Field Verification of Manufactured BMPs Subject to Rainfall-Runoff Loadings

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Abstract

Field-testing of unit operations and processes (nominally called BMPs) requires critical planning and implementation through all steps of the verification process from initial watershed selection through defensible statements of BMP behavior based on field verification results. The desired goals and outcomes must be known and designed into the entire verification process. A continual evaluation, quality assurance and feedback protocol must be part of the testing protocol. What are the basic component categories of a well-designed and defensible field-testing protocol? In general, while watershed processes can be categorized and modeled, each watershed is different and unique with respect to BMP loadings of hydrologic, chemical, biological and particulate matter (PM) quantities. We must recognize these challenges and collect sufficient representative data so that the role of such uniqueness can be quantified for the specific BMP or BMPs tested. These challenges are significant because at this time there are very disparate methodologies of PM protocols that range from gravimetric index tests such as the traditional total suspended solids (TSS) method adopted from wastewater treatment evaluations, or the more recent suspended sediment concentration (SSC) method, index tests such as turbidity testing, to more fundamental methods of particle size distributions (PSDs). Each index method provides an indication of BMP performance with respect to PM; however a more fundamental, transferable and defensible methodology includes PSD and turbidity testing that is combined with a representative gravimetric index test for PM. The committee is envisioning developing a multi-tiered approach to field testing predicated on the intended utilization and rigor required for the defensible and transferable application of BMP performance results. This committee is focused on manufactured BMP separation of PM. It should be recognized that the entire gradation of PM should be representatively characterized for a BMP, in particular the suspended fraction because of the mobility and acute bio-availability of this finer fraction.

This approach requires hydrologic information that measures event-based rainfall-runoff phenomena and continuous simulation of the hydrology, water chemistry and PM transport. A second component of this approach is a quantitative description of the BMP system, including dimensions, materials, installation, intended function. Additional requirements for this component include, demonstration that tested BMP is identical to "potentially-certified" BMP that will be sold on the market, mass balances and residual recovery and testing between each event or at the end of the testing campaign, identification of the BMP management strategy between events; and evaluations should be on a concentration and load basis. While percent reductions can be reported they are secondary to concentration and load specifications. A third component of the approach is basic information on water chemistry and PM. Under this component, questions to be answered include, are chemistry and PM collected by compositing individual samples; i.e. on an event-mean basis, or shall there be a minimum number of representative samples taken throughout the event and analyzed separately? What minimum chemistry parameters should be included if this protocol is focused on PM? What is the

maximum sample holding time? Are any chemistry constituents separated between dissolved and particulate fractions for each influent and effluent sample? In addition to SSC and particle size distributions for influent and effluent, what addition PM shall be collected? Shall PM specific gravity be determined? What are the required sample volumes? Given the widespread recognition that automatic samplers cannot provide an accurate representation of water chemistry and PM, is all sampling, manual sampling? Shall there be sample replication for each sampling interval? Given that the PM size gradation ranges from colloidal to gravel and trash size material shall laser diffraction and sieve analysis be required for PSD analysis? What level of analytical or numerical modeling should be required to support the field performance of a BMP? Along with event-based monitoring and modeling; the need for modeling BMP performance using continuous simulations and historical loadings is critical.

It is recognized that some of these components are considered controversial. However, one of the goals of this task committee is to move the industry forward and provide a protocol that generates a level playing field with databases of lasting value. As long as all the pertinent parameters are measured for the hydrologic system, the BMP system, water chemistry and PM, field testing databases can serve as a long-term benefit for the profession where we no longer view BMPs as "black boxes" but as combinations of unit operations and processes. What about the proprietary nature of these databases? How shall the protocol address this? Are the databases even proprietary in such a protocol? What about the requirements for outside review of field testing of a BMP, with some level of compensation by an independent party? All of these questions need to be addressed in a defensible field testing protocol.

Keywords

Best Management Practices, Unit Operations, Unit Processes, Stormwater, Rainfall-Runoff, Mass Balances, Watersheds, Hydrology, Particulate Matter

Introduction

Without identifying specific protocols, there are a plethora of disparate field verification protocols for water quality BMPs across North America. Nearly all of these protocols include some index measurement of PM, most commonly measured as total suspended solids (TSS) or more recently as suspended sediment concentration (SSC). The differences between many of the protocols arise from a multitude of reasons that can range from targeting local water quality needs or specific hydrologic conditions to more regional protocols that introduce, at some level, a statistical foundation for the requirements of the protocol. None the less, all of these protocols either implicitly or explicitly are faced with the ability of the protocol to represent the performance of the BMP (as a unit operation) for separation of PM under representative field conditions. Additionally, such protocols are also faced with a level-of-effort consideration that ranges from a basic hydrologic/hydraulic loading assessment with regional tabular water quality values, to research-level assessments that focus on the unique and coupled hydrologic-chemical-particulate complexity of each rainfall-runoff event in order to identify not only performance of the BMP, for example to satisfy a regulatory requirement, but the fundamental mechanisms of the BMP so that the BMP does not have to be considered a black-box. Beyond a baseline of BMP performance on a unique event basis or a statistically representative series of events the issue of the non-stationary temporal behavior of a BMP is an important phenomenon.

Stakeholders have long been familiar with the challenges of regular operation and maintenance (O and M) for BMPs. It does not come as a surprise to stakeholders that the lack of O and M for appurtenances ranging from catch basins to BMPs has a very significant impact on the hydraulic and water quality performance of such appurtenances. Therefore, field verification has the added complexity of the non-stationary (generally declining) temporal performance of a BMP.

General Description of BMP Field Verification and Modeling of BMP Performance

The basis of transport and fate of PM and other pollutants in natural and engineered BMPs, at the most rigorous macroscopic level of description, are the Navier-Stokes (NS) equations. Derivation of the NS equations to examine fate and mitigation strategies starts with the basic laws of conservation of mass, momentum and energy which apply to all natural and engineered BMP systems. The resulting equations would be the Navier-Stokes (NS) system of non-linear partial differential equations (PDEs) for multi-phase hydrodynamics and the fate (separation) of entrained pollutants (for example, particles) and the partitioning to these particles. While such a defensible analysis of field BMP performance is rare it is important to recognize that BMPs are amenable to such rigorous analysis whether the BMP is a simple batch settling tank or a screened hydrodynamic separator. The transport and fate of particles and pollutants (such as phosphorus that partition and distribute to particles) with such a defensible methodology for a BMP requires the following components.

Field Verification Components (with general BMP assessment needs)

1. **Geometric data component**: These are the data which geometrically define the domain of the BMP, essentially the BMP control volume (overall dimensions of the BMP system). For example the BMP system could be a wet vault, a hydrodynamic separator pre-treatment device or a combination of multiple unit operations and processes (UOPs) such as a wet vault followed by a cartridge filter. The geometric data are commonly generated by as-built drawings, as-built surveying data, manufacturer's drawings/specifications and surveying data for inflow and outflow geometries (pipe dia., slope, material, outflow geometry, soil cover, elevations, etc.). In modeling efforts, a Computer Aided Design (CAD) module is used to generate and modify (in the case of design or retrofits) the geometry of the BMP system. The data inputs are:
   a. A three dimensional description of BMP system through detailed CAD drawings or engineered drawing, including all inflow and outflow conveyance geometries. From such data, stage-storage, stage-outflow, inflow-storage functions are developed.
   b. This should be a common and conventional requirement for urban drainage and BMP system design/construction. Those who are carrying out the modeling, the CAD tasks, and those gathering field data and geometric data inputs should have the background and experience for such tasks.
   c. This is not significantly different than conventional as-built data, but with the need for standardization across protocols.

2. **Boundary-initial conditions data component:** These are the data that define the "quantity" and "quality" parameters at the BMP system boundaries. These parameters are classified as:
   - **Hydrologic** (rainfall, previous dry hours, wind, air temperature, relative humidity, infiltration, evaporation, watershed storage, watershed characteristics),

- **Hydraulics** (flow rate, velocity, cross-sectional flow area, wetted perimeter, roughness, shear stress, hydrodynamic regime, temperature, degree of saturation, residence time distributions, RTD as developed from tracer studies),
- **Chemistry** (chemical species concentrations, temperature, turbidity, dissolved gas concentrations, partitioning, kinetics, pH-redox couples), and
- **Particulate** (particle size distributions, PSDs, particulate matter measured as suspended sediment concentration - SSC, suspended solids measured as TSS, trash, floatables, constituent distribution on PSDs, specific gravity, surface area, surface charge, solubility, exchange capacity, leaching, sludge and sediment properties including depth, density and cohesive-frictional properties)
- **Porous medium, soil or filter matrix** (porosity, pore size distribution, media or soil size distribution, tortuosity, effective porosity, surface area, exchange capacity, mineralogy, aquifer dynamics, equilibria, kinetics, breakthrough, hydrodynamics, moisture content – hydraulic conductivity relationships and head loss, leaching)
- **Vegetation** (species, hydraulic and friction properties, uptake and release equilibria, growth and uptake kinetics, leaching, specific gravity, flexural properties)
- **Microbiological** (species, size, charge, number, specific gravity, growth kinetics, uptake rates, hydrodynamic selection criteria and washout)

These parameters apply to the inflows, the BMP system and outflows. Even this list of parameters provided herein is not exhaustive and it should be recognized that the scope of this committee is most directly towards PM separation. However, these are coupled phenomena, and as such the role of vegetation (such as in an infrastructure-constrained bio-detention cell), microbiology and chemistry are important for the fate of PM across a BMP. It is readily apparent that such boundary and initial condition data requirements are significant and many are significantly different as compared to conventional data collection practices, as can be seen from the list of parameters in each category. Therefore, at this point in time, three levels of boundary/initial conditions field verification requirements are proposed. These field verification requirements will be defined in three levels:

- "***Level 1***" field verification requirements are for event-based BMP examinations. ***"Level 2***" field verification requirements are more detailed, are appropriate for modeling unsteady-state BMP examinations, and require temporal input and output data as well as event-based system data.
- "***Level 3***" requirements are research or specialized datasets for BMP examinations.

Commensurate with the available length of the paper, the following is a draft summary of the field verification requirements for a BMP under a detailed Level 1 requirement.

Number of Events Monitored: (12 calibration, 3 verification events for modeling)

a. A minimum of 12 calibration and 3 verification events are required for a BMP system. Events should occur in a one year period, and event rainfall depth should be at least 0.25 inches. There should be at least 24 previous dry hours. This is similar to other BMP testing protocols around North America. Event mean flows should be reasonably distributed between 25 and 75 % of the BMP design flow rate.

Hydrologic: (initial storage depth required for CFD)

a. A ***watershed delineation*** so that a rainfall-runoff model can translate rainfall loadings to runoff loadings at the BMP system location for the watershed of interest. This is a hydrologic modeling input and should be a current and conventional requirement for BMP systems in any protocol.

b. A ***frequency distribution of the historical rainfall record*** for the watershed or locality. The maximum time increment between rainfall depth measurements during the event should be no greater than the time of concentration for the watershed. This is a hydrologic modeling input and should be a current and conventional requirement for BMP systems in any protocol.
c. A ***watershed-based and event-based temporal rainfall record*** for storm events captured. Representative rainfall depths should be recorded in increments of 0.01 inches or in time at increments no greater than 5 minutes for the watershed. This is a hydrologic modeling and should be a current and conventional requirement for BMP systems in any protocol.
d. A measurement of ***previous dry hours (pdh), wind speed and direction, air temperature, evaporation indices, and relative humidity*** for the watershed or locality on an event-basis. These data are readily available from a number of sites around most MS4s and do not require a weather station for the watershed where the BMP system is located.
e. A measurement of ***initial runoff storage depth and sludge depth*** should be made in the BMP.

Hydraulic:

a. ***Flow depths and velocities*** at increments no greater than 5 minute intervals for the entire inflow and outflow duration for each inflow and each outflow of the BMP system. These are direct BMP verification inputs and should be a current and conventional on-line measurement requirement for BMP systems.
b. ***Temperature***, for simplicity at increments to match hydraulic flow measurements for the entire inflow and outflow duration for each inflow and each outflow of the BMP system, as well as initial storage and final storage temperatures. These are indirect BMP inputs (to specify aqueous viscosity and density), and should be conventional on-line measurement requirement for BMP systems.
c. A ***temporal RTD*** for a high-flow calibration event and a lower-flow calibration event using a conservative tracer. This is carried with a known mass input of conservative tracer in the influent and temporal automated sampling of effluent with temporal discrete samples (not composited).
d. ***Pressure measurements*** should be made as a function of volume treated for BMP systems that contain a porous media including in-situ soil filters, taken on-line just upstream and downstream of filter. This is a critical need for porous media systems.
e. A ***calibration curve*** should be provided for each hydraulic measurement for each event. This should be required in any quality assurance plan.

Chemistry:

a. ***Constituent species and phases*** are analyzed from duplicated composite samples to provide event mean concentrations (EMCs). Recognizing that automated samplers cannot reproduce a representative PM; but to avoid endless debate over this topic, this methodology will nominally refer to “sampling” but not a method. These duplicate composited samples for an event will be composited by representative samplers for the entire duration of influent and effluent flow. The sampler is setup to house 4, 4 L (minimum composite volume) samples, unless larger volumes (i.e. 6 L composite samples) are possible. This additional volume is important for effluent samples. It is fully recognized that EMCs eliminate any temporal understanding of influent and effluent transport, and automated samplers cannot representatively sample influent and effluent flows (particularly influent particulate matter (PM) larger than approximately 75 μm and neutrally-buoyant material). However, for the sub-75 μm PM and the operationally-dissolved fraction of constituents such index methods will have to suffice until more representative measurements become more viable for common "Level 1" applications. Constituent selection is dependent on the receiving water impairments, BMP system and watershed. Calcium and alkalinity are also important measurements. An event-mean analysis of rainfall should be conducted.

b. All ***constituent analyses are conducted on fractionated (filtered) samples***; creating a dissolved fraction and a particulate fraction, operationally-separated using a 0.45 μm membrane filter. As with automated sampling and EMCs this masks the continuum of partitioning, but is a Standard Method, recognized by most laboratories, and will have to suffice. A digestion process is utilized to examine the constituent concentration associated with the dry PM (as TSS) retained on the membrane filter after the dry filter with dried TSS is weighed and the dry filter weight subtracted. The exact volume filtered to generate the TSS is also recorded along with the dry TSS mass retained on the membrane filter. It is noted that this fractionation occurs after the sample is pre-screened by passing each composite sample separately through a #200 (75 μm) stainless steel or nylon sieve (discussed in the particulate section).

c. A ***sample holding time of less than 24 hours***. No sample shall be held for more than 24 hours before analysis between the time the sample was taken and fractionation between dissolved and particulate-bound fractions, even under refrigerated conditions. While partitioning occurs at much shorter time intervals, within hours, there is currently no practical technology to fractionate rapidly without on-site personnel.

d. ***On-line temporal chemistry measurements*** should include pH, redox (hydrogen-based offset provided), temperature, turbidity, total dissolved solids – TDS and conductivity for influent and effluent. The on-line measurement technology has advanced to the point that these are commonly deployed applications for BMP systems.

e. A ***calibration curve*** should be provided for each chemistry measurement for each event. This should be required in any quality assurance plan.

<u>Particulate:</u>

a. A ***measured volume for each duplicated composite sample*** should be determined to the nearest 10 mL. Duplicated 4-L (or larger if possible) and 20-L composite sample should be prepared with the exact volumes recorded. The 4-L duplicated influent and effluent composite samples will be used for obtaining datasets d, e and f. The 20-L influent and effluent composite samples will be used for obtaining datasets b, c and h.

b. ***A pre-screening through a #200 (75 μm) stainless steel or nylon sieve*** of each duplicated 4 L composite sample and 20 L composite sample should be first carried out before fractionation at the 0.45 μm level by passing the entire volume that is free of any holes or grid weighed and gently disaggregated. This dried material will then be dry-sieved through the standard (#50) 300 μm, (#80) 180 μm, (#100) 150 μm and

(#140) 106 μm sieves. A mass balance shall be made by summing the mass components on each sieve allowing no greater than a 5% mass balance error from the original dry weight.

c. A ***determination of constituent mass distribution as a function of PSD*** is made through the appropriate extraction or digestion process for each particle size. This is more easily carried out for the influent samples. For the effluent samples, there may only be sufficient PM to carry out a larger than 75 μm analysis and a smaller than 75 μm analysis since a digestion process requires approximately 0.2 to 0.4 g of dry PM. This may require the utilization of larger effluent volumes to pass through the 75 μm pre-screen and the 0.45 μm membrane filter.
d. A ***set of 3, 500 mL TSS sub-aliquots is taken*** from each pre-screened duplicated composite sample that is well-mixed and these aliquots are taken and labeled in a consecutive manner. Before each sub-aliquot is taken, a turbidity measurement at mid-depth is taken. Each aliquot is taken from mid-depth of the composite volume. Each aliquot shall be completely filtered through a 0.45-μm filter, dried and analyzed for TSS and VSS using Standard Methods protocol. The relative percent difference between sub-aliquots must be < 10% on a gravimetric basis for TSS. The filtrate is saved, separated as required, and preserved for dissolved constituent analyses.
e. A ***set of 3 alkalinity sub-aliquots*** are also taken for alkalinity and other constituent measurements of choice for the filtrate.
f. A ***set of 3 PSD sub-aliquots***, approximately 750 mL will be used for PSDs for the sub 75 μm fraction. It is recommended that as part of any database these sub 75 μm fractions be compiled and also combined with the matching fraction larger than 75 μm to create a database that is available for BMPs, land use, cover conditions, hydrologic regions, seasons, etc. These PSD sub-aliquots must be matched with their TSS or SSC sub-aliquot partners in order to convert % volume of particles to an absolute gravimetric value in mg. Note that turbidity measurements are also included to examine the relationship for a site between turbidity and TSS (or SSC).
g. An ***estimation of sludge (sediment) depth*** should be made at the beginning and end of the monitoring. A 2000 dry grams sludge (sediment) sample should taken from the BMP (location determined from modeling or measurement of short-circuiting) for determination of PSD, specific gravity and contamination levels as a function of PSD.
h. ***A determination of specific gravity for the sub 75 μm and larger than 75 μm fractions*** for each 20 L composite sample should be made for 2 calibration events. Analysis will require the entire dry mass for each fraction of influent and effluent.

<u>Porous medium, soil or filter matrix:</u> (datasets a and b are required for CFD)

a. A ***representative set of porosities*** of a porous medium, whether surrounding soil of an infiltrating BMP or as a filter matrix should be measured.
b. A ***representative set of filter or soil media size distributions*** should also be measured.

<u>Vegetation:</u>

a. An ***identification of the vegetation species*** and approximate size should be provided.

<u>Microbiological:</u>

a. An ***identification of the redox conditions and microbial consortium*** and their numbers in the water column or media (or soil) column should be approximated.

Rationale for Level 1 Methodology

Particulate matter in stormwater ranges from sub-micrometer-sized colloidal organic matter to millimeter-sized sand, silt and gravel, sometimes more than six-order of magnitude. Particulate matter in the stormwater runoff indicates any particles larger than nominal size of 1 µm and is categorized into two fractions by size: coarse and fine particles.

The "coarse" fraction includes all particle sizes larger than 75 µm and this size is from published classifications that separate "coarse" from "fine" particles and silt from sand at 75 µm. This fraction includes not only coarse sand (inorganic particulates) but also litter (i.e. paper, plastic, metal, glass) and biogenic detritus (i.e. leaves, twigs and grass). This is the size fraction which pre-treatment stormwater BMPs can be effective. The "fine" fraction represents particles with size smaller than 75 µm and larger than 1 µm. From a treatability perspective, fine particles are far more difficult to be removed by most pre-treatment of BMPs. Primary and secondary unit operations and processes such as hydrodynamic separators are effective in reducing the concentration and load of the coarse fraction of PM, but have varying effectiveness in reducing concentration as a function of flow rate, residence time, design, PSD, and maintenance for PM smaller than 75 µm.

Table 1 PM fractions, corresponding nominal size ranges, analysis method in stormwater

Particle fraction		Nominal size range	Operational Analysis Method
Particulate matter	*Fine fraction of particulate matter, PM*	1 to 75 µm	Particles pass through the #200 sieve (ASTM D422 1993) (ASTM 1998)and remain on standard fiber glass filter (Standard Method 2540 D) (APHA 1995)
Particulate matter	*Coarse fraction of particulate matter, PM*	larger than 75 µm	Particles remaining on the #200 sieve (ASTM D422 1993) (ASTM 1998)

For both of individual manually-taken discrete samples or composite automatic samples, coarse fraction of particles is operationally separated by pre-screening (wet sieving using the original stormwater matrix). Particles separated on the surface of #200 (75 µm) stainless steel or nylon sieve are the coarse fraction. This pre-screening of coarse fraction of particles is important since for raw stormwater influent the existence of this coarse fraction results in the coarse fraction dominating the gravimetric load, represents an O and M issue and is a labile fraction from which constituents can desorb. However, it should be recognized that it is the suspended fraction that is most mobile and bio-available; and if the BMP is effective in reducing concentrations of suspended PM the coarse PM will also be effectively removed. To characterize the BMP performance for both fractions is critical, but for different reasons. Recognizing that automated sampling increasingly mis-represents the PSD gradation as PM sizes become larger, are fewer in number and become less dispersed (more stratified) in the stormwater matrix (i.e. the coarse fraction), the "Level 1" methodology should develop a protocol to minimize this mis-representation, recognizing that adoption of more appropriate sampling methods is years away. The coarse fraction is processed and analyzed in the particulate component section.

Particle size distribution (PSD) analysis

Constituent partitioning and distribution is a function of the PSD of PM in stormwater. For the measurement of PSD in stormwater, sieve analysis is generally appropriate for the coarse fraction larger than 75 µm which can illustrate significant variability depending on availability and hydrology; or laser diffraction (or similar) methods for the fine fraction less than 75 µm. Since many stormwater BMPs such as wet vaults or hydrodynamic separators function in reducing concentrations of the coarse fraction of particles, particles larger than 75 µm are pre-screened and recovered prior to an effluent PSD analysis. This is reasonably consistent with the modeled behavior of many BMPs that illustrate significant concentration reductions in PM larger than 75 µm as conceptually illustrated in Figure 1; and the analysis of these two PM fractions is in keeping with Betty Ruston's Gross Solids Committee to ASCE. The PSDs for stormwater influent EMCs and effluent (after 60 minutes of quiescent settling) EMCs are illustrated in Figure 2 for rainfall-runoff events before and after settling from a Baton Rouge watershed. There are two options for PSD analysis of this fine fraction less than 75 µm: particle volume or number techniques and parametric analysis. Several particle analysis techniques have been utilized to characterize stormwater.

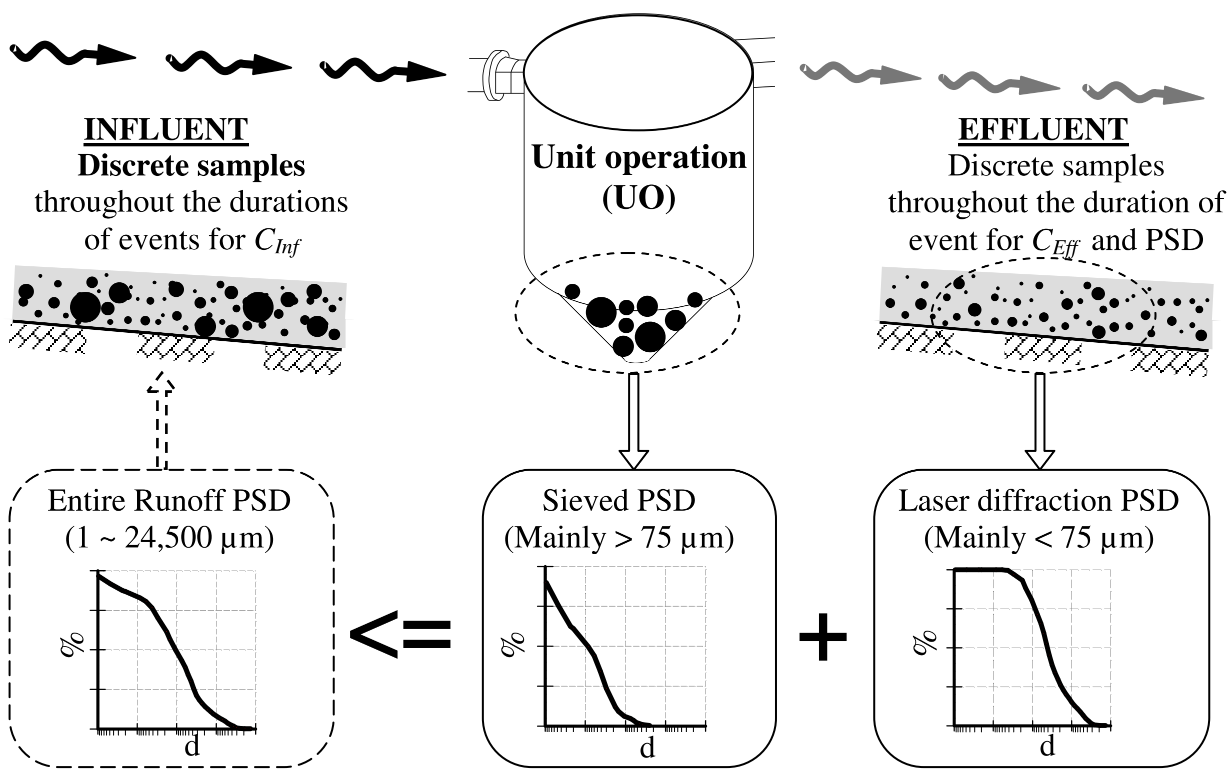

Figure 1. Conceptual diagram of the methodology to fully characterize the entire non-colloidal range of particle size distribution (PSD) of PM (PM) transported in runoff. (d: PM diameter)

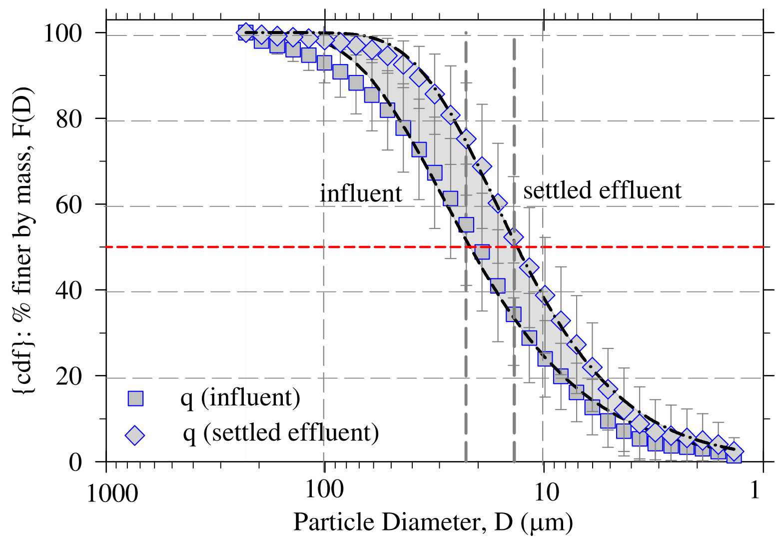

Figure 2. Figure 2 illustrates the influent PSD transported from the downstream outfall of a Baton Rouge watershed after hydrodynamic separation into a settling basin and the effluent PSD from the basin after 1 hour of quiescent settling. It is noted that the d_{100m} of effluent PSD is approximately 70 μm.

For a situation where such technologies are not available, parametric analysis is proposed as an alternative option. The key idea of this parametric analysis is from the assumption that the temporal and inter-event variations of size distribution of particles less than 75 μm are relatively small compared to the coarse fraction (particles larger than 75 μm). In addition, the fine fraction of particles is the size range where most typical BMPs have difficulty in removing particles. These finer particles are more mobile and more bio-available. Therefore, from a practical and mechanistic point of view, it would be reasonable to put the focus on the PSD analysis for the size range less than 75 μm.

Conclusions

The Field Verification Sub-Committee of the Guidelines for Certification of Manufactured Stormwater BMPs Task Committee is in the process of developing guidance for field verification protocols for manufactured stormwater BMPs. This paper outlines one level of requirements involved with defensible and transferable field verification for a BMP. The requirements and level-of-effort increase with the level of field verification required; in this case, a level 1verification is illustrated. When combined with controlled laboratory testing and scaling for the same BMP; that allow rigorous mechanistic analysis and model development, the combination of such testing/monitoring campaigns with field verification of the same BMP results in a tripartite verification of BMP behavior. Even though the focus is limited to PM the Sub-Committee and Task Committee have much more work to carry out. This document as well as future documents will not be without controversy but are intended as a significant step forward. The creation of a more uniform defensible and transferable laboratory, scaling and field verification program for BMPs allows a representative "chili-cookoff" for BMPs which benefits all stakeholders and most importantly the environment.