AN INNOVATIVE METHOD FOR MODELING, ANALYSIS, AND PREDICTION OF STRUCTURAL STORMWATER BMP PERFORMANCE

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Many stormwater structural Best Management Practices (BMPs) rely on gravitational particle settling for sediment removal. The University of Minnesota's St. Anthony Falls Laboratory (SAFL) and BaySaver Technologies, Inc. (BaySaver), a manufacturer of hydrodynamic structural BMPs, have been able to establish statistically valid empirical correlations between the dimensionless Peclet Number (Pe) and sediment removal efficiencies in BaySaver's hydrodynamic separators. The Pe is defined here as the ratio of advection (particle settling velocity) to diffusion (turbulence) in the hydrodynamic environment [1].

The use of the Pe has practical significance in areas such as stormwater treatment because it provides a basic dimensionless framework for sediment removal efficiency prediction that is independent of the specific dimensions of a given BMP design. Hence, the performance of a particular design can be adequately predicted once the underlying Pe-sediment removal functionality is established via experimental measurements. This article outlines the use of Pe-sediment removal relationships and experimental data to develop models for projecting BMP sediment removal performance. The use of the Pe in stormwater treatment is a new approach useful towards both characterizing and predicting the sediment removal efficiency of a hydrodynamic BMP.

INTRODUCTION

Rigorous analysis of solid-liquid separators such as hydrodynamic BMPs can be a very complex task. From the theoretical perspective, the explicit solution of the fluid mechanics equations that govern single-phase fluid flow under laminar conditions in relatively simple geometries can be complex. For turbulent flow regimes, the equations and their corresponding solutions are even more complex. If solids (sediment particles) are added, the fluid flow equations increase in complexity.

In many instances, the approximate solution of such fluid flow equations is approached via numerical methods. More recently, with the widespread use of computational fluid dynamics software (CFD), the characterization of fluid flow patterns in hydrodynamic BMPs has also been achieved [2]. CFD models are very useful in providing graphical visualizations of fluid flow patterns and behavior. CFD techniques often require a rigorous understanding of the theoretical aspects of fluid flow, expertise in setting up the problem, and ability to use the CFD software. Still, solutions resulting from either numerical solutions or CFD techniques often need to be calibrated in order to get more useful solutions.

Another technique that has been used for many years to model complex fluid flow problems has been the use of empirical correlations involving dimensionless numbers such as the Reynolds Number (Re), Peclet Number (Pe), and other dimensionless numbers. This technique does not require a complete analytical formulation of the phenomena per se, but a general understanding of the factors that affect the process being studied [3,4]. The use of empirical correlations involving dimensionless numbers is of widespread use in many areas of engineering such as fluid flow and heat and mass transfer.

The benefit of using empirical correlations involving dimensionless numbers is that once the equations are developed for a particular process, these same correlations can be used to predict the behavior of similar processes having different relative dimensions. These empirical correlations are developed based on experimental techniques and statistical data analysis. Hence, the solutions obtained from this technique are approximate solutions. Still empirical techniques often provide very useful solutions to real life problems. This article outlines the development and use of correlations involving Pe – sediment removal in a hydrodynamic BMP.

THE BAYSAVER SEPARATOR

The BaySaver® System is a physical separator, relying on gravity settling, flotation, and other related mechanisms, to remove sediments, floating debris, and free oils from stormwater. The system is comprised of three main components: the BaySaver Separator Unit, the Primary Manhole (PM), and the Storage Manhole (SM). The SM is an offline pollutant storage structure. Figure 1* displays a simple schematic of the BaySaver Separation System. Influent flow containing pollutants enter the system by first passing through the PM. In this structure, coarse sediment settles while the flow passes into the Separator Unit and is routed to the SM. The influent flow to the SM, at this point, still contains pollutants of concern, such as fine sediments, oil and grease, floating trash, and other debris. Floatable trash, oils, and grease float to the surface of the SM and the influent flow returns to the outfall of the system through the Separator Unit. Both manholes are of standard concrete construction and function as sediment accumulation sites.

During a storm event, as the rate of flow Q increases through the treatment system, the Separator Unit acts as a dynamic flow control to route the influent flow through the most effective flow path for treatment. For example, under low flow conditions the entire influent flow is treated as described in the previous paragraph. Under moderate flows and up to the Maximum Treatment Rate (MTR), water is continuously treated through both the PM and SM, with a portion of these flows diverted through the T-pipes and the remainder flowing into the Separator Unit and then to the SM. The T-Pipes are structures that enhance the performance of the system during higher intensity storm events that are below the MTR of the Separator. This flow path allows for full treatment of floatable pollutants, while still treating sediments under moderate flow conditions. During maximum flow conditions or Maximum Hydraulic Rate (MHR), most of the influent flow passes over the bypass plate and will not be treated.

In summary, during all storms, stormwater flows through the Primary Manhole and, depending on the MTR of the Separator, might be treated in its entirety ($Q \leq MTR$) or bypass the system ($Q > MTR$) in the case of high intensity storms. For stormwater flows with $Q \leq MTR$, stormwater can flow through the SM and T-Pipes depending on the magnitude of Q. BaySaver Separators are designed based on the Maximum Hydraulic Rate (MHR), MTR, and the % suspended sediment removal requirements.

**Figures are located at the end of document.*

EXPERIMENTAL FACILITY

The test stand set-up at the University of Minnesota St. Anthony Falls Laboratory is depicted in Figure 2. The water supply for the tests was from the Mississippi River. Figure 3, shows a simplified diagram of the data collection procedure. A sediment feeder was used to control sediment supply rates and concentrations. Weirs were used to measure discharge flows. The weirs were equipped with electronic level sensors and connected to a PC-based data acquisition system.

The next sections describe the experimental results and how the Peclet Number (Pe) was used to derive empirical correlations for sediment removal in the Separator System.

THE PECLET NUMBER

The Peclet number is one of the several dimensionless numbers commonly used in engineering and science. This dimensionless number was named after Jean Claude Eugene Peclet who was a notable French scientist born in the eighteenth century [5].

In studying sediment transport and settling, Pe can be defined as the ratio of advective mass transport to turbulent mass transport [1,6] in the vertical direction. Specifically, in studying particle settling phenomena, Pe has been defined as [1]:

$$Pe = \frac{Vs\ L_1}{Diff} \qquad \textit{Equation 1}$$

Where Vs is the particle settling velocity (ft/s), L_1 a length scale (ft), and Diff is the turbulent diffusion coefficient (ft^2/s). It can be seen that the Pe has no dimensions. The gravitational settling velocity Vs can be calculated using the well known Stokes Law for particles having a particle Reynolds Number < 1 [3,10]. According to the Stokes Law, gravity driven particle terminal velocity (Vs in ft/s) is proportional to the difference in density between the particle (ρ_p in lbs/ft^3) and the fluid (ρ_f in lbs/ft^3) and to the square of particle diameter (d_p in ft); and inversely proportional to the absolute fluid viscosity (μ in $lb_f\text{-}sec/ft^2$). The Stokes terminal velocity is the steady state settling velocity of the particle [3].

$$Vs = \frac{g\ (\rho_p - \rho_f)\ d_p^2}{g_c\ 18\ \mu} \qquad \textit{Equation 2}$$

It is important to note that real systems are complex and that theoretical equations , such as Equation 2, yield numbers that represent a simplified and ideal world. Still, Vs estimation via the Stokes Law provides a useful starting point towards understanding particle settling velocities in real engineering systems and for that reason the Stokes Law is of common use [7]. From examining the Stokes Law equation, one can observe that the heavier the particle and the larger it is, the faster it will fall. Also, as temperature decreases, water viscosity increases slowing down the falling particle.

Of the three terms that make the Pe, Vs and L_1 are, in most cases, relatively easy to determine. The Diff term, or turbulent diffusion coefficient, is much more difficult to establish, both theoretically and experimentally, as mentioned in research papers that deal with numerical simulations of particle settling dynamics [6,8]. Based on experimental work and theoretical understanding, the turbulent diffusion term in the BaySaver separator has been approximated by researchers [1] to be:

$$Diff \sim \frac{Q}{L_2} \qquad \textit{Equation 3}$$

Where L_2 (ft) is a scale length, Q is the flow through the manhole (ft^3/s), and ~ is the proportional symbol. The scale length refers to a particular and functionally relevant dimension of the BMP device being studied. It is important to emphasize that only similar systems having the same Pe will exhibit similar particle removal dynamics. In other words, if one develops sediment removal correlations based on Pe for a specific BMP design, those specific correlations cannot used to predict the behavior of a geometrically dissimilar BMP design that might have the same Pe.

The final form of the Pe arrived by SAFL and used in the analysis of the separator is:

$$Pe = \frac{Vs\, D_m}{Q/h} \qquad \textit{Equation 4}$$

Where Vs is the settling velocity for the d_{50} particle in the sediment gradation, D_m is the diameter of either the PM or the SM, Q is the flow through the separator with $Q \leq$ MTR, and h is a dimensional scale characteristic of every BaySaver separator. It is important to note that each manhole will have its own Pe-sediment removal correlation.

How can the Pe be used to predict the behavior of a stormwater BMP? An approach that was used by SAFL and BaySaver Technologies was to develop a family of dimensionless equations for the BaySaver separators as a function of flow (Q) through the system, MTR, and mass accumulation measurements in both the PM and the SM (See Figure 3). Mass accumulation measurements were then used to calculate sediment removal efficiencies in the BaySaver System. F-95, a sediment gradation manufactured by US Silica, was added to the source water as the source of sediment mass (see Table-2).

Table 2 - F-95 grain size distribution

Sediment Size (µm)	Percent Finer
425	100
300	99
212	90
150	60
106	18
75	3
53	0

**Figures are located at the end of document.*

In general terms, sediment removal efficiency of a BMP is defined in Equation 5: This definition has been used in the past in other types of BMP efficiency analysis efforts [2].

$$\text{Removal Efficiency} = \frac{\text{Mass of Sediment Collected}}{\text{Mass of Sediment Injected}} \qquad \text{Equation 5}$$

Based on the experimental work at SAFL, dimensionless relationships were developed for percent sediment removal (100 x Removal Efficiency) in the SM and PM as a function of Pe in each structure (Pe_{PM} and Pe_{SM}). The empirical equations developed as a result of this ongoing experimental program are presented in Figures 4 and 5. As can be seen from the previous discussion, Pe correlations can provide a very useful approach towards understanding and predicting sediment removal mechanisms and efficiencies in storm water BMPs.

Given the practical impossibility to perform these experiments at a controlled temperature, the temperature during these tests varied approximately between 54 °F and 76 °F. As predicted by Stokes Law, higher sediment removal efficiencies were observed at higher temperatures than at lower temperatures.

For a given BaySaver Separator configuration, the sediment removal efficiency was evaluated over a range of flows. The results of this evaluation were synthesized into an individual equation having the following general form:

$$\text{Percent Sediment Removal for Separator}_i = A \ln (Q/MTR) + B \qquad \text{Equation 6}$$

Where A, MTR, and B are specific to each Separator design. A and B are also numerical constants. Q is the stormwater flow with $Q \leq MTR$. These equations then formed the basis for the development software model for the optimum design of BaySaver separators based on target percent sediment removal requirements, precipitation data, and economics (See Figure 3).

As can be seen in Figures 4 and 5, the percent sediment removal efficiency in both the PM and SM increase as the Pe increases. The following observations can be made based on Equation 4 and Table 2.

1. As the particle settling velocity increases, the efficiency of the separator increases. The opposite being also true.

2. As the depth of the manholes increases, the efficiency of the separator also increases. It is believed that an increased distance between the turbulent region in the manholes and the sediment rich strata towards the bottom of the manhole mitigate particle resuspension and upward sediment transport resulting in more effective particle settling.

3. As the diameter of the manholes increases, the efficiency of the separator also increases. A larger manhole diameter creates a longer horizontal trajectory and a correspondingly greater hydraulic retention time between the inlet and the outlet. Therefore particles have a larger chance of reaching the quiescent areas of the manhole increasing settling efficiency.

4. As the flow increases system efficiency decreases. It is believed this is caused by a decrease in residence time in the system and on increased turbulence that work against particle settling and removal.

Table 2- Effect of Pe Changes on Percent Sediment Removal Efficiency[1]

Factor	**Increase Vs** (1)	**Increase h** (2)	**Increase D_m** (3)	**Increase Q** (4)
Pe in PM	Increases	Increases	Increases	Decreases
Pe in SM	Increases	Increases	Increases	Decreases
% Sediment Removal Efficiency	Increases	Increases	Increases	Decreases

[1] See Figures 4 and 5 for details.

CONCLUSIONS

1. The Peclet Number is a very useful tool in characterizing the performance of hydrodynamic separators. It is believed that statistically valid correlations between the Peclet Number and sediment removal in the BMP structure can be obtained through the use of robust data collection and data analysis procedures.

2. In a hydrodynamic BMP, particle settling is opposed by turbulence in the BMP structure. The Peclet Number predicts that the higher the particle settling velocities (advection) relative to the turbulence in the BMP, the more effective the separator will be in removing sediments, all other factors being equal. Hence higher Peclet Numbers lead to higher sediment removal efficiencies.

3. It is likely that resultant particle removal efficiencies in the BaySaver System are also influenced by other mechanisms such as particle interactions, particle characteristics, wall effects, etc. These factors were not quantified, in terms of their influence, during this project.

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Figure 1: BaySaver System Layout

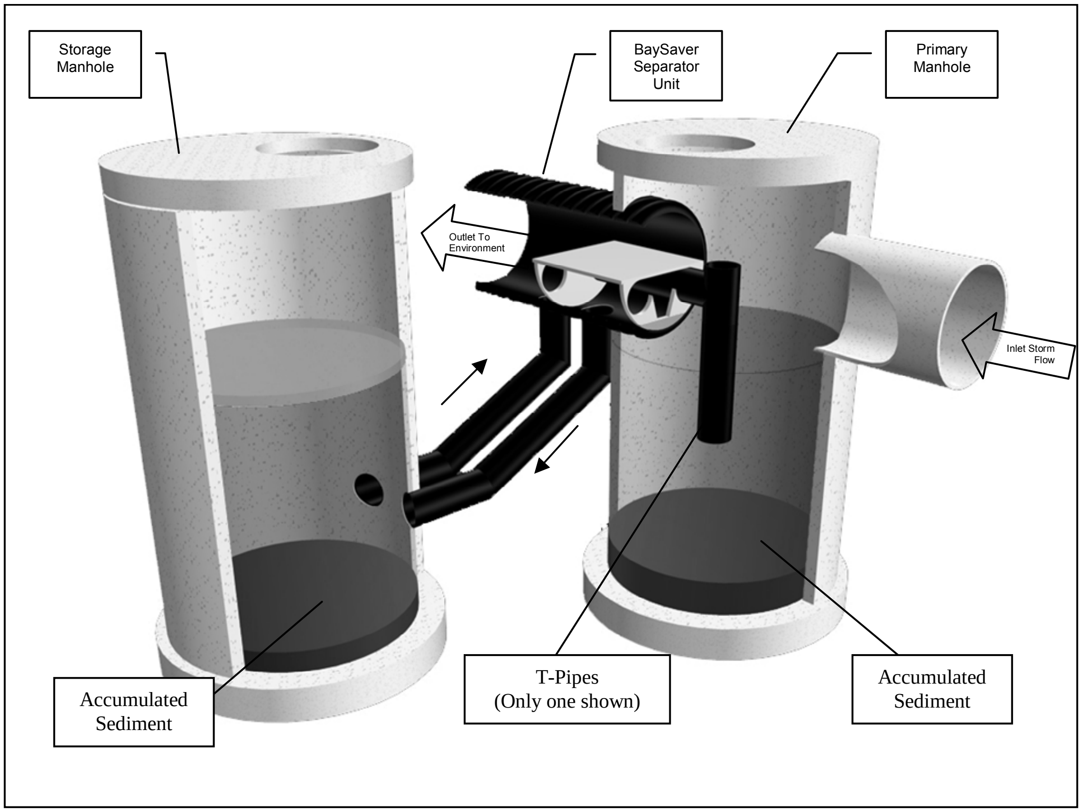


Figure 2 - Testing Facility Diagram (Carlson, 2005)

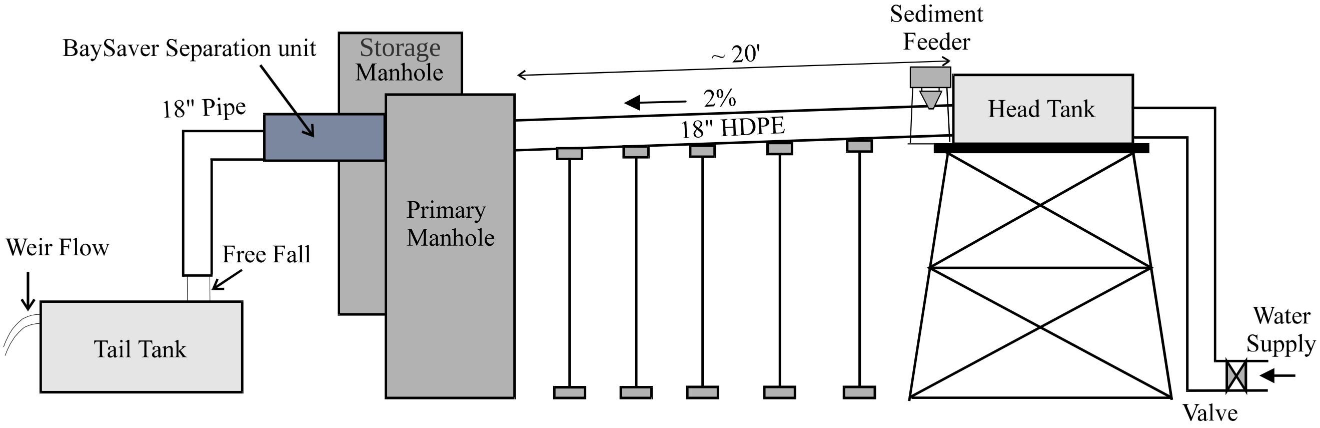
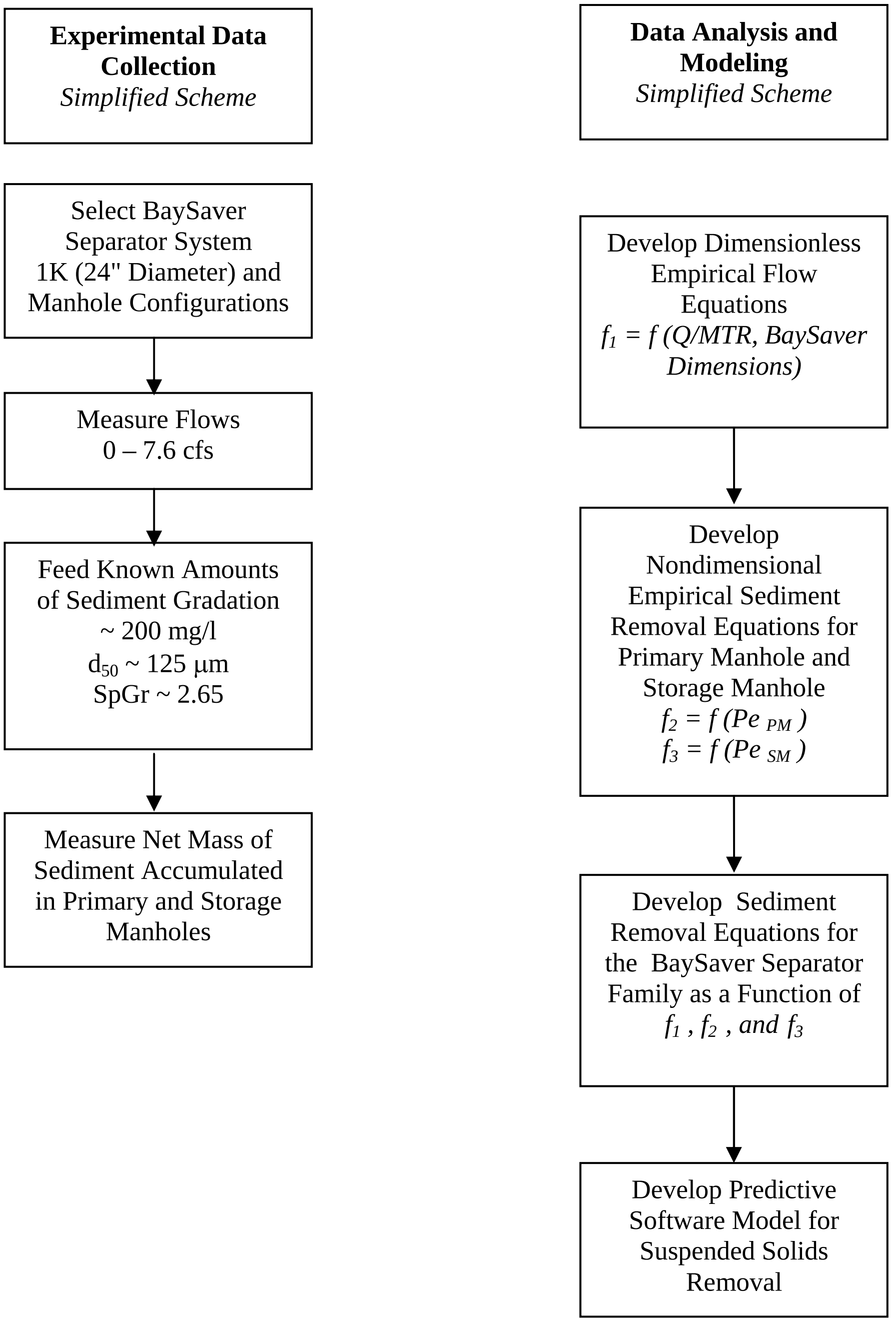
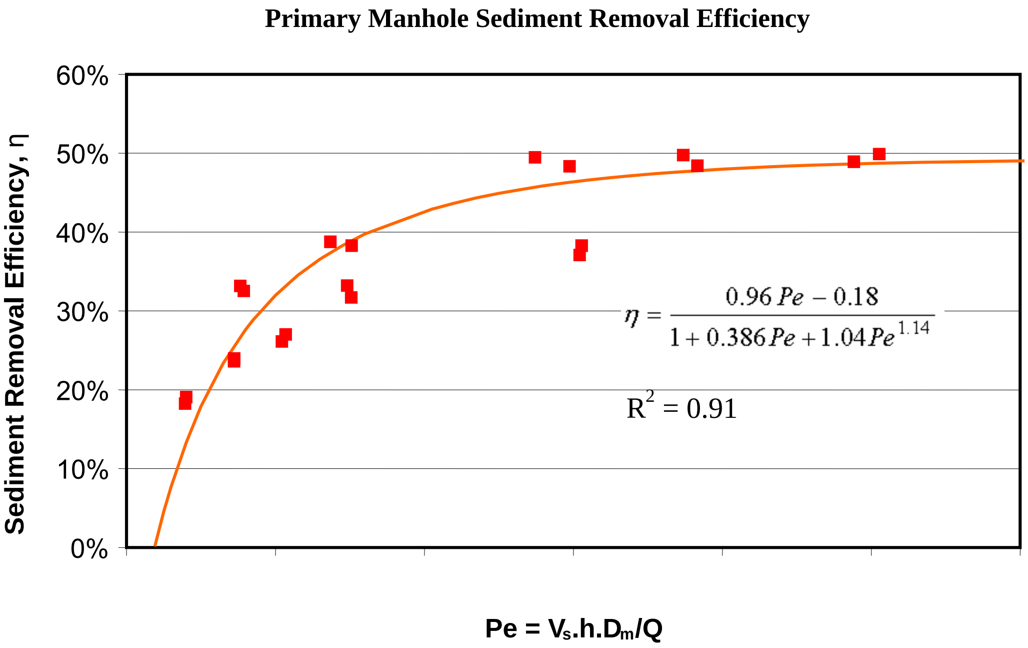


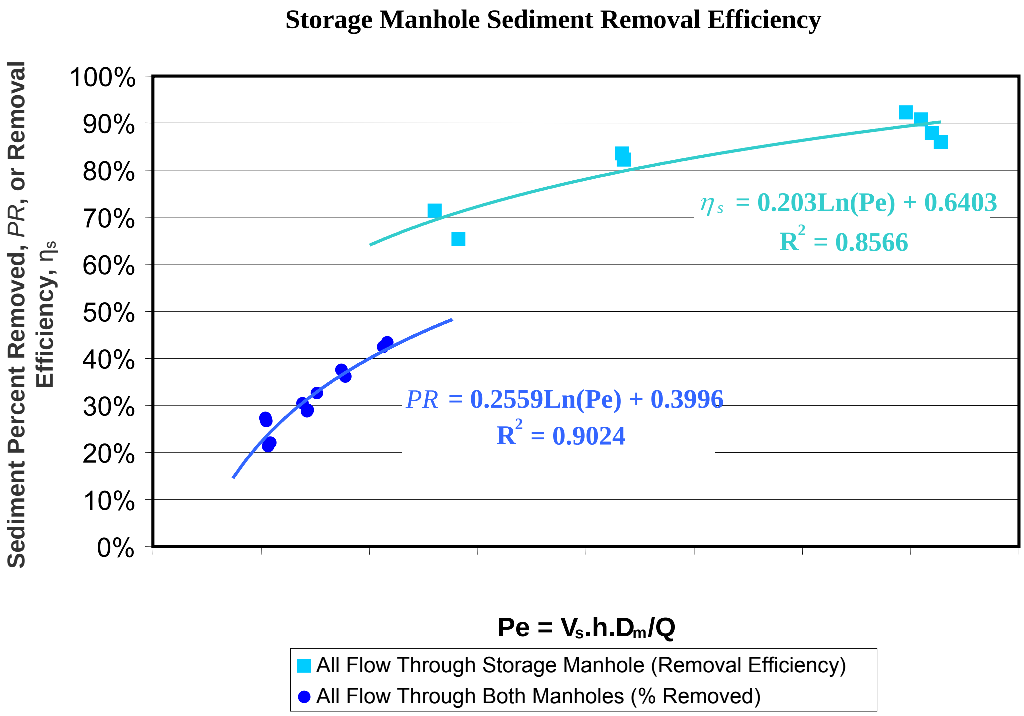
Figure 3 – Simplified Experimental and Data Analysis Procedure – BaySaver Separator Modeling





Primary Manhole Sediment Removal Efficiency

Figure 4 Measured removal efficiency of the Primary Manhole vs. Peclet Number and the proposed function to describe the relationship (Carlson, 2005).



Storage Manhole Sediment Removal Efficiency

Figure 5 Measured removal efficiency and the percent removed in the Storage Manhole vs. Peclet number and the proposed functions to describe the relationships (Carlson, 2005).