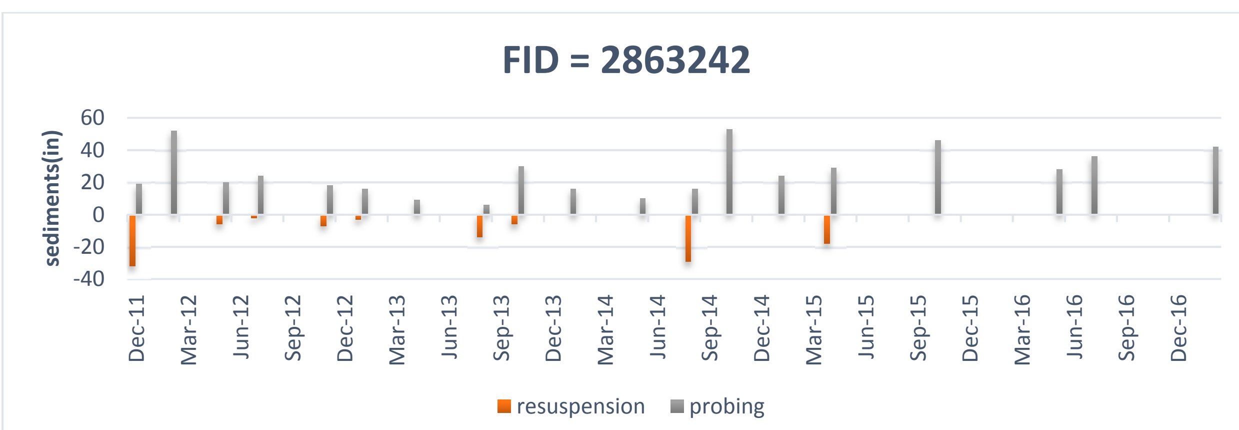

Figure B-23: 4637 West Browning Ave

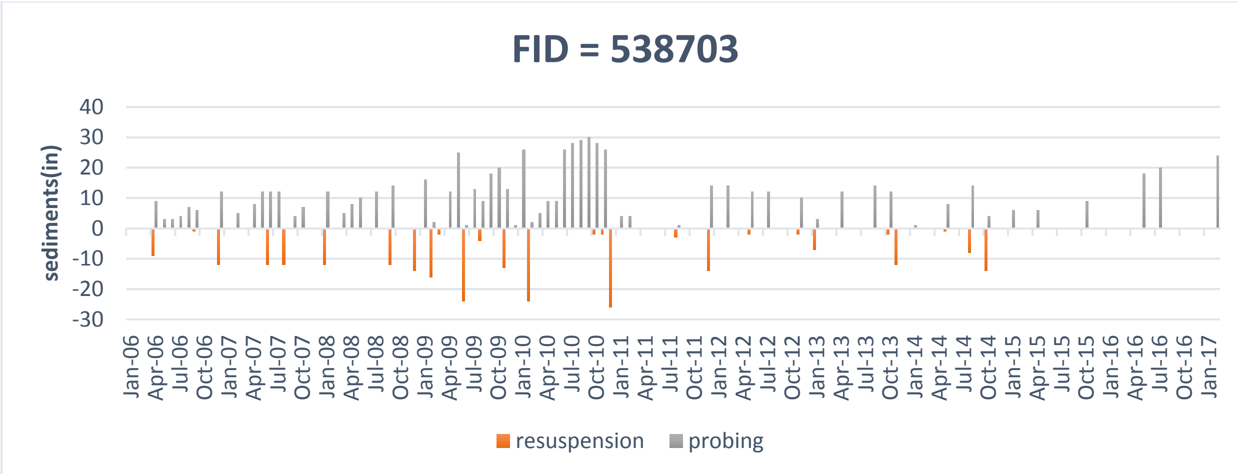

Figure B-24: 4805 South Bayside Drive 2

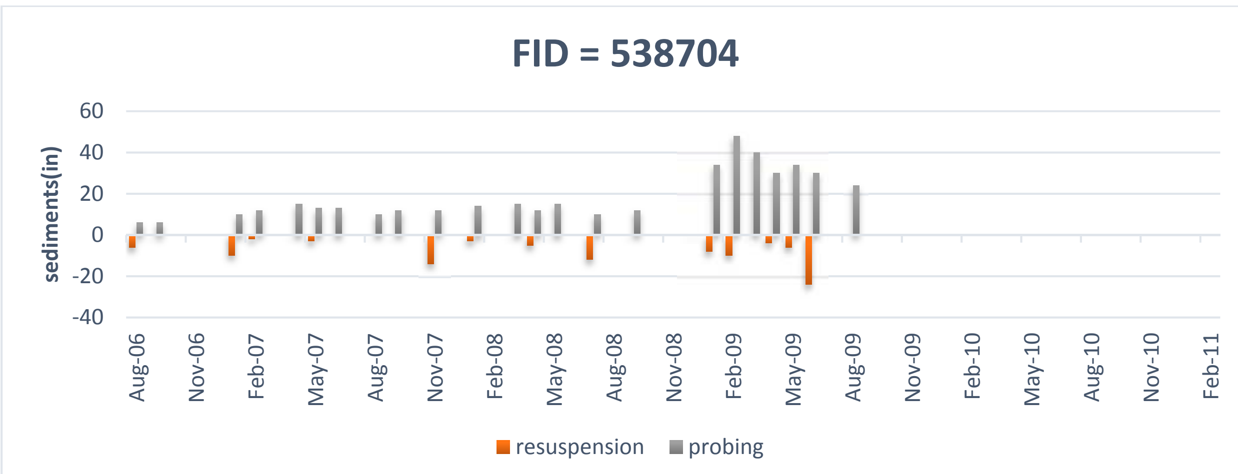

Figure B-25: 4807 West Sunset Blvd 2

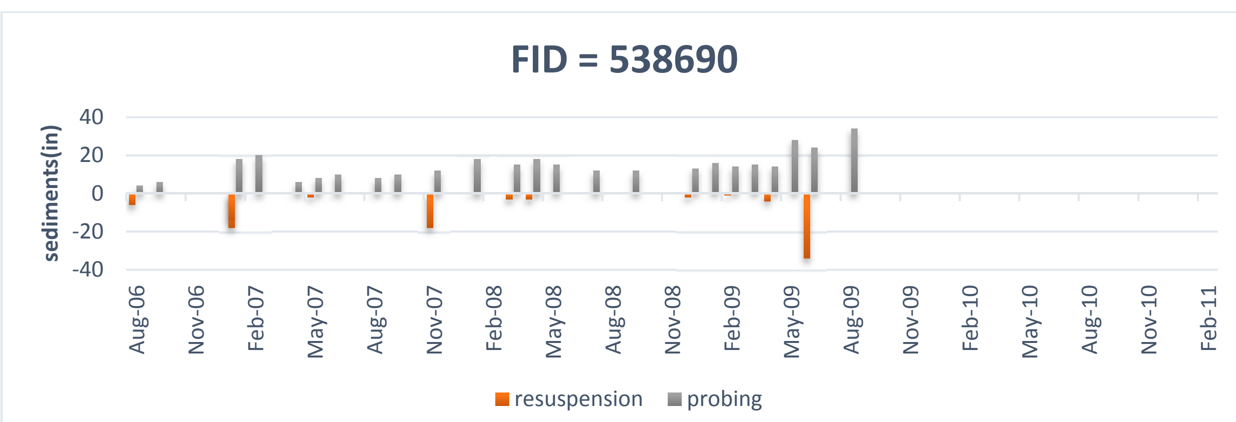

Figure B-26: 4807 West Sunset Blvd

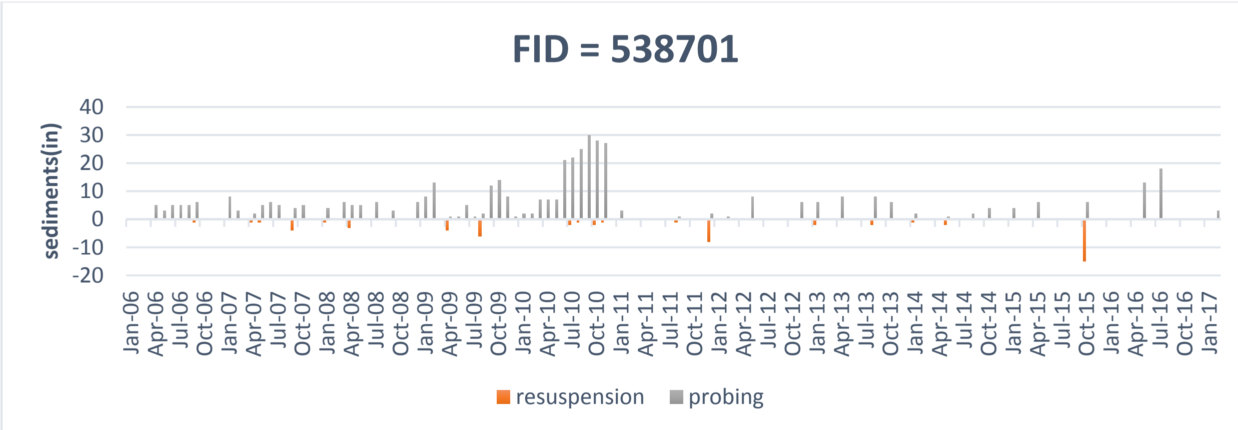

Figure B-27: 4900 West Neptune Way 2

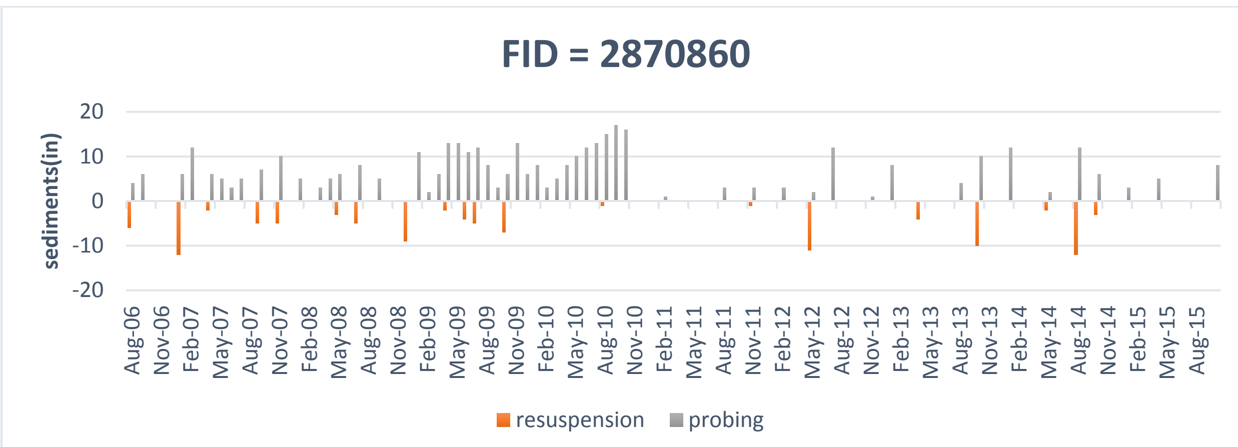

Figure B-28: 4901 West Spring Lake Drive

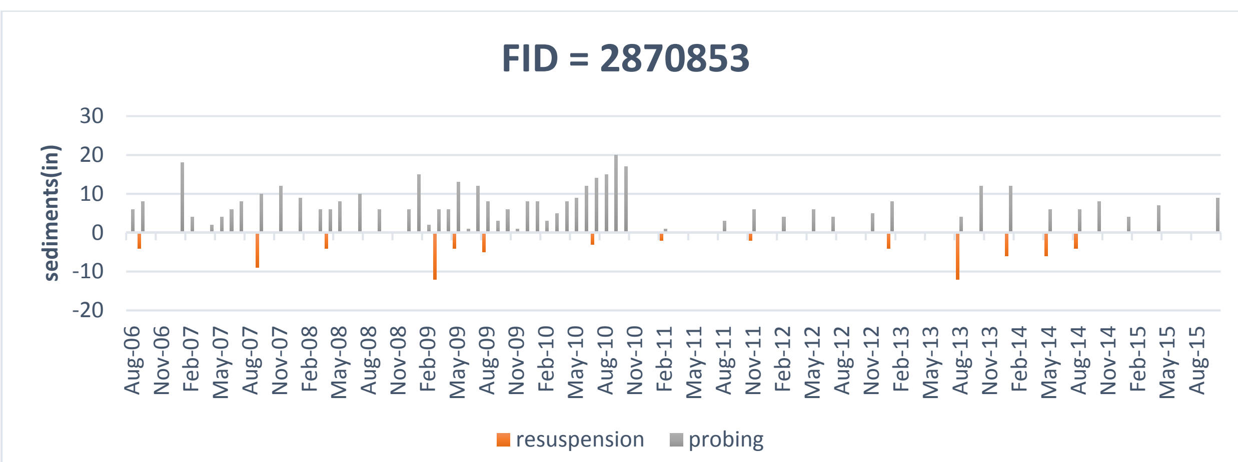

Figure B-29: 5005 West Spring Lake Drive

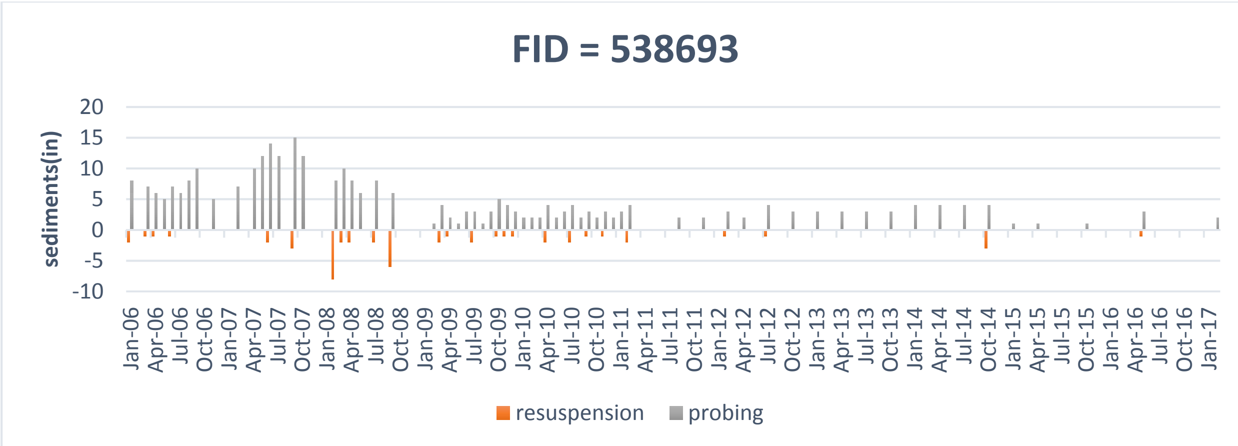

Figure B-30: 6404 North Otis Ave. 2

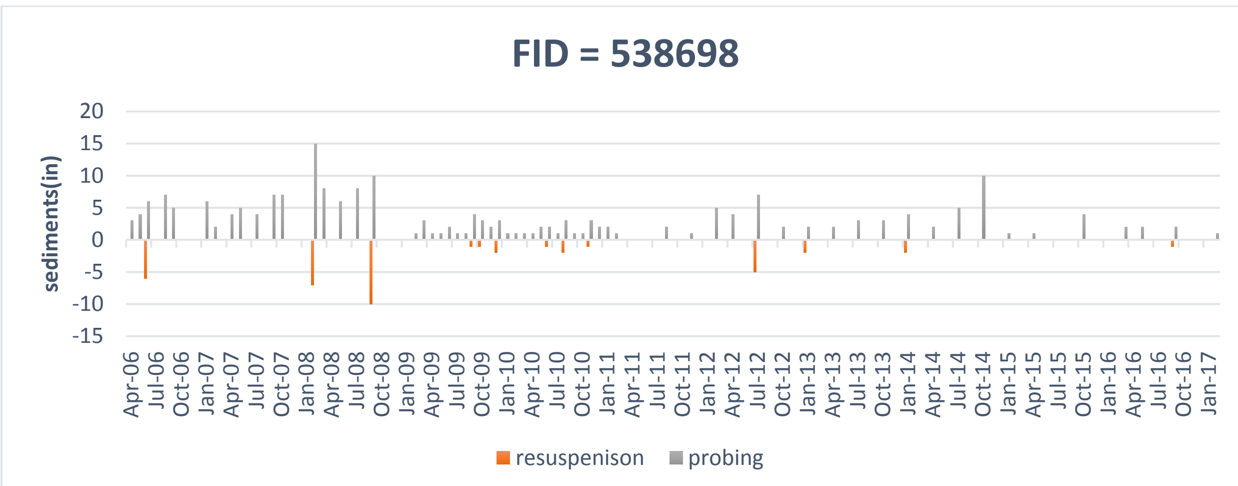

Figure B-31: East Clifton Street / Roberta Circle

APPENDIX C: 2009 AND 2010 RAINFALL AND CATCHMENT DATA

Table C.1: 2009 Rainfall and catchment calculations from drainage areas

FID	Sediment (in)			Rainfall sum (in)			Catchment (%)		Baffle box type/Chamber	MaxSed.
	mean	max	median	mean	max	median	Impervious	Buildings		
538691	3.0	3.0	3.0	3.8	3.8	3.8	6.3	12.8	Typ-1/ single	10"
538692	1.4	2.0	1.0	3.5	6.8	3.8	8.8	16.6	Typ-1/ single	10"
538698	2.0	3.0	2.0	2.0	3.6	1.6	34.0	11.7	Typ-2/ single	10"
538703	13.4	25.0	14.5	3.7	14.3	1.5	14.8	14.1	Typ-1/ single	12"
2870853	8.1	15.0	7.0	2.3	10.1	1.1	16.5	20.1	Typ-1/ single	12"
2870860	10.2	13.0	11.5	2.3	10.1	0.7	22.7	16.1	Typ-1/ single	12"
538694	4.2	15.0	2.0	4.4	13.4	2.8	15.1	18.9	Typ-1/ single	15"
538695	3.6	6.0	3.0	4.5	11.5	3.8	11.6	11.4	Typ-1/ single	15"
538696	3.0	5.0	3.0	4.5	11.5	3.3	3.2	10.7	Typ-1/ single	15"
538700	2.4	3.0	3.0	4.9	11.3	2.9	9.9	9.6	Typ-1/ single	15"
538704	23.3	34.0	22.0	4.9	17.4	0.9	17.0	18.1	Typ-1/ single	15"
2870852	10.2	16.0	12.5	3.8	10.1	1.2	12.3	8.3	Typ-1/ single	15"
538716	9.0	12.0	9.5	3.3	6.8	2.5	19.7	14.5	Typ-1/ single	24"
1347609	9.2	12.0	10.0	5.4	13.1	2.9	23.4	14.8	Typ-1/ single	24"
1347610	7.8	24.0	5.0	3.8	6.8	4.0	18.4	13.0	Typ-1/ single	24"
2861783	19.3	21.0	19.0	3.2	4.2	4.0	25.8	13.6	Typ-1/ single	24"
2811693	2.8	2.8	2.8	4.4	7.1	3.9	6.4	6.8	Typ-1/ single	30"
2861789	1.3	2.0	1.0	3.6	12.9	2.1	5.1	7.2	Typ-2/ three	30"
538717	4.5	5.0	4.5	7.6	11.4	7.6	33.1	20.4	Typ-1/ single	6"
538697	2.5	4.0	2.0	3.4	5.9	3.2	7.2	11.9	Typ-1/ single	8"
538701	7.0	7.0	7.0	3.9	9.3	3.0	1.3	0.2	Typ-1/ single	8"
2870798	7.8	14.0	8.5	3.3	9.7	1.8	21.4	15.4	Typ-1/ single	8"
2870802	8.6	14.0	7.0	3.8	10.6	1.4	8.2	10.9	Typ-1/ single	8"
2870856	11.4	30.0	11.0	3.9	10.1	1.3	17.4	24.6	Typ-1/ single	8"
3065604	18.7	32.0	20.0	2.7	10.1	1.2	6.7	7.1	Typ-1/ single	8"

Table C.2: 2010 Rainfall and catchment calculations from drainage areas

FID	Sediment (in)			Rainfall sum (in)			Catchment (%)		Baffle box type/Chamber	Max. Sed.
VALUE	mean	max	median	mean	max	median	Impervious	Buildings		
538691	3.0	3.0	3.0	4.6	5.4	4.6	6.3	12.8	Typ-1/ single	10"
538692	2.5	5.0	2.0	19.4	40.4	18.4	8.8	16.6	Typ-1/ single	10"
538698	2.0	3.0	2.0	2.0	3.6	1.6	34.0	11.7	Typ-2/ single	10"
538703	21.9	30.0	26.0	5.1	9.9	4.3	14.8	14.1	Typ-1/ single	12"
2870853	10.8	20.0	10.5	4.5	10.6	3.3	16.5	20.1	Typ-1/ single	12"
2870860	10.1	17.0	10.0	4.2	10.6	2.7	22.7	16.1	Typ-1/ single	12"
538694	2.3	3.0	2.0	4.9	3.0	2.0	15.1	18.9	Typ-1/ single	15"
538695	2.6	4.0	2.0	5.8	11.1	4.2	11.6	11.4	Typ-1/ single	15"
538696	1.8	2.0	2.0	2.6	4.2	2.6	3.2	10.7	Typ-1/ single	15"
538700	2.5	3.0	2.5	2.8	5.3	2.8	9.9	9.6	Typ-1/ single	15"
2870852	16.9	27.0	17.0	4.2	10.6	2.7	12.3	8.3	Typ-1/ single	15"
538716	20.0	23.0	20.5	3.8	5.9	3.4	19.7	14.5	Typ-1/ single	24"
1347609	18.9	23.0	18.0	5.2	9.7	5.0	23.4	14.8	Typ-1/ single	24"
1347610	13.6	19.0	14.0	4.1	8.6	3.6	18.4	13.0	Typ-1/ single	24"
2861783	10.2	25.0	8.0	4.3	9.7	3.6	25.8	13.6	Typ-1/ single	24"
2811693	1.7	1.7	1.7	2.8	3.8	3.0	6.4	6.8	Typ-1/ single	30"
2861789	1.9	6.0	1.0	3.3	9.5	3.3	5.1	7.2	Typ-2/ three	30"
3062600	2.0	3.0	2.0	3.6	9.5	2.6	11.4	9.3	Typ-2/ three	30"
2865620	21.3	30.0	22.0	8.6	10.8	10.3	57.2	26.4	Typ-2/ three	40"
538717	4.4	9.0	4.0	5.0	9.1	4.2	33.1	20.4	Typ-1/ single	6"
538697	2.8	5.0	2.0	2.1	5.3	0.8	7.2	11.9	Typ-1/ single	8"
538701	15.6	30.0	21.0	4.3	9.0	2.9	1.3	0.2	Typ-1/ single	8"
2870798	10.0	18.0	10.5	4.5	10.6	3.4	21.4	15.4	Typ-1/ single	8"
2870802	6.4	11.0	7.0	4.7	9.0	4.1	8.2	10.9	Typ-1/ single	8"
2870856	12.4	21.0	12.0	4.0	10.6	2.7	17.4	24.6	Typ-1/ single	8"
3065604	12.3	24.0	11.0	4.5	10.6	3.4	6.7	7.1	Typ-1/ single	8"

APPENDIX D: COPYRIGHT PERMISSIONS

The following email is a copyright permission for Figure 2-2.

Copyright perimission. Inbox x

Awet Tsegay <awet@mail.usf.edu> 12:25 pm (1 day ago)

to info

Dear sir/madam:

I am a graduate student at USF, Tampa in Environmental Engineering. I am currently writing my thesis titled "Underground stormwater treatment performance in urban coastal catchments: Case study of baffle boxes in the City of Tampa". I would like to use a picture on the website https://www.suntreetech.com/nsbb.html titled nutrient separating baffle box.

I am writing this email to ask for a copyright permission to use the above-mentioned figure on my thesis.

Regards,

...

Carol Happel <Carol@suntreetech.com> 12:49 PM (23 hours ago)

to me

Hi Awet, I am very interested in your research and would be willing to help with images or information that might be of help to you.

We likely have photos taken during construction/installation of the Nutrient Separating baffle boxes in Tampa.

You are welcome to use the photos for the purpose of non-commercial/academic use for your thesis. (with citation)

Please contact me and I will be happy to assist however I can.

Best of luck on your thesis, and congratulations.

Carol Happel, CPESC,CPMSM, Leed Green Associate
Suntree Technologies Inc
798 Clearlake Road
Cocoa, FL 32922
321-637-7552 X222
www.suntreetech.com

From: Carol Happel
Sent: Sunday, June 3, 2018 12:26 PM
To: Larry Herald <larryh@suntreetech.com>; Darci Meriedeth <DarciM@suntreetech.com>; Carol Happel <Carol@suntreetech.com>
Subject: FW: Copyright perimission.

The following email is a copyright permission for Figure 2-3.

Copyright permission. Inbox x

Awet Tsegay <awet@mail.usf.edu>
to Pkalinosky

Jun 3 (1 day ago)

Dear Mrs Kalinosky:

I am a graduate student at USF-Tampa in Environmental Engineering. I am currently writing my thesis titled "Underground stormwater treatment performance in urban coastal catchments: Case study of baffle boxes in the City of Tampa". I would like to use a picture on the manual titled 'Estimating nutrient removal by enhanced street sweeping" you and your colleagues wrote.

I am writing this email to ask for a copyright permission to use the above-mentioned figure on my thesis.

Regards,

...

--
Tsegay Awet
University of South Florida
Water Resources Engineering, ENG227G
Phone Number: (713)560-4330

Paula Kalinosky
to me

9:07 AM (3 hours ago)

Permission Granted.

Best wishes,

Paula

Paula Kalinosky, EIT
EOR: water | ecology | community
d: 651.203.6015 o: 651.770.8448

From: Awet Tsegay [mailto:awet@mail.usf.edu]
Sent: Sunday, June 3, 2018 11:39 AM
To: Paula Kalinosky
Subject: Copyright permission.

...

The following email is a copyright permission for Figure 2-4.

Copyright permission. Inbox x

Awet Tsegay <awet@mail.usf.edu>

to bps

11:48 am (1 day ago)

Dear Mr. Stack:

I am a graduate student at USF, Tampa in Environmental Engineering. I am currently writing my thesis titled "Underground stormwater treatment performance in urban coastal catchments: Case study of baffle boxes in the City of Tampa". I would like to use two pictures on the report "Gross Solids Characterization Study in the Tred Avon Watershed Talbot County, MD" you and colleagues wrote. They are Figures 3b and 3c in the report. I am recommending bag filters as an alternative solution on some sites that are accessible to vehicles.

I am writing this email to ask for a copyright permission to use the above-mentioned figures on my thesis.

Regards,

Tsegay Awet
University of South Florida
Water Resources Engineering, ENG227G
Phone Number: (713)560-4330

Bill Stack

to me

12:20 pm (1 day ago)

Yes as long as you cite CWP as the source of the photos. Thanks for asking.

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