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EXPERIMENTAL AND NUMERICAL ANALYSES ABOUT THE EFFICIENCY OF FLOW THROUGH DEVICES FOR THE SEDIMENT CONTROL IN URBAN RUNOFF

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“A little experience often upsets a lot of theory.”

Cadman

CONTENTS

Abstract

As land is developed, the impervious surfaces that are created increase the amount of runoff during rainfall events, disrupting the natural hydrologic cycle, with an increment in volume of runoff and in pollutant loadings. Pollutants deposited or derived from an activity on the land surface will likely end up in stormwater runoff in some concentration, such as nutrients, sediment, heavy metals, hydrocarbons, gasoline additives, pathogens, deicers, herbicides and pesticides. Several of these pollutants are particulate-bound, so it appears clear that sediment removal can provide significant water-quality improvements and it appears to be important the knowledge of the ability of stromwater treatment devices to retain particulate matter. For this reason three different units which remove sediments have been tested through laboratory. In particular a roadside gully pot has been tested under steady hydraulic conditions, varying the characteristics of the influent solids (diameter, particle size distribution and specific gravity). The efficiency in terms of particles retained has been evaluated as a function of influent flow rate and particles characteristics; results have been compared to efficiency evaluated applying an overflow rate model. Furthermore the role of particles settling velocity in efficiency determination has been investigated. After the experimental runs on the gully pot, a standard full-scale model of an hydrodynamic separator (HS) has been tested under unsteady influent flow rate condition, and constant solid concentration at the input. The results presented in this study illustrate that particle separation efficiency of the unit is predominately influenced by operating flow rate, which strongly affects the particles and hydraulic residence time of the system. The efficiency data have been compared to results obtained from a modified overflow rate model; moreover the residence time distribution has been experimentally determined through tracer analyses for several steady flow rates. Finally three testing experiments have been performed for two different configurations of a full-scale model of a clarifier (linear and crenulated) under unsteady influent flow rate condition, and constant solid concentration at the input. The results illustrate that particle separation efficiency of the unit is predominately influenced by the configuration of the unit itself. Turbidity measures have been used to compare turbidity

with the suspended sediments concentration, in order to find a correlation between these two values, which can allow to have a measure of the sediments concentration simply installing a turbidity probe.

1. Introduction: stormwater quality and sediment removal measures

1.1. Sommario

Il continuo incremento delle aree urbanizzate e la necessità di tutelare i corpi idrici riceventi richiedono un'ampia comprensione dei fenomeni di accumulo e dilavamento del materiale particolato presente sulle superfici impermeabili, nonché delle caratteristiche dello stesso. È infatti noto che buona parte delle sostanze inquinanti presenti sulle superfici urbane aderisce alle particelle solide, in quantità e con modalità che variano in base alla granulometria delle particelle stesse. Diverse sono le misure che si possono adottare per trattare le acque di pioggia: dalle best managment practices, come trincee filtranti, bacini di ritenzione, bacini per la fitodepurazione, ecc., a soluzioni tipiche del nostro Paese come le vasche di prima pioggia.

Tra le varie modalità di rimozione delle particelle solide, la più semplice è la sedimentazione; l'efficienza nel trattenere il materiale solido è funzione delle caratteristiche del materiale stesso (granulometria e peso specifico) e del funzionamento del manufatto. Le attività sperimentali sia di laboratorio sia di campo sono ancora oggi uno degli strumenti più utilizzati per determinare quali grandezze influiscono sulla funzionalità idraulico-ambientale di tali unità, al variare delle caratteristiche degli eventi di pioggia e del materiale dilavato dalla sede stradale. Inoltre le prove sperimentali forniscono dati utili all'elaborazione di modelli sofisticati, che permettono di fare previsioni e fornire indicazioni sulle tempistiche di manutenzione di tali manufatti. Con tale scopo nella presente tesi sono stati testati tre diversi manufatti, caratterizzati dall'essere dispositivi in continuo, ossia che trattano tutta la portata in ingresso; i manufatti oggetto di studio sono i seguenti: una caditoia stradale, un separatore idrodinamico e una vasca di sedimentazione. Essi risultano caratterizzati da geometria e capacità notevolmente differenti tra loro, ma funzionano tutti sfruttando il principio della gravità. Le prove sperimentali sono state condotte in condizioni di portata sia costante che variabile e utilizzando materiale solido in ingresso caratterizzato da granulometrie di vario tipo (materiale solido sia monogranulare sia assortito). I risultati sperimentali sono stati confrontati con quelli che si ottengono dall'applicazione di formule sintetiche desunte da letteratura. Tali risultati, inoltre, possono essere utilizzati per applicazioni future come parametri di calibrazione di modelli più complessi.

1.2. Introduction

Sediments and dusts transported and stored in the urban environment are well known to provide high loadings of solid particles to receiving waters; for this reason urban runoff has been identified as a major contributor to the degradation of water bodies. Studies conducted by Pitt, et al.(1995) characterized the toxic contributions to urban runoff from sources such as roofs, parking areas, storage areas, streets, loading docks, vehicle service areas, and landscaped areas. From this investigation it turned out that roof, vehicle service area and parking lot runoff samples had the greatest organic toxicant detection frequencies and the highest levels of detected metals. Moreover these areas are particularly subjected to spills and leaks of automotive products and exhaust emissions from frequently starting vehicles. The organic compounds are associated especially with automobile and pesticide use, or are associated with plastics; heavy metals present in runoff water are originated by automobile use activities, including gasoline combustion, brake lining, fluids (brake fluid, transmission oil, anti-freeze, grease, etc.), undercoatings, and tire wear (Durum 1974; Koeppe 1977; Rubin 1976; Shaheen 1975; Solomon and Natusch 1977; Wilber and Hunter 1980).

The transport of this type of constituents is controlled by dry depositional processes (Wu et al. 1998), physiochemical interactions between water and the various phases of solids, suspension of constituents by turbulent water flow, and aquatic chemistry (Deletic and Maksimovic, 1998). Many deterministic rainfall-runoff models, to determinate runoff rate and volume, have been used to design hydraulic structures to convey rainfall runoff. On the contrary, due to the complexity of the phenomenon of transport and dispersion of pollutant during rainfall events, the history of pollutant transport modeling is relatively brief (Tomanovic 1990; Bertrand-Krajewski et al. 1993; Phan et al. 1994) and it is possible to state that a deterministic model reliable in the prediction of the pollution discharge does not yet exist (Bertrand-Krajewski et al. 1993). Rainfall-runoff simulation models consider some processes in the pollution generation and runoff process, like the build-up on impervious surfaces during dry periods, the wash-off during rainfall events, the conveyance in structures as gully pots, catch basins, etc. This suggests that the runoff phenomena is very complex; its modeling is essentially a problem of fluid mechanics controlled by the rainfall rate. As regards pollutants, their entrapment and their transport involve the interaction of atmospheric deposition processes (availability); chemical and physical interactions between water and solids (mobilization); hydrodynamic interactions between turbulent water flow and settleable solids (transport); and chemistry (mobilization and transformation). The contribution of individual components of the urban hydrological cycle to the transport and storage of particles and heavy metals has been studied: gully pots (Morrison et al., 1988), street and road surfaces (Xanthopoulos and Hahn, 1993; Gibson and Farmer, 1984; Hamilton et al., 1984), etc.

The wash-off and transport of solids cause a double problem: the presence of sediments in downstream sewers (*engineering issue*); pollution of downstream water bodies (*environmental issue*). Accumulations of sediments within pipelines and other network components can result in operational difficulties, like restrictions that reduce the passage of flows, premature overflows, and the inevitable pollution of watercourses (Fraser and Ashley, 1999). Sediment deposition in sewers is extremely widespread, because of the wide range of types of solids which enter the sewer system, and the intermittent and highly variable nature of inflow regimes. The use of sediment interceptors within sewer systems or downstream of stormwater intakes represents one way of alleviating these problems. Regarding pollutants, any pollutant deposited or derived from an activity on the land surface ends up in stormwater runoff in some concentration. However, there are certain pollutants and activities that are consistently more likely to result in degradation of a stream or receiving water, as previously stated. The direct effects of these pollutants on receiving waters are often a function of the size of the receiving water and the sensitivity of the inhabiting organisms. Sensitive species such as trout and stoneflies may be more susceptible to a range of pollutants than more pollution-tolerant organisms such as the black-nosed dace or certain leeches. However, assessing a toxic response from stormwater requires analyses that consider variable concentrations with variable durations of exposure. Certain pollutants even at low levels are of greater concern when receiving waters have specific beneficial uses such as swimming or fishing. Drinking water reservoirs require more sensitive stormwater controls to lower levels of pollutants because the water is being managed for human consumption.

1.3. Impacts of urbanization on runoff

1.3.1. Increased runoff

The porous and varied terrain of natural landscapes like forests, wetlands, and grasslands traps rainwater and snowmelt and allows them to filter slowly into the ground. Development and urbanization can change the hydrologic response of the watershed in an impressive way. Considering the environment conditions before and after the development, it is evident how the vegetation has a fundamental role in the interception of precipitation; indeed the rainfall water can be directly intercepted by the vegetation, or can be infiltrated into the ground. Urbanization can remove this beneficial vegetation, replacing it with impervious surfaces, like roofs, parking lots, roads, thereby reducing the site's pre-developed evapotranspiration and infiltration rates. In addition, construction activities may also compact the soil and diminish its infiltration rate, resulting in increased volumes of stormwater runoff from the development site. Impervious areas discharge rainfall water directly to gutters, channels, and sewer systems; this water transfer occurs more quickly than vegetated conveyances; this shortening of the travel time quickens the rainfall-runoff response of the site, causing faster and higher pick flow in downstream waterways than under natural or pre-developed site conditions. These increases can create downstream flooding and erosion problems and can increase the quantity of sediment and other pollutants in the waterways. With the increasing of the impervious areas the opportunities for the runoff to be infiltrated by natural surfaces decrease and the groundwater recharge decreases as well. Reduced base flows and increased peak flows during wet weather produce greater fluctuations between normal and storm flow rates, which can negatively impact the health of biological communities that depend on these base flows.

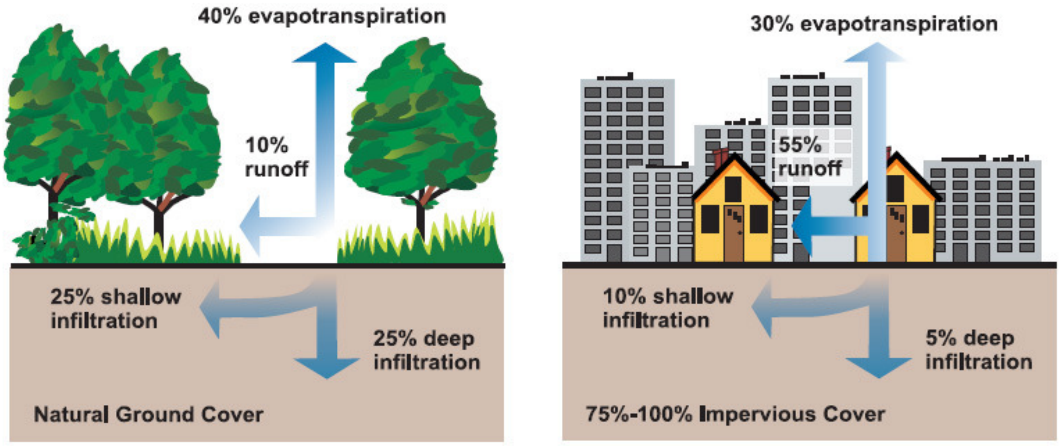

Figure 1.1 - Relationship between impervious cover and surface runoff: impervious cover in a watershed results in increased surface runoff and a reduction in infiltration (by the Federal Interagency Stream Restoration Working Group – FISRWG)

1.3.2. Runoff quality

Land development causes an increase in runoff volume and pollutant concentrations. On the impervious areas the accumulation of a variety of pollutants from the atmosphere, fertilizers, animal wastes, and leakage and wear from vehicles occurs. Pollutants can include metals, suspended solids, hydrocarbons, pathogens, and nutrients. Common pollutants found in stormwater runoff are shown in table 1.1.

Pollutant Typical Concentration	
Total Suspended Solids (a)	80 mg/l
Total Phosphorus (b)	0.3 mg/l
Total Nitrogen (a)	2.0 mg/l
Total Organic Carbon (d)	12.7 mg/l
Fecal coliform bacteria (c)	3600 MPN/1000 ml
E. Coli bacteria (c)	1450 MPN/100 ml
Petroleum hydrocarbons (d)	3.5 mg/l
Cadmium (e)	2 µg/l
Copper (a)	10 µg/l
Lead (a)	18 µg/l
Zinc (e)	140 µg/l
Chlorides (f)	230 mg/l
Insecticides (g)	0.1 to 0.2 µg/l
Herbicides (g)	5.0 µg/l
Notes 1. Data sources: a Schueler (1987), b Schueler (1995), c Schueler (1997), d Rabanal and Grizzard (1996), e USEPA (1983), f Oberts (1995), g Schueler (1996). 2. Concentrations represent mean or median storm concentrations measured at typical sites and may be greater during individual storms. Mean or median runoff concentrations from stormwater hotspots are higher than those shown. 3. Units: mg/l = milligrams/liter ug/l = micrograms/liter; MPN = Most Probable Number	

Table 1.1 - Common pollutants found in stormwater runoff

Solids and floatables

Solids and floatables are one of the most concerning surface water pollutant. They are wastes or debris floating or suspended; these materials include debris such as bottles, jars, cans, paper bags, newspapers, plastic containers and wrappings, leaves, branches. Solid/floatable materials are wastes that have been disposed of either on land or directly into stormwater conveyances and during rainfall event they are transported by runoff to receiving waters. Solid/floatable material can create odors, aesthetic problems, and even toxic or corrosive gases that can emanate from bottom mud deposits.

Suspended solids are of concern in runoff because they are able to clog infiltration areas (Crites, 1985) and treatment devices that use infiltration. During percolation suspended and colloidal particles are trapped by pores of small diameter. Coarse texture soils allow deep penetration of these particles and if the water table is close to the surface, the suspended particle enter the aquifer and increase the turbidity and pollutant content of the groundwater (Bouwer, 1985; Treweek, 1985).

Sediments

Sediment is one of the most significant pollutants created by development and transferred by runoff. Sediments consist largely of soil materials eroded from uplands as a result of natural processes and human activities. The greatest sediment loads are exported during the construction phase of land development. Sediment and other nonpoint source pollution from agricultural sources is also a major contributor to water quality problems. High concentrations of suspended sediment in streams and lakes cause many adverse consequences (increased turbidity, reduced light penetration, …). Solids also enter the runoff stream from vehicle emissions, vehicle tire, engine and brake wear, as well as through pavement wear and atmospheric deposition. Sediment is also an efficient carrier of toxins and trace metals. Once deposited, pollutants in these enriched sediments can be remobilized under suitable environmental conditions and threaten benthic life.

Solids in storm water runoff are classified using various methods, mostly as a function of size. Total solids (TS) encompass all solids found in runoff, both suspended and dissolved. Total suspended solids (TSS) and total dissolved solids (TDS) are separated by what does and does not pass through a 0.45 µm filter (APHA, 1998). A PSD analysis further categorizes solids into size ranges. The American Association of State Highway and Transportation Officials (AASHTO) divide size classes for solids into gravel, sand, silt, and clay. Solids larger than 2000 µm are referred to as gravel, between 75 and 2000 µm as sand, 2 and 75 µm as silt, and less than 2 µm as clay (Das, 1998). The sizes of particles in storm water runoff can significantly affect various physical and chemical processes. Fine particles may agglomerate, causing PSD to vary along the longitudinal path of storm water runoff (Minton, 2002). Larger particles settle faster than smaller particles. This settling mechanism affects the relative concentrations of different sizes of particles depending on runoff velocity and depth of flow.

Dissolved solids refer to any minerals, salts, metals, cations or anions dissolved in water. This includes anything present in water other than the pure water molecule and suspended solids. In general, the total dissolved solids concentration is the sum of the cations (positively charged) and anions (negatively charged) ions in the water. Parts per million (PPM) is the weight to weight ratio of any ion to water. Some dissolved solids come from organic sources such as leaves, silt, and industrial waste and sewage. Other sources come from runoff from urban areas, and fertilizers and pesticides used on lawns and farms. Dissolved solids also come from inorganic materials such as rocks and air that may contain calcium bicarbonate, nitrogen, iron, phosphorous, sulfur, and other minerals. Many of these materials form salts, which are compounds that contain both a metal and a nonmetal. Salts usually dissolve in water forming ions; water may also pick up metals such as lead or copper as they travel through pipes used.

Suspended solids are small solid particles, which remain in suspension in water as a colloid or due to the motion of the water. Generally the amount of particles that suspend in a sample of water is called total suspended solids (TSS). It is used as one indicator of water quality. Suspended solids are important as pollutants and pathogens are carried on the surface of particles. The smaller the particle size, the greater the surface area per unit mass of particle, and so the greater the pollutant load that is likely to be carried. To remain permanently suspended in water (or suspended for a long period of time), particles have to be light in weight (they must have a relatively low density or specific gravity), be relatively small in size, and/or have a surface area that is large in relation to their weight. The greater the TSS in the water, the higher its turbidity and the lower its transparency.

Nutrients

Phosphorus and nitrogen are nutrients used by plants during photosynthesis. In general, undeveloped land produces relatively few nutrients; agricultural, residential, industrial, and commercial areas produce more nutrient loadings. In rural and residential areas, substantial amounts of nutrients originate from commercial fertilizers, manure from livestock feeding operations, or dairy farming. Pet wastes contribute nutrients to runoff in residential areas. Detergents and raw sanitary waste also contribute to nutrient loading. Highway runoff also contains phosphorous from motor oils, fertilizers, …. The action of phosphates and nitrates can be quite different. Although both can be transported by groundwater, phosphorus often combines with fine soil particles and remains locked in the soil until it is either utilized by plant life or eroded away with the soil. In the latter case, the phosphorus will flow along with the soil particles as suspended sediment. Nitrates in the soil remain much more soluble. During rainfalls, nitrates may pass below the root zone into the groundwater. This movement of nitrates into groundwater may cause a public health hazard. Under normal conditions, phosphorus and nitrogen are not generally regarded as problem chemicals. However, in excessive amounts, phosphorus and nitrogen present a problem by over-stimulating plant growth within the aquatic environment.

Pesticides

Pesticides are toxic substances, used routinely for agricultural purposes and in residential and commercial property maintenance to affect specific unwanted organisms. Pesticides are mostly found in dry weather flows from residential areas (Pitt and McLean, 1986) and have been related in some locations to the amount of impervious cover and to the distance the runoff must travel before infiltration (Lager, 1977; Pruitt et al., 1985; Butler, 1987; German, 1989; Domagalski and Dubrovsky, 1992; Wilson et al., 1990). These substances can produce toxic effects on ecosystems and human life by contaminating soil, water, and air. Numerous acute and chronic effects on humans and other organisms are associated with pesticide exposure. Pesticides are carried in stormwater from application sites by becoming dissolved or suspended in runoff or by binding to particulate matter carried in runoff. These pesticides can contaminate surface or groundwater through infiltration devices or overflow. The fate and transport of pesticides are dependent on their physical and chemical properties and their chemical interactions with the environment. Some pesticides are highly soluble in water and are easily flushed into aquatic ecosystems or groundwater. These substances reach groundwater when their residence time in soils is less than the time required to filter them or biologically or chemically convert them (Jury et al., 1983). Pesticides with low solubility may accumulate in sediments by adhering to particulate matter. Adsorption and absorption increase with the amount of organic matter present. These factors and the resistance to degradation of certain pesticides increase the persistence of these substances in the environment.

Metals

Concentrations of metals found in water can have adverse effects upon public health as well as upon aquatic biota: lead, which is often used as an indicator for other toxic pollutants in stormwater, can be harmful or deadly for human and aquatic life; zinc, although not harmful to humans at concentrations normally found in stormwater, can be deadly for aquatic life; cadmium can bio-accumulate in an ecosystem, soil microorganisms are especially sensitive to it, and it is harmful to human health; chromium damages fish gills, causes birth defects in animals, and is also dangerous to human health; mercury is a neurotoxin that bio-accumulates.

Some metals bind to soils and organic matter and are transported in sediment, while other metals dissolve in water. Rainwater is naturally slightly acidic, which increases its ability to dissolve heavy metals and compounds the health and environmental effects of stormwater runoff from urban areas. The transportation system is a primary source of metals in stormwater runoff to urban streams and groundwater. Cadmium, copper, cobalt, iron, nickel, lead and zinc are deposited into the environment by vehicle exhaust, brake linings, and tire and engine wear. They accumulate on roads, waiting to be washed into storm drains with the next rainfall. Pollutant concentrations in roadway runoff are positively correlated with traffic volume: all cars, even the cleanest vehicles, shed small amounts of metals, fluids, and other pollutants. Galvanized metal rooftops, gutters and downspouts are also a source of zinc in stormwater. Some copper comes from architectural uses and treated wood, and a primary source is brake pads. The land use produces different amounts of metals (Figure 1.2).

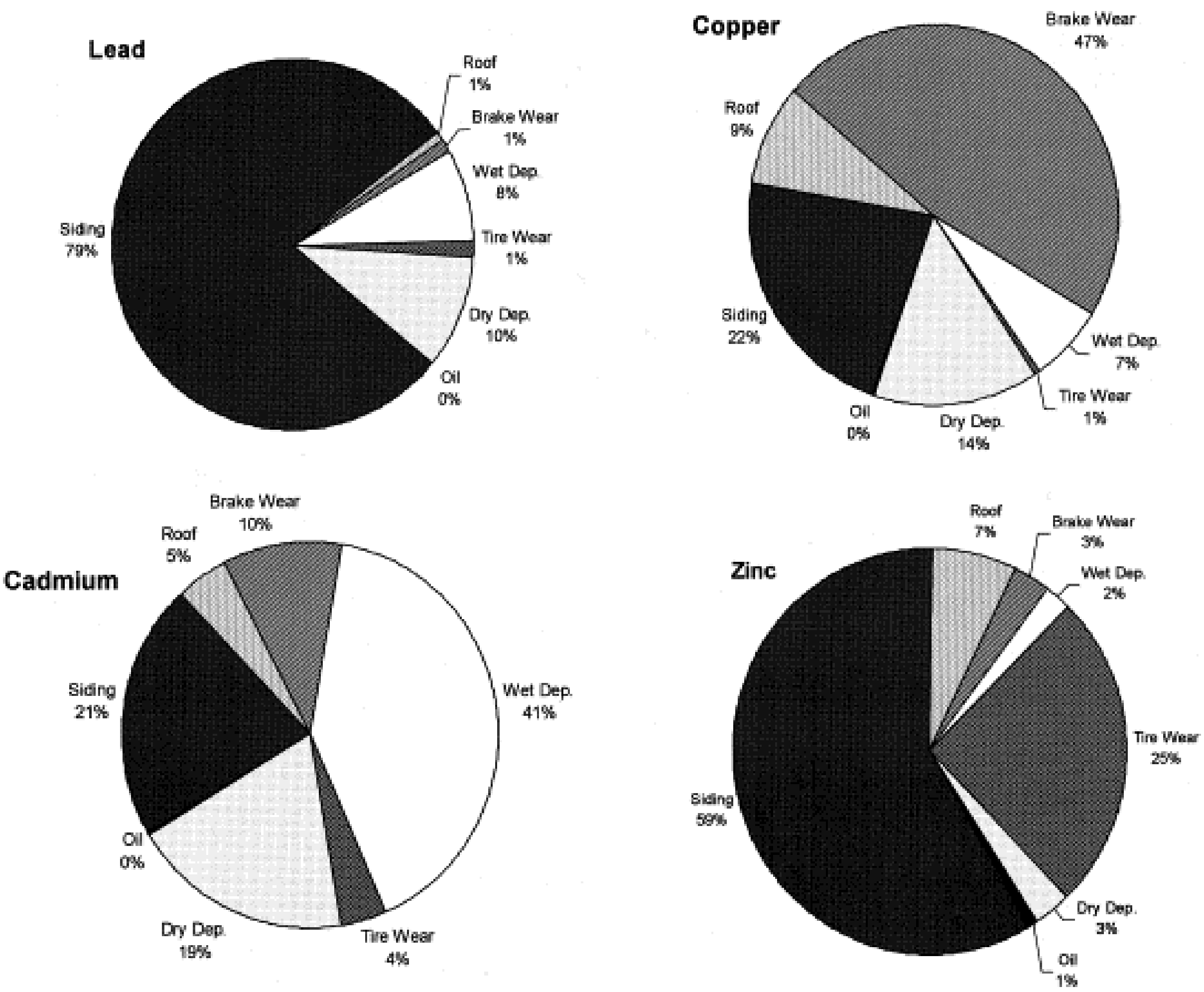

Figure 1.2 - Estimated contributors of various sources of metals in urban residential stormwater runoff (brick buildings); total loadings: Pb = 0.069 kg/ha/yr, Cu = 0.038 kg/ha/yr, Cd = 0.0012 kg/ha/yr, Zn = 0.646 kg/ha/yr (Davis et al., 2001)

Road Salt

Road salt is commonly used in order to melt snow and ice. During rainfall events precipitation falling on salted surfaces creates runoff containing dissolved salt, which has the potential to compromise vegetation, water quality and the aquatic ecosystem. Indeed the convey of dissolved salt by runoff can contaminate ground and surface waters, which may render them unusable or require expensive treatment procedures, since the increase in sodium chloride concentrations create displeasing drinking water and interfere with pristine manufacturing processes. Because of salt's long residence time, salt water often tends to build up concentration in groundwater. The input of high concentrated saline water into fresh water lakes can retard springtime mixing. The density of the bottom layer of water increases, thereby overriding the normal thermal density gradients responsible for vertical mixing. This saline buildup can decrease oxygen levels and cause high mortality among bottom dwelling organisms. Increased salt loading to bays and estuaries can alter natural saline concentrations and disrupt shellfish reproduction and fish spawning. Aside from contaminating surface and groundwater, high levels of sodium chloride can kill roadside vegetation and corrode infrastructure such as bridges, roads, and stormwater management devices. In addition, some industrial operations can be impaired by an increase in the salinity of intake water.

Figure 1.3 - Road salt used in winter period on road surface

Petroleum Hydrocarbons

Petroleum hydrocarbons in water are considered very harmful to natural biota; in addition, some constituents are carcinogenic and toxic to humans. No numerical criteria exist for petroleum hydrocarbons in ground or surface water quality standards. In both cases and in most waters, the basic criterion is “none noticeable.” Additional requirements for surface water prohibit hydrocarbons on aquatic substrata, along the shore in quantities detrimental to the natural biota, and where they would render waters unsuitable for their designated uses. The same standards are generally applicable to oil and grease, which, except for petroleum hydrocarbons, are not considered especially dangerous. Control efforts are mainly directed toward hydrocarbons. Although the hydrocarbons harmful to water quality are mostly liquid at ambient temperatures, they are absorbed and adsorbed onto solid particles of sediment so rapidly that they are found mainly as particulates in runoff. Only considerable masses of oil will remain in liquid form in the larger storm drains. Petroleum hydrocarbons are also biodegradable in an aerobic environment, although at a relatively slow rate.

Pathogens

Pathogens (viral and bacterial) and non-pathogenic bacteria are found in the intestinal tracts of humans and other warm-blooded animals and are excreted with fecal wastes. A number of human diseases can be transmitted by runoff contaminated by fecal sources (typhoid fever, cholera, gastroenteritis, …). Deficient water treatment and groundwater contamination of wells are responsible for most of the outbreaks (65 percent) and cases (63 percent). The ingestion of shellfish harvested from contaminated waters can lead to disease as well. Human fecal contamination is primarily a sewage treatment problem complicated by cross-connections or interconnections between sanitary and storm sewers, where combined sewer overflows degrade surface waters and where faulty, improperly sized, or improperly located septic systems contaminate groundwater. Animal fecal material from livestock operations, domestic pet populations, and concentrated wildlife populations contaminate surface waters via overland runoff and stormwater sewer discharges. Groundwater contamination occurs in areas with very permeable soils and/or high groundwater tables and where sinkholes, fractured rock, and well casings provide possible entry routes. It is generally accepted that urban runoff will exceed desired bacterial limits. When considering stormwater contributions to the flow in a combined sewer system, the importance of stormwater control for bacterial water quality should be considered. While not directly responsible for disease, fecal coliform bacteria have traditionally served as the microbiological indicators for the potential presence of waterborne pathogens.

1.4. Stromwater quality control measures

To address these impacts it is necessary to rethink traditional approaches in the design of stormwater management measures. New approaches that can provide a mitigation to these problems are for example nonstructural stormwater management measures, also known as Low Impact Development Best Management Practices (LID-BMPs), which include reduction of impervious cover, maintenance of natural vegetation, and reduction of nutrient inputs. LID-BMP techniques can significantly reduce and even prevent the negative effects of land development on stormwater runoff described above. Among different practices that have the goal to prevent stormwater generation an creation of stormwater impacts (such as the protection of riparian areas with the use of vegetated buffers, the reduction of impervious covers, with the use of permeable pavers, …), the street sweeping on a programmed basis allows to remove larger debris material and smaller particulate pollutants, preventing this material from clogging the stormwater management system and washing into receiving waterways/waterbodies.

Besides non-structural BMPs, there are engineered stormwater control measures to mitigate changes to both quantity and quality of urban runoff caused through changes to land use (structural BMPs); among them, structural BMPs able to remove particulate matter (PM) are the following:

- *Wet detention basin*: depression or basin created by excavation or berm to create a permanent pool of water; above this permanent pool a temporary water quality pool holds the runoff that results from a 1 inch rain event and release this water over a period of two to five days; this allows the majority of the suspended sediment, and pollutants attached to the sediment, to settle out.
- *Detention wetland (extended and pocket)*: constructed wetland, similar to a wet pond, that incorporate wetland plants into the design; stormwater wetlands are fundamentally different from natural wetland systems, since they are designed specifically for the purpose of treating stormwater runoff, and typically have less biodiversity than natural wetlands in terms of both plant and animal life.
- *Dry detention pond*: depression or basin created by excavation or berm construction that temporarily store runoff and release it slowly via surface flow or groundwater infiltration following storms.
- *Dry extended detention basin*: depression created by excavation or berm construction that temporarily stores runoff and releases it after the storm; dry extended detention basins are designed to dry out between storm events, in contrast with wet ponds, which contain standing water permanently. Extended detention uses a control low flow outlet that releases water over time.
- *Sand filters*: device that filters stormwater runoff through a sand layer into an underdrain system that conveys the treated runoff to a detention facility or to the

ultimate point of discharge. The sand-bed filtration system consists of an inlet structure, sedimentation chamber, sand bed, underdrain piping, and liner to protect against infiltration.

- *Bioretention area (also called rain garden)*: excavated shallow surface depression planted with specially selected native vegetation to treat and capture runoff and underlain by a sand or if needed gravel infiltration bed.
- *Grassed swales*: typically long open drainage channels integrated into the surrounding development or landscape that are lined with grass or other vegetation. They are often used in residential and commercial developments as well as along highway medians as alternatives or enhancements to conventional storm.
- *Vegetated filter strip*: permanent, maintained strip of planted or indigenous vegetation located between nonpoint sources of pollution and receiving water bodies for the purpose of removing or mitigating the effects of nonpoint source pollutants such as nutrients, pesticides, sediments, and suspended solids.
- *Infiltration device*: infiltration refers to the process of stormwater entering the soil; there are many infiltration devices such as infiltration trenches, dry wells, infiltration basins, and so on. Infiltration devices can be used as a sole approach or in unison with other measures to manage stormwater. An infiltration device collects the rain that falls on site, stores it temporarily and then releases it slowly into the ground.
- *Hydrodynamic structure:* device designed to improve quality of stormwater using features such as swirl concentrators, grit chambers, oil barriers, baffles, micropools, and absorbent pads that are designed to remove sediments, nutrients, metals, organic chemicals, or oil and grease from urban runoff.

Figure 1.4 - Wet detention basin (left); dry detention basin (right)

Figure 1.5 - Residential on-lot rain garden (left); grassed swale(right)

These BMPs can be used alone or in combination to achieve the desired/required pollutant removal of PM (usually identified with the Total Suspended Solids - TSS). High sediment input can limit the longevity of certain BMPs, especially sand filters, bioretention, infiltration systems and stormwater wetlands. These BMPs should be placed in locations where not too high sediment loads are expected upstream in the future. The choice of the right BMP depends on several factors (besides the treatment capability requirement), such has required space, construction cost, maintenance effort, community acceptance and wildlife habitat. For these reasons (especially in case of site constraints) other solutions different from those presented can be taken in consideration.

During heavy rainfall, land developments increase the rate or volume of stormwater runoff; historically, this increased runoff was managed through regulations that required peak runoff rates leaving a site after development to be equal to those that existed prior to development. This control was accomplished using retention basins that store and then gradually release the runoff; a *first flush tank* is a tank designed to store stormwater corresponding to the first flush of the rainfall event, allowing its treatment; the first flush according to Italian regulation (Regional Law of Lombardia 62/1985) is identified as the first 5 mm of rainfall runoff uniformly distributed on the entire urban surface drained by the sewer system. The first flush tank can be inserted in both combined and separate sewer system, with different layouts, which depend on the position of the tank with respect to the main conduit of the sewer system.

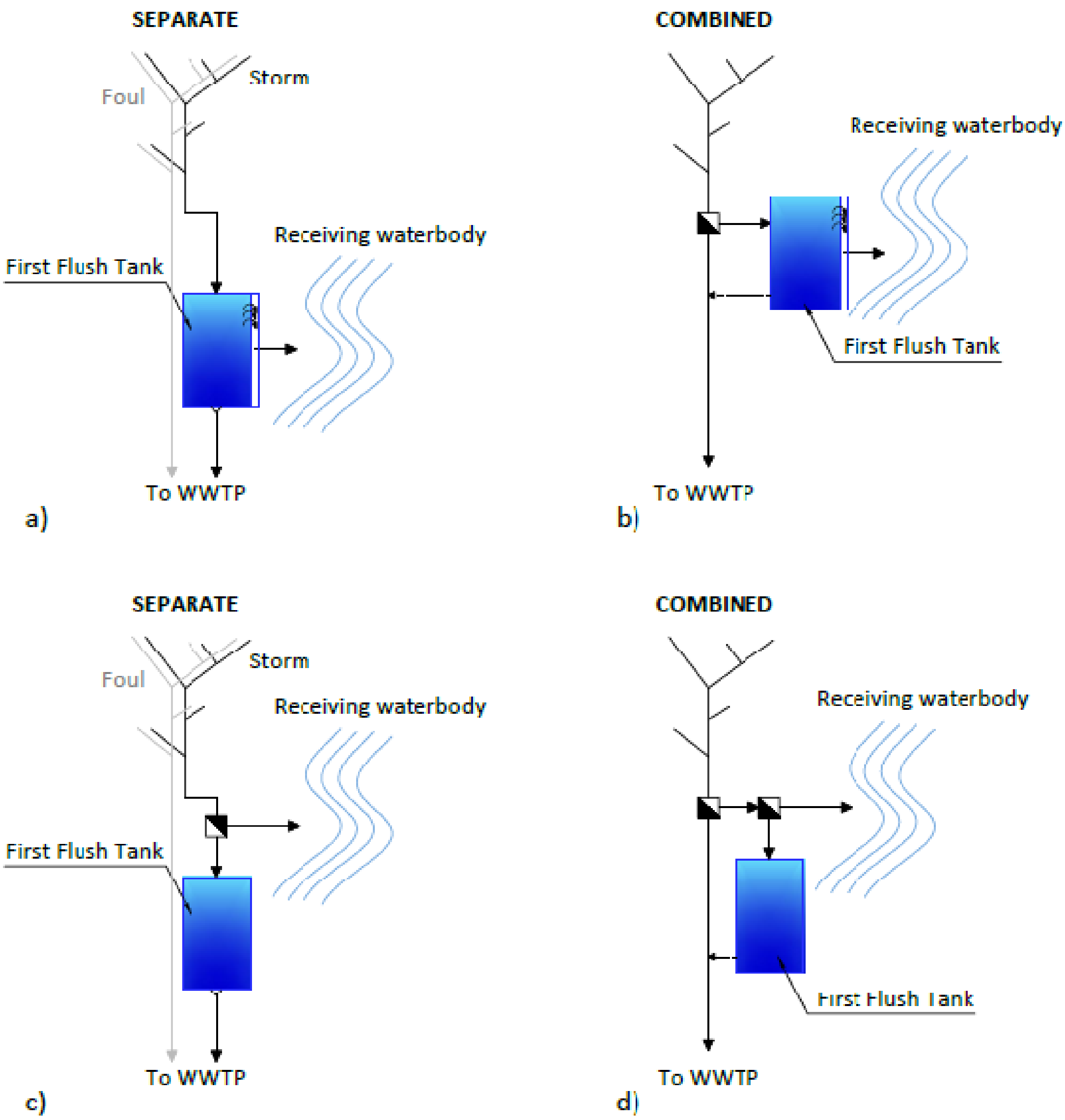

Figure 1.6 - Different layouts for a first flush tank

Figure 1.6 shows some possible layouts for a first flush tank for a separate and a combined sewer system. For the cases a) and b) the whole rainfall event passes through the tank, which can be considered as a *flow-through* device. For cases c) and d), instead, once the tank's capacity is over, a flow divider diverts the influent stormwater downstream, directly to the receiving waterbody; so in these cases the second part of the rain event is not treated, even if the level of pollution of this water runoff is unknown. In fact, the particles mobilization due to raindrops depends on their power and so on the rainfall intensities, which is not constant during a rainfall event. So it is not possible to be sure that the first volume of runoff is the most polluted.

In Italy the legislative decree 152/1999 and the subsequent 152/2006 delegate to each Region the assignment to regulate in which cases and ways the first flush rainfall water has to be dispose of. For example, Emilia Romagna Region in the regional committee resolution 286/2005 defines the amount of first flush rainfall water that need to be collected as the first 2.5 to 5 mm of water uniformly distributed on the entire drainage catchment, corresponding to 25-50 m^3/ha of contributing area; the volume stored have be gradually sent to the wastewater treatment plant. In Europe the most detailed regulatory indications are the German ones (ATV, 1992), which states that for the first flush tanks the capacity has to be determinate considering to retain a level of rainfall (ranging from 1.5 to 4 mm) equivalent to 15-40 m^3/ha of impervious surface. For the sizing of a first flush tank, the United States Environmental Protection Agency (USEPA) has provided the following table, which summarizes the parameters necessary to calculate the volume of rainfall to store within the tank.

Pollutants	Catchment surface	Examples of industries	Rainfall level to be contained
Substances easily mobilized, such as soluble materials, fine dusts and silts	Impervious: concrete, cement, bitumen	Concrete batching plants	10 mm
Substances that are more difficult to mobilise, such as oil, grease and other non-volatile hydrocarbons	Impervious: concrete, cement, bitumen	Petrochemical plants, motor vehicle courtyards, chemical manufacturers, hot mix bitumen emulsion plants, roadways	15 mm
All types of pollutant	Pervious surfaces (including natural ground surface) that are not as easily cleansed of deposited pollutants	Market gardens, nurseries	20 mm

Table 1.2 - Sizing parameters for first flush tanks, according to USEPA (2005)

1.5. Regulations

1.5.1. Italian regulation

In Italy legislation concerning water quality has been initiated with law 319/76 establishing for the first time emission standards for all discharges into watercourses and public sewers ("Legge Merli"). In 1999 the Italian government approved a law (DLgs 152/99) motivated by the need to transpose the European Directives (91/271/CEE "Treatment of urban sewage" and 91/676/CEE "Water protection from nitrate pollution") into the Italian Legislation; the main goals of the law were:

a) preventing and reducing pollution as well as restoring polluted water bodies ;
b) achieving improvement of the status of natural waters and adequate protection of water bodies, after defining objectives for their environmental quality accounting for their specific use;
c) promoting long term sustainable water use, with special attention to drinking waters, integrating protection of both quantity and quality of water resources in each hydrographic basin, and devising an appropriate system of controls and penalties;
d) preserving the natural capacity of auto depuration of water bodies, as well as their capacity to host wide communities of diverse animals and vegetal species.

The ultimate aim of the law was to achieve, within 2016, a status of "good environmental quality" for all the significant water bodies (sufficiently large rivers, lakes, transitional waters, artificial reservoirs, aquifers and water bodies with specific use, such as drinking use). In order to pursue these goals the law imposed respect of emission limit values set by the State such to achieve environmental quality standards for the receiving water bodies: in other words, the level of treatment required for waste waters was defined on the basis of the need to insure that the receiving water body meets minimum quality requirements. DLgs 152/99 had somehow anticipated the European Directive 2000/60/EC, which has the purpose to establish a framework for the Community action in the field of water policy or, in short, the EU Water Framework Directive(WFD) was finally adopted. However, a full transposition of the WFD has been enforced in Italy through DLgs 152/06 and its most recent modifications (DLgs 4/08), which provide a comprehensive treatment of the whole subject concerning the legislation on environmental matters. In particular DLgs

152/06 copes with the problems connected to the rainfall runoff pollution; in particular art. 113 establishes that Regions are the competent authorities for the managing of rainfall runoff water. For example Emilia Romagna Region issued the regional committee resolution 286/2005, concerning the management of the first flush rainfall water and the washoff of the external areas; subsequently, the Region has issued guidelines to address the management of stormwater runoff and rainwater (regional committee resolution 1860/2006). In order to achieve the water quality goals required by the WFD, Emilia Romagna has approved the water quality protection plan (PTA) with the resolution No. 40, December 21, 2005. The water quality protection plan defines the measures to protect water quality, in particular regulating the drainage of rainfall runoff water into water bodies.

Since the main goal of this study is testing devices for the sediment control, it is taken into account the limits prescribed by law for the maximum concentration of total suspended solids (TSS). DLgs 152/06 (attachment 5) reports TSS limit concentration for the discharges into water bodies and sewer conduits, respectively equal to 80 mg/l and 200 mg/l; Regions in order to protect and better water bodies quality can set lower limits.

1.5.2. American regulation

In the United States, Water Quality Standards are created by state agencies for different types of water bodies and water body locations per desired uses. The Clean Water Act (CWA) was the primary federal law in the United States that regulated the discharge of pollutants into the nation's surface waters, including lakes, rivers, streams, wetlands, and coastal areas. The principal body of law currently in effect was based on the Federal Water Pollution Control Amendments of 1972; major amendments were enacted in the Clean Water Act of 1977 and the Water Quality Act of 1987. The original goal of the CWA was to eliminate the discharge of untreated waste water from municipal and industrial sources and thus make American waterways safe for swimming and fishing.

The CWA requires each governing jurisdiction (states, territories, and covered tribal entities) to submit a set of biennial reports on the quality of water in their area. These reports are known as the **303(d)**, **305(b)** and **314** reports, named for their respective CWA provisions, and are submitted to, and approved by, EPA. These reports are completed by the governing jurisdiction, typically a Department of Environmental Quality or similar state agency The **305(b)** report (National Water Quality Inventory Report to Congress) is a general report on water quality, providing overall information about the number of miles of streams and rivers and their aggregate condition. The **314** report has provided similar information for lakes. The CWA section **402** introduced the National Pollutant Discharge Elimination System (NPDES), which is a permit system for regulating point sources of pollution; point sources include: industrial facilities (including manufacturing, mining, oil and gas extraction, and service industries); municipal governments and other government facilities (such as military bases); some agricultural facilities, such as animal feedlots. Point sources may not discharge pollutants to surface waters without a permit from the National Pollutant Discharge Elimination System (NPDES). This system is managed by the U.S. Environmental Protection Agency (EPA), which sets water quality standards, handles enforcement, and helps state and local governments develop their own pollution control plans.

Other sources, called nonpoint sources, were not subject to the permit program; for example agricultural stormwater discharges and irrigation return flows were specifically exempted from permit requirements; the CWA congress, however, provided support for research, technical and financial assistance programs at the U.S. Department of Agriculture to improve runoff management practices on farms. Stormwater runoff from industrial sources, municipal storm drains, and other sources were not specifically addressed in the 1972 law. EPA declined to include urban runoff and industrial stormwater discharges in the NPDES program and consequently was sued by an environmental group. The courts ruled that stormwater discharges must be covered by the permit program. A growing body of water research during the late 1970s and 1980s indicated that stormwater runoff was a significant cause of water quality impairment in many parts of the U.S. Between 1979 and 1983, EPA conducted the Nationwide Urban Runoff Program (NURP) to document the extent of the urban stormwater problem. The agency began to develop regulations for stormwater permit coverage, but encountered resistance from industry and municipalities; however in the Water Quality Act of 1987 (1987 WQA) Congress responded to the stormwater problem by requiring that industrial stormwater dischargers and municipal separate storm sewer systems (often called "MS4") obtain NPDES permits, by specific deadlines. The permit exemption for agricultural discharges continued, but Congress created a nonpoint source pollution demonstration grant program at EPA to expand the research and development of nonpoint controls and management practices.

The CWA introduced new rules that encouraged individual states to identify dirty waterways and establish standards to help eliminate sources of pollution; states, territories, and authorized tribes are required to develop lists of **impaired waters**. These are waters that do not fully support beneficial uses such as aquatic life, fisheries, drinking water, recreation, industry, or agriculture. These inventories are known as **303(d)** Lists and characterize waters as fully supporting, impaired, or in some cases threatened for beneficial uses. The law requires that these jurisdictions establish priority rankings for waters on the lists and develop TMDLs for these waters. A Total Maximum Daily Load, or TMDL, is a calculation of the maximum amount of a pollutant that a waterbody can receive and still safely meet water quality standards. Then the jurisdictions had to decide which local landowners or businesses needed to reduce their pollution levels to meet the TMDL. The jurisdictions were also required to evaluate future development plans near the waterways to make sure they would not increase pollution levels. A TMDL is the sum of the allowed pollutant loads for point sources, non-point sources, projected growth and a margin of safety:

TMDL = Point Sources + Nonpoint Sources + Projected Growth + Margin of Safety

Load allocations are determined through the review of monitoring data and watershed modeling. The tools used depends upon the complexity of the problem.

The Florida Department of Environmental Protection (FDEP) has adopted a methodology called “Identification of Impaired Surface Waters rule” (Chapter 62-303, Florida Administrative Code) to identify those ambient surface waters with quality characteristics that do not meet the standards; once a TMDL is developed, the FDEP works with stakeholders to remedy the causes of the poor water quality. TMDLs are designed to identify the reductions needed to restore the waterbody, such that the criteria are met. The lists of impaired water as well as final TDMLs adopted can be consulted at the FDEP web page. Limits are only set for water quality parameters that have a water quality criterion; in Florida, and many states, there is no water quality standard or criterion for TSS; for most Florida waters a turbidity standard set at 29 NTU above background is (Chapter 62-302, Florida Administrative Code).

1.6. The importance of sediment removal

Sediment is the largest, by mass, pollutant in our waterways. In addition, soil particles can absorb other contaminants such as phosphorus, hydrocarbons and metals, thereby providing a mode of transport. A number of techniques have emerged for the quantity and quality control of urban runoff. These have involved the use of 'soft' engineered structures such as swales, wetlands and ponds (Wilson et al., 2004), and 'hard' engineered structures, such as underground storage, treatment and flow control facilities (Faram et al., 2005), as previously observed. Both have been widely and successfully applied. In practice, the applicability of particular techniques depends on the context of the situation (overall management objectives, site factors, including space availability).

Research has highlighted the role of sediment in pollutant transport and dispersion (Pitt et al., 1995; Sansalone and Buchberger, 1997). As previously reminded, sediment particles absorb some chemical pollutants; as such, sediment entrained in urban run-off should ideally be prevented from entering the natural water environment. The optimal design of systems to remove pollutants from stormwater relies somewhat on an understanding of pollutant characteristics. In particular, for sediment removal, it is useful to have an understanding of the physical and chemical characteristics of the sediments, such that those presenting most potential to pollute can be specifically targeted. It is evident that the effectiveness of most stormwater control practices present in the urban environment is dependent on their capacity to remove these particles from the runoff. The removal of these particles depends on their characteristics, as size and specific gravity. In particular concerning particle size, large-sized particles are easier to trap with gravitational settling practices. Instead clay particles are chemically more active and therefore more likely to bond with land-applied chemicals; they also settle so slowly that is difficult to remove them by sedimentation.

1.6.1. Sedimentation process

Settling is the process by which the particulate matter in a liquid is removed by allowing the particles to settle under the influence of gravity, and it is classified into four types based on the concentration of particles in the liquid. It is important to classify the type of settling as it helps to better understand the mechanisms of settling. The four major types of settling are classified as Type I, Type II, Type III, and Type IV which are detailed below:

- **Type I:** discrete settling, is characterized by the free settling of particles without the influence of other particles and typically occurs in very dilute suspensions. Particles with a given settling velocity follow a straight trajectory and other particles with the same settling velocity follow parallel trajectories. Particles in Type I settling accelerate with a constant velocity until the drag force becomes equal to the impelling force, after which they travel with a constant velocity called the terminal velocity or the settling velocity.
- **Type II:** flocculent settling, describes sedimentation of larger concentrations of solids that tend to stick to one another and form flocculants, which settle at a faster rate than in single particle settling. To determine the settling velocities of the flocculent, batch settling tests are used. Batch tests are carried out in quiescent conditions and the temperature is held constant throughout the column to avoid convection. The overflow rate and percent removal can be calculated from these batch tests by measuring the volume of the overflow and determining the weight of the dry solids in it.
- **Type III:** hindered settling or zone settling, describes sedimentation of a suspension with solids concentration sufficiently high that particles are so close together that the inter-particle forces hinder the settling of neighboring particles. The particles settle at a constant velocity so the particles remain in the same position relative to the other particles, which causes the particles to settle in zones. A discrete solid-liquid interface exists above the settling particles.
- **Type IV:** compression settling, which occurs when the concentration of particles is much higher than is required for Type III settling. In compression settling, the concentration of particles is so high that they touch each other and settling can occur only by compaction of the particles; that is, the particles are pushed downward. The common types of particles to undergo compression settling are flocculent particles, though even discrete particles can settle by compression settling.

In this research only type I settling is taken into consideration.

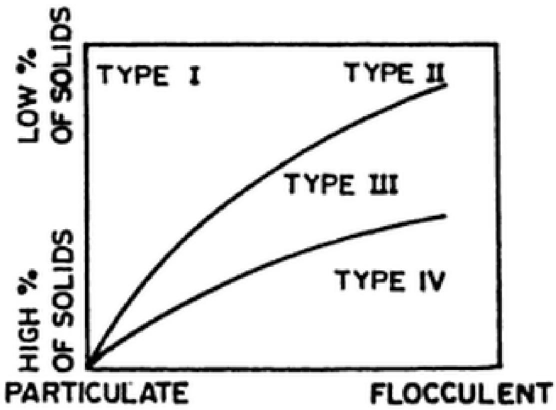

Figure 1.7 - Types of settling

Type I sedimentation is concerned with the settling/removal of non flocculating, discrete particles. The assumptions for Type I settling are the following: discrete particle settling; quiescent settling; constant particle settling velocities; linear particle motion; steady state conditions; absolute viscosity independent of the velocity gradient ; fluid viscosity are a function of temperature (Metcalf and Eddy 1990). When a discrete particle is placed in a quiescent fluid, it will accelerate until the frictional resistance (drag force, F_D) of the fluid equals the driving force acting on the particle. At this stage, the particle attains a uniform of terminal velocity and settles. The driving force is equal to the effective weight of the particle:

$$F_I = (\rho_s - \rho_w) \cdot g \cdot V \tag{1.1}$$

Where ρ_s = density of settling particle; ρ_w = density of water; V = volume of particle = $\frac{\pi \cdot D^6}{6}$, where D is the diameter of a spherical particle.

Considering the turbulent settling (Newton's Law), the drag force depends upon: dynamic viscosity (μ) of the fluid; the mass density (ρ) of the fluid; shape and size of the particle:

$$F_D = C_D \cdot A \frac{\rho \cdot v_s^2}{2} \tag{1.2}$$

From equations (1.1) and (1.2), the settling velocity results:

$$v_s = \left[\frac{4}{3} \frac{(\rho_s - \rho) \cdot g \cdot D}{C_D \rho} \right]^{1/2} \tag{1.3}$$

Equation (1.3) requires the determination of the drag coefficient C_D, which is related to Reynold's number Re by the following observational relationships:

i) For Re between 0.5 to 10^4:

$$C_D = \frac{24}{Re} + \frac{3}{\sqrt{Re}} + 0.34 \tag{1.4}$$

ii) For high Reynold's number ($Re > 10^3$ to 10^4), $C_D \approx 0.4$

iii) For low Reynold's number ($Re < 0.5$)

$$C_D = \frac{24}{Re} \tag{1.5}$$

Where Reynold's number is $Re = \frac{\rho \cdot D \cdot v}{\mu}$

Stokes' Law for the drag of small settling spheres in a viscous fluid neglects the inertia force and the drag coefficient becomes the (1.5) and the settling velocity:

$$v_s = \frac{(\rho_s - \rho_w) \cdot g \cdot D^2}{18\mu} \tag{1.6}$$

Where v_s = terminal settling velocity of particle; g = gravitational acceleration; ρ_s = density of settling particle; ρ_w = density of water; D = diameter of particle; μ = dynamic viscosity.

The above law is applicable for laminar or stream line settling of particles of diameter up to 0.1 mm, involving the value of Re less than 1.

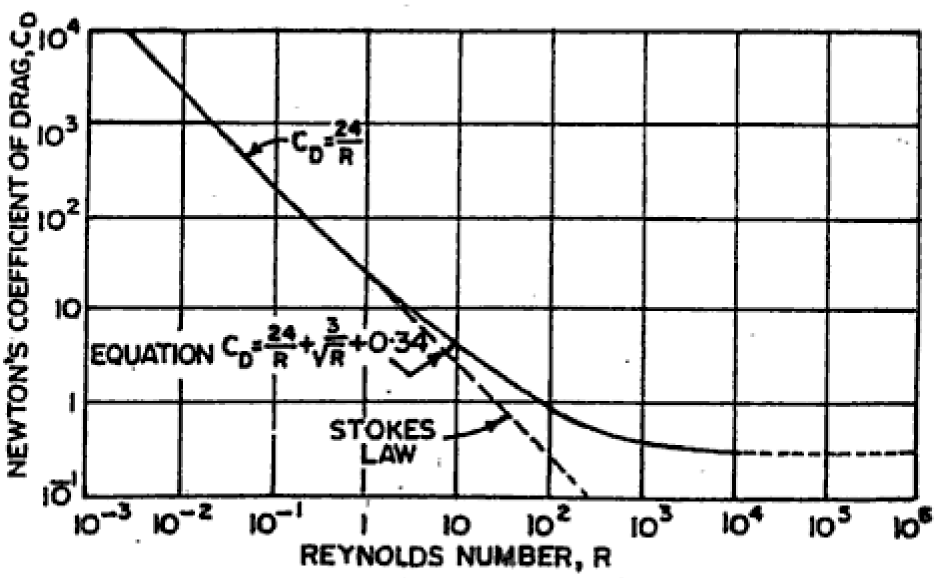

Figure 1.8 - Variation of the drag coefficient C_D, as a function of Reynold's number

To allow a particle to settle, it is necessary that its permanence within the treatment unit allows the settling of the particle itself. If a rectangular tank is considered, a particle within the tank begins to settle at its characteristic velocity (v_0); the detention time of the particle that enters at point 1 and get removed at point 2 (Figure 1.9) is given by:

$$t = \frac{H}{v_0} \tag{1.7}$$

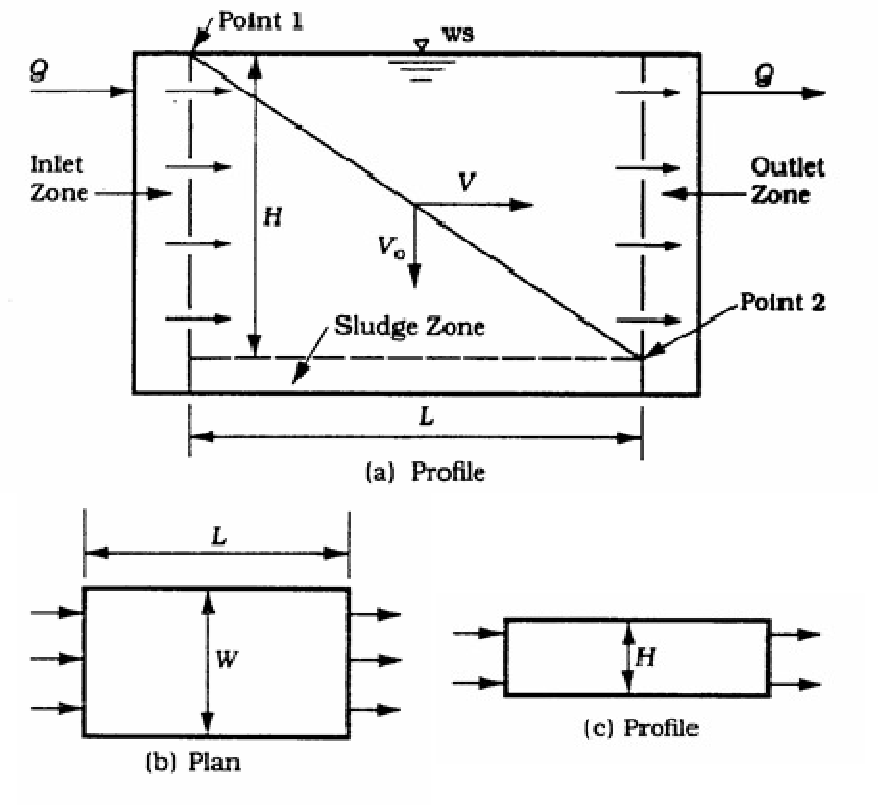

Figure 1.9 - Ideal rectangular tank (Type I settling)

The detention time is also equal to the length divided by the horizontal velocity (v):

$$t = \frac{L}{v} \tag{1.8}$$

The horizontal velocity is equal to flow rate (Q) divided by cross-sectional area:

$$v = \frac{Q}{H \cdot W} \tag{1.9}$$

In order to retain the particle with settling rate equal to v_0, it is necessary that:

$$\frac{H}{v_0} = \frac{L}{v} = \frac{L \cdot H \cdot W}{Q} \tag{1.10}$$

Which means a settling rate at least equal to:

$$v_0 \geq \frac{Q}{L \cdot W} = \frac{Q}{A_p} \tag{1.11}$$

With A_p plan area of the basin. The ratio Q/A_p is called "overflow rate"; it is important to notice that the removal efficiency is governed not by the depth but by the plan area of the tank. The same happens in case of a circular device.

In general the efficiency in terms of fraction of particles removed is given by the fraction of particles that have a settling rate greater than the overflow rate ratio:

$$\eta = 1 - \frac{1}{1 + \frac{Q/A_p}{v_0}} = \frac{v_0}{v_0 + Q/A_p} \tag{1.12}$$

When short-circuiting occurs, the ideal overflow rate model is no longer verified, as presented by equation (1.12); Hazen's non-ideal semi-empirical model allows to determinate the efficiency as a function of the short-circuiting factor "n" (Malcom 1989; Fair et al 1968):

$$\eta = 1 - \left[1 + \frac{v_s}{n(Q/A)}\right]^{-n} \tag{1.13}$$

Short-circuiting effects can be caused by eddy currents, surface wind currents, thermal convection currents, density gradients, and the irregular morphology of the basins; these factors generate functioning conditions different from ideal ones (plug-flow reactor). Conceptually, Hazen's short-circuiting factor "n" can be seen as the number of hypothetical continuously stirred tank reactors (CSTR) of which the basin is comprised. As "n" approaches infinity, the basin approaches plug flow.

1.7. Objectives

Since it has been clarified the importance of sediment removal in stormwater treatment, different types of devices have been taken into account in this study. The analyzed units differ for their geometrical characteristics (size and volume), but they guarantee particle removal through the settling mechanism (described in Section ***1.6.1***);

therefore each device will have a certain particle removal efficiency, which depends on its own dimensions and functioning. It is considered important the knowledge of this functioning, considering different inlet hydraulic conditions and particles characteristics; therefore the devices have been tested under different hydraulic conditions (steady and unsteady) and inlet particles loadings (mono-disperse and hetero-disperse samples, with constant concentration). The studied units are the following:

- **Roadside gullypot:** Roadside gully pot is a major component of many drainage systems used to protect the downstream sewers and receiving waters from excessive sediment deposits; their low capacity and the continuous feed of solids lead unavoidably to gradual silting and eventually to clogging problems.
- **Hydrodynamic separator:** Hydrodynamic separators (HS) use the physics of flowing water to remove a variety of pollutants; they are designed to separate floatables (trash, debris and oil) and settleable particles, like sediments, from stormwater. HS systems are not effective for the removal of very fine solids or dissolved pollutants.
- **Clarifier:** Clarifiers or settling tanks are large tanks in which water is made to flow very slowly in order to promote the sedimentation of particles; sediments settle out at the bottom of the unit and can later be removed during maintenance operations.

All these devices are *flow-through* units, designed to intercept all the influent flow and store pollutants such as sediments and floatables for later removal and safe disposal. The effectiveness of a *flow-through* treatment unit can be denoted by two key variables:

– Pollutants removal efficiency, that is the ability to ‘remove’ pollutants from the influent; typically the highest removal efficiencies is obtained at the lower hydraulic loading ranges;

– Pollutants retention efficiency, that is the ability to ‘retain’ pollutants, once collected; while related to hydraulic loading rate in most practical cases, retention efficiency is also strongly dependent on unit configuration.

Usually, the performance of this type of devices is stated only in terms of ‘ability to remove pollutants from the inflow’ (especially in terms of sediments), often at discrete flowrates. Retention efficiency, however, is rarely given consideration, since the the difficulties associated with measuring and quantifying the scour of material previously settled;

difficulties arise due to the fact that retention efficiency is time-dependent, in addition to being dependent upon hydraulic loading rates and stored pollutants characteristics and quantities.

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Internet web sites

http://www.dep.state.fl.us/legal/Rules/rulelistnum.htm

http://www.dep.state.fl.us/water/watersheds/assessment/index.htm

http://www.dep.state.fl.us/water/tmdl/final_tmdl.htm

2. Roadside gully pots: experimental tests and numerical model application

2.1. Sommario

Le caditoie stradali sono il punto di collegamento tra il deflusso superficiale e la fognatura, pertanto devono essere considerate come una parte rilevante e integrante dei sistemi di drenaggio urbano. È opinione ormai consolidata che la loro funzione principale è quella di proteggere il sistema di drenaggio a valle, gli impianti di trattamento e i corpi idrici riceventi da carichi eccessivi di sedimenti. Le caditoie, infatti, raccolgono le acque di dilavamento delle superfici impermeabili, che trasportano il materiale solido presente su tali superfici, carico di sostanze inquinanti. Il continuo approvvigionamento di materiale solido per un dispositivo che ha lo scopo principale di trattenere tale materiale, conduce inevitabilmente a problemi di intasamento, con conseguente perdita di efficienza. Questi aspetti risultano rilevanti nelle città italiane, principalmente servite da fognature miste, caratterizzate dalla presenza di caditoie provviste di sifone, per impedire la fuoriuscita di cattivi odori, ma particolarmente soggette a problemi di interrimento e intasamento. Questo studio ha l'obiettivo di analizzare il funzionamento di tali manufatti, determinando quali variabili influenzano la capacità di una caditoia stradale nel trattenere il materiale solido in ingresso (efficienza). A tale scopo, presso il laboratorio di Idraulica della facoltà di Ingegneria di Bologna, sono state eseguite svariate prove su una caditoia in plastica a base quadrata (40 x 40 cm), variando le caratteristiche degli eventi di precipitazione (portata in ingresso) e dei solidi in ingresso (diametro, distribuzione granulometrica e peso specifico). I risultati ottenuti sono stati confrontati con quelli ottenuti da precedenti studi e hanno verificato la validità di modelli sintetici desunti da letteratura. Tali modelli erano stati ricavati da prove sperimentali condotte in condizione di portata costante ed utilizzando esclusivamente campioni monogranulari come materiale in ingresso; le prove condotte in questo studio, invece, sono state eseguite utilizzando sia materiale monogranulare sia campioni assortiti, verificando quindi l'applicabilità di tali modelli anche a condizioni non precedentemente verificate. L'efficienza calcolata con le formule desunte da letteratura è funzione della velocità di sedimentazione delle particelle solide; si è quindi deciso di approfondire il ruolo della velocità di sedimentazione nella determinazione dell'efficienza del manufatto. L'efficienza è stata quindi calcolata applicando diverse formule della velocità di sedimentazione ed è stata confrontata con i dati sperimentali. L'applicazione di modelli sintetici permette di formulare ipotesi sui tempi di interrimento delle caditoie, fornendo un supporto alle strategie di manutenzione di tali manufatti, senza la necessità di applicare modelli più complessi che richiedono tempi di calcolo elevati.

2.2. Introduction

Roadside gully pots are the first entry point of pavement runoff into urban sewer system. Whether by intention or otherwise, it is a well-established observation that such appurtenances retain solids washed off urban surfaces during wet weather or reconstruction operations. For European design consideration given the prevalence of combined sewers, the intent is to reduce the probability of particulate matter deposition in drainage systems, protect the treatment plant operations, and eventually protect the receiving water environment (Fletcher and Pratt, 1981; Butler and Karunaratne, 1995; Butler and Memon, 1999; Memon and Butler, 2002). However, the wet weather continuous feed of solids leads to significant deposition in these appurtenances, loss of conveyance capacity and eventually to clogging. In Italian municipal practice proper design and periodic maintenance of gully pots is considered essential to ensure intended functionality (retaining solids and hydraulic efficiency). In addition to mentioned requirements, gully pots may have a significant influence on water quality aspects (Gromaire et al., 1998, 2001; Memon and Butler, 2002). In fact they act as small storage devices, where short residence times don’t allow finer particles, known to be the main responsible for pollutant load (Deletic et al., 2000), to be trapped. Proper design and periodic maintenance of gully pots appear therefore essential to ensure their good functionality. Nevertheless, many cities (and stakeholders) in Italy do not have a predetermined maintenance plan for the gully pots and even with such plans the enormity of the maintenance requirement relegates such plans to elimination until there is an operational failure (Silvagni and Volpi, 2002). Maintenance is often ad-hoc to cope with emergency situations (serious clogging and/or flooding). Hence a better understanding of settling phenomena can provide valuable guidance in terms of both design and management practices. The aim of this study is therefore to determine which variables influence the sedimentation of solid material, main reason for the progressive loss of gully pots’ efficiency.

2.2.1. Gully pots overview

Roadside gullies are collocated sideways to the roadside and have the function to receive rainfall water, which is subsequently headed into the sewer system. The distance between each device depends on the surface to be drained; in Bologna, for example, the town planning scheme provides a mutual distance between each gully pot of 12.5 m, or less in case of particular functioning requirements. The units must be installed in order that the wet surface create no hindrance to the road traffic. There are different types of gully pots available and the choice regarding the model to install depends not only on its capacity to intercept rainfall run-off and the reasonable silting expectation, but also on the safety for pedestrians and cyclists. In general a gully pot is made up by an inlet, an underlying tank and a pipe, which collect the unit outflow to the closest sewer conduit (Figure 2.1).

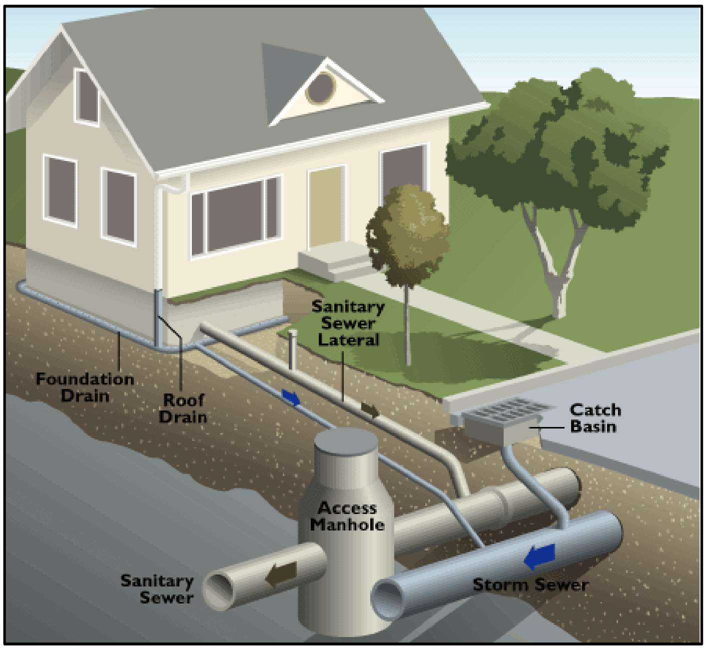
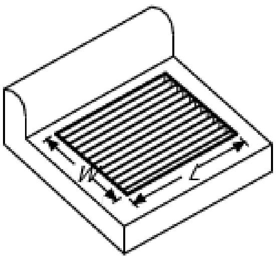


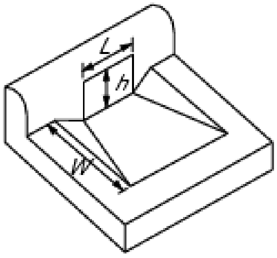
Figure 2.1 - Connection to a separate sewer system

Considering the inlet, it is possible to distinguish among (Figure 2.2):

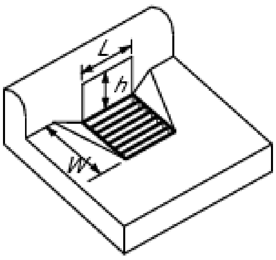
- Grate inlet;
- Curb opening inlet;
- Combination inlet
- Slotted drain inlet



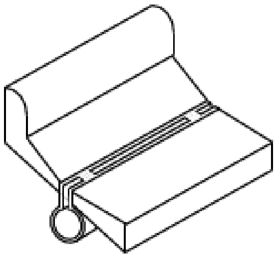
a. Grate inlet



b. Curb opening



c. Combination



d. Slotted drain

Type a: Grate inlet

Type b: Curb opening inlet

Type c: Combination inlet

Type d: Slotted drain inlet

Figure 2.2 - Gully pots typologies

The underlying tank allows the sedimentation of the trapped solid material: a trapped connection to the sewer pipe avoids bad odors and prevents septic conditions, guaranteeing the entrance of oxygen. The tank can have a depth raging from 40 cm to over 1 m and it can be manufactured in plastic, concrete or SG iron (Spheroidal Graphite cast iron). In some countries, to facilitate cleaning operations, a perforated metal basket is positioned under the grid. These devices intercept large material, but their use require frequent maintenance operations, since the clogging occurs very quickly. Moreover the presence of the basket favors the exhalation of odors and mosquitoes proliferation.

As previously stated, maintenance operations often occur to solve emergency situations, such as flooding. Gully pots cleaning has the goal to re-establish their hydraulic efficiency, so that these devices can be functioning during rainfall events. Street sweeping is very important as well, and it can be considered as the first level of maintenance operations; indeed this operation prevent the inlet clogging, removing leaves, trash, etc. which avoid the regular flow of rainfall run-off within the unit. Moreover roadside cleaning removes from urban surface particles settled during dry periods, so it is a method to decrease the pollutant load to stormwater. Gully pots cleaning is performed using an eductor truck (Figure 2.5), which uses hydrodynamic pressure and a vacuum to loosen and remove solids and standing liquid from the unit. This procedure is more complex.

Figure 2.3 - Plastic and concrete gully pots

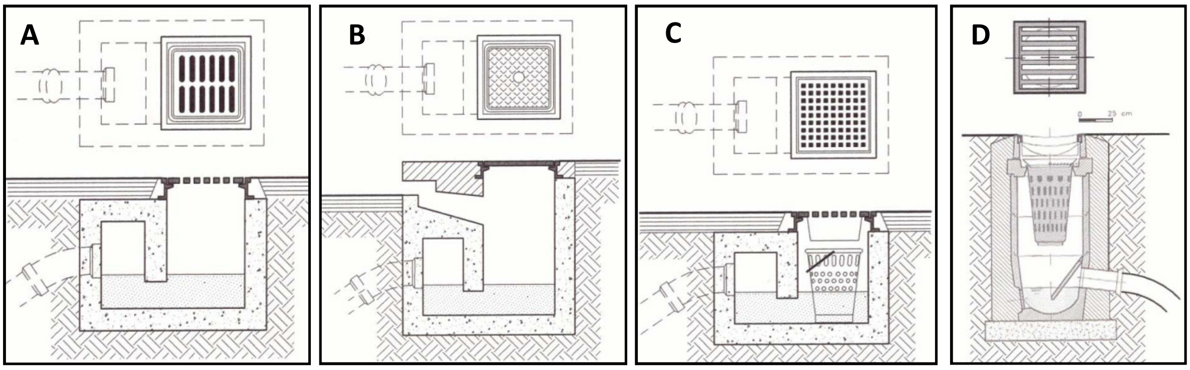


Figure 2.4 - Grate inlet (A) and curb opening inlet (B) gully pot with trapped outlet and gully pot with basket within (C and D)

Figure 2.5 - Gully pot cleaning operations

2.3. Previous experiences

2.3.1. Laboratory studies

Lager et al. (1977) were probably the first to perform tests on American catch basins. Their results anticipate what will be later verified by other authors: the capability of retaining solids is inversely proportional to inflow and directly proportional to the diameter of particles; however no analytical relation was developed. Subsequent studies in the U.K.

(Fletcher et al., 1978; Fletcher and Pratt, 1981) analysed the erosion and sedimentation processes inside gullies through tests conducted on a wet gully pot; they observed that the removal rate was linearly dependent on the liquid inflow rate and on the mass of sediment available, according to a single coefficient of erosion K. For this coefficient other authors (Wada and Miura, 1987) proposed alternative experimental regression. Grottker (1990) instead found the removal rate to be a power function of inflow, by mean of two empirical coefficients depending on particle size and on the soil used.

Studies proposed by Karuranatne (1992), subsequently developed with Butler (1995) focused on sedimentation, providing for the first time an analytical formulation to determine the trap efficiency of a gully pot as a function of the inflow rate, of the influent material particle size and specific gravity, as well as of the dimensions of the gully itself:

$$\eta = 1 - \frac{1}{1 + \frac{Q/A}{v_s}} = \frac{v_s}{v_s + Q/A} \tag{2.1}$$

Where η is the trap efficiency, v_s is the particle settling velocity (m/s), Q is the flow rate (m^3/s), A is the cross section of the gully pot (m^2).

The (2.1) is nothing but the well known Hazen's law (Fair, 1968) when the short-circuiting factor "n" is equal to 1:

$$\eta = 1 - \left[1 + \frac{v_s}{n(Q/A)}\right]^{-n} = 1 - \left[\frac{Q/A}{Q/A + v_s}\right] = \frac{v_s}{Q/A + v_s} \tag{2.2}$$

The formula chosen by Butler for the settling velocity is the Stokes' law (1851):

$$v_s = \alpha \frac{g \cdot D^2 \cdot (S-1)}{18\nu} \tag{2.3}$$

Where D is the particle diameter (m), S is their specific gravity, ν is the kinematic viscosity (m^2/s), α is a correction factor.

Stokes' law is known to be applicable under almost quiescent conditions (Reynolds particle number < 1), but inside a gully pot during rain events turbulence effects can't be neglected. A reduction factor is then necessary to avoid overestimating the settling velocity; Butler sets its value to 0.6. The trap efficiency formulation introduced by Butler and Karunaratne (1995), integrated with additional considerations from Butler and Memon

(1999), is based on general assumptions made by Fletcher and Pratt (1981) and then resumed by Deletic et al. (2000). They observed by tracer tests that the hydraulic regime in the pot reservoir can be approximated as a completely mixed reactor, where:

- inflow rate equals effluent flow rate (due to the gully small retention volume);
- sediment concentration in the liquid volume inside the gully pot is uniform;
- effluent sediment concentration at any given moment is similar to that present in the gully pot at the same time.

These assumptions are reinforced by the results of the mentioned studies, according to which solid mass contribution due to re-suspension of bed sediments is not quantitatively significant and limited to the first 20-40 seconds of the event.

2.4. Objectives

Experimental tests have been performed to examine the performance of a simple square gully pot, under steady flow conditions. The efficiency of the device has been estimated based on PM removal rate, evaluating also the particle size of material retained within the unit, using mono-disperse and hetero-disperse PM. Another aim has been to validate the assumptions stated in previous experiences, testing them even under conditions different from those proposed by original authors. The formulation chosen as a benchmark is the one by Butler and Karuranatne (1995), as it considers deterministic and measurable parameters relative to the physical characteristics of solids and to the gully pot size, in addition of course to the inflow value.

2.5. Materials and methodology

2.5.1. Experimental setup

The experimental tests have been performed at the Hydraulics Laboratory of the University of Bologna. The experimental facility consisted of a commercial gully pot with a square base (40 x 40 cm) and a prismatic open-channel to simulate the behavior of a street gutter and to allow for the setting up of shallow flow, suitable for transporting PM, pre-wetting the PM and delivering the PM with constant velocity and concentration (Figure 2.6).

Two different outlet configurations for the gully pot have been tested, a simple direct one and a second one simulating the presence of a trap, widely adopted in combined sewers to prevent odors escaping (Figure 2.7).

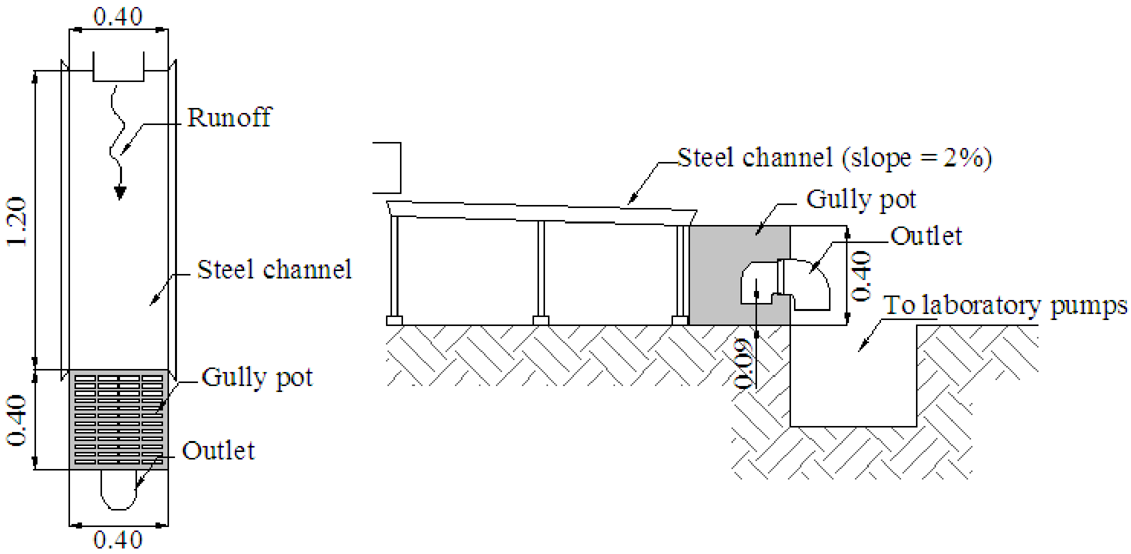


Figure 2.6 - Overall schematic plan and profile of the experimental setup of gully pot

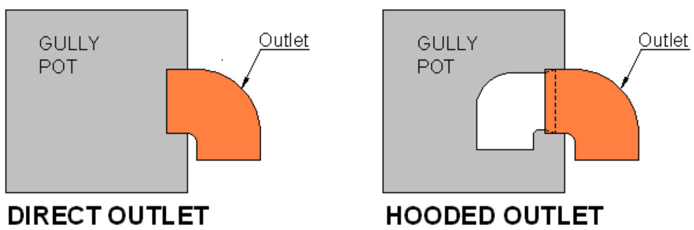


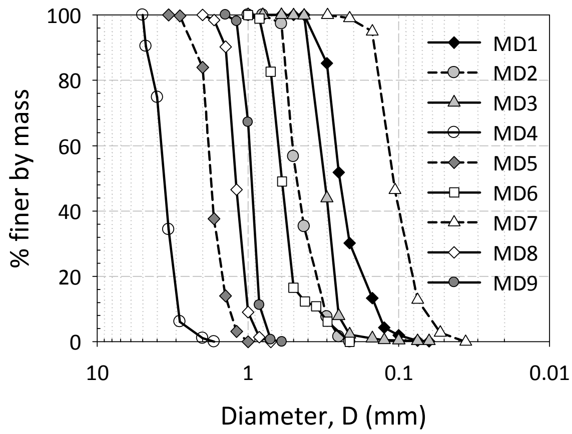
Figure 2.7 - Schematic representation of the two different outlets

Solids have been supplied manually at the channel inlet, keeping the influent concentration as constant as possible (about 1000 - 3000 mg/l). However this value is indicative and does not affect the gully efficiency; indeed previous studies indicate PM influent concentration value does not have a significant influence on gully pot efficiency (Butler and Karunaratne, 1995). All tests have been performed in steady state conditions. Incoming flow has ranged from 0.2 to 1.5 l/s, representing rainfall intensities between 8 and

60 mm/h, assuming hypothetical gully pot drained area equal to 100 m^2. Butler's tests and the consequent formula refer to almost mono-granular quartz sand.

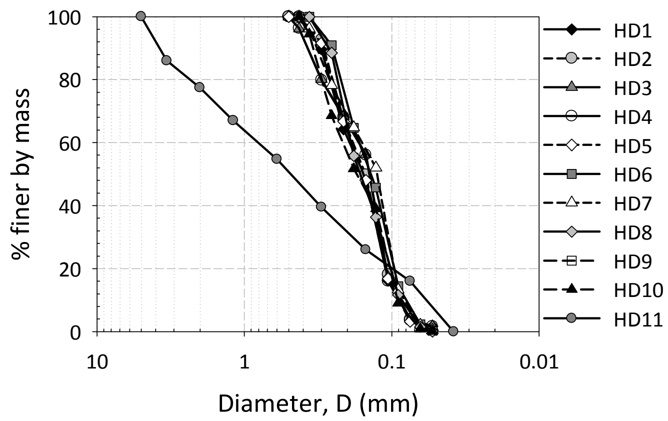
2.5.2. Gradation and injection

Tests have been performed using quartz sand samples (specific gravity S = 2.65); tests "M" have been carried out using mono-disperse sand, as shown on figure 2.8. To evaluate the gully pot efficiency in case of hetero-disperse material, tests "H" have been performed using quartz sand samples with the particle size distribution shown on figure 2.9 (HD1 to HD10 curves). However, since real sediments accumulated on road surfaces show a greater hetero-dispersivity, for a set of tests different types of sand have been mixed (HD11 PDS curve), in order to obtain a particle size distribution similar to that of real street sediments (Sartor and Boyd, 1972; Maglionico and Pollicino, 2004; Ying and Sansalone, 2008). Finally, further tests (Tests "S") have been carried out using particulate matter directly sampled from the pavement. These PM illustrate hetero-disperse PSDs (Figure 2.10) and a variable specific gravity range from 2.0 to 2.7. This PM have been collected from an asphalt paved section along "Via del Lazzaretto", in Bologna, with low to medium traffic (7500 vehicles/day). Solid material has been collected by vacuuming from three sections of pavement for a width up to one meter from the curb. Sampling occurred on April 10th and 26th, 2007 for the first section, on April 16th and 26th, 2007 for the second section and on April 23th, 2007 for the third portion, yielding PM with different antecedent dry periods (Table 2.1). For these samples, besides PSDs, the specific gravity of each fraction was determined, using a liquid pycnometer.



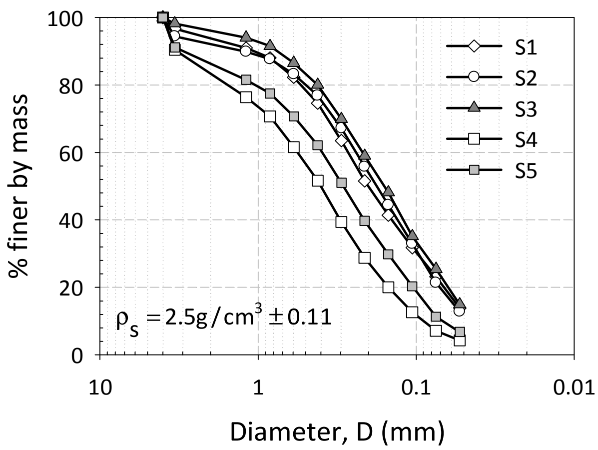
Sand	D_{50} (mm)	D_{90} (mm)
MD1	0.240	0.337
MD2	0.466	0.603
MD3	0.311	0.388
MD4	3.609	4.442
MD5	1.740	2.124
MD6	0.594	0.766
MD7	0.107	0.154
MD8	1.202	1.414
MD9	0.956	1.088

Figure 2.8 - PSDs of sands used for Tests "M" (mono-disperse), with a specific gravity S = 2.65



Sand	D_{50} (mm)
HD1	0.168
HD2	0.163
HD3	0.164
HD4	0.165
HD5	0.166
HD6	0.146
HD7	0.149
HD8	0.161
HD9	0.154
HD10	0.178
HD11	0.603

Figure 2.9 - PSDs of sands used for Tests "H" (hetero-disperse), with a specific gravity S = 2.65



Sand	D_{50} (mm)
S1	0.211
S2	0.198
S3	0.175
S4	0.461
S5	0.333

Figure 2.10 - PSDs of solids collected directly from road surface and used for Tests "S"

Sample #	Date	# of sweeping	Antecedent dry period (days)	Recovered PM mass (g/m curb)
S1	10 April	1	5	51.10
S2	16 April	2	11	38.17
S3	23 April	3	18	69.12
S4	26 April	1	14	95.48
S5	26 April	2	8	61.92

Table 2.1 - Schedule of particulate matter (PM) collection at Via del Lazzaretto (Bologna), in 2007

Sample S1		Sample S2		Sample S3		Sample S4		Sample S5	
D (mm)	S	D (mm)	S	D (mm)	S	D (mm)	S	D (mm)	S
3.680	2.49	3.680	2.50	2.275	2.40	3.680	2.56	3.680	2.56
2.275	2.40	2.275	2.40	1.016	2.19	2.275	2.56	2.275	2.56
1.016	2.19	1.016	2.36	0.718	2.45	1.016	2.50	1.016	2.50
0.718	2.45	0.718	2.35	0.508	2.47	0.718	2.40	0.718	2.40
0.508	2.47	0.508	2.65	0.359	2.46	0.508	2.53	0.508	2.53
0.359	2.46	0.359	2.42	0.255	2.56	0.359	2.44	0.359	2.83
0.255	2.31	0.255	2.51	0.181	2.63	0.255	2.48	0.255	2.63
0.181	2.55	0.181	2.46	0.128	2.54	0.181	2.53	0.181	2.47
0.128	2.74	0.128	2.54	0.091	2.55	0.128	2.59	0.128	2.50
0.091	2.43	0.091	2.46	0.045	2.51	0.091	2.49	0.091	2.49
0.045	2.64	0.045	2.51			0.045	2.48	0.045	2.49

Table 2.2 - Specific gravity of PM collected on road pavement, for each particle size fraction

Figure 2.11 - A view of “Via del Lazzaretto”, in Bologna (left); vacuum cleaner used to collect solid material (right)

2.5.3. Testing procedure and mass recovery

Prior to every test the experimental facility has to be cleaned carefully using potable water to remove particles possibly left within the gully or above the channel. The flow rate has been set at the desired value, and it has been checked using a flow meter. Once ended the experimental run, the material inside the unit has been manually recovered to be dried in glass trays at 110 degrees Celsius in an oven. The dry material has been then weighed and for tests “H” and “S” a dry phase PSD analysis has been performed, using sieve analysis. After this procedure it has been possible to calculate the overall efficiency of the unit based on recovered mass. Moreover sieve analysis allows to estimate the efficiency for each particle size fraction.

2.5.4. Efficiency calculation and mass balance

Efficiency calculation

The gully pot efficiency has been determined as the percentage of incoming PM that is retained by the device:

$$Eff_{meas}(\%) = \frac{m_{capt}}{m_{in}} \cdot 100 \qquad (2.4)$$

With m_{in}, amount (in grams) of solids entering the unit; m_{capt}, amount of sediment trapped in the unit (in grams).

2.6. Experimental runs and results

Tests “M”

41 runs have been carried out using mono-disperse sands, characterized by PSDs shown on figure 2.8; the influent mass load has ranged from 250 to 2000 g, while the inlet flow rate has been varied from 0.2 to 1.5 l/s. Table 2.3 summarizes tests’ parameters, such as mean diameter of the injected sand (D_{50}), inlet flow rate (Q), and injected mass (m_{in}) and the test results, that is the measured efficiency (Eff_{meas}), calculated with the (2.4). In the table, tests follow their chronological order; some tests have been performed using sand obtained as fraction trapped within a sieve, to have some other mono-disperse samples.

Test #	D_{50} (mm)	Sample #	S (-)	Q (l/s)	m_{in} (g)	Eff_{meas} (%)
1*	1.202	MD8	2.65	1.00	1000.00	99.66
2*	0.956	MD9	2.65	1.00	1000.00	99.74
3*	0.594	MD6	2.65	1.00	1000.00	98.87
4*	1.740	MD5	2.65	1.00	1000.00	99.59
5*	0.107	MD7	2.65	1.00	1000.00	58.73
6*	0.107	MD7	2.65	0.50	500.00	68.24
7*	0.594	MD6	2.65	1.00	500.00	98.38
8*	0.594	MD6	2.65	1.00	2000.00	97.17
9*	0.594	MD6	2.65	1.00	500.00	99.12
10	0.594	MD6	2.65	1.00	500.00	99.48
11	0.107	MD7	2.65	1.00	500.00	45.56
12	0.107	MD7	2.65	0.50	500.00	64.13
13	0.107	MD7	2.65	1.50	500.00	39.97
14	0.107	MD7	2.65	1.00	500.00	50.68
15	0.107	MD7	2.65	0.50	500.00	71.39
16	0.594	MD6	2.65	1.00	500.00	97.50
17	0.107	MD7	2.65	1.00	500.00	58.50
18	0.240	MD1	2.65	1.10	500.00	84.64
19	0.240	MD1	2.65	0.94	500.01	83.81
20	0.240	MD1	2.65	0.95	504.84	81.90
21	0.091	75-106um	2.65	0.95	437.41	40.15
22	0.091	75-106um	2.65	0.95	451.84	38.95
23	0.128	106-150um	2.65	0.96	472.98	50.94
24	0.128	106-150um	2.65	0.95	480.10	51.84
25	0.128	106-150um	2.65	0.35	428.04	85.58
26	0.128	106-150um	2.65	0.34	425.88	84.07
27	0.091	75-106um	2.65	0.35	333.75	70.77
28	0.091	75-106um	2.65	0.35	354.54	73.11
29	0.064	53-75um	2.65	0.35	259.50	56.27
30	0.128	106-150um	2.65	0.61	439.55	64.8
31	0.128	106-150um	2.65	0.91	477.90	52.8
32	0.240	MD1	2.65	0.52	491.08	94.8
33	0.311	MD3	2.65	0.20	499.95	95.29
34	0.240	MD1	2.65	0.18	500.02	99.21
35	0.466	MD2	2.65	0.21	500.00	99.79
36	0.091	75-106um	2.65	0.18	498.35	90.67
37	0.128	106-150um	2.65	0.17	500.20	95.98
38	0.091	75-106um	2.65	0.18	500.51	87.39
39	0.128	106-150um	2.65	0.18	499.26	94.78
40	0.091	75-106um	2.65	0.48	499.68	64.14
41	0.128	106-150um	2.65	0.48	500.01	76.30

Table 2.3 - Summary of tests “M”, mono-disperse; (*) tests performed with simple direct outlet

The first 9 experiments have been carried out the gully pot with a simple direct outlet; since no difference between direct and hooded outlet has been noticed all the next experiments have been performed with the hooded outlet, more similar to the gully pots installed in Italian cities.

Tests “H” and “S”

In order to have hetero-disperse samples (samples “HD”), different mono-granular sands have been mixed (Figure 2.9); these samples are characterized by having a specific gravity equal to 2.65. In order to have some PM assorted in terms both of particle size and specific gravity, samples for tests “S” have been directly sampled form road surface (Figure 2.10); in this case for each size fraction the specific gravity has been measured using a volumetric pycnometer (Table 2.2). For experimental runs “H” and “S” it has been measured the overall efficiency, as well as the efficiency over each single particle size fraction. Tables 2.4 and 2.5 summarize tests’ parameters, such inlet flow rate (Q), injected mass (m_{in}) and measured efficiency (Eff_{meas}), calculated with the (2.4).

Test #	Sample #	S (-)	Q (l/s)	m_{in} (g)	Eff_{meas} (%)
1	HD1	2.65	0.20	639.63	94.03
2	HD2	2.65	0.29	657.01	90.53
3	HD3	2.65	0.20	628.28	93.07
4	HD4	2.65	0.30	617.99	89.41
5	HD5	2.65	0.95	99.77	67.61
6	HD6	2.65	0.52	594.79	88.98
7	HD7	2.65	0.96	552.55	64.82
8	HD8	2.65	0.51	411.92	87.09
9	HD9	2.65	0.91	529.26	72.32
10	HD10	2.65	0.51	358.15	88.06
11	HD11	2.65	1.00	500.00	79.41
12	HD11	2.65	1.00	500.00	79.65
13	HD11	2.65	1.00	500.00	79.99
14	HD11	2.65	1.00	500.00	76.67
15	HD11	2.65	1.00	500.00	73.54

Table 2.4 - Summary of tests “H”, hetero-disperse

Test #	Sample #	S (-)	Q (l/s)	m_{in} (g)	Eff_{meas} (%)
1	S1	variable	1.00	500.00	64.47
2	S2	variable	0.50	528.90	71.88
3	S3	variable	0.50	500.00	70.72
4	S3	variable	1.00	500.00	61.43
5	S4	variable	0.47	897.30	87.73
6	S5	variable	0.47	476.00	91.78

Table 2.5 - Summary of tests "S", hetero-disperse with sampled material

In general it is possible to observe that for a constant value of influent flow rate and specific gravity, the efficiency increases with the increasing in particle size diameter, while for a constant value of particle size diameter, the efficiency results to be inversely proportional to the flow rate (Figure 2.12, for S = 2.65).

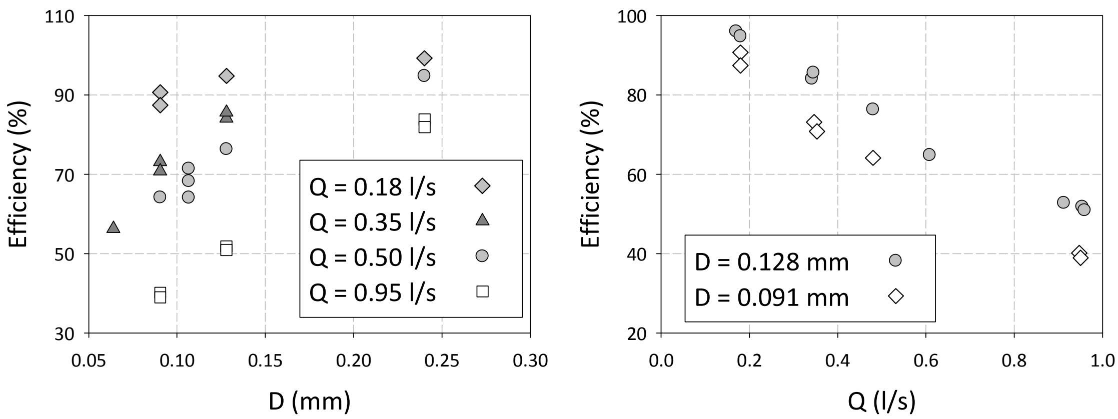


Figure 2.12 - Efficiency vs. diameter (left); efficiency vs. flow rate (right)

2.7. Comparison of modeled and measured PM separation

In view of the direct proportion between efficiency and diameter and the inverse proportion between efficiency and flow rate, it has been decided to compared the experimental data to the efficiency values obtained applying the analytical formula developed by Butler and Karuranatne (1995):

$$\eta = \frac{v_s}{v_s + Q / A} \tag{2.5}$$

The particle settling velocity, v_s, is a function of the square of the particle diameter and the specific gravity. As previously observed, the (2.5) is the overflow rate model. The formulation chosen by Butler for the settling velocity is the Stokes' law (1851), multiplied by a correction factor, assumed equal to 0.6. For a first comparison this formulation has been applied to compare experimental data, evaluating the difference between the calculated efficiency, η, and the experimental value, Eff_{meas}.

$$\Delta Eff = \eta - Eff_{meas} \tag{2.6}$$

Tests "M"

Figure 2.13 shows the comparison of measured and modeled PM removal efficiency; the cumulative distribution of residuals ΔEff is plotted on figure 2.13 (right), showing an almost unbiased distribution slightly shifted to the left which means an acceptably small systematic error.

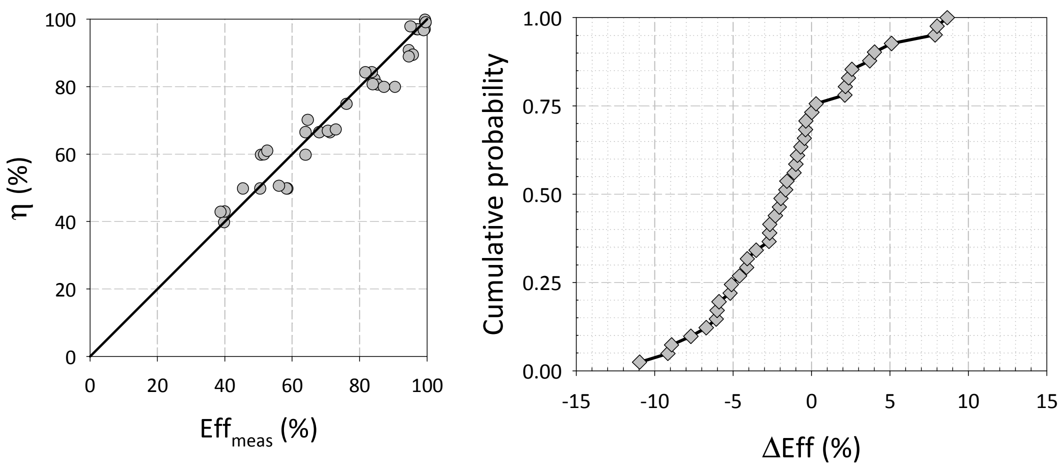


Figure 2.13 - Comparison between measured and calculated efficiency (left); cumulative distribution of residuals (right) for tests "M"

The goodness of fit for application of equation (2.5) is assessed by the Root Mean Square Error (RMSE) and Nash-Sutcliffe index (Nash and Sutcliffe, 1970). Scatter plots of figure 2.14 illustrate the relationship between residuals (difference between calculated and measured efficiencies) and particle size; it is possible to notice a symmetrical trend, that complies with the confidence intervals given by the linear propagation of error.

RMSE	4.78
N-S index	0.94
Median	-1.64

Root Mean Square Error (RMSE), Nash-Sutcliffe index and median for tests "M"

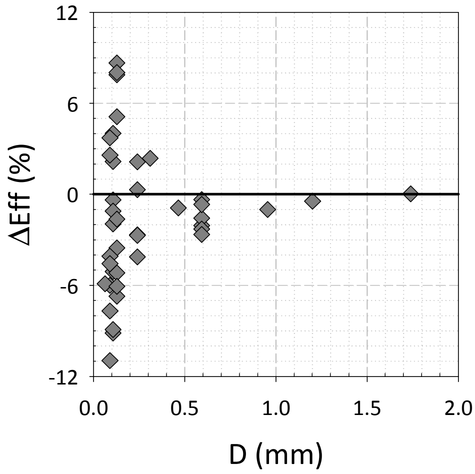


Figure 2.14 - Correlation between residuals and particle size for tests "M"

Tests "H" and "S"

For experimental runs with hetero-disperse material and PM directly collected from the road pavement (tests "H" and "S"), the overall trapping efficiency has been calculated by application of (2.5) to each single particle size fraction, then performing a weighting on a mass fraction basis for each particle size:

$$\eta = \sum_i \eta_i \frac{m_i}{m_{tot}} \tag{2.7}$$

In the (2.7): η_i is the efficiency of the i-th particle size size; m_i is the mass of the i-th fraction size present in the sample; m_{tot} is the total mass of the sample.

Figure 2.15 shows a good correspondence between efficiency calculated according to (2.7) and experimental data. The cumulative distribution of residuals for tests "H" and "S" shows an unbiased distribution (figure 2.16). In order to emphasize the importance to know the particle size distribution of the influent PM, gully pot's efficiency has been calculated with formula (2.5) considering the D_{50} of each hetero-disperse sample. The error between measured and calculated efficiencies rises significantly, and in particular the more the sample graded is, the more rises this difference (tests with sample "HD11" an tests "S").

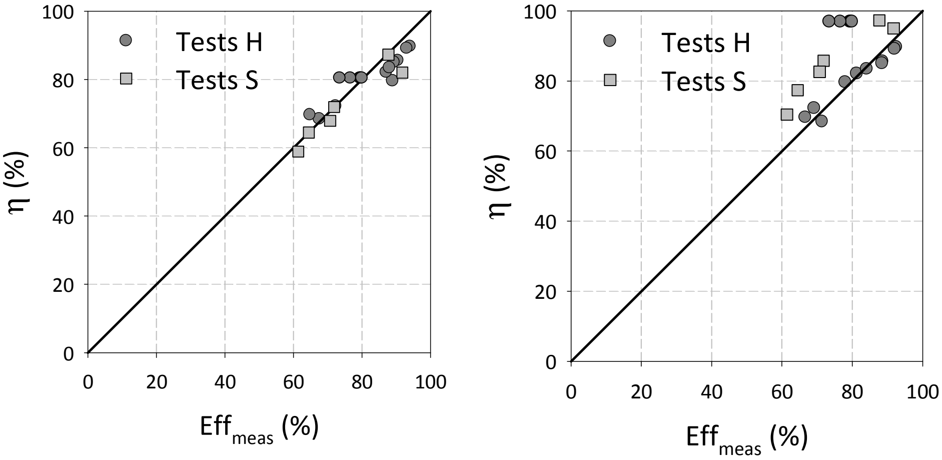


Figure 2.15 – Tests "H" and "S": comparison between measured and calculated efficiency using equation (2.7) (left); comparison between measured and calculated efficiency, with the modeled efficiency calculated with the D50 (right)

RMSE	**4.41**
N-S index	**0.81**
Median	**-0.49**

Root Mean Square Error (RMSE), Nash-Sutcliffe index and median for the overall efficiency of tests "H" and "S"

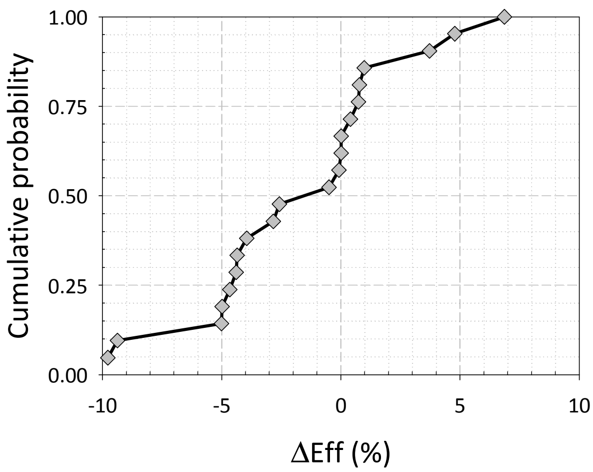


Figure 2.16 - Cumulative distribution of residuals for tests "H" and "S", using equation (2.17)

Regarding tests "S", at the end of each run the total mass of PM trapped into the gully pot has been recovered, weighted and the PSD determined. Separation efficiencies have been measured and modelled for each particle size fraction. Comparison between measured and modelled efficiency is illustrated in figure 2.17. The distribution of residuals and potential correlations between residuals and specific granulometric characteristics of the PM (diameter and specific gravity) have been examined; there is no correlation between error (ΔEff) and specific gravity, while a positive trend is exhibited with increasing particle size (data have been taken into account for diameters smaller than 2 mm for quarteing problems).

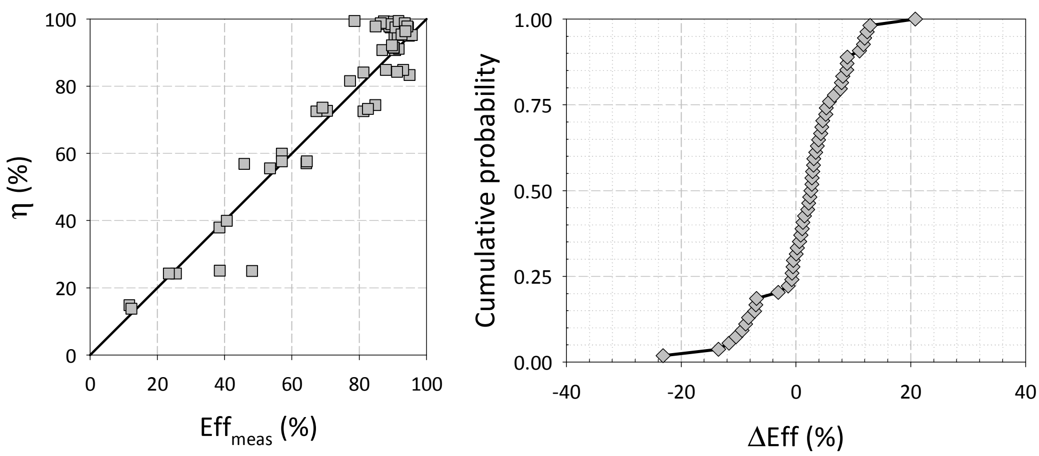


Figure 2.17 - Tests "S": comparison between calculated and experimental efficiency for each size fraction (left); cumulative distribution of residuals (right)

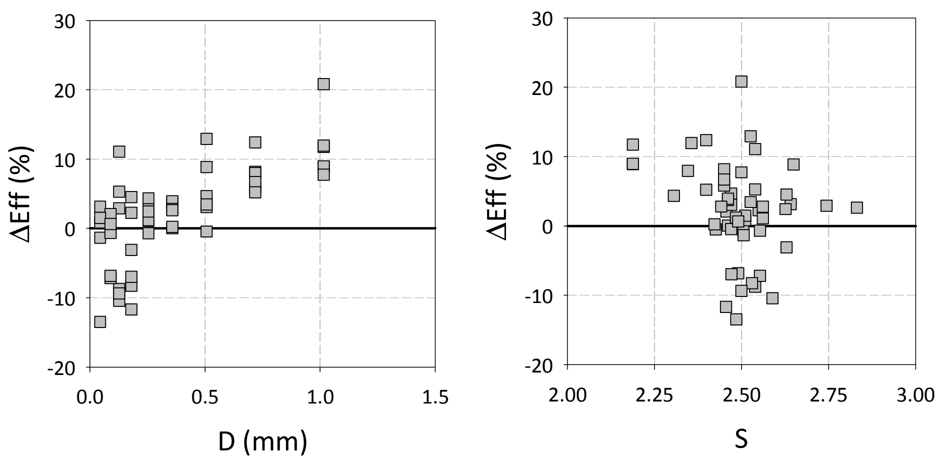


Figure 2.18 - Tests "S": correlation between calculated error and diameter (left) and between error and specific gravity (right)

RMSE	**7.75**
N-S index	**0.88**
Median	**2.92**

Table 2.6 - Root Mean Square Error (RMSE), Nash-Sutcliffe index and median for the efficiency of tests "S", considering each single fraction efficiency

To obtain a subsample from the total amount of material collected from the road pavement the manual cone and quartering method has been used: the bulk is mixed and transferred on a clean surface to form a conical pile; the cone is then flattened and divided into quarters, and opposite quarters removed; these are mixed to form a smaller conical pile, and then quartered. This procedure is repeated until a sample of suitable weight is obtained (Jeffery et al., 1989). The drawback of this methodology is that finer particles can escape. The dots on the top of graph which shows the comparison between calculated and measured efficiency display that the error for coarser particles is significant and in general the modeled efficiency is greater than the experimental value. Errors could be increased by experimental errors in the sub-sampling procedure.

For this reason for some of tests "H" (with samples from HD1 to HD10) the following procedure has been used: before each test the PSD of the injected sample has been checked, to know the exact amount of each particle fraction that composes the sample. After the experiment, the material retained within the gully pot has been taken to the laboratory to perform PSD analysis.

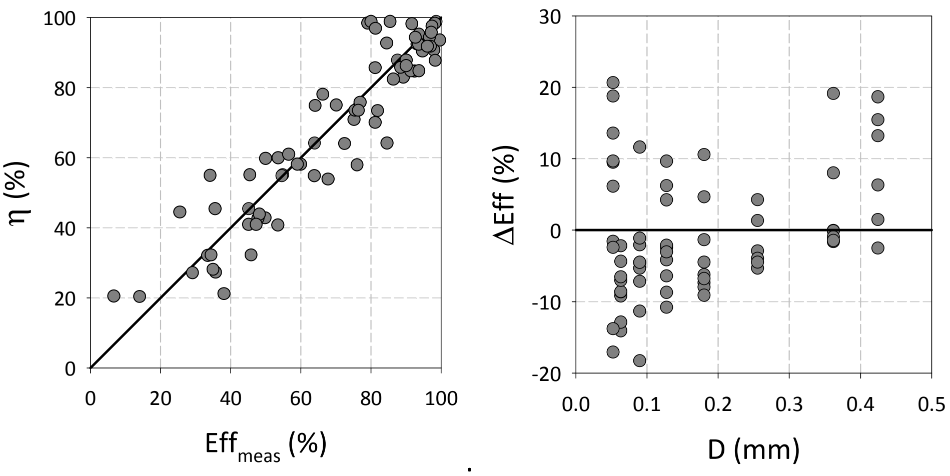


Figure 2.19 - Tests "H": comparison between calculated and experimental efficiency for each size fraction (left); correlation between calculated error and diameter (right)

RMS	**9.26**
N	**0.85**
Mediana	**-2.50**

Table 2.7 - Root Mean Square Error (RMSE), Nash-Sutcliffe index and median for the efficiency of tests "H", considering each single fraction efficiency

Figure 2.19 shows that if each particle size fraction is considered the plot "ΔEff vs. D" has an unsymmetrical trend; it is maybe possible that interactions between particles of different diameters can occur and modify the regular settling of particles; this interaction is not explained by the model. The calculation of overall efficiency gives better results probably due to the different percentage of size fractions present in the whole sample, which affect the final error in a different way.

2.8. Influence of settling velocity formulation

The settling velocity of a sphere in a fluid at rest can be estimated by solving the balance between the gravitational force and the drag resistance:

$$(S-1)\rho g\frac{\pi}{6}D^3=\frac{1}{2}\rho C_D\frac{\pi}{4}D^2 v_s^2 \tag{2.8}$$

Where S is the specific gravity of the sediment given by ρ_s/ρ, respectively density of the sediment and the fluid; g is the gravitational acceleration; D is the sediment diameter; C_D is the drag coefficient and v_s is the settling velocity.

The balance equation can be solved to obtain the settling velocity:

$$v_s=\left[\frac{4}{3}\frac{(\rho_s-\rho)\cdot g\cdot D}{C_D\rho}\right]^{1/2} \tag{2.9}$$

Stokes's law for spherical particles is given by equation (2.9), when the drag coefficient is equal to $24/Re_d$. Stokes' formulation is apply to conditions where the particle Reynolds number, Re_d, is less than 1, while Newton's law (2.9) applies for $Re_d > 1000$

$$Re_d=\frac{D\cdot v}{\upsilon} \tag{2.10}$$

For particles of quartz in water Re_d equal to 1 and to 1000 represents an upper size limit of around 0.11 mm for Stokes' law and a lower limit of around 3.5 mm for Newton's law. Thus for particles between 0.11 and 3.5 mm neither equation accurately describes the settling velocity. A number of researchers have developed empirical correlations to fill this size gap.

The over-flow rate model (2.5) used to determinate the gully pot efficiency is function of the settling velocity. Therefore other formulations in addition to the one chosen by Butler have been substituted into the (2.5); the modeled efficiencies have then been compared to experimental values. All formulas considered depend on particles diameter and specific gravity; Dietrich and Camenen include also particle shape factor and roundness, here assumed equal to 0.7 and 3.5.

Obviously the condition within the gully pot cannot be considered as quiescent; this is the reason why Butler's formulation introduces the reduction coefficient.

Formulations for settling velocity

- Newton's Law (see Tchobanoglous, 1991)

$$v_s = \left[\frac{4}{3} \frac{(\rho_s - \rho) \cdot g \cdot D}{C_D \rho} \right]^{1/2} \tag{2.11}$$

$$C_D = \frac{24}{Re_d} + \frac{3}{\sqrt{Re_d}} + 0.34 \tag{2.12}$$

For higher values of Reynolds numbers.

- Stokes' Law (1851)

$$v_s = \frac{(S-1) \cdot g \cdot D^2}{18\nu} \tag{2.13}$$

For spherical particles with very small Reynolds numbers.

- Butler (1995)

$$v_s = \alpha \frac{(S-1) \cdot g \cdot D^2}{18\nu} \tag{2.14}$$

Stokes' Law reduced by a factor equal to 0.6.

- Zanke (1977)

$$v_s = 10 \frac{\nu}{D} \left[\left(1 + \frac{0.01 \cdot (S-1) \cdot g \cdot D^3}{\nu^2} \right)^{0.5} - 1 \right] \tag{2.15}$$

For diameter ranging from 100 to 1000 μm.

- Dietrich (1982)

$$v_s = \frac{\nu}{d} R_3 10^{R_1 + R_2} \tag{2.16}$$

$$\begin{aligned} R_1 = & -3.76715 + 1.92944 \left(\log_{10} D^* \right) - 0.09815 \left(\log_{10} D^* \right)^2 + \\ & - 0.00575 \left(\log_{10} D^* \right)^3 + 0.00056 \left(\log_{10} D^* \right)^4 \end{aligned} \tag{2.17}$$

$$R_2 = \log_{10}\left(1 - \frac{1 - CSF}{0.85}\right) \tag{2.18}$$

$$R_3 = \left[0.65 - \left(\frac{CSF}{2.83}\tanh\left(\log_{10} D^* - 4.6\right)\right)\right]^{\left(1 + \frac{3.5 - P}{2.5}\right)} \tag{2.19}$$

$$D^* = \frac{(S-1)\cdot g}{\nu^2}\cdot D^3 \tag{2.20}$$

This formulation allows to consider the particle shape, besides diameter and specific gravity. In this case the factor CSF, which characterizes the shape, is assumed equal to 0.7, while P is assumed equal to 3.5, considering a natural particle.

- Cheng (1997)

$$v_s = \frac{\nu}{D}\left(\sqrt{25 + 1.2\left(d^*\right)} - 5\right)^{1.5} \tag{2.21}$$

$$d^* = \left(\frac{(S-1)\cdot g}{\nu^2}\right)^{1/3}\cdot D \tag{2.22}$$

For a large range of Reynolds numbers.

- Ahrens (2000)

$$v_s = \frac{\nu}{D}\left(C_L \cdot D^* + C_T \cdot \sqrt{D^*}\right) \tag{2.23}$$

$$D^* = \frac{(S-1)\cdot g}{\nu^2}\cdot D^3 \tag{2.24}$$

$$C_L = 0.055\cdot\tanh\left[12\cdot(D^*)^{-0.59}\exp(-0.0004\cdot D^*)\right] \tag{2.25}$$

$$C_T = 1.06\cdot\tanh\left[0.016\cdot(D^*)^{0.50}\exp\left(-\frac{120}{D^*}\right)\right] \tag{2.26}$$

C_L and C_T are associated to condition of laminar and turbulent regime.

- Ferguson and Church (2004)

$$v_s = \frac{(S-1)\cdot g\cdot D^2}{C_1\cdot\nu + \left[0.75\cdot C_2\cdot(S-1)\cdot g\cdot D^3\right]^{1/2}} \tag{2.27}$$

C_1 and C_2 are constants related to the shape and smoothness of the grains, assumed respectively equal to 18 and 1, considering natural grains.

- <u>Camenen (2007)</u>

$$v_s = \frac{\nu}{D}\left[\sqrt{\frac{1}{4}\cdot\left(\frac{A}{B}\right)^{2/m} + \left(\frac{4}{3}\cdot\frac{(d^*)^3}{B}\right)^{1/m}} - \frac{1}{2}\left(\frac{A}{B}\right)^{1/m}\right]^m \tag{2.28}$$

$$d^* = \left(\frac{(S-1)\cdot g}{\nu^2}\right)^{1/3}\cdot D$$

This formula takes into account the particle shape and roundness; its parameters can be deduce from the following table:

Material	CSF	P	A	B	m
Spherical particles	1.0	6.0	24.0	0.39	1.92
Smooth cobbles	0.7	5.0	24.5	0.62	1.71
Natural sand	0.7	3.5	24.6	0.96	1.53
Crushed sand	0.7	2.0	24.7	1.36	1.36
Long cylinders	0.4	5.0	36.0	1.51	1.40
Silt, cohesive particles	0.4	2.0	38.0	3.55	1.12
Flocs	0.6	1.0	26.8	2.11	1.19

Table 2.8 - Coefficients A, B, and m for typical particles

Fixing, for instance, specific gravity equal to 2.65 (quartz sand), it is possible to compare settling velocity values as a function of particle diameter, according to the different authors (Figure 2.20). Figure 2.21 shows a comparison with Newton's law, often reported to model the settling velocity of non cohesive particles silt- and sand-size (Sansalone, 2009).

Plots show how Stokes' law tends to overestimate the settling velocity, especially for increasing values in diameter; the reduction coefficient introduced by Butler reduces this overestimation, for diameter smaller than 0.4 mm. Instead the other formulations give comparable settling velocity values for the entire range of diameters. The ratio between the settling velocity for a specific author and Newton's law shows that Stokes' and Newton's formulations give almost the same value for small diameter (D < 0.1 mm), while with other formulations, such as Ahrens' and Cheng's, smaller values are obtained.

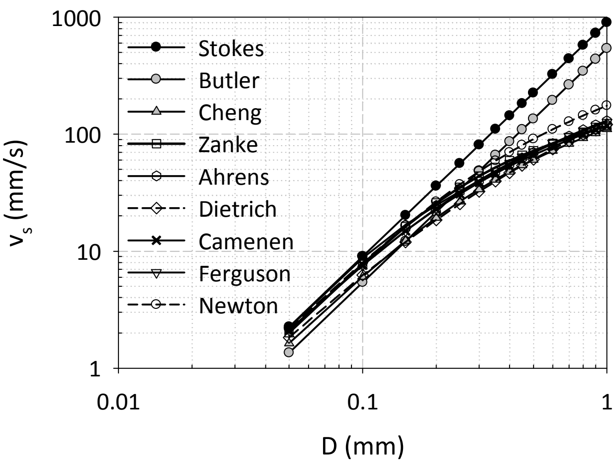


Figure 2.20 - Settling velocity as a function of particle diameter, according to different authors, for a fixed value of specific gravity (S = 2.65)

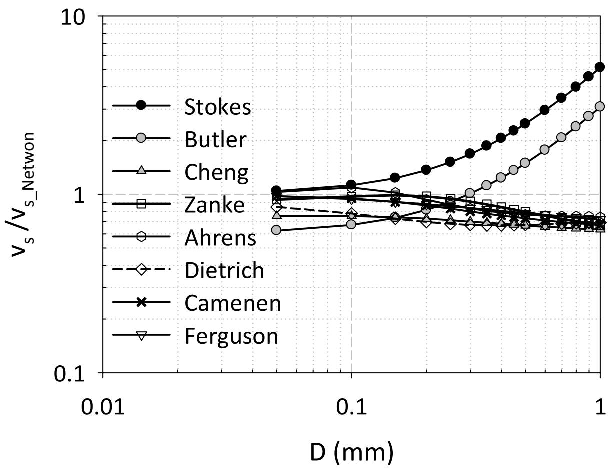


Figure 2.21 - Settling velocity as a function of particle diameter, according to different authors compared to Newton's law

To compare the modeled efficiency obtained adopting settling velocity formulations by different author's, the root mean square error (RMSE), the Nash-Sutcliffe index values and the median have been calculated as indicators. For mono-disperse tests, figure 2.21 shows that data obtained applying Dietrich's and Cheng's settling velocity expressions are less distant from the bisector line; the same happens using Stokes' law multiplied by 0.6, as proposed by Butler. The other expressions tend to overestimate the efficiency of the unit, especially for small particles.

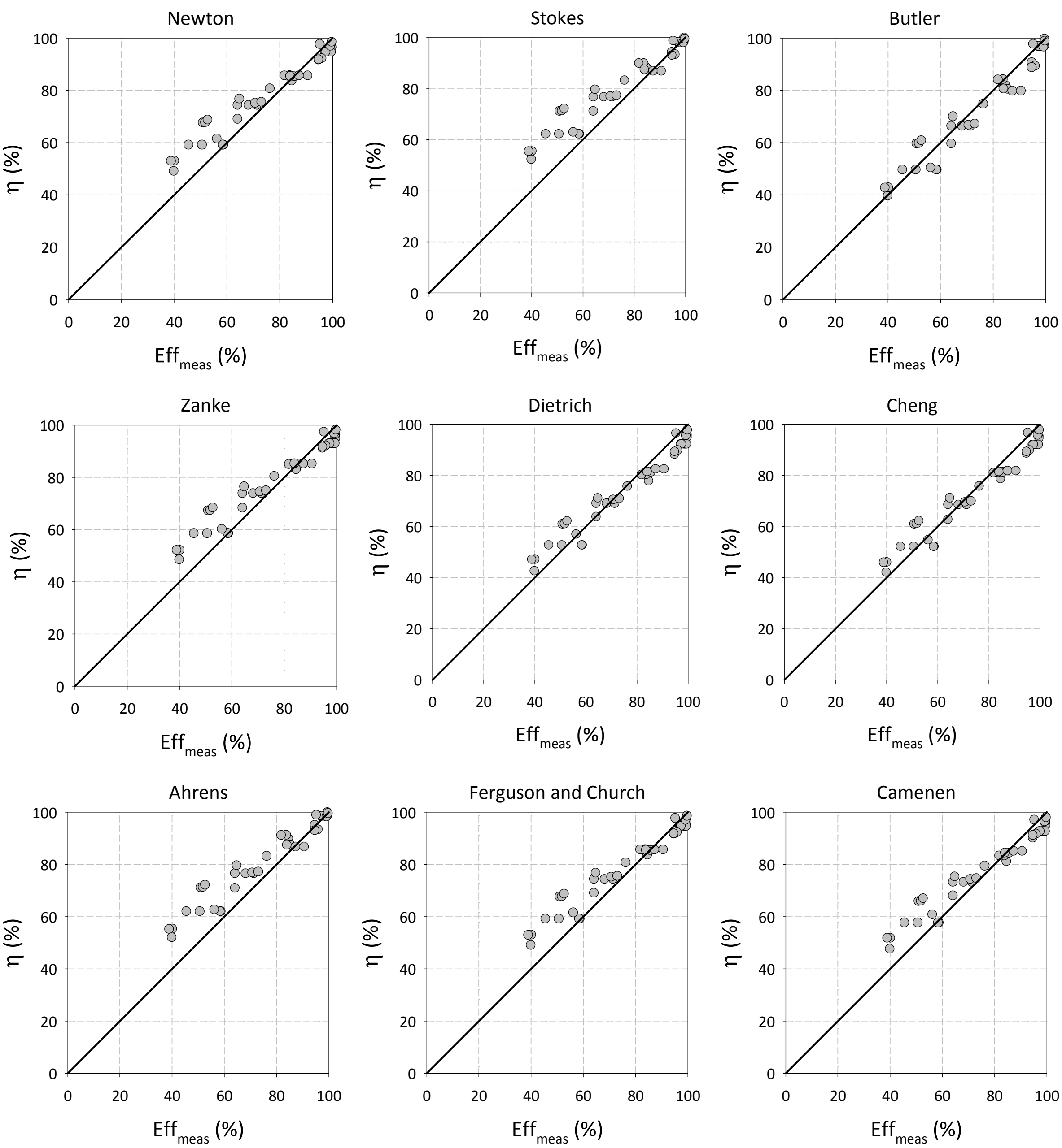


Figure 2.22 - Comparison between calculated and experimental efficiency for tests "M", considering different formulations for settling velocity

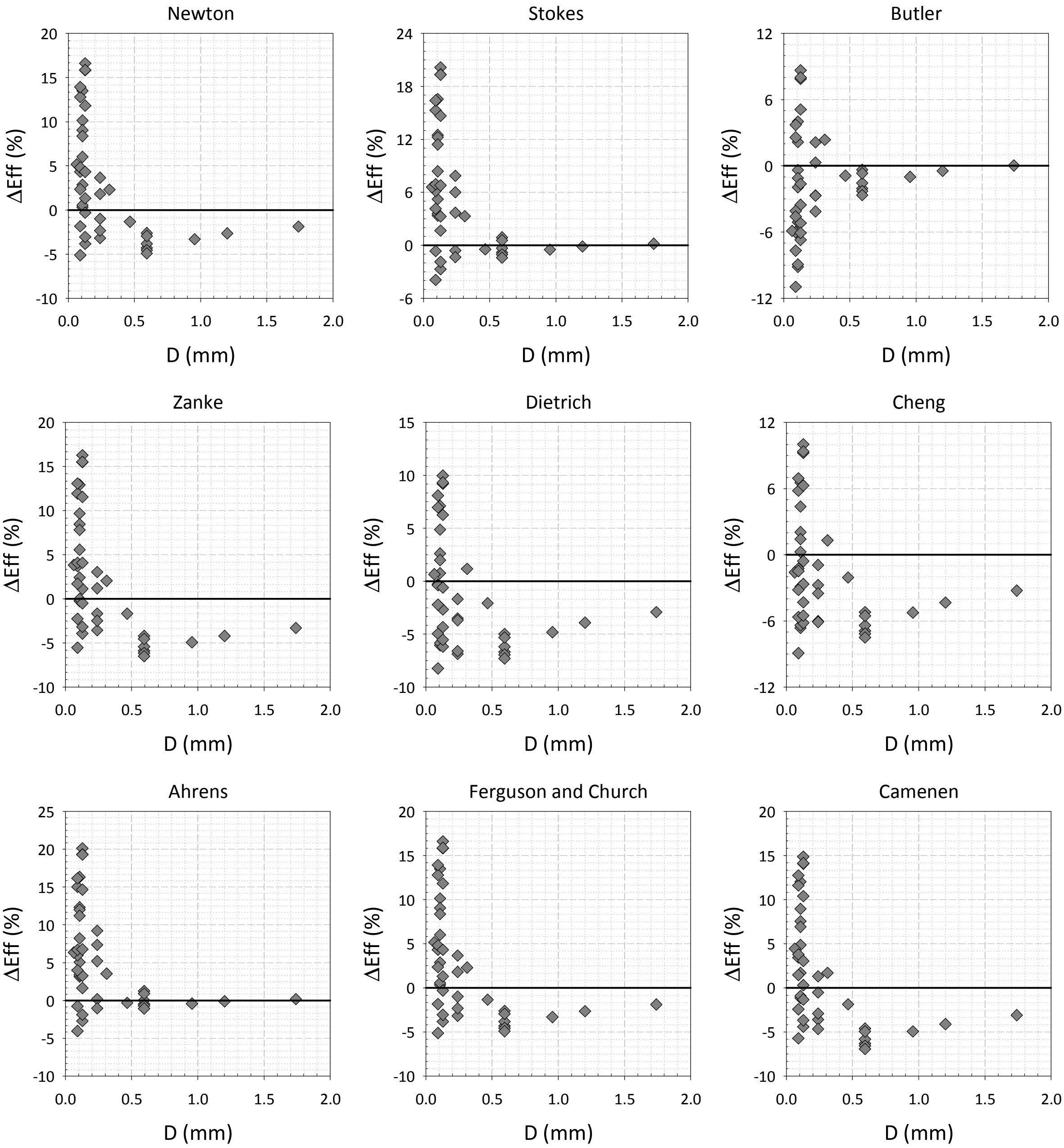


Figure 2.23 - Correlation between calculated error and diameter for tests "M", considering different formulations for settling velocity

Plots on figure 2.23 show that Butler's formulation, as previously observed, has a symmetric correlation between ΔEff and diameter, that complies with the confidence intervals given by the linear propagation of error; in general all other formulations tend to overestimate the efficiency for small diameter (ΔEff > 0 means modeled greater than experimental efficiency); for coarser particles every formula underestimate the efficiency, but Stokes' and Ahrens'. If the applied model is considered to be correct, for coarser particles the settling velocity should be higher. It is known that Stokes' law does not take into account the drag effects; nevertheless for coarser particles it gives a good estimation of the efficiency. It can be assumed that some other phenomena, such as local turbulence effects, tend to decrease the settling rate for coarser particles, while smaller particles (which in case of quiescent conditions should be well described by Stokes' law) could be subjected to re-suspension phenomena.

For mono-disperse experimental runs, table 2.9 shows that the best result is given adopting the Stokes' law multiplied for 0.6, as suggested by Butler; Dietrich's, Cheng's and Ferguson's formulations appear to give good results, even if figure 2.22 shows a general overestimation for smaller particles and an underestimation for coarser diameters.

	Newton	Stokes	Butler	Zanke	Dietrich	Cheng	Ahrens	Ferguson Church	Camenen
RMSE	7.09	8.65	4.78	7.03	5.39	5.39	8.64	6.55	6.67
N-S index	0.88	0.82	0.94	0.88	0.93	0.93	0.88	0.90	0.89
Median	1.32	3.60	-1.64	1.13	-2.68	-2.89	3.55	-0.13	-0.53

Table 2.9 - Root Mean Square Error (RMSE), Nash-Sutcliffe index and median for the efficiency of tests "M", adopting different formulations for the settling velocity in (2.5)

The same comparison has been done considering the overall efficiency calculated for hetero-disperse runs, with equation (2.7). In this case it is possible to observe that all the settling velocity formulations provide similar results, except Stokes', which does not give a good representation of experimental data.

	Newton	Stokes	Butler	Zanke	Dietrich	Cheng	Ahrens	Ferguson Church	Camenen
RMSE	4.49	6.17	4.42	4.33	4.31	4.14	4.46	4.01	3.98
N-S index	0.81	0.64	0.81	0.82	0.82	0.84	0.82	0.85	0.85
Median	1.57	4.14	-0.49	-1.41	-1.24	0.75	1.60	0.65	0.54

Table 2.10 - Root Mean Square Error (RMSE), Nash-Sutcliffe index and median for the overall efficiency of tests "H" and "S", adopting different formulations for the settling velocity in (2.5) and (2.7)

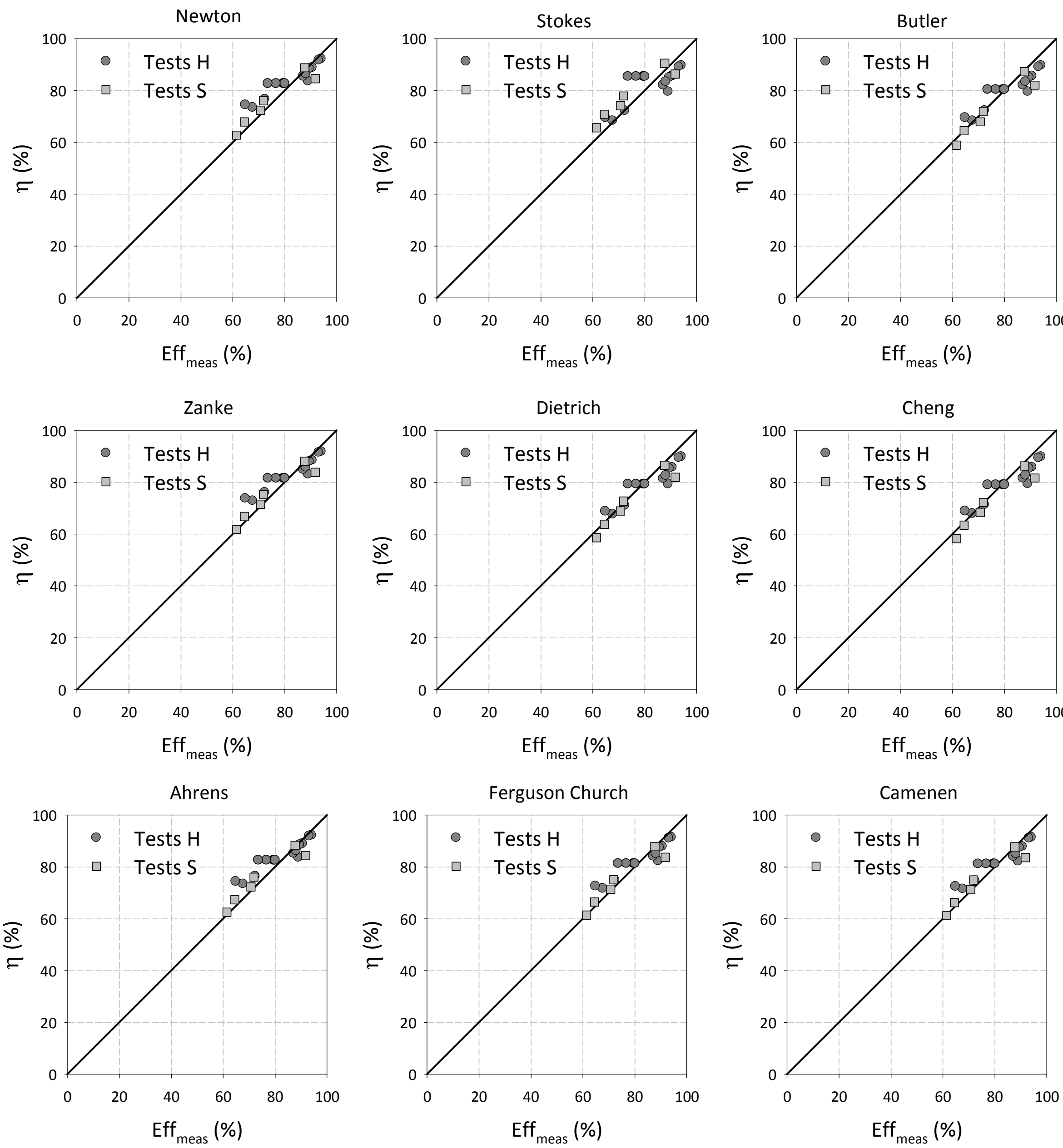


Figure 2.24 - Comparison between calculated and experimental overall efficiency for tests "H" and "S", considering different formulations for settling velocity

For tests "H" and "S", the comparison of the overall efficiency with the experimental data gives better results rather than the comparison between efficiencies for the mono-disperse tests, and almost all the settling velocities formulations give the same result; this fact is probably due to the different percentage of size fractions present in the whole sample and their errors that affect in a different way the final error on the overall efficiency.

2.9. Conclusions

The experimental runs have had the goal to determine experimentally the gully pot capability (efficiency) of trapping the solid material washed off during rainfall from road surface. Among the analytical formulations found in literature for the evaluation of the efficiency, this study has focused on the one by Butler and Karunaratne (1995), since physical characteristics of solids (particle size and specific gravity) as well as the gully pot dimensions are taken into account. Tests conducted with mono-disperse sand have confirmed that the efficiency of gullies is inversely proportional to flow rate and directly proportional to the particle size and specific gravity. Besides experiments "M", tests with hetero-disperse sand have been performed, in order to evaluate the efficiency in case of material characterized by a hetero-disperse particle size distribution, more similar to material accumulated on urban surface during dry periods. These experimental runs have shown that in the case of hetero-disperse samples, efficiency can be estimate as a weighted average of the efficiencies calculated for each individual size fractions, which was so far not explicitly mentioned in literature. To confirm that, further tests have been carried out using samples directly collected from road pavement, assorted both in terms of particle size and of specific gravity. All tests have been performed in steady state conditions, with influent flow rate representative of rainfall intensities between 8 and 60 mm/h, with a constant solid concentration at the inlet. Since the gully pot efficiency is directly function of the settling velocity, different formulations have been applied (Newton's law, Stokes' law, Zanke, Dietrich, Cheng, Ahrens, Ferguson and Church, Camenen); it has been noted that efficiencies calculated by applying the formulation proposed by Butler (modified Stokes' law) give the best result for mono-disperse tests; therefore it is possible that the turbulence within the unit (due to the power of the water jet, the reduced height of the gully pot and the small retention volume) affects the settling rate in a different way for finer and coarser particles. The reduction coefficient introduced by Butler and Karunaratne helps to reduce the error due to these effects, effects that the model does not reproduce. For hetero-disperse tests if the efficiency for each particle size fraction is considered, it is possible to notice an unsymmetrical trend for error vs. diameter, different from what observe for the mono-disperse tests; in this case probably there is an interaction between particles, which should be more deeply investigated. Concerning the determination of the overall efficiency, all the settling velocity formulations give comparable results, except for Stokes' law. Certainly the weighted average and the different percentage of size fractions present in the whole sample affect the final error in a different way.

Therefore it is possible to state that results obtained do not contradict those obtained by previous studies, but usefully extend their substantial validity also to contexts and conditions for which they had not been directly verified. Real applications of proposed and verified formulas are possible if associated to road solids build-up data, rainfall data and to an appropriate runoff model. It could be then possible to formulate hypotheses on gully pot clogging times and also on the characteristics of solids not trapped and directly delivered to the sewer system, providing a useful support to the gully pots maintenance strategies, in terms of both hydraulic and environmental efficiency.

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3. Hydrodynamic separators: PM separation efficiency and residence time distribution studies

3.1. Sommario

Con l'aumento dell'urbanizzazione, i problemi riguardanti il dilavamento delle superfici impermeabili ad opera delle acque di pioggia sono diventati sempre più significativi; il deflusso di tali acque infatti comporta un elevato carico di materiale particolato (PM), universalmente riconosciuto come una delle principali cause di degrado dei corpi idrici (EPA, 2009). Al fine di ridurre l'impatto ambientale delle acque di dilavamento nei corsi d'acqua, sono state proposte varie tecnologie di trattamento, al fine di intercettare e trattenere sedimenti e materiali galleggianti. I dispositivi comunemente utilizzati funzionano secondo i principi dell'idrodinamica e possono essere divisi in tre categorie: dispositivi che utilizzano solo la gravità; separatori a vortice semplici; separatori a vortice avanzati (Faram e Harwood, 2003). Per la progettazione di tali dispositivi e per la pianificazione della loro manutenzione è essenziale conoscere le caratteristiche del materiale solido in ingresso, in particolare la dimensione delle particelle (Kim & Sansalone, 2008a; Greb & Bannerman, 1997).

In particolar modo i separatori idrodinamici sono ampiamente utilizzati nelle aree urbane per la rimozione di sedimenti e oli dalle acque di dilavamento delle superfici pavimentate, dove si ha poco spazio a disposizione e non è quindi possibile realizzare dispositivi di trattamento di ingombro elevato (come BMPs). I test eseguiti sino ad ora su questo tipo di unità sono stati condotti in condizioni di portata costante; pertanto si è ritenuto importante effettuare test in condizioni di portata variabile, al fine di avere una migliore comprensione del comportamento del manufatto in condizioni simili a quelle che si verificano durante un evento meteorico. Le prove sono state eseguite presso il laboratorio del Dipartimento di Ingegneria Ambientale dell'Università della Florida, a Gainesville. In particolar modo il manufatto è stato testato adottando tre diversi idrogrammi in ingresso (di tipo SCS Synthetic Unit Hydrograph), determinati una volta fissata la portata massima e il tempo in cui si verifica tale picco di portata. La portata massima è stata assunta pari al 100%, 50% e 25% la portata di progetto del prototipo sul quale sono state eseguite le prove, pari a 18 l/s; inoltre si è mantenuto costante il volume totale d'acqua in ingresso al manufatto durante l'intera durata della prova (numero di turn overs del manufatto durante la prova). Il materiale soldo in ingresso è stato ottenuto mixando quattro tipi di sabbia silicea (peso specifico pari a 2.65), al fine di ottenere una granulometria conforme a quella del programma New Jersey Corporation for Advaced Technology (NJCAT, 2009); la concentrazione del materiale in ingresso è stata mantenuta costante. Durante lo svolgimento delle prove sono stati prelevati dei campioni in corrispondenza della sezione di scarico dell'unità. Le analisi su tali campioni hanno incluso: analisi della distribuzione granulometrica delle particelle (PSD) e misura della concentrazione dei sedimenti in sospensione (SSC); inoltre è stata effettuata un'analisi granulometrica del materiale trattenuto all'interno del manufatto, raccolto al termine di ogni prova. I risultati ottenuti dalle prove sperimentali hanno dimostrato che l'efficienza del separatore idrodinamico dipende notevolmente dalla portata in ingresso (e dal suo valore massimo), sia in termini di percentuale di materiale solido trattenuto, sia in termini di riduzione percentuale della concentrazione massima di solidi allo scarico, rispetto al valore costante in ingresso. I dati misurati sono stati utilizzati per verificare l'applicabilità di modelli sintetici del tipo overflow-rate (SOR), per la determinazione della percentuale di materiale solido trattenuto. Infine sono state eseguite delle misure con tracciante in condizioni stazionarie, per diversi valori di portata, al fine di determinare sperimentalmente la distribuzione del tempo di permanenza. La determinazione sperimentale del residence time distribution (RTD) permette di determinare il grado di miscelazione all'interno dell'unità per le varie condizioni di portata e l'eventuale presenza di "zone morte" che non sono interessate dal flusso di portata. La stima del tempo medio di permanenza inoltre permette un confronto tra il manufatto oggetto di studio e un reattore ideale.

3.2. Introduction

With the increasing of urbanization, problems concerning the wash-off of impervious surfaces by rainwater have become increasingly significant; indeed runoff water carries a high load of particulate matter (PM), which is widely recognized as one of the main cause of deterioration to receiving waters (EPA, 2009). In order to reduce the environmental impact of stormwater into water bodies, different treatment technologies are designed to intercept and retain sediments and floating materials, that can be removed later. The commonly used devices are installed immediately downstream of the entry points of runoff water and they function through the hydrodynamics principles. This kind of units can be divided into three categories: units that use only gravity; simple vortex separators, which favor the sedimentation using a rotating flow; advanced vortex separators (Faram & Harwood, 2003). For the design of such devices and for scheduling their maintenance it is essential the knowledge of the characteristics of input solid material, especially its particle size (Kim & Sansalone, 2008a; Greb & Bannerman, 1997). Several studies on stormwater treatment devices have been continuously developed in literature, either through tests or monitoring conducted on the units (Kim & Sansalone, 2008b, Walker et al., 1999) or through the use of more advanced computational fluid dynamics models (Pathapati and Sansalone, 2009a, b; Sansalone and Pathapati, 2009).

Hydrodynamic separators (HS) are widely used in urban areas for removal of suspended sediments and floatables from stormwater due to limited land availability for the installation of above ground stormwater best management practices (BMPs). Hydrodynamic separators favor oil and sediments removal, in condition of more or less intense rainfall, thanks to their circular geometry that facilitates the sedimentation of PM. The tests conducted so far on this type of unit have been done under conditions of constant flow; therefore it has been considered important to perform tests under unsteady flow conditions in order to have a better comprehension of the unit behavior under conditions similar to these that occur during a meteoric event.

3.2.1. Hydrodynamic separators overview

Hydrodynamic separators are used as stormwater best management practices (BMPs) in urban areas for removing contaminants from stormwater. These underground devices are attractive in areas where land is at a premium because of their small footprint. Hydrodynamic separators are flow-through devices used as pre-treatment in a multi-BMP treatment train or as stand-alone BMPs. They have no moving parts and rely on flowing water as their source of energy, so they require no power. Hydrodynamic separators principally function as enhanced settling devices over a small space and commonly include a mechanism for capturing hydrocarbon products (e.g. oil) and gross solids. Consequently, they are most effective at removing heavy particulates and floatables from stormwater (EPA, 1999), and to the extent that they are bound to larger sediments, nutrients and heavy metals. Hydrodynamic separators are less effective at removing fine particulates (EPA, 1999) and cannot remove dissolved compounds. There are two important criteria to consider when determining the overall performance of hydrodynamic separators: 1) their efficiency at removing contaminants under treatment flow conditions and 2) their ability to retain accumulated sediments under high flow conditions. Hydrodynamic separators are sized based on the runoff from the drainage basins they serve. As most rainfall events result in flow rates less than the maximum design treatment rates (MDTR) for the installed devices, removal efficiency under treatment rates is an important characteristic for assessing the performance of these devices. However, during less frequent storm events, MDTRs are exceeded, and previously captured sediment can be subjected to scouring, resuspension and washout from these devices.

Historically, monitoring programs have been used to assess the performance of hydrodynamic separators. Monitoring offers the advantage of assessing the performance of BMPs under a wide range of actual hydraulic and pollutant loading conditions for a given drainage basin (Wilson et al., 2007 and 2009). However, monitoring is limited by the accuracy of sample collection strategies as well as the magnitude and frequency of storm events. In addition, due to numerous uncontrolled variables in actual runoff events, it is difficult to use the results of a monitoring study to estimate a device's performance under different flow and sediment particle size conditions. As a result, new protocols for testing the performance and sediment retention of hydrodynamic separators utilizing controlled field and laboratory testing need to be developed. Carlson et al. (2006) and Wilson et al. (2007 and 2009) have developed laboratory and field testing methods to assess removal efficiency of these devices.

A number of studies have been conducted to determine the effectiveness of hydrodynamic separators at removing sediments from stormwater under design water flow conditions. However, research on the retention of sediments under high water flow conditions is limited. Avila and Pitt (2008 and 2009) pre-loaded a full scale physical model with solid particles and collected effluent samples to determine sediment washout. The studies also included velocity measurements in the physical model, and development and calibration of a 3D computational fluid dynamics (CFD) model. This work was the continuation of a project by Avila, Pitt and Durrans (2007). A number of studies have investigated CFD models of hydrodynamic separators, including recent work by Pathapati and Sansalone (2009a and b).

A number of factors are relevant in selecting an hydrodynamic separator product for a specific site.

- *Sizing and treatment performance*

Hydrodynamic separator systems should be sized based on treatment objectives such as desired level of pollutant removal, drainage basin characteristics, climate of the region, and particle size to be targeted. Care must be taken to avoid routing excess flow through the device and compromising performance, favoring scouring phenomena. Each vendor's product has different pollutant removal rates that should be evaluated before selecting the system. The TAPE and TARP programs are evaluation programs sponsored by several state agencies in the U.S. These programs include lab and field testing and provide specific sizing criteria for hydrodynamic separation systems. Currently, the EWRI-ASCE and the ASTM International are developing comprehensive verification guidelines and standard test methods for assessing the performance of these devices.

- *Installation and operating costs*

Costs for hydrodynamic separator systems depend on site-specific conditions such as land characteristics, amount of runoff to be treated, system depth and performance requirements. Not all hydrodynamic separator systems are alike in treatment performance, and basing a decision solely on the installation and operating cost of a system may compromise system performance and the environment. Long-term maintenance costs should also be considered with overall costs when purchasing or selecting a stormwater BMP as initial installation and operating costs may not reflect the long-term investment needed to maintain the system.

- *Maintenance and inspection requirements*

Hydrodynamic separator systems are not maintenance-intensive, when compared with land-based BMP's. Maintenance is fundamental to the long-term performance of any stormwater quality treatment device; if neglected, oil and sediment gradually build up and diminish any BMP's efficiency, harming the environment. Vacuum trucks are typically used for maintenance (Figure 3.2), so unobstructed access to accumulated pollutants for removal is critical. In general vendors give the following recommendations:

- Inspect the unit post-construction, prior to being put into service;
- Inspect the unit every six months for the first year of operation to determine the oil and sediment accumulation rate;
- In subsequent years, inspections can be based on first-year observations or local requirements;
- Cleaning is required once the sediment depth reaches 15% of storage capacity;
- Inspect the unit immediately after an oil, fuel or chemical spill.

- *Land costs*

According to the U.S. Environmental Protection Agency (EPA), "Using structural BMPs that can be placed underground and are design to withstand site specific soil, groundwater and traffic loading conditions provide valuable savings in land area compared to conventional volume-based stormwater treatment practices such as ponds, wetlands, and swales.". Hydrodynamic separator systems may be ideal for areas where land is not readily available and/or tight retrofits are needed as they are installed underground.

Figure 3.1 - Installation of an hydrodynamic separator

Figure 3.2 - Maintenance operations of a hydrodynamic separator

- *Regulations and approvals for hydrodynamic separators*

As stormwater regulations become increasingly stringent, many states and municipalities have developed criteria to govern the use and sizing of these devices. It is increasingly common the use of hydrodynamic separator as the first component of a treatment train, a combination of BMPs in series, to remove coarse solids and floatable pollutants that can rapidly clog other BMPs thus prolonging their maintenance cycle.

3.3. Description of the device and its purpose

An hydrodynamic separator is a flow through device, with the function of treating rainfall runoff. The treatment system separates the particulate matter from stormwater through the gravitational settling and captures and stores free and floating oils, grease, hydrocarbons, and petroleum products through natural buoyancy. In particular the unit in this study is a full-scale fiberglass model, shown on figures 3.3 and 3.4.

The unit consists of a cylindrical structure, with an insert which has a weir, an inflow drop pipe and an outflow riser (Figure 3.3); this insert divides the unit into two chambers: the lower one, which has the function of trapping PM an free oils, and the upper one, which functions as bypass chamber. Within the lower treatment chamber, which is always full of water, the material is stored at the bottom by settling and can be removed during the maintenance activities. Oil and liquids with a specific gravity less than water rise in this chamber and are trapped under the insert by the outlet riser. The system operates according to this scheme: flow coming from the storm sewer pipe is directed by the weir into the treatment chamber through the drop tee inlet pipe, where particulate matter and oils are separated. Water in the treatment chamber is then conveyed through the outlet riser to the downstream side of the weir to be finally discharged into the outlet pipe. During high flow, the inflow in excess of the maximum design flow rate overflows the weir and directly exits the unit through the outlet, bypassing the lower treatment chamber.

In particular this research the unit studied is characterized by having a minimum storage capacity of 3400 liters and the maximum design treatment rates (MDTR) without bypass is 18 l/s (0.64 cfs), while additional flow will overflow the weir and bypass the lower chamber.

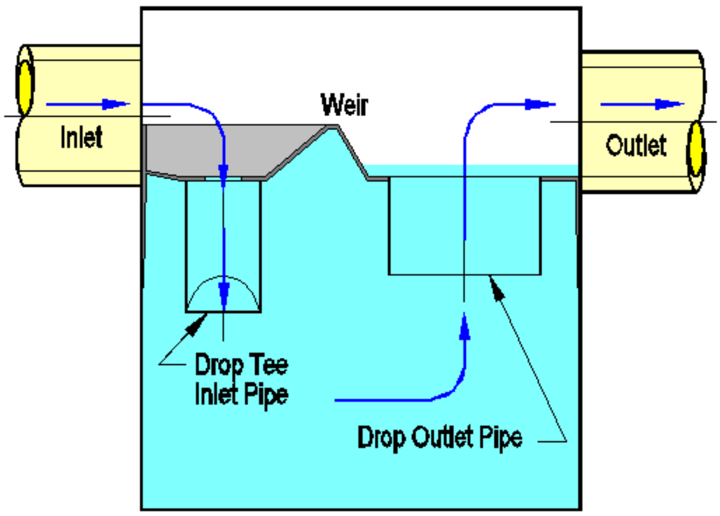


Figure 3.3 - Section view of the HS model

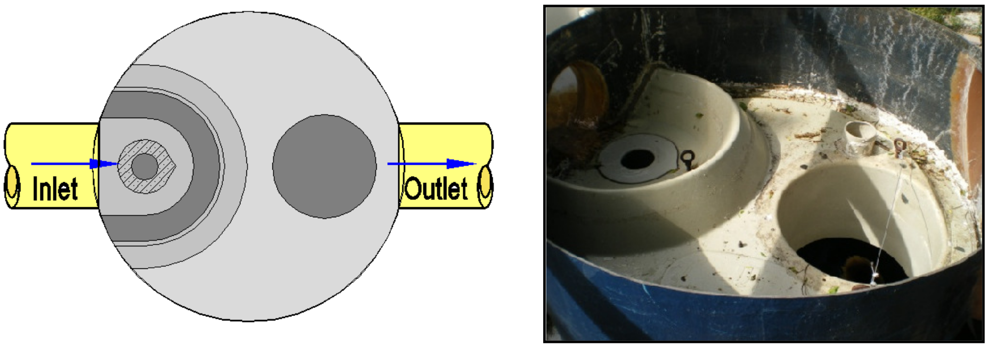


Figure 3.4 - Plan view of the HS model

3.4. Objectives

The purpose of this study has been to examine the performance of model of an hydrodynamic separator loaded with the NJCAT specified gradation (NJCAT, 2003) and tested under unsteady flow conditions. The performance of the unit has been evaluated based on PM removal efficiency and in terms of ΔEMC (event mean concentration) between the influent and effluent. Furthermore, particle size distribution (PSD) data have been collected to characterize both PM discharged in the effluent as well as PM separated and retained within the treatment chamber of the HS.

3.5. Materials and methodology

3.5.1. Experimental setup

The experimental tests for this study have been performed at the Stormwater Unit Operations and Processes Laboratory (UOP) located at the University of Florida, in Gainesville. The main components of the experimental system are the following: a pumping station with Programmable Logic Control (PLC) system, two electromagnetic flow meters, and a slurry mixing and feeding system, that for this set of tests has not been used.

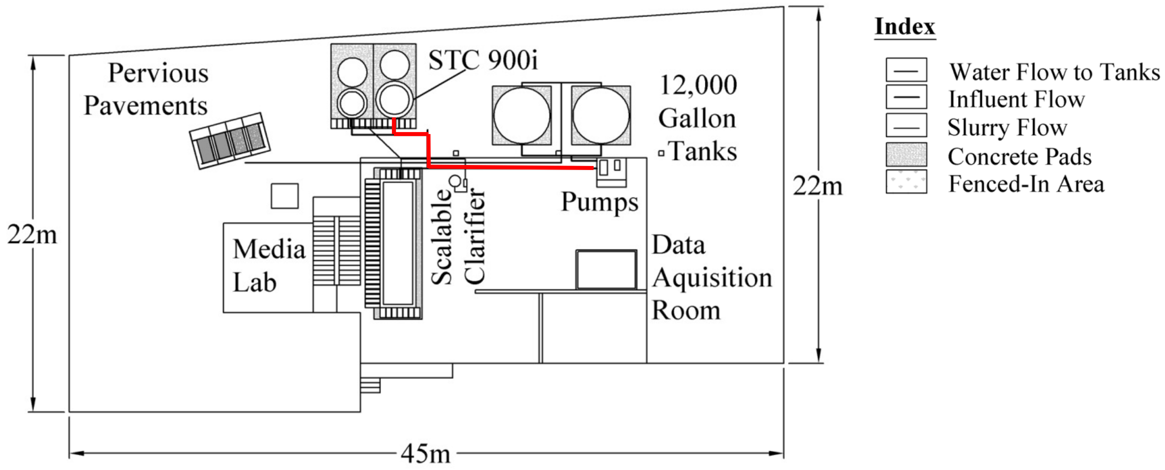


Figure 3.5 - Site layout of the Stormwater Unit Operations

3.5.2. Description of equipment and components

<u>Pumping station with Programmable Logic Control (PLC) system</u>

The site is equipped with a pumping station with two variable speed centrifugal pumps which operate in parallel; this system allows to control the flow rate inlet into the unit. The pumping system takes water from two water tanks (45 cubic meters) fed by pressured municipal water supply line. A series of two magnetic flow meters, valves, and VFDs (variable frequency drives) are integrated with the PLC to provide a feedback control loop to maintain the desired flow rate and for logging real-time data. Before a run, the PLC is pre-programmed with the target flow rate for the particular test run, which is calculated as shown in section **3.10**. In the data acquisition room a data logger has been installed (CR3000 Micrologger, manufactured by Campbell Scientific Inc.); this instrument is useful to have a real-time monitoring and data collection. Data are transferred from the data logger to a data acquisition notebook computer after the experimental run.

<u>Electromagnetic flow meters</u>

The flow rate inlet into the unit has been measured by two volumetric flow measuring devices (Mx UltraMag electromagnetic flow meters), equipped with a remotely mounted signal converter that indicates both rates of flow and total flow as well as providing analog and pulse outputs. The electromagnetic flow meter consists of a non-ferromagnetic measuring tube with an electrically insulating inner surface, and magnetic coils and electrodes that are arranged diametrically on the tube and are in contact with the process liquid through the tube wall. The moving flow generates a voltage which is then amplified and converted to give a direct flow rate reading with 4 to 20 mA and frequency outputs. The signal converter is remotely mounted and signal is split by a multiplexor to simultaneously communicate with the PLC pump controller and the CR 3000 data logger.

3.5.3. Data acquisition and management

During each test, a set of data has been collected in order to check the values of the inlet flow rate and concentration. As described before two flow meters are integrated with the PLC to provide a feedback control loop to maintain the desired flow rate. Two YSI 600 OMS probes have been installed at the inlet and at the outlet of the unit to measure influent and effluent turbidity data. With the turbidity data is possible to monitor influent and effluent particle concentration, once developed a relationship between particle concentration and turbidity. The data stored in the YSI have been downloaded after each run.

The OMS also incorporates sensors for the measurement of conductivity and temperature. Temperature data is an important input variable for models such as a CFD model and surface overflow based-models. Conductivity data can be used to experimentally measure hydraulic residence time distributions.

3.5.4. NJCAT gradation preparation and injection methodology

The target influent particle size distribution loading for the system is the gradation indicated by the New Jersey Corporation for Advanced Technology Program (NJCAT). NJCAT is a not-for-profit corporation to promote the retention and growth of technology-based businesses in fields such as environmental and energy technologies. NJCAT provides innovators with the regulatory, commercial, technological and financial assistance required to bring their ideas to market successfully.

In order to comprise the proposed NJCAT four different gradations of non-cohesive silica sand have been mixed to form slurry based on their calculated mass ratios: the 20/40 Oilfrac (5%), #1 Dry (15%), F-110 (25%) and SCS-106 (55%), in the order of coarser to finer.

The particle size of each silica sand gradation have been provided by US Silica, whose product data sheets which show the individual particle size and other details for the used silica sand particles are attached in Appendix **3.16**. The gradation obtained mixing the four types of silica has been verified by analyzing its PSD and comparing it to the target PSD provided by NJCAT. For this verification the PSDs have been measured in aqueous phase, using the laser particle diffraction analyzer Malvern Mastersizer 2000 (Figure 3.7).

The slurry injection system would have allowed to have an automated delivery of the slurry, as a function of the hydraulic flow rate, in order to maintain an incoming constant concentration; however due to its functioning the peristaltic pump was not able to convey a low slurry flow rate. Therefore for this set of experiments a manual injection has been used, preparing the solid material in one liter bottles, filled with water; it has been decided to pour each injection bottle during an interval of one minute, so the quantity of material in each bottle has been evaluated considering to keep the desired constant concentration. This time step has been taken according to the pumping station setup, since the PLC has been programmed with the value of the target flow that changes every minute. The wet solid material has entered at the unit under conditions of constant concentration (200 mg/l for the first two tests and 300 mg/l for the third test).

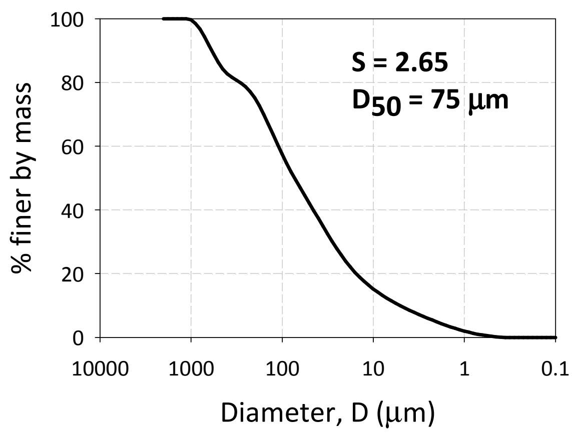


Figure 3.6 - NJCAT specified PSD and prepared influent PM PSD (left); injection bottles (right)

3.6. Testing procedure: sampling methodology and mass recovery

At the beginning of every experimental run this procedure has been followed: setting of the PLC set with the target flow rate; initialization of the data logger to start recording the flow rate; initialization of the YSI turbidity meters to log the turbidity every 5 seconds and their installation within the unit. At the end of the run the YSI probes have been removed and the data downloaded from the YSI probes and CR3000. The sample bottles have been taken to the laboratory to perform PSD and SSC analyses. In the meanwhile the PM inside the device has been allowed to settle overnight, before the supernatant (material still in suspension) has been sampled for concentration quantification and PSD analysis. The material within the unit has been manually recovered and then taken to the laboratory for drying, weighing, and dry phase PSD analysis. Finally the device has been cleaned with potable water for the next run, to ensure to remove any particulate matter that might have been inside of it.

Sampling methodology

The sampling procedure is described as follows (Pathapati and Sansalone, 2009a). During the test a certain number of effluent samples has been manually taken in 1 liter bottles; the samples number depends on the test duration and the hydrograph trend. Samples have been collected in duplicate to perform two measures for PSD and suspended sediment concentration.

The supernatant has been collected at the device's geometric midpoint after overnight settling, to quantify the PM remaining in suspension at various depths inside of it, after a period greater than 8 hours. In particular, four samples have been collected at 4 separate times calculated so that the samples have been taken at four evenly spaced intervals of height of the draining supernatant. The measure of the quantity of PM still in suspension has been needed to evaluate the mass balance error.

Mass recovery

Once the supernatant samples have been collected, the wet material has been recovered from the bottom of the unit by manually sweeping it through the washout into buckets and taken to the laboratory where they have been dried in glass trays at 110 degrees Celsius in an oven. Then the dry silica has been disaggregated, weighed and collected in glass bottles; after this procedure it has been possible to calculate the overall efficiency of the device based on mass and the mass balance. Laser diffraction analysis for the collected dry sample has been then performed to analyze the PSD of the captured particles.

3.7. Laboratory analyses

The laboratory analyses have consisted of measuring the suspended sediment concentration (SSC) and analyzing the particle size distribution (PSD) of the aqueous phase of the effluent samples and the dry phase of the captured mass using the Malvern Mastersizer 2000; these data have been necessary to perform the mass balance for the efficiency of the system. Both the SSC and the PSD analyses have been performed on each sample (A and B), and the final estimation of SSC and PSD has been evaluated as the average of the two values.

Suspended sediments concentration analysis has been performed to quantify particle concentration for each effluent sample and to calculate the effluent mass load knowing the operating flow rates. The protocol specifically followed for this laboratory analysis is the ASTM D 3977 (ASTM, 2002).

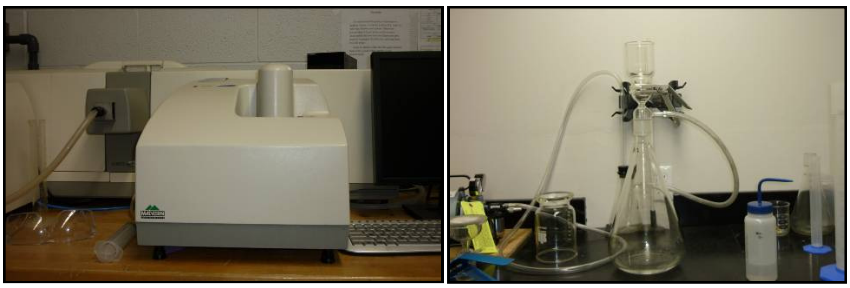


Figure 3.7 - Malvern Mastersizer for the determination of the PSD using the laser diffraction technology (left); equipment for the measure of SSC (right)

Since the PM transport depends on the particle size and moreover the sedimentation efficiency and the maintenance of unit operations depend strongly on both gravimetric indices and granulometric parameters, it has been considered very important to characterize the effluent PM by a PSD analysis, using a laser diffraction analyzer. The Malvern Mastersizer 2000 is a laser diffraction analyzer and has been utilized in this experimental analysis to characterize particle sizes. The instrument technology is based on laser diffraction, occurring when a laser beam passing through a dispersion of particles in air or in a liquid is diffracted at the particle surface. The angle of diffraction is influenced by the size and the shape of the particle. As the particle size decreases, the scattering angle increases (Jillavenkatesa A. et al., 2001). The Mastersizer 2000 detects particle sizes in the range of ~0.1 to 2000 μm in spherical diameter.

For the effluent and supernatant samples a liquid phase measure has been performed. During a measurement, the instrument characterizes the particle gradation three times; the three PSD curves for the individual sample have been averaged into a representative curve for that sample. An event mean PSD has been generated from averaging the individual Mastersizer measurements (both A and B). For the captured material, instead, a dry phase measure has been conducted. To representatively sub-sample the dry mass, the silica has been uniformly mixed. Duplicate samples are taken for the dry phase of the laser diffraction analyzer; the PSDs measured have been averaged.

3.8. Efficiency calculation and mass balance

Efficiency calculation

The hydrodynamic separator's efficiency has been determined as the percentage of incoming PM that is retained by the device, defined as follows:

$$Eff_{mis}(\%) = \frac{m_{in} - m_{eff}}{m_{in}} \cdot 100 \approx \frac{m_{capt}}{m_{in}} \cdot 100 \tag{3.1}$$

Where m_{in} indicates the amount (in grams) of solids entering the unit, while m_{capt} is the amount of sediment retained by the unit itself.

The efficiency was also evaluated in terms of percentage reduction of the maximum concentration, evaluated as:

$$\Delta EMC(\%) = \frac{C_{in} - C_{max\_out}}{C_{in}} \cdot 100 \tag{3.2}$$

where C_{in} is the concentration of sediment at the inlet (constant for each test) and C_{max_out} is the maximum SSC at the outlet.

To determine the total amount of material escaped from the unit, m_{eff}, the following expression has been used:

$$m_{eff} = \sum_{k=1}^{n} \overline{C}(t_k) \cdot \overline{Q}(t_k) \cdot \Delta t \tag{3.3}$$

where k is the effluent individual k-th samples, $\overline{Q}$ and $\overline{C}$ are respectively average flow rate (l/s) and the average concentration (mg/l) during the time interval, Δt is the time interval between samples (s) and n is the total number of discrete effluent samples.

Verification of Mass Balance for each experimental Run

The mass balance has been calculated for each run from captured mass, effluent mass load, and supernatant mass load. The mass balance error (MBE) criteria is ±10% MBE and MABE is determined by the equation:

$$MBE(\%) = \frac{m_{in} - (m_{eff} + m_{capt})}{m_{in}} \times 100 \tag{3.4}$$

3.9. Experimental runs and results

SCS Synthetic Unit Hydrograph

In order to investigate the behavior of the device under hydraulic unsteady conditions, it has been decided to adopt a SCS Unit Hydrograph as input (Sansalone & Teng, 2005).

The Soil Conservation Service (SCS) dimensionless unit hydrograph procedure is one of the most well-known methods for deriving synthetic unit hydrographs in use today (the agency is now known as the Natural Resources Conservation Service or NRCS, but the acronym SCS is still used in association with its UHG method). The primary reference for this method may be considered as the Soil Conservation Service - National Engineering Handbook, Section 4, Hydrology (SCS 1972). The dimensionless unit hydrograph used by the SCS was developed by Victor Mockus and was derived based on a large number of unit hydrographs from basins which varied in characteristics such as size and geographic location. The unit hydrographs were averaged and the final product was made dimensionless by considering the ratios of Q/Q_{max} (flow/peak flow) on the ordinate axis and t/t_{max} (time/time to peak) on the abscissa, where the units of Q and Q_{max} are flow/inch of runoff/unit area. This final, dimensionless unit hydrograph has a time-to-peak located at approximately 20% of its time base and an inflection point at 1.7 times the time-to-peak. The dimensionless unit hydrograph is illustrated on figure 3.8, which also illustrates the cumulative mass curve for the dimensionless unit hydrograph. The table that provides the ratios for the dimensionless unit hydrograph and the corresponding mass curve is shown in Appendix **3.17**.

The pattern hydrograph used has been a step-function approximation of the SCS dimensionless hydrograph (Malcom, 1980), as described by equations (3.5) and (3.6), once defined the maximum, Q_{max}, the time, T_{max}, in which this flow occurs:

- $0 \le t \le 1.25 \cdot T_{max}$

$$Q = \frac{Q_{max}}{2}\left[1 - \cos\left(\frac{\pi \cdot t}{T_{max}}\right)\right] \tag{3.5}$$

- $t > 1.25 \cdot T_{max}$

$$Q = 4.34 \cdot Q_{max} \cdot \exp\left(-1.30 \cdot \frac{t}{T_{max}}\right) \tag{3.6}$$

For the three experimental run the time when the maximum flow rate occurs has been assumed equal to 15 minutes; the values of Q_{max} considered have been equal to 100, 50 and 25% of the design flow rate for the HS, which is approximately 18 l/s (Qp = 0.64 cfs). In order to keep constant the volume of water used during the tests, the peak flow has been kept constant for a certain duration for the second and third test (Figure 3.8).

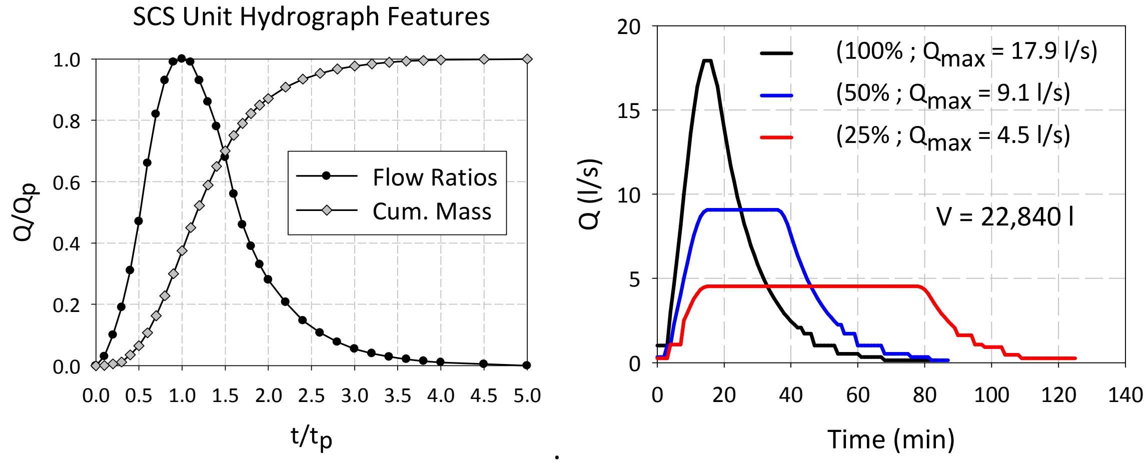


Figure 3.8 - Soil Conservation Service (SCS) dimensionless unit hydrograph – Flow ratios and cumulative mass (left); hydrographs used in the three experimental runs (right)

Experimental Design for the hydrodynamic separator

The parameters selected in the experimental design include:

1. Particle concentration (200 mg/L and 300 mg/L);
2. Unsteady flow rate (with a peak equal to 25%, 50%, and 100% of the given design flow rate);
3. Influent particle gradation based on an NJCAT gradation.

Results

The following table shows a summary of the input data and the results for the three experiments. The device's efficiency is greater than 55% for every run and in general it is possible to notice that with the decrease of the maximum flow rate the efficiency tends to increase; at the same way the percentage reduction of the maximum concentration (ΔEMC) decreases with increasing maximum flow hydrograph (Table 3.1). The mass balance errors have provided values inferior than 10% for all three tests.

Run	% Q_p	Q_{max} (l/s)	C_{in} (mg/l)	Duration d (min)	Vol (l)	Eff (%)	ΔEMC (%)	MBE (%)
1	100	17.9	200	84	22,840	**56.17**	**54.15**	**6.13**
2	50	9.1	200	87	22,840	**63.53**	**55.18**	**2.14**
3	25	4.5	300	125	22,840	**69.69**	**62.50**	**1.96**

Table 3.1 - Summary of the experimental runs, input data and results

Samples taken at the unit outlet have allowed to investigate the PSD and SSC trend during the experiments, that is during the flow rate variation. In particular SSC measures allow to observe the peak of discharged PM's concentration, which occurs with a lag compared to the peak flow (Figure 3.9). For tests 2 and 3, the hydrograph shows a plateau of constant flow equal to the maximum, and for both tests it can be observed that the SSC tends to remain roughly constant for a certain interval. Moreover it can be observed that the PSD curves tend to shift to larger diameters with the increasing of the flow rate, while this trend is reversed during the decreasing part of the hydrograph (Figure 3.10, where d indicates the total duration of each test, summarized in Table 3.1); this inversion occurs after 17, 34 and 25 minutes respectively since the beginning of the first, the second and the third test.

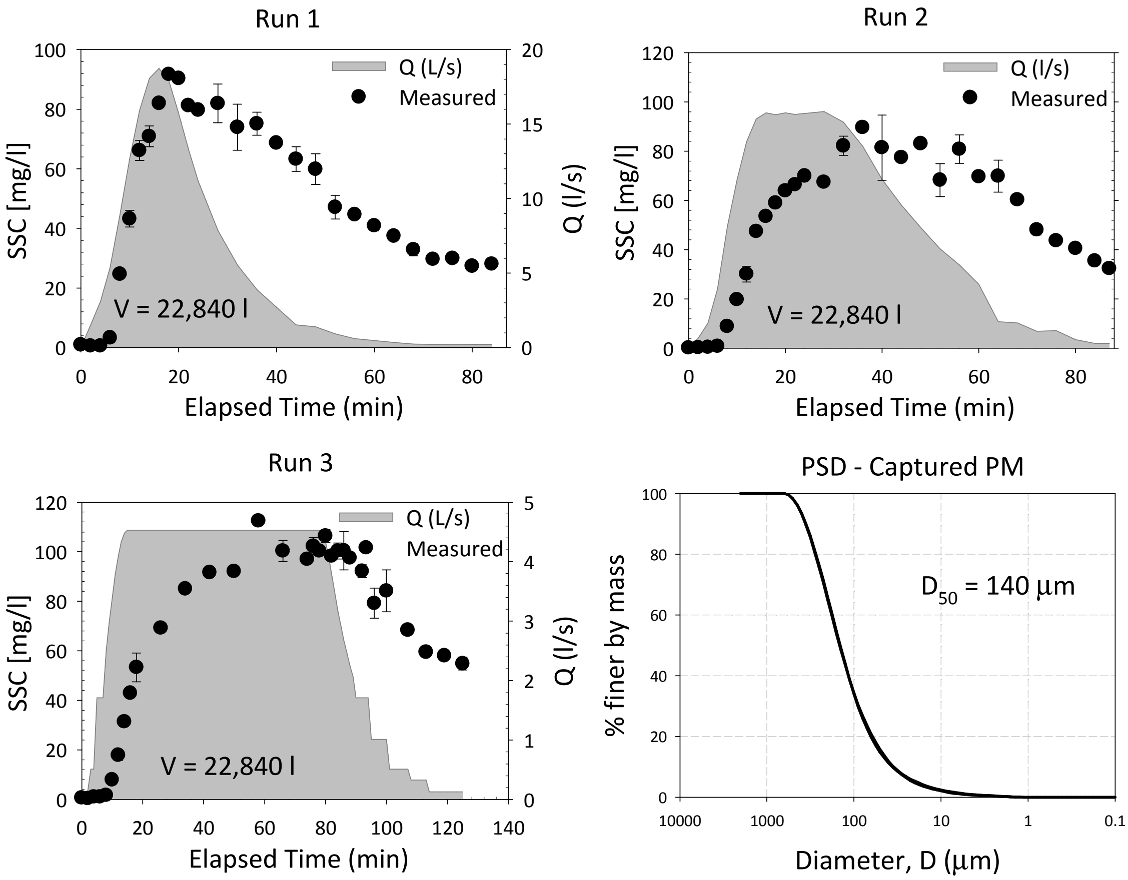


Figure 3.9 - SSC measures of PM collected at the outlet of the HS and PSD of material settled within the unit

PM can categorized into three fractions by size: suspended, settleable, and sediment fraction. The “sediment” fraction includes all particle sizes larger than 75 µm and this size is consistent with published classifications that separate “coarse” from “fine” particles and silt from sand at 75 µm (ASTM, 1993; Kim and Sansalone, 2008a). The “settleable” fraction is usually defined as a part of PM settled out in 1 h Imhoff cone by following the Standard Method 2540F (APHA, 1995). PM remaining in Imhoff suspension after 1 h is defined as the “suspended” fraction (APHA, 1995). Since the impossibility to separate the “settleable” and the “suspended” fraction for each sample, and that this classification is here uniquely used to show results in a more comprehensive way, it has been decided to considerate 25 µm the particle size which divide the two factions (Kim and Sansalone, 2008b). Figure 3.11 shows the percentage of each fractions (“sediment”, “settleable” and “suspended”) within the effluent samples collected at the outflow. It is possible to notice that the increase of flow rate causes an increment of the percentage of the “settleable” and “sediment” fractions. For the first three samples of run 3 it is clear that there has been a measurement error by the instrument, since these three samples present an high percentage of “sediment” fraction but the SSC value is almost zero.

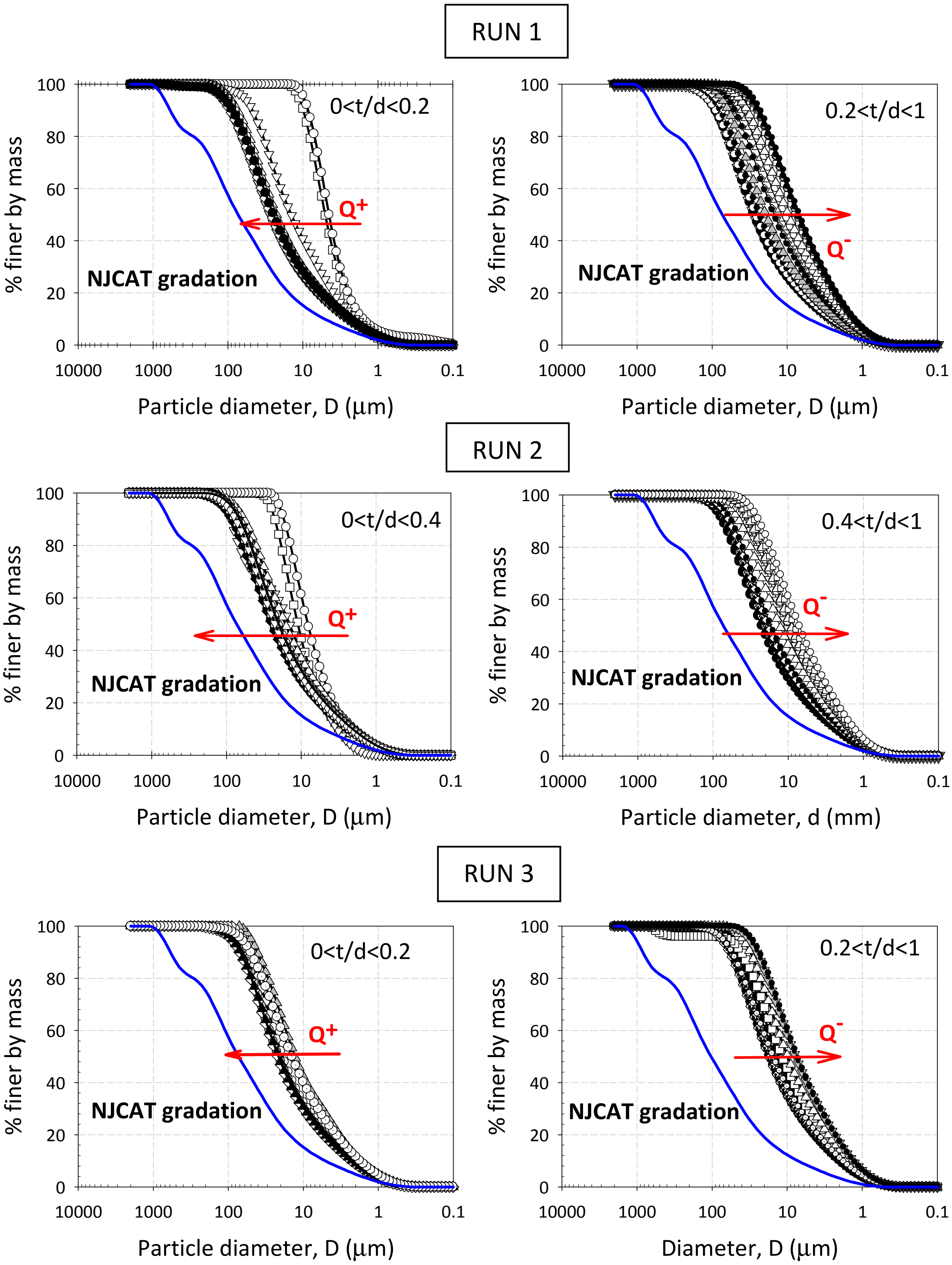
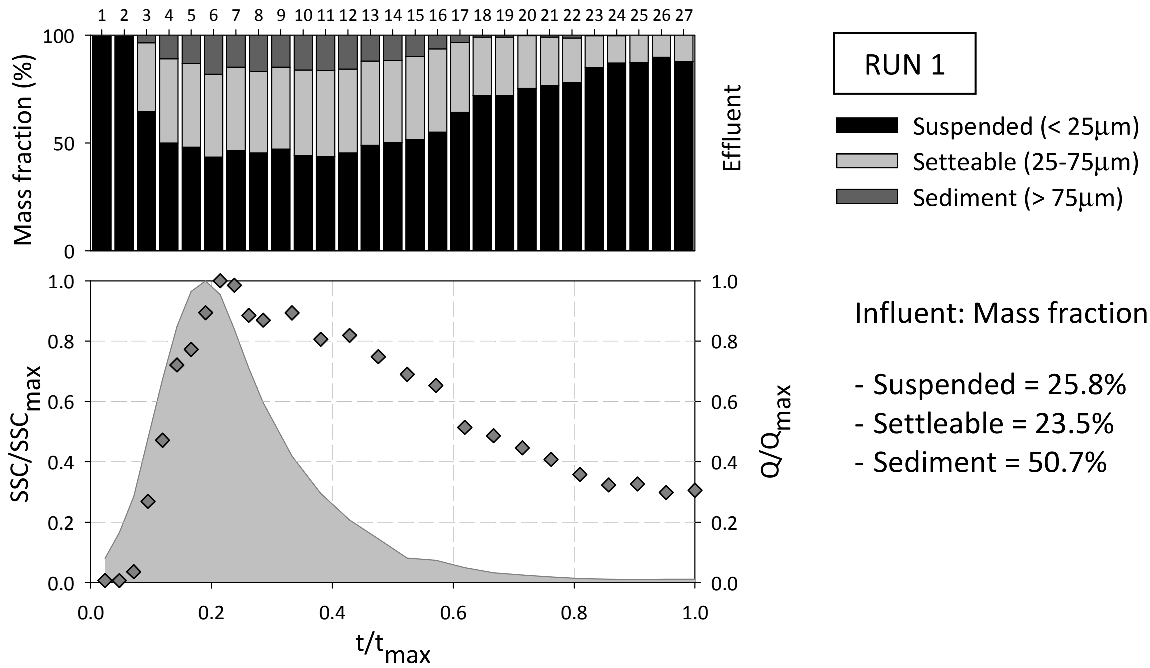
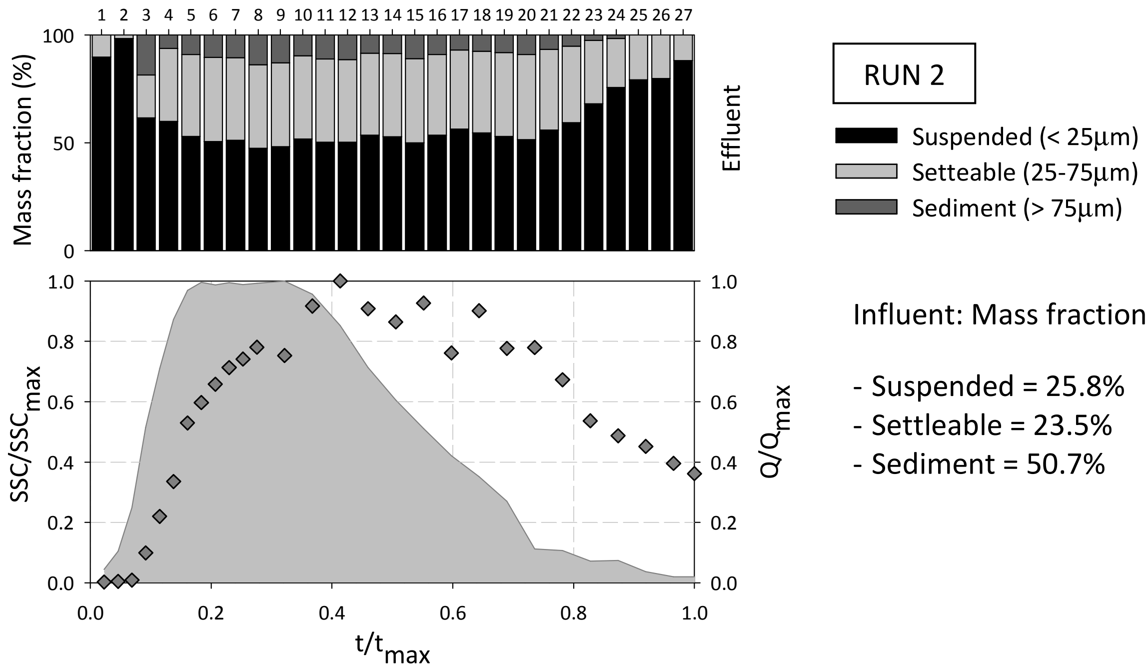


Figure 3.10 - PSD of PM collected at the outlet of the HS during the increasing (left) and decreasing (right) phase of the hydrograph



Influent: Mass fraction:

- Suspended = 25.8%
- Settleable = 23.5%
- Sediment = 50.7%



Influent: Mass fraction:

- Suspended = 25.8%
- Settleable = 23.5%
- Sediment = 50.7%

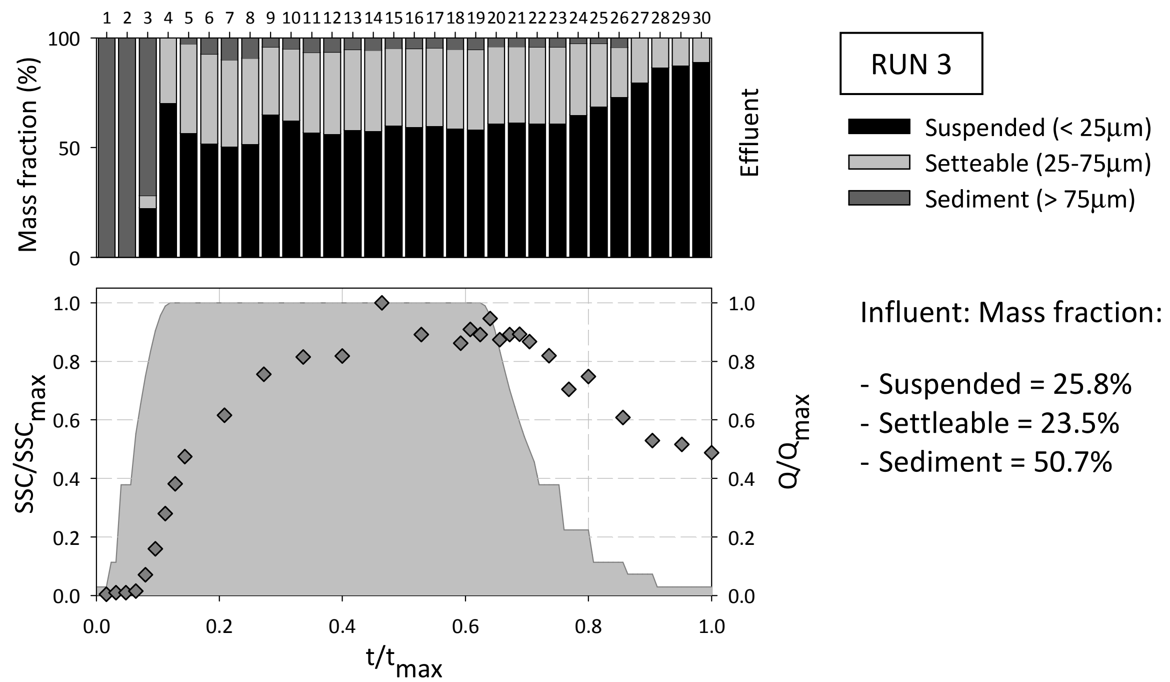


Figure 3.11 - PSD of PM collected at the outlet of the HS divided by fractions

From the results it appears to be clear that the sedimentation efficiency and the maintenance of unit operations depend strongly not only on gravimetric indices, such as mass loading and SSC, but also on granulometric parameters and the hydraulic conditions. The particle size in fact has a significant effect on the PM transport and fate. Therefore, the characterization of PSD becomes a prerequisite in the design phase for development of water quality controls or in situ BMPs (Christina et al., 2002; J.Y. Kim et al., 2008).Non-point pollution has been identified as one of the leading sources of pollution in developed urban areas (US EPA, 1998; Drapper et al., 2000); in particular road/highway storm runoff is considered as an important source of pollutants such as heavy metals, polycyclic aromatic hydrocarbons (PAHs), etc. (Barrett et al., 1998; Furumai et al., 2002). Unlike organic contaminants, heavy metals do not degrade in the environment, and can exert both short- and long-term toxicity impacts by mass accumulation. Since many of the pollutants are particulate-bound in stormwater runoff, it appears clear that sediment removal can provide significant water-quality improvements. Indeed particle-bound heavy metals (Zn, Pb, and Cu) account for more significant pollutant loads than soluble fractions. For these reasons the ability of the device to retain PM is fundamental in terms of environmental protection of water bodies, concerning both total mass and peak concentration discharged into them. Results show in fact how the device can reduce the effluent particles concentration.

3.10. Comparison of SOR modeled and measured PM separation for the hydrodynamic separator

The experiments' results of in term of unit's efficiency have been compared with the values obtained applying an overflow rate model. In particular the formulation proposed by Hazen (1904) evaluates the efficiency as a function of the inflow Q (variable during the run), the geometrical characteristics of the unit (surface area of the system), the particles settling velocity v_s, which depends on diameter and specific gravity, and the short-circuiting factor "n":

$$\mathrm{Eff} = 1 - \left[1 + \frac{v_s}{n(Q/A)}\right]^{-n} \tag{3.7}$$

Since the input hydrograph is unsteady, the efficiency has been calculated for the single i-th particle size fraction for the different flow rates (considering time intervals of 1 minute); the overall efficiency has been determined as a weighted average, using as weight the percentage mass of each size fraction of the total sample of injected PM:

$$\sum \mathrm{Eff}_i \frac{m_i}{m_{tot}} \tag{3.8}$$

where Eff_i is the efficiency corresponding to the i-th particle size fraction of mass m_i; m_{tot} is the total mass of input PM in the interval considered.

Known the geometrical characteristics of the hydrodynamic separator and the hydrographs, it is necessary to determinate the settling velocity and the short-circuiting factor. The particle settling velocity depends on fluid characteristics, such as density and viscosity, particles characteristics, as density, size, shape, roundness and surface texture. In literature there are several formulations for determining the settling velocity. In this study it has been decided to adopt three different expressions to calculate the particle settling velocity: Newton's law (Metcalf & Eddy, 2003); Cheng's formulation (Cheng, 1997); Stokes' law multiplied by a reductive factor equal to 0.6 as used by Butler and Karunaratne (1995). Cheng's formulation has been chosen since in studies performed on the gully pot it was the best one to replicate the experimental data (Bolognesi et al., 2007; Bolognesi et al., 2008); in that case also applying the modified Stokes' law good results had been obtained.

Considering increasing values of the short-circuiting factor, the efficiency has been calculated by adopting the different formulations for the settling velocity; the results have been compared to experimental data in terms of mass of PM retained by the unit (Table 3.2).

The results show that the behavior of the device is best represented with increasing values of the coefficient "n". According to the classification provided by Fair et al. (1968) and referred to the capability of retaining solids:

- $n=1$ → low efficiency;
- $5<n<8$ → very good performance;
- $n \rightarrow \infty$ → excellent performance (here associated with 100).

n = 1

		Newton		Cheng		Butler		Stokes	
	MEAS	CALC		CALC		CALC		CALC	
Run	m_{capt}(kg)	m_{capt}(kg)	Diff %	m_{capt}(kg)	Diff %	m_{capt}(kg)	Diff %	m_{capt}(kg)	Diff %
1	2.539	2.345	**7.6**	2.196	**13.5**	2.176	**14.3**	2.414	**4.9**
2	2.884	2.516	**12.8**	2.370	**17.8**	2.340	**18.9**	2.573	**10.8**
3	4.741	4.202	**11.4**	3.999	**15.7**	3.928	**17.2**	4.260	**10.1**

n = 5

		Newton		Cheng		Butler		Stokes	
	MEAS	CALC		CALC		CALC		CALC	
Run	m_{capt}(kg)	m_{capt}(kg)	Diff %	m_{capt}(kg)	Diff %	m_{capt}(kg)	Diff %	m_{capt}(kg)	Diff %
1	2.539	2.604	**-2.6**	2.459	**3.1**	2.398	**5.5**	2.643	**-4.1**
2	2.884	2.775	**3.8**	2.636	**8.6**	2.568	**11.0**	2.806	**2.7**
3	4.741	4.581	**3.4**	4.390	**7.4**	4.275	**9.8**	4.609	**2.8**

n = 100

		Newton		Cheng		Butler		Stokes	
	MEAS	CALC		CALC		CALC		CALC	
Run	m_{capt}(kg)	m_{capt}(kg)	Diff %	m_{capt}(kg)	Diff %	m_{capt}(kg)	Diff %	m_{capt}(kg)	Diff %
1	2.539	2.661	**-4.8**	2.517	**0.9**	2.450	**3.5**	2.695	**-6.15**
2	2.884	2.830	**1.9**	2.693	**6.6**	2.620	**9.2**	2.857	**1.0**
3	4.741	4.658	**1.8**	4.470	**5.7**	4.351	**8.2**	4.681	**1.3**

Table 3.2 - Comparison between the mass of PM trapped within the unit, m_{capt}, calculated with the expressions (3.7) and (3.8) and the experimental data (MEAS), considering different formulations of settling velocity and different values of short-circuiting factor "n"

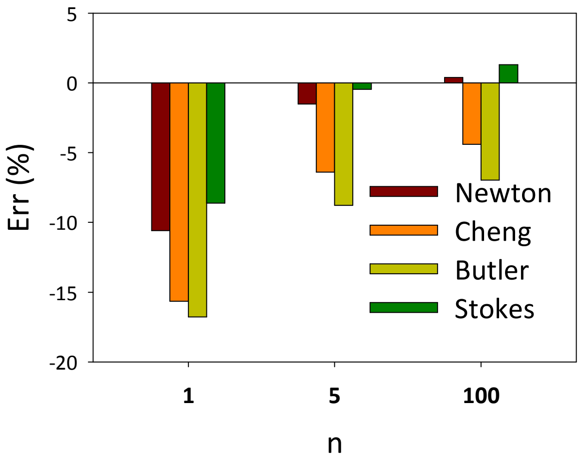


Figure 3.12 - Mean values of errors between calculated and measured efficiency, obtained applying different formulations of v_s and different values of short-circuiting factor "n"

Compared to a traditional gully pot, well represented by Hazen's model when n = -1, the hydrodynamic separator shows higher performance. Regarding the particle settling velocity formulation, the best results are obtained with Newton's law, while the error between measured and calculated efficiency using Butler's hypothesis (Stokes' settling velocity reduced by 0.6) appears to be high. Indeed, using the simple Stokes' law the results are not dissimilar to those obtained with Newton's law, in terms of absolute values.

3.11. Residence Time Distribution curves

Modeling of the hydraulic characteristics of reactors is important because the results can be use to determine the actual amount of time a given volume of water will remain in the reactor and its average age. In turn, the average ages can be related to the degree of treatment achieved. The measurement and analysis of residence time distribution are an important tool in the study of continuous flow systems. The theoretical analysis is normally based on the ideal assumption of either plug (or piston) flow or perfect mixing. Neither assumption corresponds to the flow situation existing in most practical cases (Figure 3.13). The use of RTD allows to characterize the mixing and flow within reactors and to compare the behavior of real reactors to ideal models. A knowledge of the actual behavior is necessary for the design of reactors, for the evaluation of designs, and to gain an insight into the physical process.

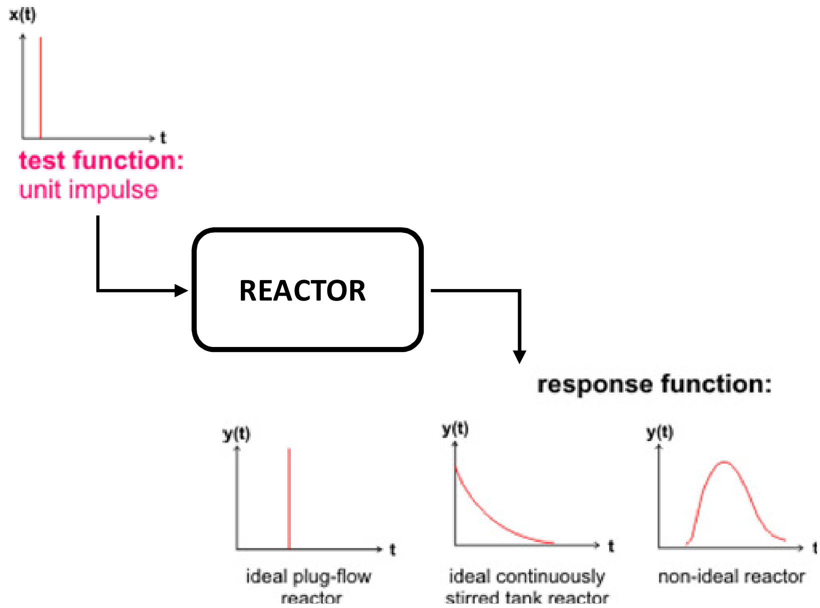


Figure 3.13 -Response function for ideal plug-flow reactor, complete mix-reactor and non-ideal reactor

Considering the two ideal situations:

- A pulse input of a conservative (i.e. nonreactive) tracer injected into an ideal complete mix-reactor (CMR), with a continuous inflow of clear water, the output tracer concentration would appear as shown on figure 3.14(a-1). If a continuous step input of a conservative tracer at concentration C_0 is injected into the inlet of an ideal CMR, initially filled with clear water, the appearance of the tracer at the outlet would occur as shown on figure 3.14(a-2).
- In case of an ideal plug-flow reactor (PFR), the reactor is initially filled with clear water before being subjected to a pulse or a step input of a tracer. If an observer were positioned at the outlet of the reactor, the appearance of the tracer in the effluent for a pulse input, distributed uniformly across the reactor cross section, would occur as shown on figure 3.14(b-1). If a continuous step input of a tracer were injected into such a reactor at an initial concentration C_0, the tracer would appear as shown on figure 3.14(b-2).

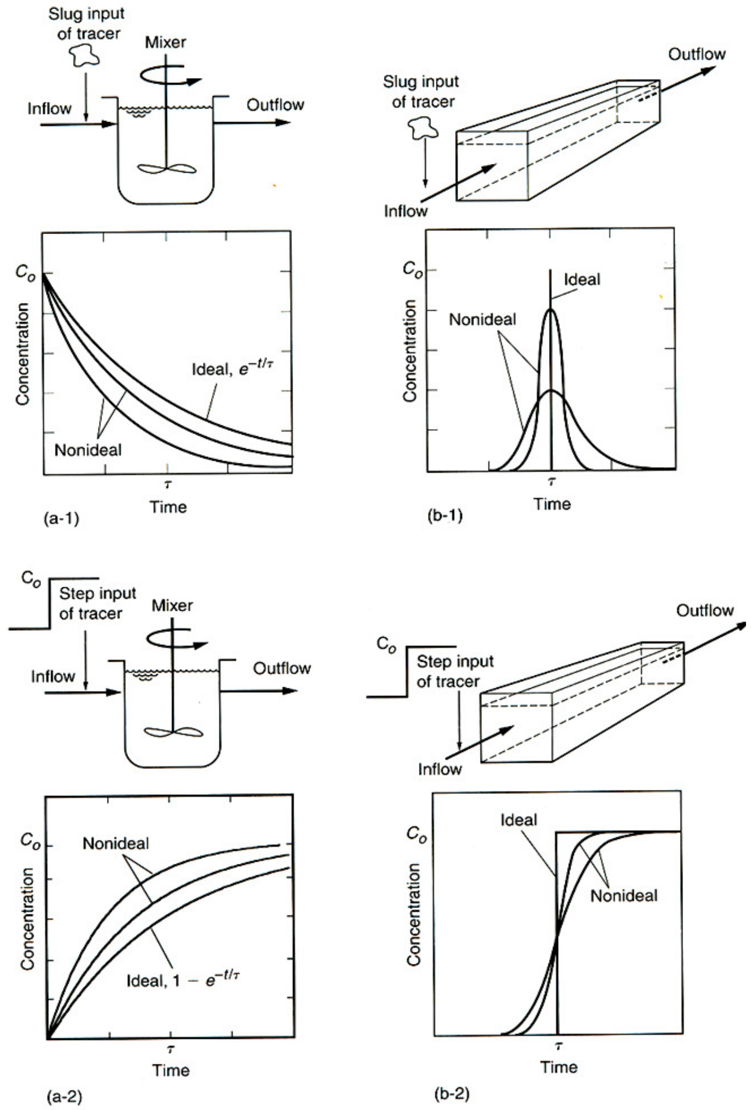


Figure 3.14 - Output tracer response curves from reactors subject to pulse and step inputs of a tracer: (a) complete-mix reactor and (b) plug-flow reactor

In practice, the flow in CMR and PFR is ideal; there is always some deviation from ideal conditions. Non-ideal flow occurs when a portion of the flow that enters the reactor during a given time period arrives at the outlet before the bulk of the flow that enter the reactor during the same time period arrives. Non-ideal flow is illustrated on figure 3.14 a and b. The important issue with non-ideal flow is that a portion of the flow will not remain in the reactor as long as may be required for a biological or chemical reaction to go to completion.

The function RTD, E(t), has the units of time-1 and is defined as follows:

$$\int_0^{\infty} E(t)dt = 1 \tag{3.9}$$

The average residence time is given by the first moment of the age distribution:

$$\bar{t} = \int_0^{\infty} t \cdot E(t) dt \tag{3.10}$$

If there are no dead or stagnant zones within the reactor then $\bar{t}$ will be equal to τ, the residence time calculated from the total reactor volume (V) and the volumetric flow rate of the fluid (Q):

$$\tau = \frac{V}{Q} \tag{3.11}$$

The higher order central moments can provide significant information about the behavior of the function E(t). For example, the second central moment indicates the variance (σ^2), the degree of dispersion around the mean:

$$\sigma^2 = \int_0^{\infty} (t - \bar{t})^2 \cdot E(t) dt \tag{3.12}$$

The residence time distribution of a reactor can be used to compare its behavior to that of two ideal reactor models (CMR and PFR). This characteristic is important in order to calculate the performance of a reaction with known kinetics.

In an ideal PFR there is no axial mixing and the fluid elements leave in the same order they arrived. Therefore, fluid entering the reactor at time t will exit the reactor at time t+τ. The residence time distribution function is therefore a dirac delta function at τ:

$$E(t) = \delta \cdot (t - \tau) \tag{3.13}$$

The variance of an ideal plug-flow reactor is zero.

An ideal CMR is based on the assumption that the flow at the inlet is completely and instantly mixed into the bulk of the reactor. The reactor and the outlet fluid have identical, homogeneous compositions at all times. An ideal CMR has an exponential RTD:

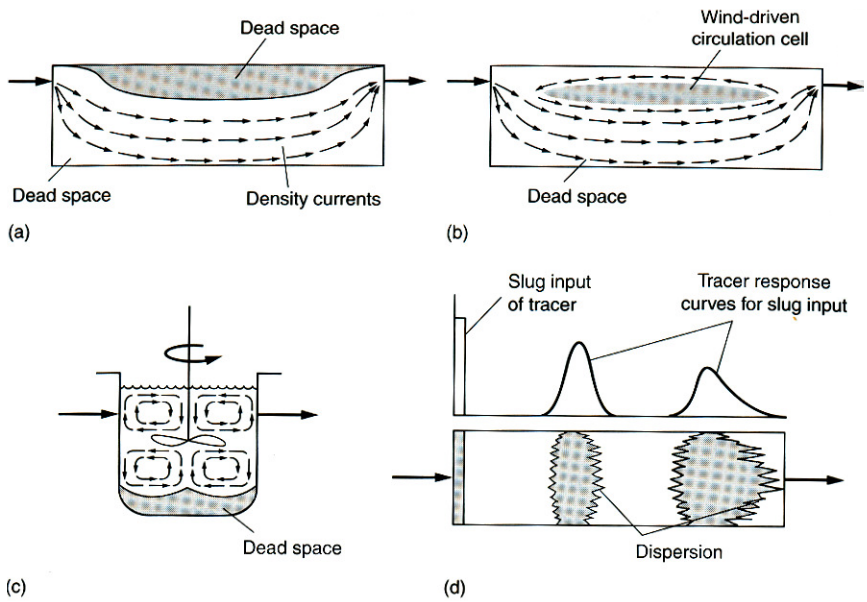
$$E(t) = \frac{1}{\tau} e^{-t/\tau} \tag{3.14}$$

The RTD of a real reactor deviate from that of an ideal one, depending on the hydrodynamics within the vessel. A non-zero variance indicates that there is some dispersion along the path of the fluid, which may be attributed to turbulence, a non-uniform velocity profile, or diffusion. If the mean of the E(t) curve arrives earlier than the expected time τ it indicates that there is stagnant fluid within the vessel. If the RTD curve shows more than one main peak it may indicate channeling, parallel paths to the exit, or strong internal circulation. Short-circuiting fluid within the reactor would appear in an RTD curve as a small pulse of concentrated tracer that reaches the outlet shortly after injection.

3.11.1. Factors leading to non-ideal flow in reactors

Non-ideal flow is defined as short circuiting that occurs when a portion of the flow that enters the reactor during a given time period arrives at the outlet before the bulk of the flow that entered the reactor during the same time period arrives. Factor leading to non-ideal flow in reactors include:

- Temperature differences. In complete-mix and plug-flow reactors, non-ideal flow (short circuiting) can be caused by density currents due to temperature differences. When the water entering the reactor is colder or warmer than the water in the tank, a portion of the water can travel to outlet along the bottom of or across the top of the reactor without mixing completely (Figure 3.15a).
- Wind-driven circulation pattern. In shallow reactors, wind-circulation patterns can be set up that will transport a portion of the incoming water to the outlet in a fraction of the actual detention time (Figure 3.15b).
- Inadequate mixing. Without sufficient energy input, portions of the reactor contents may not mix with the incoming water (Figure 3.15c).
- Poor design. Depending on the design of the inlet and outlet of the reactor relative to the aspect ratio, dead zones may develop within the reactor that will not mix with the incoming water (Figure 3.15d).
- Axial dispersion in plug-flow reactors. In plug-flow reactors the forward movement of the tracer is due to advection and dispersion. *Advection* is the term used to describe the movement of dissolved or colloidal material with the current velocity. *Dispersion* is the term used to describe the axial and longitudinal transport of material brought about by velocity differences, turbulent eddies, and molecular diffusion.



- **Figure 3.15 - Definition sketch for short circuiting caused by (a) density currents caused by temperature differences, (b) wind circulation patterns, (c) inadequate mixing, (d) fluid advection and dispersion**

3.11.2. Tracer analysis

The use of tracers for measuring the RTD curves is one of the simplest and most successful methods now used to assess the hydraulic performance of full-scale reactors. Over the years, a number of tracers have been used to evaluate the hydraulic performance of reactors. Important characteristics for a tracer include:

- The tracer should not affect the flow (should have essentially the same density as water when diluted).
- The tracer must be conservative so that a mass balance can be performed.
- It must be possible to inject the tracer over a short time period.
- The tracer should be able to be analyzed conveniently.
- The molecular diffusivity of the tracer should be low.
- The tracer should not be absorbed on or react with the exposed reactor surfaces.
- The tracer should not be absorbed on or react with the particles in wastewater.

3.11.3. *Experimental determination of RTD*

Basically the residence time distribution (RTD) of a reactor is a probability distribution function that describes the amount of time a fluid element could spend inside the reactor. The concept was first proposed by MacMullin and Weber in 1935, but was not used extensively until Danckwerts analyzed a number of important RTDs in 1953.

In tracer studies, typically a tracer is introduced into the influent end of the reactor or basin to be studied. The time of its arrival at the effluent end is determined by collecting a series of grab samples for a given period of time or by measuring the arrival of a tracer using instrumental methods. The method used to introduce the tracer will control the type of response observed at the downstream end. Two types of tracer input are used: pulse input; step input. The first method involves the injection of a quantity of tracer over a short period of time. The measured output is as described on figure 3.14(a-1 and b-1). In the second method, a continuous step input of tracer is introduced until the effluent concentration matches the influent concentration. The measured response is as shown on figure 3.14(a-2 and b-2).

To plot the RTD curve it is necessary to start from the concentration curve, C versus time, of the tracer at the effluent end. For C curves the mean residence time is determined as:

$$\bar{t}_c = \frac{\int_0^\infty t \cdot C(t)dt}{\int_0^\infty C(t)dt} \tag{3.15}$$

Where C(t) is the tracer concentration at time t.

The variance $\sigma^2{}_c$ used to define the spread of the distribution is defined as follows:

$$\sigma_c^2 = \frac{\int_0^\infty (t-\bar{t})^2 \cdot C(t)dt}{\int_0^\infty C(t)dt} = \frac{\int_0^\infty t^2 \cdot C(t)dt}{\int_0^\infty C(t)dt} - \bar{t}_c^2 \tag{3.16}$$

If the concentration versus time tracer response curve is defined by a series of discrete time step measurements, the theoretical mean residence time is approximated as:

$$\bar{t}_{\Delta c} \approx \frac{\sum t_i C_i \Delta t_i}{\sum C_i \Delta t_i} \tag{3.17}$$

$\bar{t}_{\Delta c}$ = mean detention time based on discrete time step measurement;

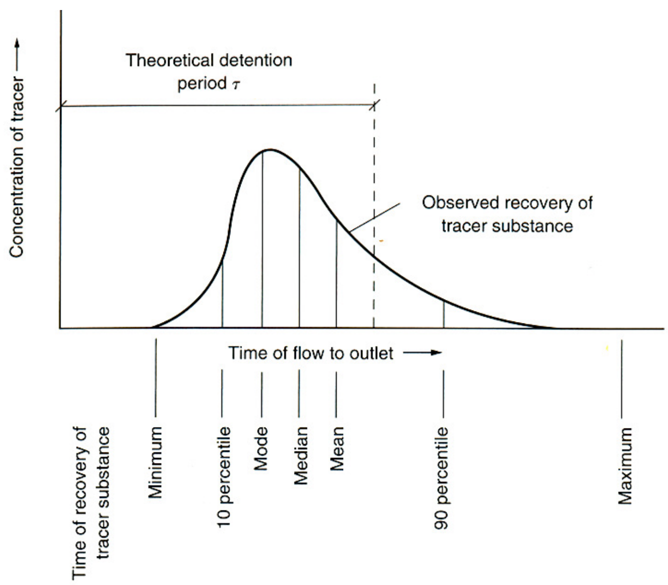
t_i = time at i-th measurement;

C_i = concentration at i-th measurement;

Δt_i = time increment about C_i.

The variance for a concentration versus time tracer response curve, defined by a series of discrete time step measurements, is defined as:

$$\sigma^2_{\Delta c} \approx \frac{\sum t_i^2 C_i \Delta t_i}{\sum C_i \Delta t_i} - \bar{t}^2_{\Delta c} \tag{3.18}$$



- **Figure 3.16 - Definition sketch for the parameters used in the analysis of concentration versus time tracer response curves**

To standardize the analysis of output concentration versus time curves for a pulse input, the output concentration measurements are often normalized by dividing the measured concentration values by an appropriate function such that the area under the normalized curve is equal to 1. The normalized curves are known as residence time distribution curves (Figure 3.17). When a pulse addition of tracer is used, the area under the normalized curve is known as an E curve (exit age curve); the area under this curve is equal to 1 and the function E(t) is the residence time distribution function. The E(t) value is related to the C(t) value by the expression:

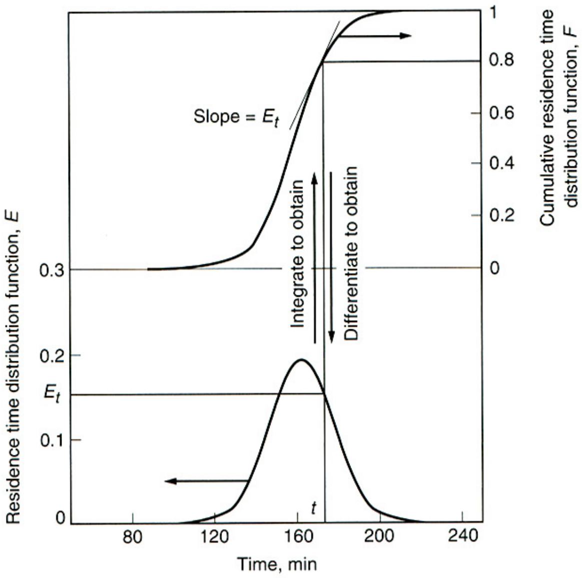
$$E(t) = \frac{C(t)}{\int_0^\infty C(t)dt} \tag{3.19}$$

The mean residence time for E(t) curve is:

$$t_m = \frac{\int_0^\infty t \cdot E(t)dt}{\int_0^\infty E(t)dt} = \int_0^\infty t \cdot E(t)dt \tag{3.20}$$

The cumulative RTD curve, F(t), is defined as the expression (3.21), and, as shown on figure 3.17, the F(t) curve is the integral of the E(t) curve and represents the amount of tracer that has been in the reactor for less than time t.

$$F(t) = \int_0^t E(t)dt \tag{3.21}$$



- **Figure 3.17 - Normalized RTD curves. The curve on the bottom is the exit age curve, E(t); the curve on the top is the cumulative residence time curve, F(t)**

3.12. Development of RTD curves

3.12.1. Methodology

To determine experimentally the residence time distribution, and hence the mean residence time, five step experiments have been run, with a steady flow rate equal to 10, 25, 50, 75 and 100% of the device design flow rate (Q_p = 18 l/s). The tests have been conducted following this procedure: once the unit is in steady condition ($Q_{output} = Q_{input}$), a certain amount of tracer (NaCl), well dissolved in water (with a concentration around 200 g/l), has been introduced within the device inlet. The presence of salt in water produce an increment in water conductivity, which has been monitored at the outlet using the YSI probe. Before each set of tests the probe has been calibrated in laboratory, with different concentration of NaCl (mg/l) as a function of their respective conductivity (µS/cm). Calibration data are reported in Appendix **3.18**.

The recommended experiment duration is approximately 3-4 times the theoretical mean residence time, τ, given by the ratio of volume to flow rate (V/Q), (Nauman and Buffham, 1983). The conducted experiments were stopped at approximately 6-9 theoretical mean residence times, as shown in the summary table 3.3.

3.12.2. RTD curves

Once obtained the concentration versus time tracer curves, it has been possible to develop the RTD curves for each tests, with the following method.

For each time t the corresponding E(t) value has been calculated as:

$$E(t) \approx \frac{C}{\sum C \cdot \Delta t} \tag{3.22}$$

with Δt constant and equal to 1 second.

The E(t) values are corrected by multiplying each one by the time step Δt, and calculating the sum, which should be 1.

$$\sum E(t) \cdot \Delta t = \sum \left(\frac{C \cdot \Delta t}{\sum C \cdot \Delta t} \right) = \sum \left(\frac{C}{\sum C} \right) = 1 \tag{3.23}$$

The mean residence time is calculated with the formulation:

$$\bar{t} = \sum t \cdot E(t) \cdot \Delta t \tag{3.24}$$

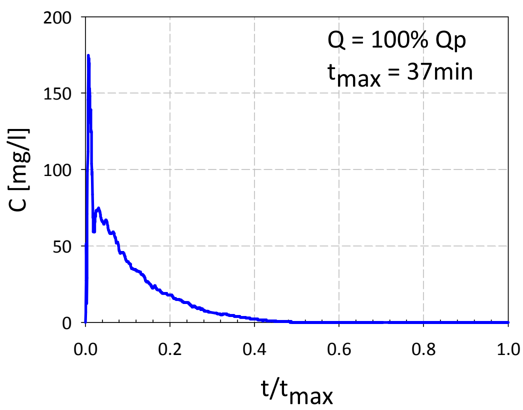
The cumulative RTD curve is obtained by summing cumulatively the E(t)·Δt values.

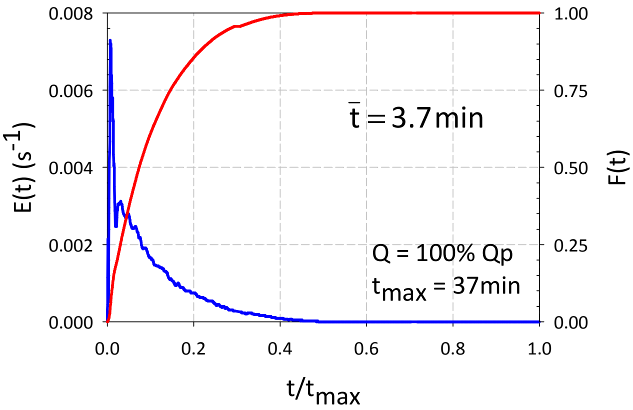
The theoretical mean residence times, τ, have been included in table 3.3, having been calculated known the volume V (3400 l) and the inlet flow rate, Q. The standard deviation $\sigma_{\Delta C}$ has been calculated as square root of the variance , defined by equation 3.18.

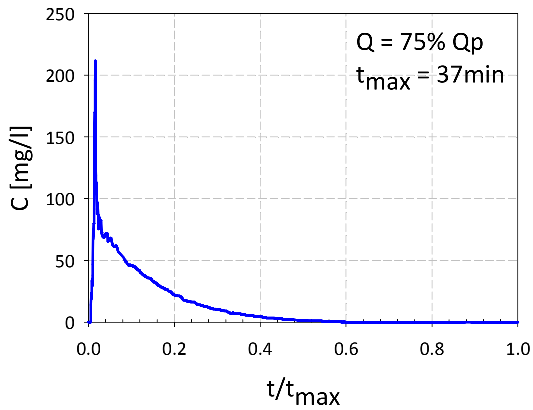
Test	% of Qp	Q (l/s)	τ (min)	Mass NaCl (g)	Duration (min)	Duration/ τ	$\bar{t}$ (min)	$\sigma_{\Delta C}$ (min)
Q100	100	18.0	3.1	350	37	6	3.7	3.3
Q75	75	13.5	4.2	450	37	9	4.8	4.1
Q50	50	9.0	6.3	400	43	7	7.4	6.3
Q25	25	4.5	12.6	350	81	6	10.8	10.2
Q10	10	1.8	31.5	350	207	7	48.6	31.8

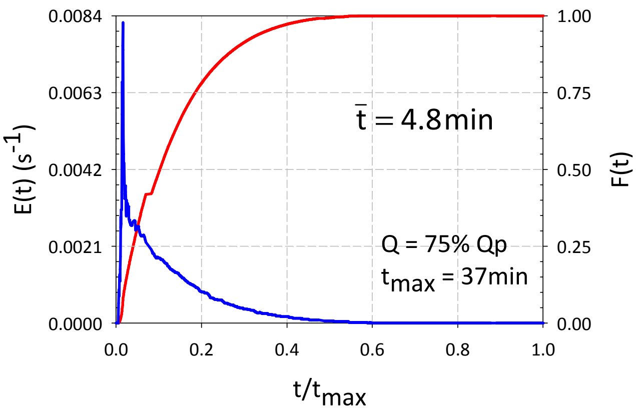
Table 3.3 - Summary table

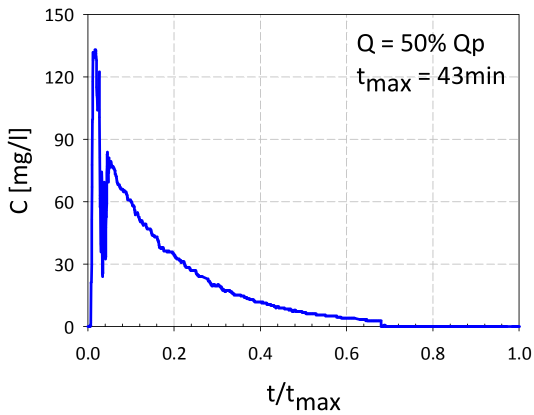
It can be observed that the experimental mean residence time, $\bar{t}$, is slightly greater than the theoretical one, τ, except for test Q25. The larger difference appears for test Q10, where $\bar{t}$ is equal to 48.6 min, while τ is 31.5 min. Therefore it is possible to state that there are no dead or stagnant zone within the reactor. For tests from Q100 to Q25 RTD curves show a peak at the early stage of the test, later followed by an exponential decrease; for test Q10 the RTD curve is more spread and more distant to a complete-mix reactor behavior.

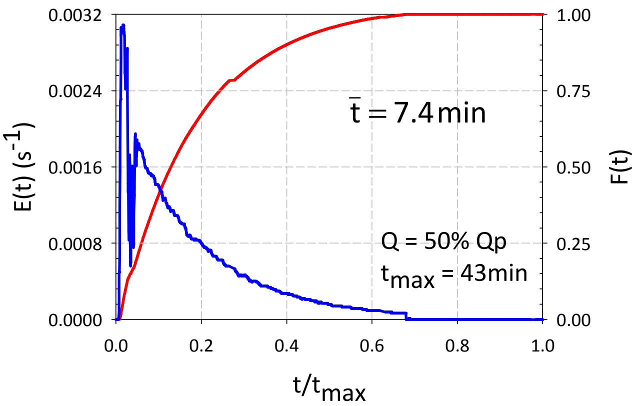

Q = 100% Qp
t_{max} = 37min
C [mg/l]
t/t_{max}

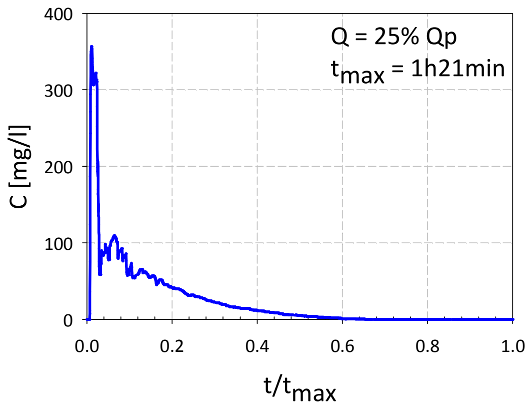

$\bar{t} = 3.7$ min
Q = 100% Qp
t_{max} = 37min
E(t) (s^{-1})
F(t)
t/t_{max}

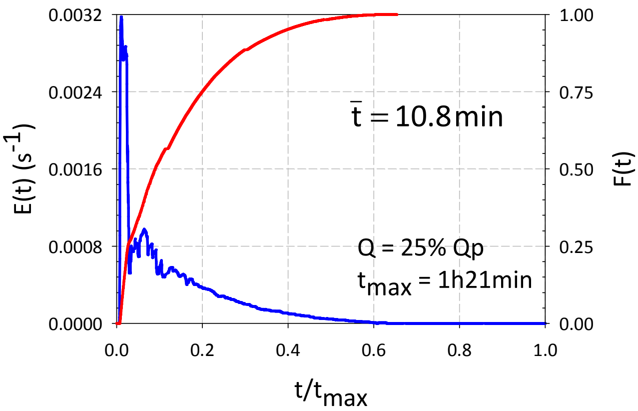

Q = 75% Qp
t_{max} = 37min
C [mg/l]
t/t_{max}

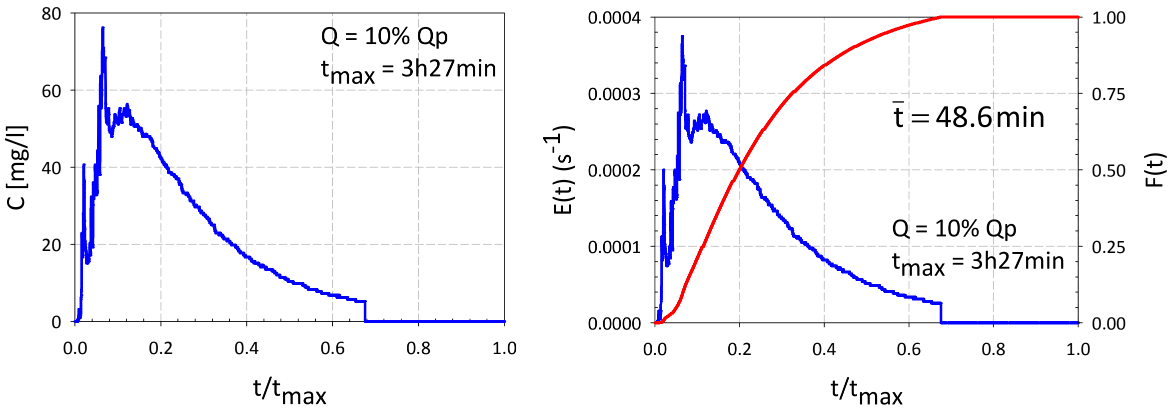

$\bar{t} = 4.8$ min
Q = 75% Qp
t_{max} = 37min
E(t) (s^{-1})
F(t)
t/t_{max}


Q = 50% Qp
t_{max} = 43min
C [mg/l]
t/t_{max}


$\bar{t} = 7.4$ min
Q = 50% Qp
t_{max} = 43min
E(t) (s^{-1})
F(t)
t/t_{max}


Q = 25% Qp
t_{max} = 1h21min
C [mg/l]
t/t_{max}


$\bar{t} = 10.8$ min
Q = 25% Qp
t_{max} = 1h21min
E(t) (s^{-1})
F(t)
t/t_{max}



- **Figure 3.18 - Concentration versus time tracer response curves (left); RTD and F(t) curves (right) for each experiments**

In 1932, based on his studies of sedimentation basins, Morril suggested that the ratio of the 90 percentile to the 10 percentile value from the cumulative tracer curve could be use as a measure of the dispersion index, and that 1 over the dispersion index is a measure of the volume efficiency. The dispersion index proposed by Morril is given by:

$$MDI = \frac{P_{90}}{P_{10}} \tag{3.25}$$

where P_{90} = 90 percentile value from log-probability plot;

P_{10} = 10 percentile value from log-probability plot.

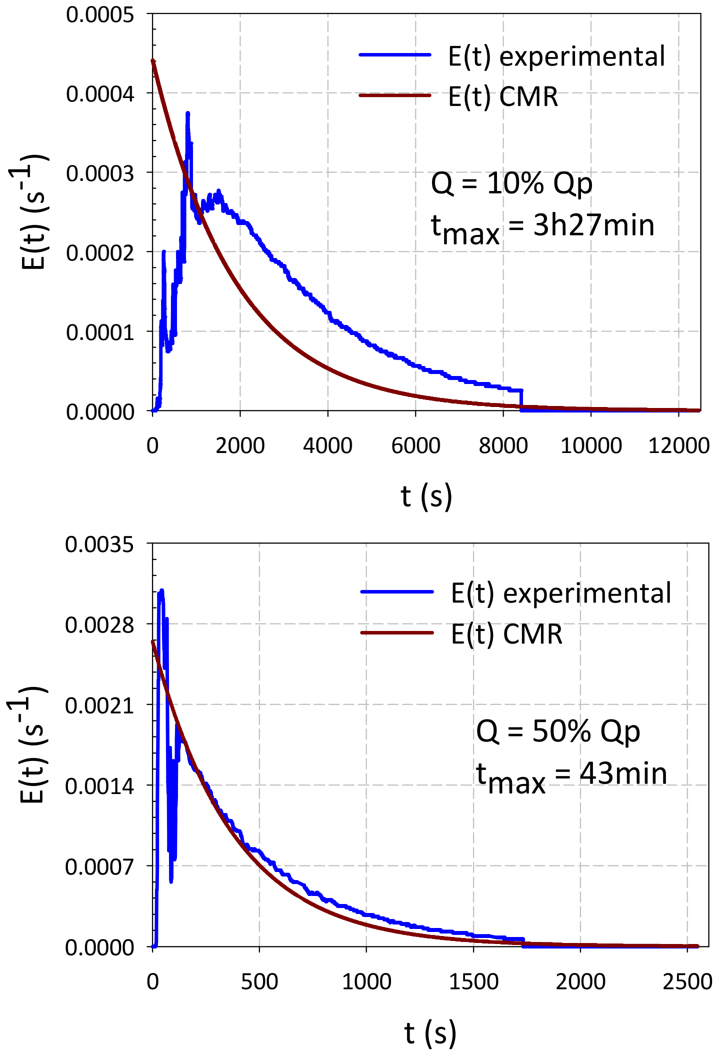
The percentile values are obtained from a log-probability plot of time versus the cumulative percentage of the total tracer which has passed out of the basin (on probability scale). The value of the MDI for an ideal PFR is 1 and about 22 for a CMR. The volumetric efficiency is given by:

$$Volumetric\_efficiency(\%) = \frac{1}{MDI} \cdot 100 \tag{3.26}$$

The MDI and the Volumetric_efficiency have been calculated for each experiment, to observe if the trend shown on RTD curves is confirmed by this dispersion index (Table 3.4). Test Q10 is the one with the lowest MDI value; that means that for this flow rate condition the unit’s behavior is non ideal, while for the other flow conditions the RTD curve is closer to the one obtained for a complete-mix reactor (Figure 3.19).

Test	P_{10}	P_{90}	MDI	Volum_eff %
Q100	24	511	21.3	4.7
Q75	42	637	15.2	6.6
Q50	58	1017	17.5	5.7
Q25	72	1562	21.7	4.6
Q10	819	5815	7.1	14.1

Table 3.4 - Morril dispersion index and volumetric efficiency for each test



- **Figure 3.19 - RTD curves for experiments Q10 and Q50; the E(t) curve is compared to the exponential E(t) for an ideal CMR**

3.12.3. Tanks-in-series model

A single parameter flow model has been used to compare model and experimental results. The tanks-in-series model (TISM) has been chosen for simplicity, although other methods of analysis are available.

The TISM arises from a system of perfectly mixed tanks in series with fluid flowing from one tank to the next. The model parameter is N, which is the equivalent number of tanks. As N increases the mixing regime closer approximates plug-flow. The model is described as follows (Levenspiel, 1972):

$$E(t) = \frac{N^N t^{N-1}}{t_m^N (N-1)!} \exp\left(\frac{-Nt}{t_m}\right) \tag{3.27}$$

The normalized variance, σ_Θ^2, is related to the model parameter by (Kadlec and Knight, 1996):

$$N = \frac{1}{\sigma_\Theta^2} \tag{3.28}$$

$$\sigma_\Theta^2 = \frac{\sigma^2}{\bar{t}^2} \tag{3.29}$$

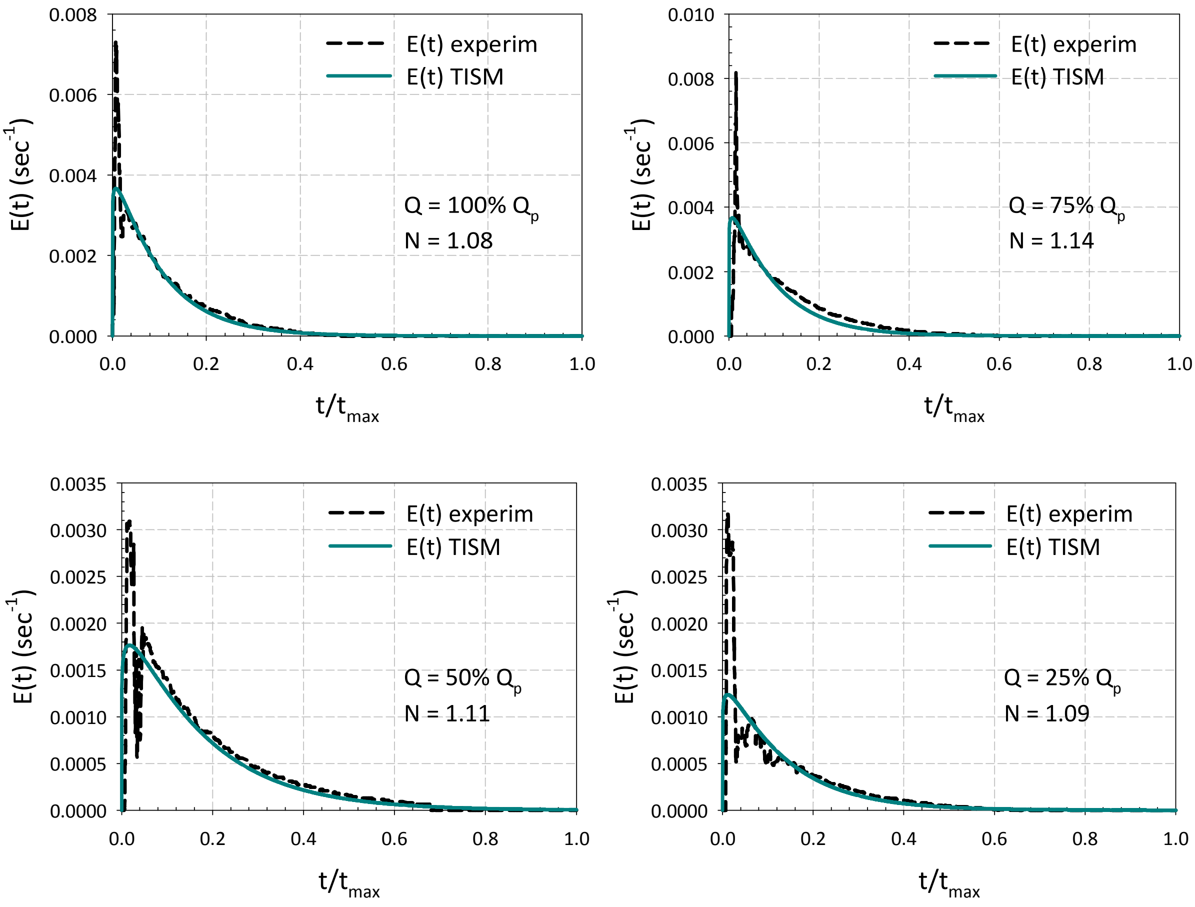
Considering the dimensionless form of the variance as proposed by Kadlec and Knight (1996):

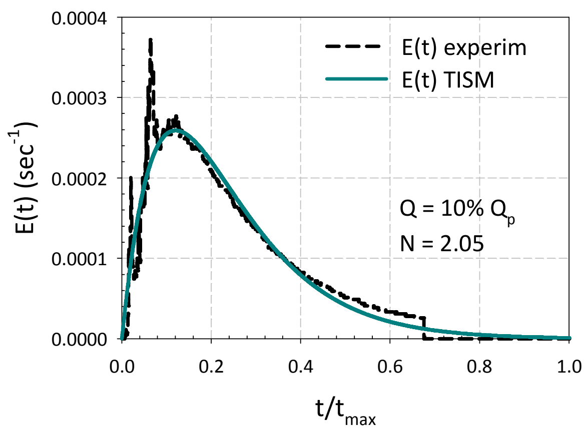
$$\sigma_\Theta^2 = \frac{\bar{t} - t_p}{\bar{t}} \tag{3.30}$$

with t_p the time when the peak of concentration at the outlet occurs.

For each test the model parameter N is within the range 1÷2. Figure 3.20 shows how the tank in series model is able to reproduce the decreasing part of the E(t) curve, while the high peak at the beginning is not so well replicated (tests Q100, Q75, Q50 and Q25). For the Q10 test the E(t) curve is more spread and is well reproduced as 2 tanks in series.

The experimental determination of RTD show how much complex is the behavior of the hydrodynamic separator and that its behavior depends on the hydraulic conditions (influent flow rate).





Test	N
Q100	1.08
Q75	1.14
Q50	1.11
Q25	1.09
Q10	2.05

Table 3.5 – Equivalent number of tanks for the TISM

Figure 3.20 - Experimental RTD curves and modeled RTD curves, based on the TISM

3.13. Conclusions

Three tests have been performed under unsteady conditions on a hydrodynamic separator in order to evaluate the device efficiency in terms of solid material retained during the simulation of a storm event; the experimental runs have been conducted using as loaded PM samples of hetero-disperse sand at constant concentration. During each test, samples have been taken at the outlet of the unit, and SSC measures and PSD analyses have been performed on each sample, in order to understand the functioning of the device during the change of inflow. The tests results appear to be innovative as the adopted hydrographs are characterized by a variable flow rate, verifying the device in conditions similar to those that occur during a rainfall event. In fact previous experiments carried out on similar units have been performed under steady conditions. The experiments' results show how the influent flow rate affect the efficiency of the unit both in terms of PM removal and reduction of the maximum sediments concentration at the discharge; indeed for lower value of peak flow rate, there is an increasing in the efficiency of the hydrodynamic separator. Therefore the knowledge of the hydraulic conditions is very important to determinate the effectiveness of the unit, as well as the characteristics of the inlet PM (size and specific gravity).

The experimental results obtained in terms of percentage of solids retained have been compared with those obtained by the application of literature formulations to determine the efficiency of devices that works with gravity (SOR model). The efficiencies have been therefore calculated assuming various formulations of the settling velocity (Newton's law, Stokes' law and Cheng's formulation) and different values of the coefficient of short-circuiting according to Hazen. The comparison with the results achieved in previous studies for smaller devices characterized by a different geometry (roadside gully pot), attributes to the hydrodynamic separator excellent performance in terms of capacity to retain solids. The tests also confirm the general validity of Newton's law as an expression of particles settling velocity. Finally, experimental data can be used as calibration values for computational fluid dynamics models.

The experimental determination of the residence time distribution for different values of the influent flow rate showed the complexity of the unit behavior, which depends on the hydraulic conditions; the RTD curves, indeed, have an exponential decay for high and medium flow rate, while for low flow rate the curve is more spread. Also these experimental data can be used as calibration values for computational fluid dynamics models.

3.14. References

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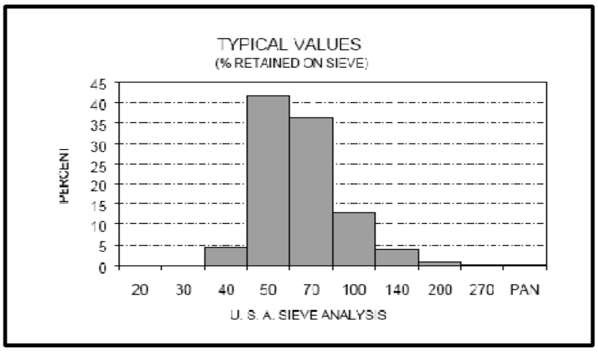
3.15. Appendix of US Silica sand product data

PRODUCT DATA

#1 DRY

UNGROUND SILICA

PLANT: BERKELEY SPRINGS, WEST VIRGINIA



USA STD SIEVE SIZE		TYPICAL VALUES		
		% RETAINED		% PASSING
MESH	MILLIMETERS	INDIVIDUAL	CUMULATIVE	CUMULATIVE
20	0.850	0.0	0.0	100.0
30	0.600	0.0	0.0	100.0
40	0.425	4.2	4.2	95.8
50	0.300	41.8	46.0	54.0
70	0.212	36.0	82.0	18.0
100	0.150	13.0	95.0	5.0
140	0.106	4.0	99.0	1.0
200	0.075	0.8	99.8	0.2
270	0.053	0.1	99.9	0.1
Pan		0.1	100.0	0.0

TYPICAL PHYSICAL PROPERTIES

GRAIN SHAPE .... **SUBANGULAR**
HARDNESS (Mohs) **7**
MELTING POINT (Degrees F) **3100**
MINERAL .... **QUARTZ**
pH **6.5**
SPECIFIC GRAVITY **2.65**

TYPICAL CHEMICAL ANALYSIS, %

SiO_2 (Silicon Dioxide).................................... **99.7**
Fe_2O_3 (Iron Oxide)....................................... **0.024**
Al_2O_3 (Aluminum Oxide)................................ **0.07**
TIO_2 (TITANIUM DIOXIDE) **0.01**
CaO (Calcium Oxide) **0.01**
MgO (Magnesium Oxide)....................................... **<0.01**
Na_2O (Sodium Oxide).. **0.01**
K_2O (Potassium Oxide).. **0.01**
LOI (Loss On Ignition).. **0.2**

April 27, 1999

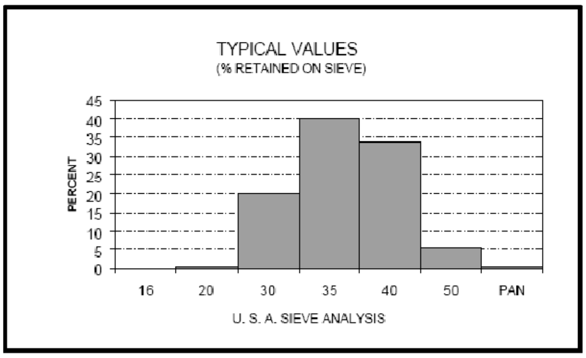
DISCLAIMER: The information set forth in this Product Data Sheet represents typical properties of the product described; the information and the typical values are not specifications. U.S. Silica Company makes no representation or warranty concerning the Products, expressed or implied, by this Product Data Sheet.

WARNING: The product contains crystalline silica - quartz, which can cause silicosis (an occupational lung disease) and lung cancer. **For detailed information on the potential health effect of crystalline silica - quartz, see the U.S. Silica Company Material Safety Data Sheet.**

U.S. Silica Company **P.O. Box 187, Berkeley Springs, WV 25411-0187** **(304) 258-2500**

U.S. SILICA
Sands of Time

PRODUCT DATA



20/40 OIL FRAC

UNGROUND SILICA

PLANT: OTTAWA, ILLINOIS

USA STD SIEVE SIZE		TYPICAL VALUES % RETAINED		% PASSING
MESH	MILLIMETERS	INDIVIDUAL	CUMULATIVE	CUMULATIVE
16	1.180	0.0	0.0	100.0
20	0.850	0.2	0.2	99.8
30	0.600	20.0	20.2	79.8
35	0.500	40.0	60.2	39.8
40	0.425	34.0	94.2	5.8
50	0.300	5.5	99.7	0.3
PAN		0.3	100.0	0.0

TYPICAL PROPERTIES

BULK DENSITY-COMPACTED (lbs/ft^3) **109**
BULK DENSITY-UNCOMPACTED (lbs/ft^3) **102**
HARDNESS (Mohs) **7**
MELTING POINT (Degrees F) **3100**

MINERAL .... **QUARTZ**
GRAIN SHAPE .... **ROUND**
SiO2 (%) **99.8**
SPECIFIC GRAVITY **2.65**

CONFORMS TO API[1] SPECIFICATION RP 56

(1) AMERICAN PETROLEUM INSTITUTE

December 15, 1997

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U.S. Silica Company | P.O. Box 187, Berkeley Springs, WV 25411-0187 | (304) 258-2500

U.S. SILICA

OTTAWA FOUNDRY SANDS

Mined and manufactured to the high standards of U. S. Silica's ISO 9002 Certified Quality System. Air sized, blended and cooled (upon request) to meet the most demanding foundry specifications.

A Sand For All Castings

COARSE GRADES

These two and three screen round grain sands yield the highest permeabilities and contain the lowest fines in the industry. They are ideal for lost foam process and any other application requiring the combination of high permeability and low fines.

	GRADE						
% RETAINED ON	F-30	F-32	F-34	F-35	F-37	F-40	F-42
20	<1						
30	21	16	9	6	2	1	2
40	71	63	57	49	44	33	32
50	8	18	28	38	46	46	34
70	<1	2	5	6	7	16	19
100		1	1	1	1	3	10
140						1	2
200							<1
AFS GFN	29	31	33	35	37	39	43

MEDIUM GRADES

Offering high permeabilities due to excellent fines control, these three and four screen round grain sands are ideal for most core and molding applications in iron, steel and non-ferrous foundries. They also demonstrate high strength in all binder systems.

	GRADE							
% RETAINED ON	F-45	#17	F-50	F-52	F-55	F-58	F-60	F-62
20								
30	1	<1	<1	<1	<1	<1		
40	21	9	11	6	4	4	4	4
50	37	36	34	27	21	19	19	17
70	27	39	37	41	41	39	35	32
100	12	13	15	22	27	28	29	31
140	2	2	3	3	6	8	11	14
200	<1	<1	<1	<1	<1	1	2	2
270						<1	<1	<1
AFS GFN	46	47	49	52	56	58	60	63

FINE GRADES

These grades consist of rounded to subangular grains, which provide high strength and excellent permeabilities. They achieve superior casting finishes in all binder systems and metals.

	GRADE						
% RETAINED ON	F-65	F-70	F-75	F-80	F-85	F-95	F-110
30	<1						
40	3	1	<1	<1	<1	<1	
50	15	9	6	5	2	1	<1
70	29	30	24	19	12	9	4
100	31	35	38	36	38	30	18
140	18	20	25	31	38	42	44
200	3	4	6	8	9	15	25
270	<1	<1	<1	1	1	3	8
Pan						<1	<1
AFS GFN	67	70	76	80	85	95	110

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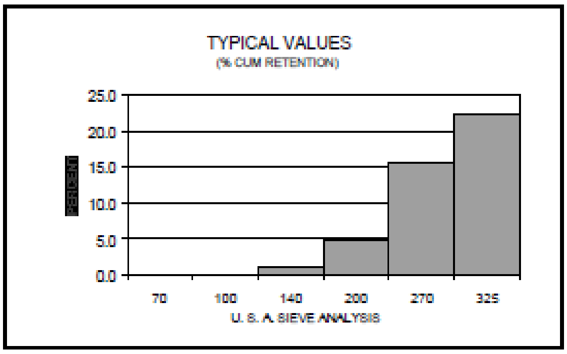
U.S. SILICA®

Sands of Time

PRODUCT DATA



SIL-CO-SIL® 106

GROUND SILICA

PLANT: MILL CREEK, OKLAHOMA

USA STD SIEVE SIZE		TYPICAL VALUES		
		% RETAINED		% PASSING
MESH	MICRONS	INDIVIDUAL	CUMULATIVE	CUMULATIVE
70	212	0.0	0.0	100.0
100	150	0.1	0.1	99.9
140	106	0.9	1.0	99.0
200	75	3.9	4.9	95.1
270	53	10.7	15.6	84.4
325	45	6.7	22.3	77.7

TYPICAL PHYSICAL PROPERTIES

HARDNESS (Mohs) 7
MELTING POINT (Degrees F) 3100
MINERAL .... QUARTZ
pH 7

REFLECTANCE (%) 89.4
YELLOWNESS INDEX 3.63
SPECIFIC GRAVITY 2.65

TYPICAL CHEMICAL ANALYSIS, %

SiO_2 (Silicon Dioxide) 99.7
Fe_2O_3 (Iron Oxide) 0.016
Al_2O_3 (Aluminum Oxide) 0.14
TiO_2 (Titanium Dioxide) .... <0.01
CaO (Calcium Oxide) .... <0.01

MgO (Magnesium Oxide) .... <0.01
Na_2O (Sodium Oxide) .... <0.01
K_2O (Potassium Oxide) 0.02
LOI (Loss On Ignition) 0.1

May 29, 1998

WARNING: The product contains crystalline silica - quartz, which can cause silicosis (an occupational lung disease) and lung cancer. **For detailed information on the potential health effect of crystalline silica - quartz, see the U.S. Silica Company Material Safety Data Sheet.**

U.S. Silica Company P.O. Box 187, Berkeley Springs, WV 25411-0187 (304) 258-2500

3.16. Appendix of SCS Unit Hydrograph

Time Ratios (t/t_p)	Discharge Ratios (q/q_p)	Mass Curve Ratios (Q_a/Q)
0.0	0.000	0.000
0.1	0.030	0.001
0.2	0.100	0.006
0.3	0.190	0.012
0.4	0.310	0.035
0.5	0.470	0.065
0.6	0.660	0.107
0.7	0.820	0.163
0.8	0.930	0.228
0.9	0.990	0.300
1.0	1.000	0.375
1.1	0.990	0.450
1.2	0.930	0.522
1.3	0.860	0.589
1.4	0.780	0.650
1.5	0.680	0.700
1.6	0.560	0.751
1.7	0.460	0.790
1.8	0.390	0.822
1.9	0.330	0.849
2.0	0.280	0.871
2.2	0.207	0.908
2.4	0.147	0.934
2.6	0.107	0.953
2.8	0.077	0.967
3.0	0.055	0.977
3.2	0.040	0.984
3.4	0.029	0.989
3.6	0.021	0.993
3.8	0.015	0.995
4.0	0.011	0.997
4.5	0.005	0.999
5.0	0.000	1.000

Table 3.6 - Ratios for dimensionless unit hydrograph and mass curve

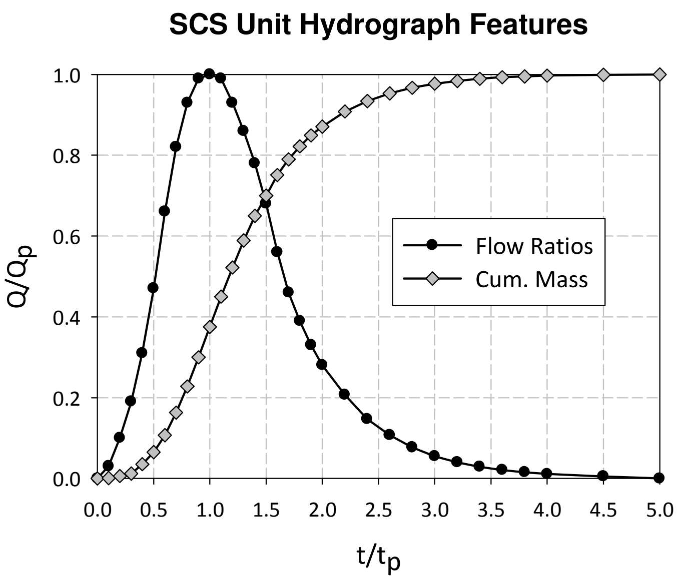
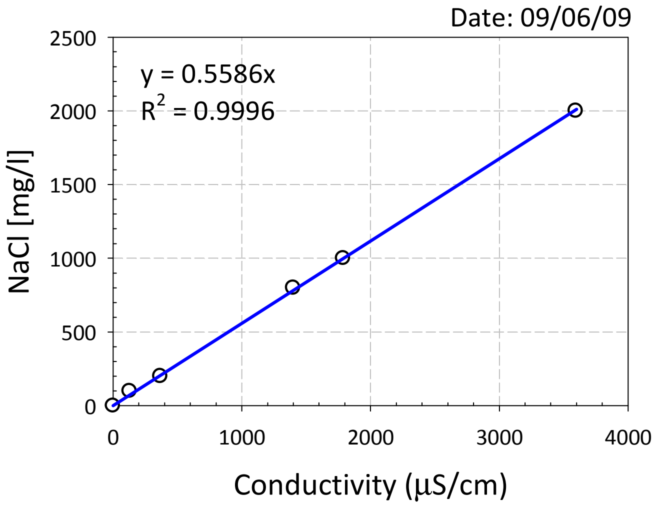


Figure 3.21 - Dimensionless unit hydrograph and mass curve

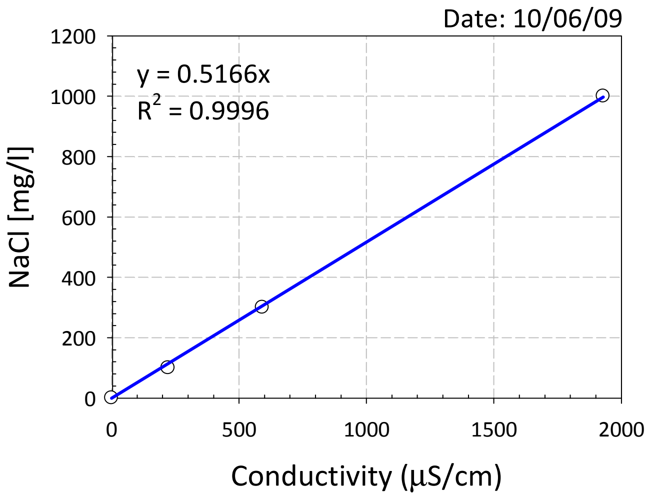
3.17. Appendix of YSI calibration for RTD analysis

Correlation between conductivity and NaCl concentration for the YSI probe. The calibration has been performed before each test. Calibration of 09/06/09 has been used for tests Q100, Q75, Q50; calibration of 10/06/09 has been used for test Q10; calibration of 11/06/09 has been used for test Q25.

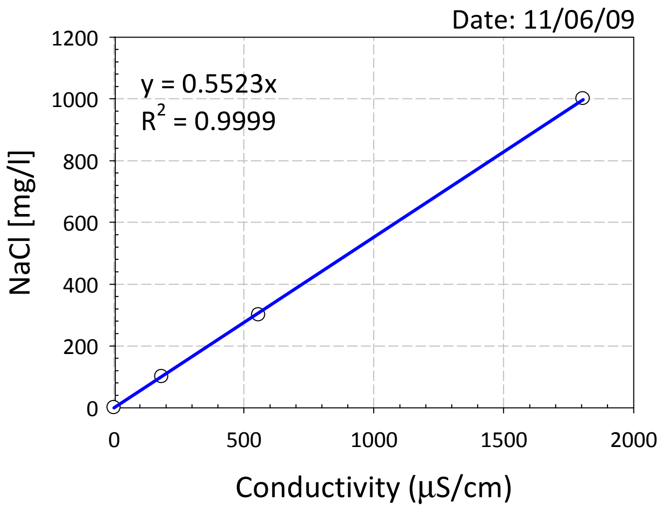
NaCl [mg/l]	Cond (µS/cm)
0	0
100	128
200	367
800	1399
1000	1788
2000	3595



NaCl [mg/l]	Cond (µS/cm)
0	0
100	222
300	592
1000	1929



NaCl [mg/l]	Cond (µS/cm)
0	0
100	184
300	557
1000	1806



4. Clarifier: comparison between the efficiencies of two different configurations and turbidity measurements

4.1. Sommario

L'impatto ambientale derivante dall'inquinamento prodotto dal deflusso delle acque di pioggia non è marginale; la realizzazione di superfici impermeabili come strade, parcheggi, pavimentazioni aeroportuali, ecc. modifica notevolmente il ciclo idrologico locale, con un incremento del volume d’acqua inviato ai corpi idrici; inoltre si verifica un aumento del carico inquinante rimosso dal bacino impermeabile: solidi, metalli, idrocarburi, diserbanti e agenti antigelo sono tra i principali contaminanti di interesse ambientale.

La sedimentazione è una tra le procedure più usate nel trattamento delle acque per rimuovere le particelle e solidi sospesi sfruttando la gravità (bacini di sedimentazione primaria). La progettazione dei sistemi a gravità si basa su quattro aspetti fondamentali:

1) Portata in transito
2) Tempo di permanenza dell’acqua nel sistema
3) Forma/design dell’unità
4) Possibilità di rimozione del materiale depositato sul fondo

Il moto dell’acqua deve essere sufficientemente lento da consentire alle particelle di depositarsi sul fondo. Un manufatto progettato correttamente favorisce la sedimentazione delle particelle solide; la presenza di setti, in particolare, aumenta il tempo di permanenza dell’acqua all’interno dell’unità, ma al tempo stesso può aumentare la turbolenza che sfavorisce la sedimentazione e può causare fenomeni di risospensione del materiale precedentemente depositato. I setti, inoltre, devono essere realizzati in modo tale che le attività di manutenzione e rimozione del materiale trattenuto avvengano agevolmente, senza difficoltà.

Al fine di aumentare l'efficienza di tali manufatti, risulta quindi di notevole importanza uno studio approfondito del loro funzionamento, confrontando diverse configurazioni. A tal proposito presso il laboratorio del Dipartimento di Ingegneria Ambientale dell'Università della Florida sono state condotte delle prove sperimentali su un modello in scala di un clarifier; in particolar modo sono state considerate due diverse configurazioni del manufatto: la prima, più semplice, a sezione trapezoidale; la seconda a sezione rettangolare con setti trasversali per aumentare il percorso dell'acqua verso lo scarico. Le due configurazioni sono state testate in condizioni di portata variabile, considerando tre idrogrammi in ingresso: un idrogramma triangolare, di durata pari ad un quarto d'ora; un idrogramma generato da un evento meteorico reale registrato presso lo stesso laboratorio, di durata circa pari a un'ora; e un idrogramma generato da una precipitazione con tempo di ritorno 25 anni e durata 24 ore. Come materiale in ingresso è stata utilizzata sabbia silicea dalla granulometria particolarmente fine, con peso specifico pari a 2.65; il materiale è stato iniettato a concentrazione costante mediante un apposito sistema di iniezione presente nel laboratorio. Durante le prove sono stati raccolti dei campioni in corrispondenza della sezione di scarico, al fine di eseguire analisi granulometriche e misure della concentrazione dei solidi sospesi; tali analisi hanno permesso di caratterizzare il material solido scaricato (al variare della portata), nonché di eseguire un bilancio di massa. Terminata ogni singola prova il materiale all'interno dell'unità è stato raccolto, asciugato in forno e pesato, per determinare l'efficienza in termini di percentuale di materiale trattenuto; inoltre di tale materiale è stata effettuata l'analisi granulometrica. I risultati ottenuti in termini di efficienza, di abbattimento della concentrazione massima allo scarico e di granulometria del materiale trattenuto sono stati confrontati idrogramma per idrogramma per le due configurazioni. È stato osservato come la presenza di setti trasversali aumenti notevolmente l'efficienza del clarifier, sia in termini di quantità di materiale solido trattenuto, sia in termini di abbattimento della concentrazione massima allo scarico. L'efficienza risulta quindi dipendere notevolmente dalla configurazione del manufatto. I risultati sperimentali ottenuti sono stati confrontati con i risultati che si ottengono dall'applicazione di modelli del tipo over-flow rate.

La misura in continuo della torbidità in corrispondenza della sezione di scarico, inoltre, ha permesso di approfondire lo studio delle correlazioni possibili tra torbidità, appunto, e concentrazione dei solidi sospesi. Le correlazioni ottenute sono state confrontate con altre presenti in letteratura.

4.2. Introduction

The environmental impact resulting from runoff pollution associated with transport activities is not marginal; the construction of an impervious surface such as a highway or airfield within a catchment extensively modifies the local hydrological cycle, with larger volumes of water being delivered in shorter periods of time to receiving waters. Moreover it occur an increase in total pollutant load washed from the surface: solids, metals, hydrocarbons, herbicides and de-icing agents as the principal contaminants of environmental concern.

Sedimentation is a procedure used in wastewater treatment in order to remove particles and suspended solids using gravity (primary sedimentation basins). Settling system design is controlled by four important elements:

1) Flow rate of the water through the settling system
2) Time that the water is in the system
3) Size/design of the system
4) Ability to remove the sludge

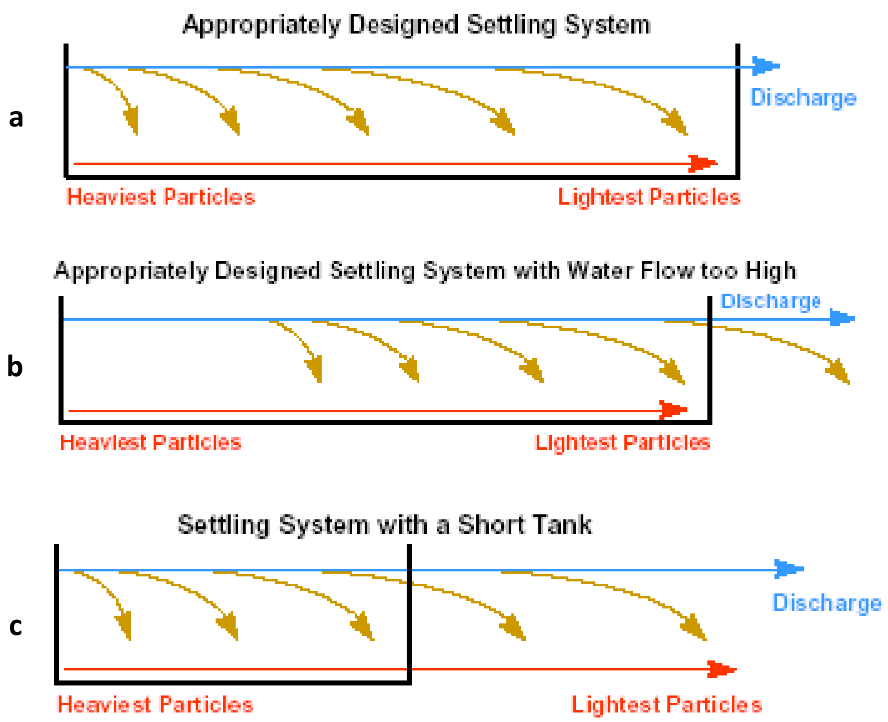


Figure 4.1 - Different design of tanks: a. Heaviest and lightest particles settle out; b. Heaviest particles settle out but some lighter particles are discharged; c. Heaviest particles may settle out but most lighter particles are discharged

Water flow rate needs to be slow enough to allow particles to settle out. If the water flow is too rapid particles will be discharged. A properly designed tank or baffle system will reduce the water flow and allow particles to settle out. The water needs to remain in the system long enough to allow the particles to settle; this 'residence time' is directly related to point 1. A properly designed tank or baffle system will reduce the water flow, but turbulence will reduce particle settling and may disturb settled sludge, causing re-suspension phenomena. Size/design of the system is important so that points 1 and 2 can occur: if the system is too small the water flow will be too rapid and the residence time too little. Proper design is necessary also to minimize sludge disturbance; for example improper baffling can cause poor settling and sludge disturbance. Finally it is fundamental for maintenance practices that sludge removal occurs easily. Allowing sludge to build up reduces the effectiveness of the settling system.

For these reasons to improve the effectiveness of such devices the study of their design is very important; therefore two clarifier configurations have been tested, one without and one with baffles.

4.2.1. Clarifiers overview

Clarifiers, also called settling tanks, are large tanks in which water is made to flow very slowly in order to promote the sedimentation of particles. Settlement is the cheapest and most satisfactory way of removing suspended solids. Any liquid which contains heavy solid particles will become clarified if allowed to stand in a tank. The solids settle out and form a sludge at the bottom of the tank from where they can be removed. Efficiently designed sedimentation devices should effect a reduction in suspended solids of up to 75%. There is no reason why this goal should not be reached unless a high percentage of colloidal matter is present. In addition to the removal of suspended solids, a reduction in biochemical oxygen demand of about 35% is also achieved. Moreover the removal of solid particles allows to remove substances, such as heavy metals, attached to suspended solids.

Clarifiers comes in two shapes: rectangular and circular (Figure 4.2).

Figure 4.2 - Primary Clarifier, Hill Canyon Wastewater Treatment Plant, Camarillo, California, USA (left); Primary Clarifier , Glenwood Springs, Colorado, USA (right)

4.2.2. Sedimentation theory

Within a sedimentation unit, such as a settling tank, the flow is extremely complex, so that any theory of sedimentation is based on a simplified model if complex analysis is to be avoided. In order to remove particles, the time of detention must be such that all particles below a certain size can fall to the bottom of the unit. Considering a particle, which enters within the tank from the point “**X**, in order that this particle is trapped within the unit, its trajectory has to reach the point “**A**” above the bottom.

If Q is the input flow rate, l, b and d the tank dimensions, the longitudinal velocity of water (and particles) is given by:

$$Q = d \cdot b \cdot V \longrightarrow V = \frac{Q}{d \cdot b} \tag{4.1}$$

The horizontal travelling time t_1 is:

$$t_1 = \frac{l}{V} = \frac{l \cdot d \cdot b}{Q} \tag{4.2}$$

The vertical travelling time t_2 is:

$$t_2 = \frac{d}{v_s} \tag{4.3}$$

Where V_s is the particle settling velocity.

$t_1 = t_2$

$$\frac{l \cdot b \cdot d}{Q} = \frac{d}{v_s} \longrightarrow v_s = \frac{Q}{S} \tag{4.4}$$

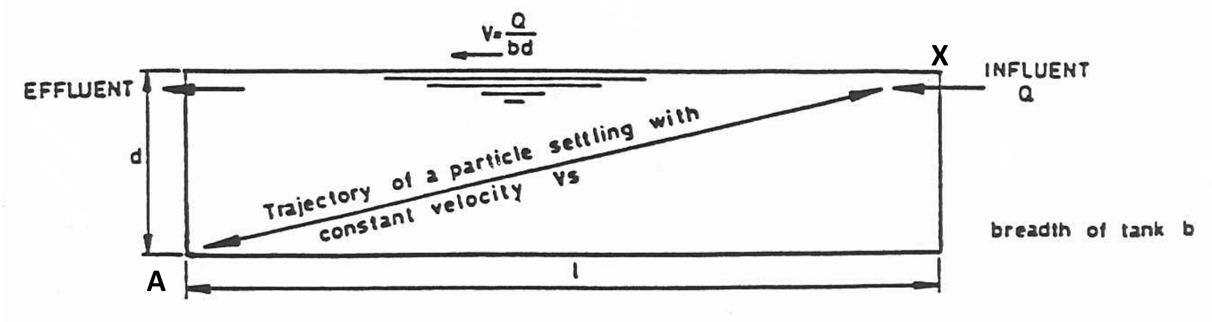


Figure 4.3 - Trajectory within a settling tank of a particle settling with constant velocity V_s

In order to a particle to be removed it is necessary that its settling velocity V_s is greater than the ratio between the influent flow rate and the surface area, from which it can be seen that, for a high percentage removal S must be large. The depth had little effect on sedimentation, and the smallest size of particle that could be settled depended on the surface area of the tank. As the larger particles tend to settle first, the smallest size of particle which can be settled is inversely proportional to the percentage removal of suspended solids and hence is an indication of the efficiency of removal.

The efficiency formulation, in case of no mixing assumption, can be the following:

$$\eta = 1 \leftarrow \text{per} \frac{Q}{A} \geq v_s \tag{4.5}$$

$$\eta = \frac{Q/A}{v_s} \leftarrow \text{per} \frac{Q}{A} < v_s \tag{4.6}$$

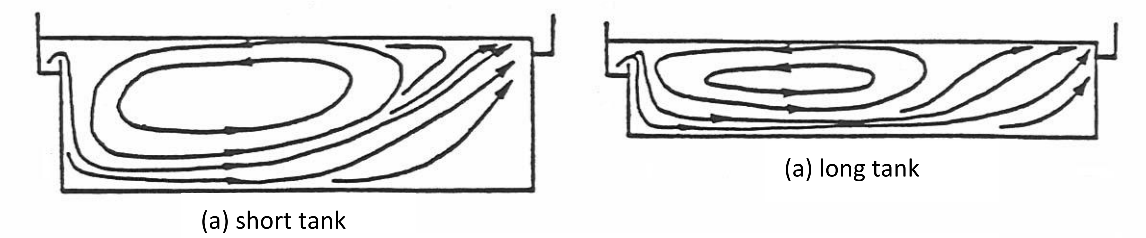
When transverse mixing only is considered, the flow creates some turbulence capable of stirring the fluid vertically and crosswise (the short dimensions of the basin). Particles may be kicked upward and sideways randomly, but not forward or backward. The efficiency becomes:

$$\eta = 1 - \exp\left(-\frac{Q/A}{v_s}\right) \tag{4.7}$$

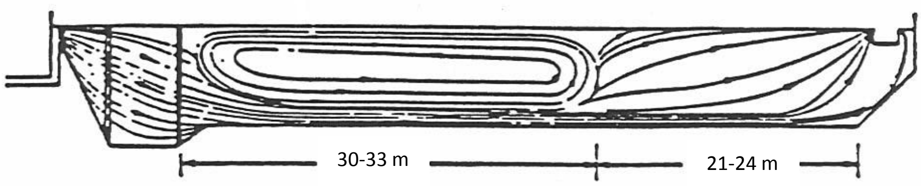
In this case of thorough mixing, the entire basin is considered as well-mixed not only vertically and transversely but also longitudinally (turbulence can now kick particles in any of the three dimensions of space). Again the efficiency assumes a different formulation:

$$\eta = 1 - \frac{1}{1 + \frac{Q/A}{v_s}} = \frac{v_s}{v_s + Q/A} \tag{4.8}$$

The flow pattern in a sedimentation tank is much more involved than that suggested by figure (4.4), and hence design is based on general rules formulated from experience with existing tanks and on empirical conclusions. Actual flow conditions arising in tanks take the form of currents and eddies, the effects of which tend to reduce the effective capacity of the tank and to scour the previously settled sludge.



Typical internal flow patterns for tanks with different length/depth rations



Pattern of flow in a horizontal-flow tank, determined by radioactive tracer

Figure 4.4 - Typical flow condition within a settling tank

4.3. Objectives

The purpose of this study has been to examine and compare the performances of the two different configurations of a rectangular clarifier, having the same foot print; these are tested under unsteady flow conditions, considering three different hydrographs. The performance of the two units have been evaluated based on PM removal efficiency and in terms of ΔEMC (event mean concentration) between the influent and effluent. Furthermore, particle size distribution (PSD) data have been collected to characterize both PM entrained in the effluent as well as PM separated and retained within the unit.

4.4. Materials and methodology

4.4.1. Experimental setup

As in the previous section, the experimental tests for this study have been performed at the Stormwater Unit Operations and Processes Laboratory (UOP) located at the University of Florida, in Gainesville. The main components of the experimental system are the following: a pumping station with Programmable Logic Control (PLC) system, two electromagnetic flow meters, and a slurry mixing and feeding system; for the detailed description of these components it can be referred to Sections **3.6.2** and **3.6.3**.

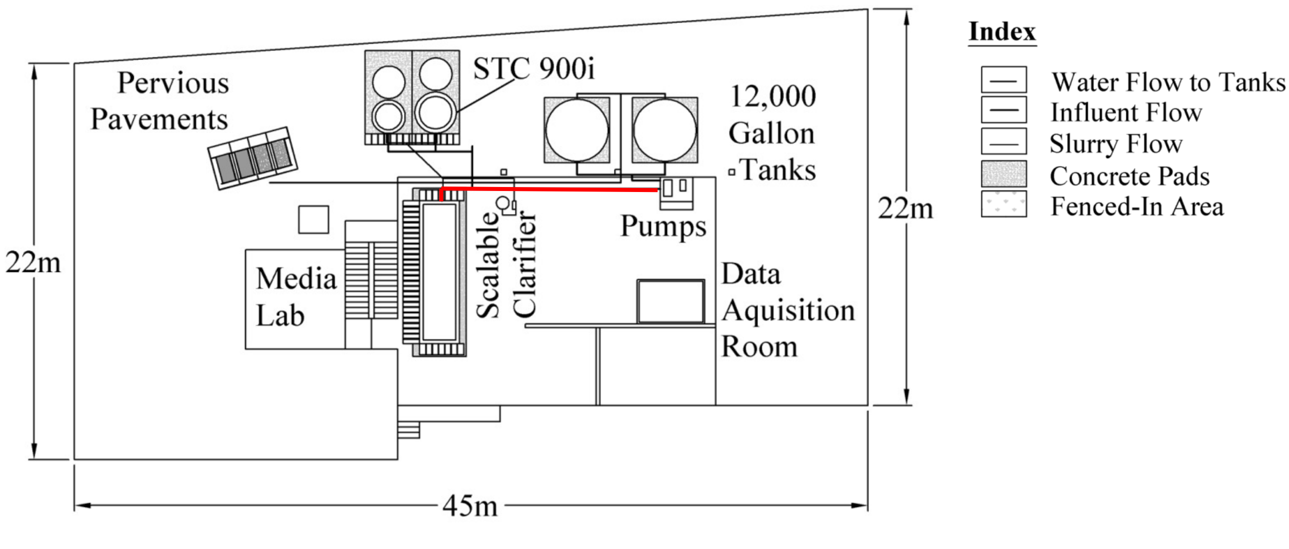


Figure 4.5 - Site layout of the Stormwater Unit Operations

Slurry mixing and feeding system

The slurry mixing and feeding system consists of a 250-liter conical slurry tank and two (one internal and one external) mixing pumps which provide vertical and horizontal mixing to keep the particles in suspension within the tank. Internal mixing is provided by a submersible pump and external mixing is done with the help of a small straight centrifugal pump. This slurry mixing system suspends the slurry and makes the particle concentration profiles consistent. The slurry mixing and injection system was volumetrically calibrated to deliver the desired quantity of slurry composed, depending on the hydraulic flow rate.

4.4.2. Data acquisition and management

To check the values of the inlet flow rate and concentration, during each test a set of data has been gathered. In particular flow meters integrated with the PLC allow to provide a feedback control loop to maintain the desired flow rate. At the outlet an ultrasonic sensor has been placed, which measures the water level in the basin. From the discharge equations, the relationship between water level and effluent flow rate is obtained. Two YSI 600 OMS probes have been installed at the inlet and at the outlet of the unit to measure respectively influent and effluent turbidity data. Turbidity data allow to monitor influent and effluent particle concentration, once developed a relationship between particle concentration and turbidity. The data stored in the YSI are downloaded after each run.

Figure 4.6 - YSI 600 OMS probes installed at the inlet (left) and at the outlet (right)

4.4.3. *Gradation and injection*

The loaded particle matter is a fine non-cohesive silica sand (SI-CO-SIL-75; specific gravity S = 2.65; D_{50} = 16.8 μm), provided by US Silica. The chosen sand appears to be very fine and this allows to test the unit with a type of material difficult to trap. The influent particle size distribution is shown in figure 4.7 and product data sheet which shows every detail for the used silica sand is attached in Appendix **4.17**.

The slurry injection system allows to have an automated delivery of the slurry, as a function of the hydraulic flow rate, in order to maintain an incoming constant concentration. The rate of slurry addition to the drop box is controlled by a peristaltic pump driven by a variable frequency drive (VFD). The rate of slurry injection is controlled by the frequency of the VFD and is calibrated volumetrically.

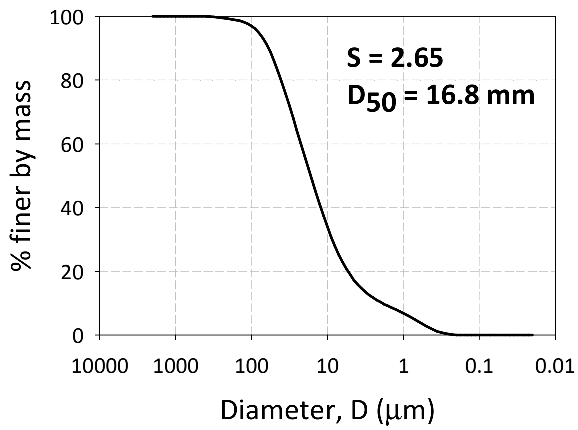


Figure 4.7 - Influent PM PSD

4.5. Testing procedure: sampling methodology and mass recovery

Prior to every experimental run the slurry tank has to be cleaned carefully using potable water to remove particles possibly left within the tank. Then the slurry tank has to be filled with 150 l or 180 l of clean water into which the first batch of particulate matter is added and the mixing pumps started; the volume of water depends on the amount of PM added. The other batches of PM are added to the slurry tank at certain times calculated for each run. The PLC is set with the target flow rate; the peristaltic pump, which delivers the slurry injection to the inlet drop box, is driven by variable frequency drive (VFD) which controls the ratio of slurry injection. The CR 3000 data logger enables the communication between the slurry injection system and the PLC system of the pumping station. Non-stationary slurry injections vary with the measured influent flow rates to maintain a constant influent concentration. The YSI in situ turbidity meters are initialized to log the turbidity every 5 seconds and are installed within the unit. At the end of the run the YSI probes have been removed, data downloaded, and the sample bottles taken to the laboratory to perform PSD and SSC analyses. Before sampling the supernatant, the PM inside the clarifier is allowed to settle overnight. The material inside the unit is manually recovered and then taken to the laboratory for drying, weighing, and dry phase PSD analysis. Finally the unit is cleaned with clean potable water for the next run, to ensure that any particulate matter that might be inside of it is removed.

Sampling methodology

The sampling procedure has been already described in the section **3.7**. During the test a certain number of effluent samples has been manually taken in 1 liter bottles, in a number depending on experiment duration and hydrograph trend. As in the previous experimental runs, samples have been collected in duplicate to perform two measures for PDS and suspended sediment concentration.

The supernatant has been collected at four different levels evenly after overnight settling. The samples have been used to perform PSD analyses and SSC measures; quantifying the amount of PM still in suspension it has been possible to evaluate the mass balance error.

Mass recovery

Once the supernatant samples have been collected, the wet material has been recovered from the bottom of the unit by manually sweeping it and taken to the laboratory to be dried in glass trays at 110°C in an oven. The dry silica has been disaggregated, weighed and collected in glass bottles; after this procedure it has been possible to calculate the overall efficiency of the unit based on mass and the mass balance. Laser diffraction analysis for the collected dry sample has been then performed to analyze the PSD of the captured particles.

Figure 4.8 - Effluent sampling (left); overnight settling (right)

4.6. Laboratory analyses

The laboratory analyses performed are the following:

- SSC and PSD of the aqueous phase of the effluent samples;
- PSD of the dry phase of the captured mass;
- SSC and PSD of the aqueous phase of the supernatant samples.

These data are necessary to perform the mass balance for the efficiency of the system. Both the SSC and the PSD analyses are performed on each sample (A and B), and the final estimation of SSC and PSD has been evaluated as the average of the two values.

Suspended sedimentation concentration analysis has been performed to quantify particle concentration for each effluent sample and to calculate the effluent mass load knowing the operating flow rates. The protocol specifically followed for this laboratory analysis is the ASTM D 3977 (ASTM, 2002). Particle size distribution analyses have been performed using the laser diffraction analyzer, Malvern Mastersizer 2000, whose characteristics have been provided in the previous Section **3.8**. Since for the effluent samples two duplicates (A and B) have been taken, an event mean PSD has been generated from averaging the individual measurements. For the captured material, instead, a dry phase measure has been conducted. After having mixed the dry mass, duplicate samples have been taken for the dry phase of the laser diffraction analyzer; the PSDs measured have been averaged.

4.7. Efficiency calculation and mass balance

Efficiency calculation

The efficiency of the clarifier has been determined as the percentage of incoming PM that is retained by the device:

$$Eff_{meas}(\%) = \frac{m_{in} - m_{eff}}{m_{in}} \cdot 100 \approx \frac{m_{capt}}{m_{in}} \cdot 100 \quad (4.9)$$

With m_{in}, amount (in grams) of solids entering the unit; m_{capt}, amount of sediment trapped in the unit.

The percentage reduction of the maximum concentration has been evaluated with the formula:

$$\Delta EMC = \frac{C_{in} - C_{max\_out}}{C_{in}} \cdot 100 \quad (4.10)$$

Where C_{in} is the concentration of sediment at the inlet (constant for each test) and C_{max_out} is the maximum SSC at the outlet.

To determine the total amount of material escaped from the unit, the following expression has been used:

$$m_{eff} = \sum_{k=1}^{n} \overline{C}(t_k) \cdot \overline{Q}(t_k) \cdot \Delta t \quad (4.11)$$

Where k is the effluent individual k-th sample, $\overline{Q}$ and $\overline{C}$ are respectively average flow rate (l/s) and the average concentration (mg/l) during the time interval, Δt is the time interval between samples (s) and n is the total number of discrete effluent samples.

Verification of mass balance for each experimental run

The mass balance has been calculated for each run from captured mass, effluent mass load, and supernatant mass load. The mass balance error (MBE) criteria is ±10% MBE and determined by the equation:

$$MBE(\%) = \frac{m_{in} - (m_{eff} + m_{capt})}{m_{in}} \times 100 \quad (4.12)$$

<u>Verification of PSD balance for each run</u>

The gravimetric PSDs of the effluent, supernatant and recovered mass have been measured and compared with that of the influent to verify the balance of influent and effluent PSDs. This measurement has been performed by quantifying the deviation between influent PSD loading and the summation PSD of the effluent, recovered, and supernatant mass.

$$PSD_{error} = \frac{\sum_{i=1}^{n} \left| \text{Influent PSD}_i - (\text{Effluent PSD}_i + \text{Recovered PSD}_i + \text{Supernatant PSD}_i) \right|}{\sum_{i=1}^{n} \text{Influent PSD}_i} \times 100 \quad (4.13)$$

Where each i is a discrete measurement at a specific particle size of the cumulative PSD.

4.8. Experimental runs and results

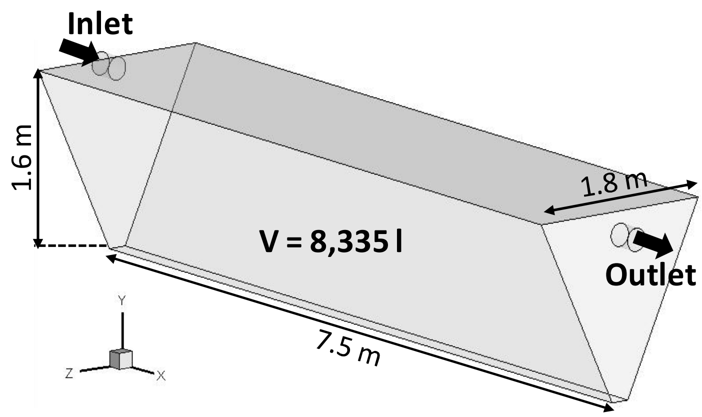
4.8.1. Description of the two configurations

Actual sedimentation basins are rectangular, square, or circular in plan area. In this project it has been requested to study a linear clarifier with a trapezoidal section; moreover another configuration, called "crenulated", has been tested.

<u>Linear pond configuration</u>

The linear pond configuration tested is shown in figure 4.9 and it has the following geometrical characteristics:

- Length (L = 7.5 m) to width ratio is 4:1
- Trapezoidal transversal section with bottom width 10% of top width
- Side slopes 1H:2V
- A maximum permanent pool depth of 1.3 m



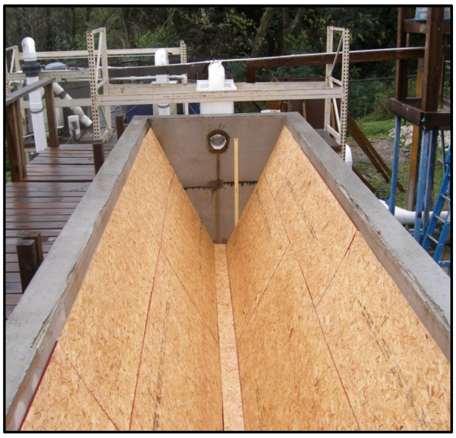


Figure 4.9 - Geometrical characteristics of the linear pond configuration

Crenulated pond configuration

The crenulated pond configuration is characterized by having a series of transversal baffles, which force the flow to pass through a longer path; its geometrical characteristics are the following:

- Length (L = 7.3 m) to width ratio is 4:1
- Rectangular transversal section
- A maximum permanent pool depth of 1.3 m
- 11 Baffles with length of 1.2 m and inter-distance of 0.6 m

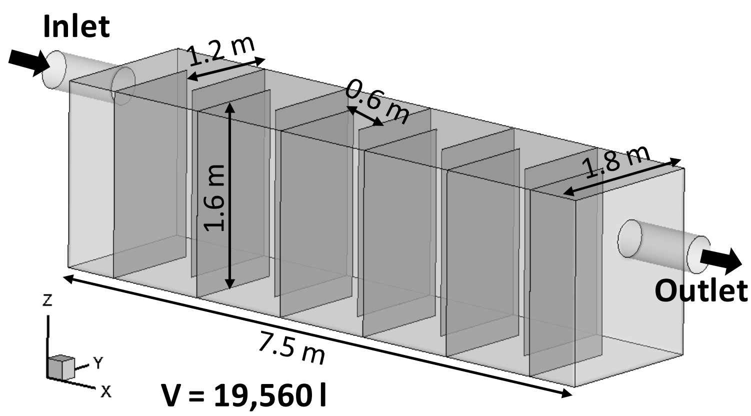


Figure 4.10 - Geometrical characteristics of the crenulated pond configuration

4.8.2. Hydrographs

In order to investigate under hydraulic unsteady conditions the behavior of the clarifier and to compare the two different configurations (linear and crenulated) three different hydrological events have been taken in consideration:

- Rainfall 1: Triangular Hydrological Event; total rainfall = 12.7 mm (= 0.5 in)
- Rainfall 2: Historical 8 July 2008 Hydrologic Event, collected by University of Florida; total rainfall = 74.2 mm (= 2.92 in)
- Rainfall 3: 24 Hours, 25 Years Hydrologic Event; total rainfall = 213.4 mm (= 8.4 in), with a duration of 24 hours and a time of recurrence of 25 years

Previous hydrological simulations had been performed using SWMM 5 to determine the hydrographs trend to be simulated in the experimental runs. The catchment has been represented as an impermeable catchment with a surface of 0.12 ha (24 m length, 50 m wide), completely impervious. The obtained run-off distribution are shown in figure 4.11.

4.8.3. Experimental design for the clarifiers (linear and crenulated configuration)

The parameters selected in the experimental design include:

4. Influent particle concentration (200 mg/L);
5. Unsteady flow rate (Figure 4.11);
6. Influent particle gradation (Figure 4.7).

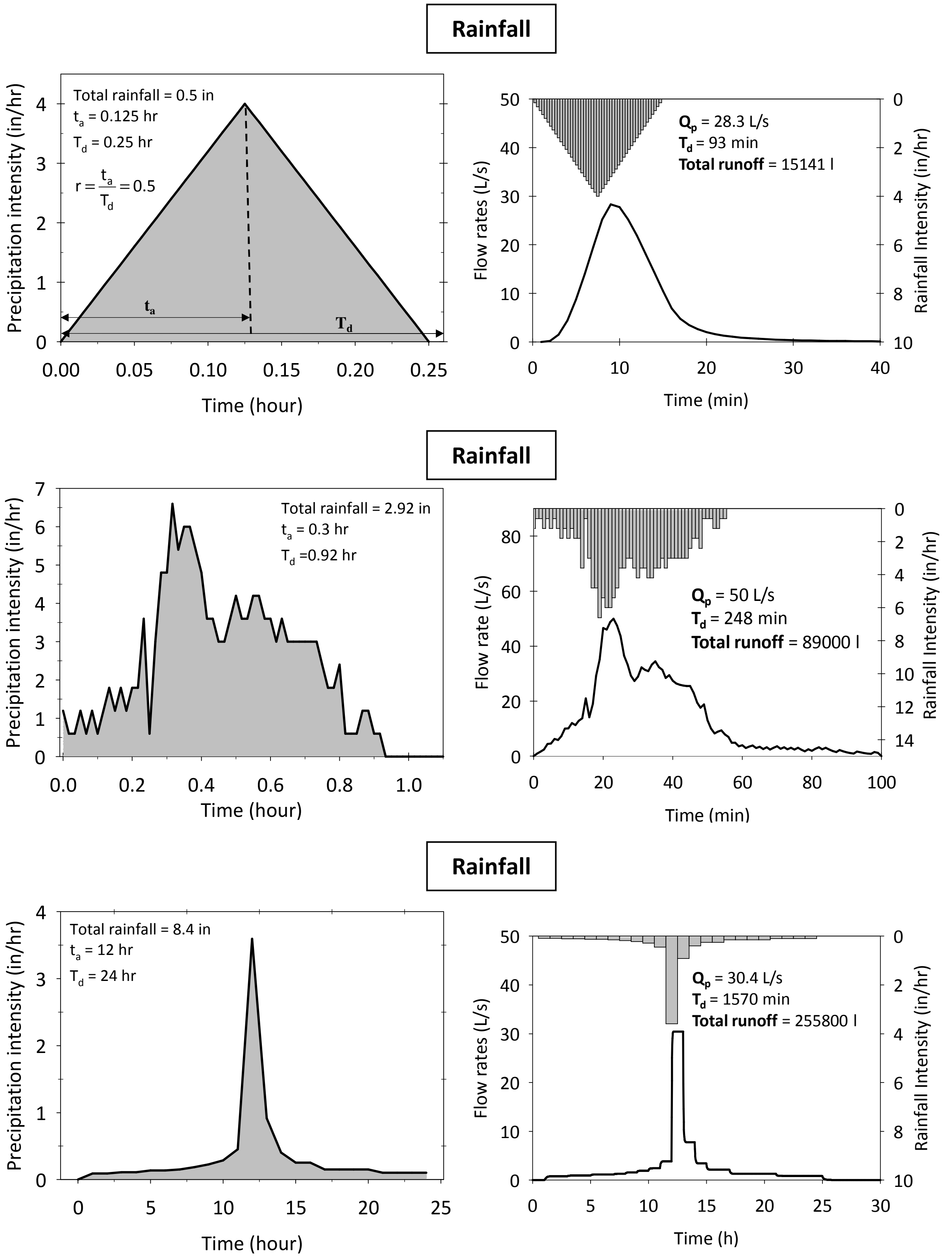


Figure 4.11 - Rainfall events (left); run-off distributions obtained by SWMM simulations (right)

4.8.4. Results

A first set of three runs has been performed on the linear clarifier (the first and the second one's data had been previously collected and here are reported only to have a comparison with the crenulated configuration), followed by the same set of runs performed on the crenulated configuration. To have a better comparison, the results are shown for each hydrograph for the two configurations.

The following table shows a summary of the input data (Q_p and experiment duration) and the results for the three experiments (total efficiency, percentage reduction of the maximum concentration observed at the discharge; D_{50} of the captured material and mass balance error) for both configurations. It is self evident that the crenulated configuration has a better efficiency in terms of quantity of trapped material, having a total efficiency greater than 50% for every considered hydrograph. At the same way the percentage reduction of the maximum concentration (ΔEMC) is considerably higher for the crenulated design than for the linear one. The mass balance errors have provided values inferior than 10% for all the tests (Table 4.1).

..LINEAR CONFIGURATION	Hydrological event	Q_p (l/S)	t_{max} (min)	Eff (%)	ΔEMC (%)	D_{50} (mm)	MBE (%)
	Triangular Hydrograph	28.33	44	39	49	25	9.6
	Actual Hydrograph	49.94	109	29	15	35	9.8
	24 hours-25 years Hydrograph	30.44	1397	32	20	35	9.4

CRENULATED CONFIGURATION	Hydrological event	Q_p (l/S)	t_{max} (min)	Eff (%)	ΔEMC (%)	D_{50} (mm)	MBE (%)
	Triangular Hydrograph	28.33	44	88	49	25	10.0
	Actual Hydrograph	49.94	109	70	15	25	6.1
	24 hours-25 years Hydrograph	30.44	1397	54	20	27	9.6

Table 4.1 - Summary of the experimental runs, input data and results

The following plots show the inflow and outflow and the measured SSC at the effluent. It is possible to notice how the crenulated configuration lowers more the suspended sediments concentration at the effluent rather than the linear configuration; that means that forcing the water to follow a longer path favors a greater number of particles to settle, having at the discharge water with a low concentration of PM. Moreover for the crenulated configuration, the increasing part of the SSC (that means increasing sediments concentrations) exhibits with a greater lag if compared to SSC results for the linear configuration. This implies a minor amount of PM discharged.

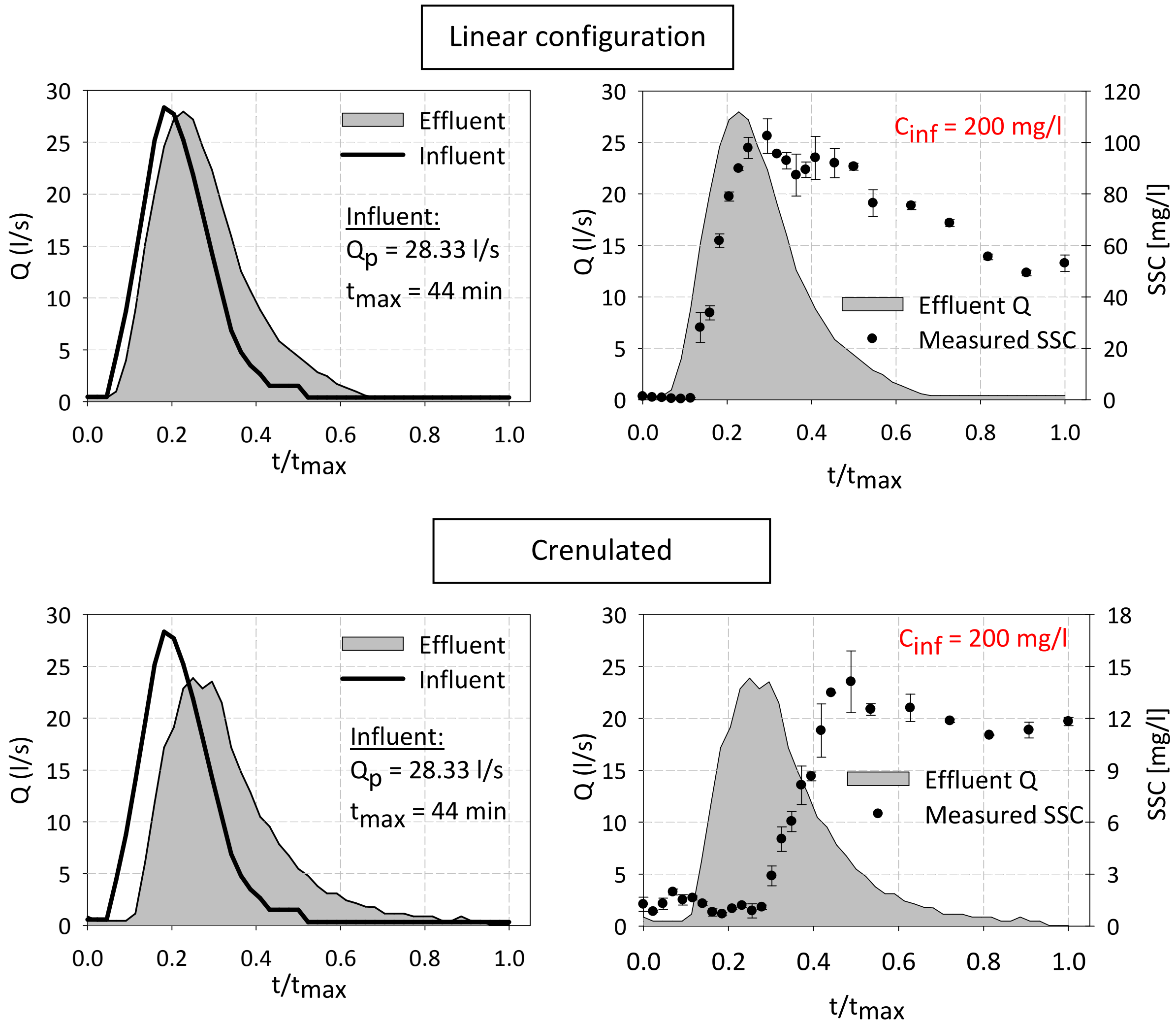


Figure 4.12 - Run 1 – Influent and effluent hydrographs (left); SSC measured at the effluent (right)

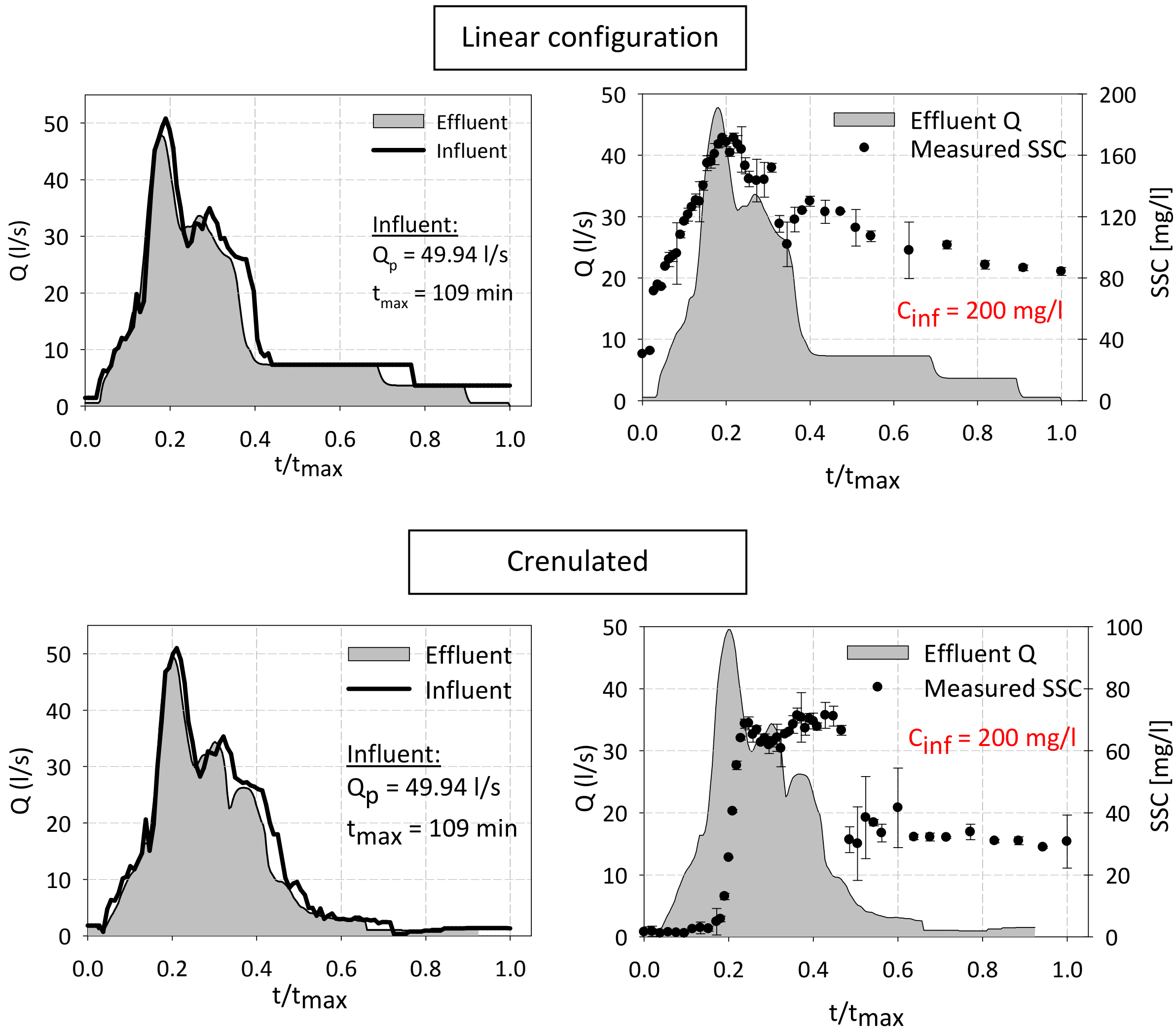
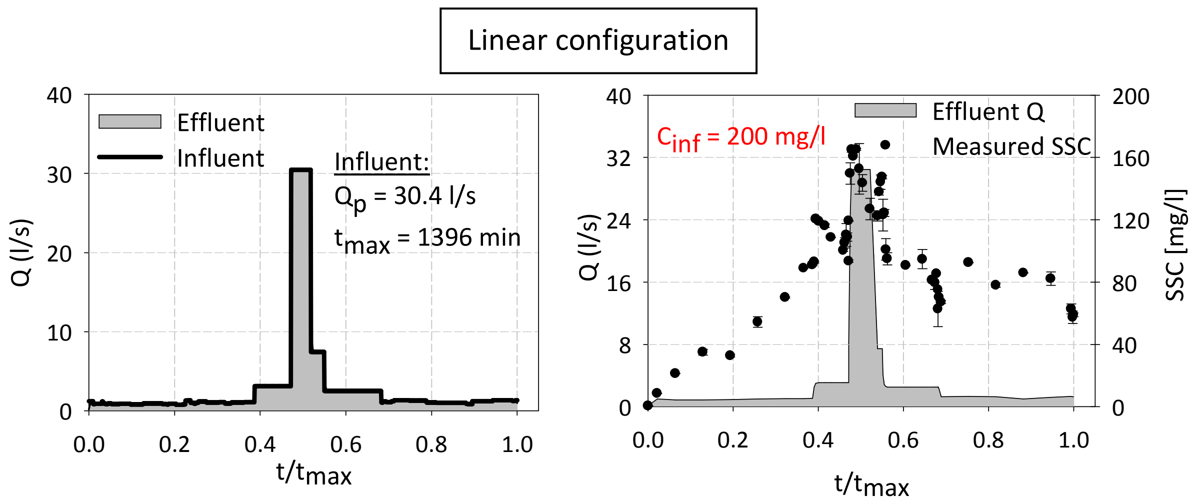


Figure 4.13 - Run 2 – Influent and effluent hydrographs (left); SSC measured at the effluent (right)



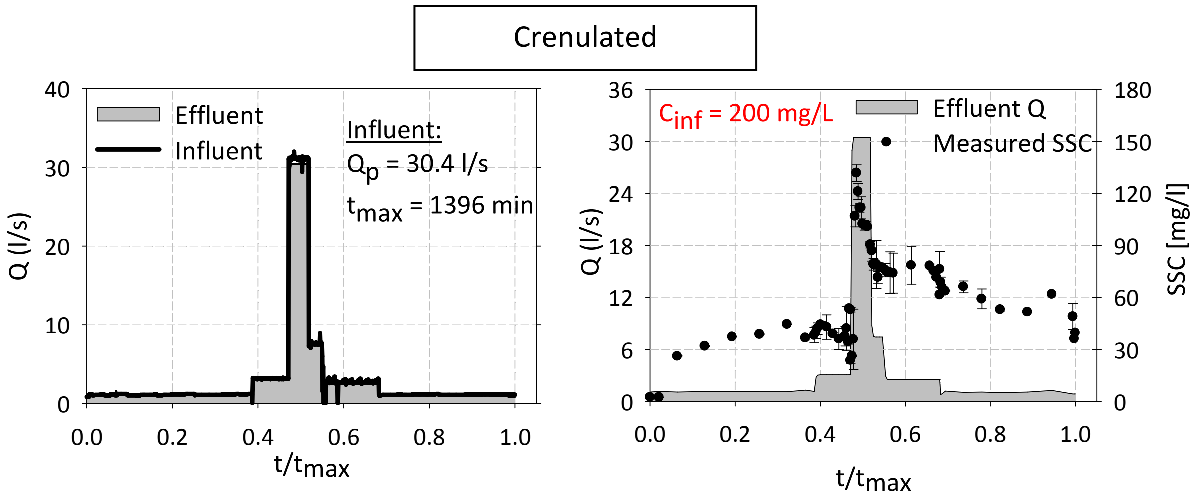


Figure 4.14 - Run 3 – Influent and effluent hydrographs (left); SSC measured at the effluent (right)

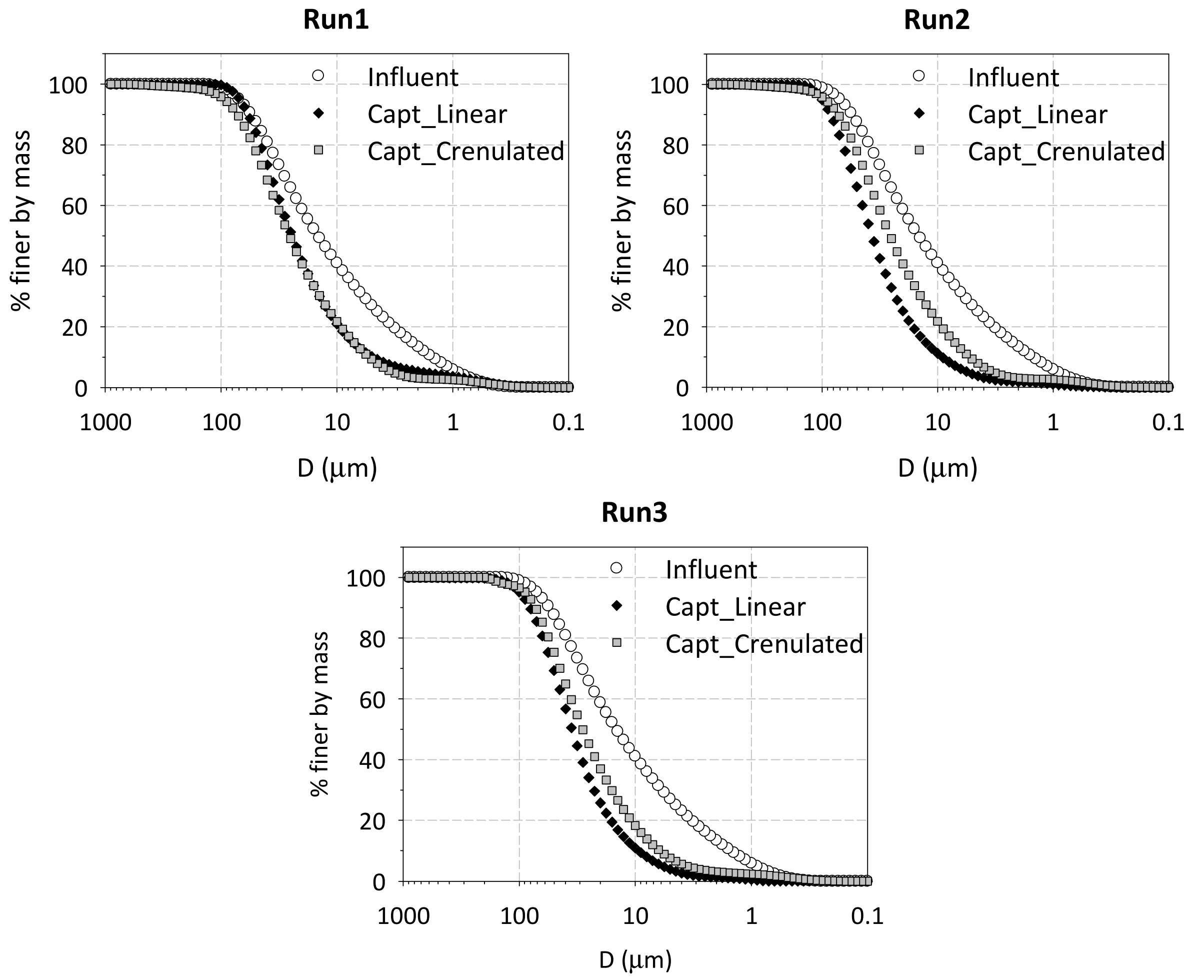


Figure 4.15 - Comparison between captured PSDs with the linear and the crenulated configuration

Comparing the particle size distribution of PM captured by the two different configurations, it is possible to notice that the crenulated configuration has the capability to retain finer particle (especially for rainfall event number 2 and 3, characterized by having a longer duration). A great proportion of pollutants such as heavy metals and polynuclear aromatic hydrocarbons are bound to particles (Oliver et al., 1974; Herrmann, 1981; Ongley et al., 1981; Hoffman et al., 1985; Bodo, 1989; Hewitt and Rashed, 1992; Legret and Pagotto, 1999). Furthermore, metal concentrations generally increase with decreasing particle size (Liebens, 2001; Ujevic et al., 2000); this is due to the relatively large surface area of fine sediments and their higher cation exchange capacity (Dong et al., 1984). It is possible to comprehend the importance of retaining (and therefore removing) finer PM before discharging water into receiving water bodies.

4.9. Comparison of SOR modeled and measured PM separation for the clarifier

As previously done with experimental results for the hydrodynamic separator, measured efficiency has been compared with the values obtained applying the modified overflow rate model proposed by Hazen (1904):

$$\mathrm{Eff} = 1 - \left[1 + \frac{v_s}{n(Q/A)}\right]^{-n} \tag{4.14}$$

Where Q is the influent flow rate (variable during the run), A is the unit's surface area, v_s is the particle settling velocity, and n is the short-circuiting factor.

The input hydrograph is unsteady, so the efficiency has been calculated for the single i-th particle size fraction for the different flow rates (considering time intervals of 1 minute) and the overall efficiency has been determined as a weighted average, using as weight the percentage mass of each size fraction of the total sample of injected PM:

$$\sum \mathrm{Eff}_i \frac{m_i}{m_{tot}} \tag{4.15}$$

Where Eff_i is the efficiency corresponding to the i-th particle size fraction of mass m_i; m_{tot} is the total mass of input PM in the interval considered.

Among the several formulations for determining the settling velocity found in literature, in this study three different formulas has been applied: Newton's law (Metcalf & Eddy, 2003); Stokes' law (1851); Cheng's formulation (1997). Cheng's formulation was the best one to replicate the experimental data in studies performed on the gully pot (Bolognesi et al., 2007; Bolognesi et al., 2008), while Newton's and Stokes' law gave good results for experiments carried out on the hydrodynamic separator.

It is necessary to consider distinctively the two configurations, since experimental data show how their functioning is completely different. For the linear configuration, the efficiency has been calculated with the (4.14), adopting the different formulations for the settling velocity. Figure 4.16 shows that varying the short-circuiting factor "n" the error between the calculated efficiency and the experimental data does not reach a satisfactory value. For this reason it is believed that the SOR model is not suitable to represent this configuration; this could be maybe due to the trapezoidal section and the slanting walls, which can influence the sedimentation of particles.

For the crenulated configuration even changing the value of the short-circuiting factor, the formulation (4.14) for the calculation of the efficiency does not provide a good replication of the experimental data. It is possible to state that the SOR model is not able to predict the efficiency of the unit with this type of configuration; for this configuration is maybe necessary a more complex model, such as a CFD model, which takes into account the variation of the flux velocity which influences the particles to settle.

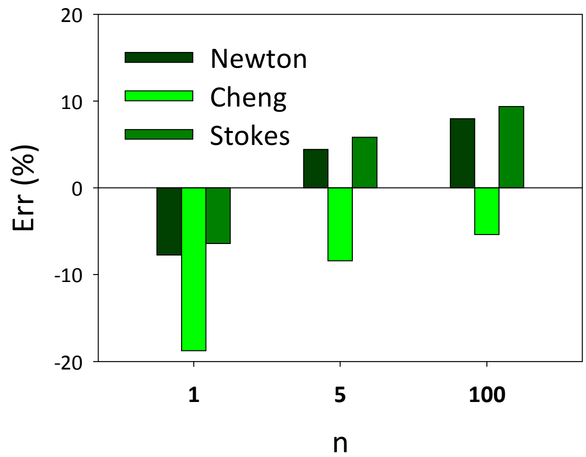


Figure 4.16 - Mean values of errors between calculated and experimental efficiency, obtained applying different formulations of v_s and different values of short-circuiting factor "n"

4.10. Turbidity measurements

During the experimental runs performed on the clarifier, effluent and influent turbidity have been measured by a portable turbidimeter probe (YSI 600OMS) (YSI, 2006). The measure of the turbidity is an important datum in order to have information about discharged PM concentration, and consequently about the amount of PM released. The discrete manual sampling at the unit outlet has allowed to evaluate the suspended sediments concentration, during the run. The continuous turbidity measurements have been compared with the discrete SSC measures, to find a correlation between the two variables, which can be used to estimate sediments concentration and discharge more efficiently.

The found correlation has been compared with others found in literature. Turbidity is affected by more than just particle concentration; temperature, as well as particle size (Clifford et al., 1995; Gippel, 1998) can significantly affect a turbidity reading. For this reason considerations about temperature and particle size distribution have been developed.

Growing awareness about environmental pollution and the realization that many pollutants are transported by attachment to sediment particles have focused attention on the adequacy of sediment transport data (Allen and Peterson, 1981). Turbidity is associated with the "cloudiness" of water, as caused by the light scattering of suspended particles. Therefore turbidity is an indirect way to measure suspended sediment in surface waters once a relationship between suspended sediment concentration and turbidity has been established (Gartner et al. 2003). Turbidity has been used in other studies to estimate suspended sediment concentrations both in fluvial systems (Brown, 1971; Brown, 1973; Reed, 1978; Beschta, 1980; Smith, 1986; Gippel, 1995; and Lewis, 1996) and in many urban- and highway-runoff studies (Irwin and Losey, 1978; Cramer and Hopkins, 1981; McKenzie and Irwin, 1983; Dupuis and others, 1985; Schiffer, 1989; Spangberg and Niemczynowicz, 1992; and Barrett and others; 1996).

Since 1960s, in addition to pump sampling devices which sample sediment concentrations directly, considerable attention has been given to the deployment of turbidity probes. In these devices, sediments suspended in the water column are indexed indirectly based upon interface with acoustic, nuclear or optical signals passing through a water column of known dimensions between an emission source and a detector. In circumstances where access are limited and it is not possible to perform a manual or an automatic sampling, turbidity probes may be the only mean of determining suspended sediments concentration (Gurnell, 1987). Additionally they offer time and cost savings over automatic pump sampling systems (Gippel and Dawson, 1986) and they allow to have a quasi-continuous record, preferable to discrete sampling for assessment of sediment loads and concentration changes. In fact SSC measurements, oven drying and weighting of samples required around three days and, together with the high number of samples, is very lengthily and expensive. Moreover turbidity can also be used to estimate loads for contaminants typically bound to sediment particles. As technology improves, turbidimeters could even be left in remote places for a long period of time and transmit data via telemetry. These turbidimeters are often built with additional features, including durability, low power consumption, minimal electronic drift, automatic temperature compensation and so on (Gippel 1989).

Of the various turbidity probe designs, optical units have been widely used because of the simple technology involved and their compact size, ease of development and potential high frequency response. Nevertheless, a variety of problems in deploying such probes and interpreting their output records has been identified. In particular, sensitivity of output to ambient lighting conditions and variation in particle shape, size and color. More recently, optical probes utilizing light in the visible wavelengths have been replaced by probes utilizing infrared sources and detectors. Moreover different types of turbidimeters can produce different numerical values of NTU measurement. These differences are introduced by variations in design features such as light source, spectral sensitivity of the detector and the light beam configuration (Davies-Colley and Smith, 2001). It is thus important to establish a turbidity-TSS (or -SSC) calibration to the specific instrument that is used in the monitoring work.

4.10.1. Bias in optical methods

Currently several types of instruments are used to measure turbidity and the mechanics of these instruments vary in the way that they measure forward and/or backscattering light. Therefore different instruments measuring the same water will produce different turbidity values (Ziegler, 2002).The location of the instruments in the water column is critical for accurate turbidity measurements. A turbidity meter monitors a softball size area of the passing water around its optical viewing area. If this area is not filled completely with water or a reflective barrier such as a wall, or the bottom of a stream is in the optical viewing area, turbidity values will not be accurate.

Organic staining of the passing water, air bubbles, particle size, shape and composition all influence turbidity measurements (Downing, 1996). This makes it very difficult to established NTU/suspended sediment relationship from one location to another monitoring location.

4.11. Turbidity monitoring: literature review

4.11.1. TSS vs. SSC

A turbidity-TSS (or turbidity-SSC) relationship is necessary in order to determine solids concentration as turbidity is not a direct measure of TSS (SSC). Before reporting previous studies from literature it is considered important to specify the difference between TSS and SSC, as well as the methodology used to estimate them.

The terms SSC and TSS are often used interchangeably in the literature to describe the concentration of suspended solid-phase material in a water-sediment mixture, usually measured in milligrams per liter (mg/l). However, the analytical procedures for SSC and TSS differ and at times can produce considerably different results, particularly when sand-size material composes a significant percentage of the sediment in the sample (Gray et al., 2000). All methods evaluate the amount of solids contained in the storm water samples through filtering the water, and drying and weighing the residue left on the filter. However, the three methods (two for TSS and one for SSC) differ in the sub-sample preparation. The EPA's TSS Method (USEPA 1999) stirs and collects the sub-sample by pouring from the whole sample container. The Standard TSS Method (also referred to as APHA's TSS Method) (APHA 1995) stirs and collects the sub-sample using a pipette to draw from the whole sample container. The ASTM's SSC Method (ASTM 1997) uses the whole sample. Sub-sampling itself can introduce error into the analysis. Also, if a sample contains a significant percentage of sand-size material, stirring, shaking, or otherwise agitating the sample before obtaining a subsample will rarely produce an aliquot representative of the sediment concentration and particle-size distribution of the original sample. This is a by-product of the relatively rapid settling properties of sand-size material, compared to those for silt- and clay-size material. Aliquots obtained by pipette might be withdrawn from the lower part of the sample where the sand concentration tends to be enriched immediately after agitation, or from a higher part of the sample where the sand concentration is rapidly depleted. Because the fine material concentration will not normally be altered by the removal of an aliquot, the differences between the two methods will tend to be more pronounced as the percent of sand in the sample increases (Gray et al., 2000).

4.11.2. Correlation between turbidity and solids concentration

Based on a review of a number of studies, the best correlations have been obtained in areas where the sediment properties were likely to be relatively constant (Gippel 1989). A simple linear regression of suspended solids concentration on turbidity for each site and storm event is usually adequate to estimate sediments load (Lewis, 1996). Load estimates could be further improved with curvilinear fits or individual fits for the rising and recession phases of a runoff event. A simple linear TSS-turbidity regression was also used by Furumai et al. (2001) based on stormwater monitoring data from an urban residential area near Tokyo, Japan. A high correlation (R^2= 0.93) was obtained between the fine size fraction (less than 45 μm) of TSS and turbidity. The turbidity correlation to particle sizes greater than 45 μm was considered to be poor (R^2=0.68). It was concluded that continuous monitoring with a turbidity sensor would be useful to measure the washoff behavior of fine TSS particles.

<u>Turbidity rating curves</u>

It is evident that the derivation of a good rating curve to use turbidity measurements as a surrogate for SSCs is a great challenge. Lammerts Van Bueren (1984) derived a linear rating relationship between turbidity and SSC for the Yarra River, Victoria, Australia, with an average slope of 1.4, obtaining R^2 values of 0.6 in winter and 0.9 in summer.

Gippel (1995) developed two equations to express relationship between turbidity and TSS, considering the particle size distribution (PSD); if PSD and particle composition do not vary with TSS:

$$\text{Turbidity (NTU)} = \alpha \cdot K_{turb} \cdot TSS + \beta \tag{4.16}$$

While if PSD varied with concentration:

$$\text{Turbidity (NTU)} = \alpha \cdot (TSS)^{c} + \beta \tag{4.17}$$

In each of these empirical expressions, TSS units are [mg/l]; α is a coefficient function of the dissolved organic matter concentration and is equal 1 for attenuance turbidity and ≤ 1 for nephelometric turbidity. β is 0 for either nephelometric or attenuance instruments, and also in the cases where the color increases with particle concentration. The exponent c is <1 when the particle size increases with particle concentration and >1 when the particle size decreases with particle concentration.

Packman et al. (1999) developed a log-linear model with a strong correlation between TSS and turbidity, monitoring different streams located in rural or forested areas in Redmond, Washington. The regression models are expressed by the following equations:

$\ln(TSS) = 1.32 \cdot (NTU) - 0.68$ Rutherford Creek;

$\ln(TSS) = 1.32 \cdot (NTU) + 0.15$ for all other stations.

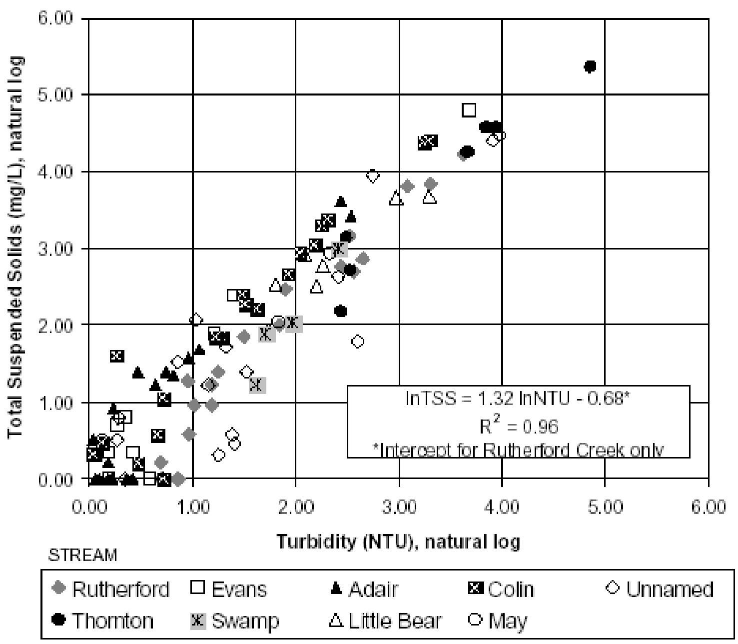


Figure 4.17 - TSS and turbidity data, natural-log transformed, with simple linear regression analysis results (Packman et al., 1999)

In Italy Pavanelli and Pagliarini (2002) monitored the suspended sediment load and water flow of the Sillaro torrent, during 1997–2000. The suspended sediment concentration and the turbidity were measured on the samples, and the water samples were analyzed by a laboratory turbidimeter. A simple linear regression was found as the best to fit the data:

SSC [kg/m^3]=0.0006·(NTU) R^2 = 0.88 (a) (4.18)

SSC [kg/m^3]=0.0005·(NTU)+1.04 R^2 = 0.94 (b) (4.19)

Fink (2005), studying the effects of urbanization in Baird Creek watershed in Green Bay, Wisconsin, analyzed the relationship between turbidity data measures with a YSI-6200 multi-parameter sonde every 10 minutes and the TSS values of discrete samples. The linear regressions obtained appear different for the two studied sites (Figure 4.19); the authors hypothesized that the difference was directly related to watershed land use and the associated hydrologic response between the primarily agricultural North Branch site and the urban storm water additions above the USGS station:

TSS (mg/l)=2.06·Turbidity (NTU) with R^2 = 0.97 at the USGS station (4.20)

TSS (mg/l)=1.01·Turbidity (NTU) with R^2 = 0.98 at the North Branch station (4.21)

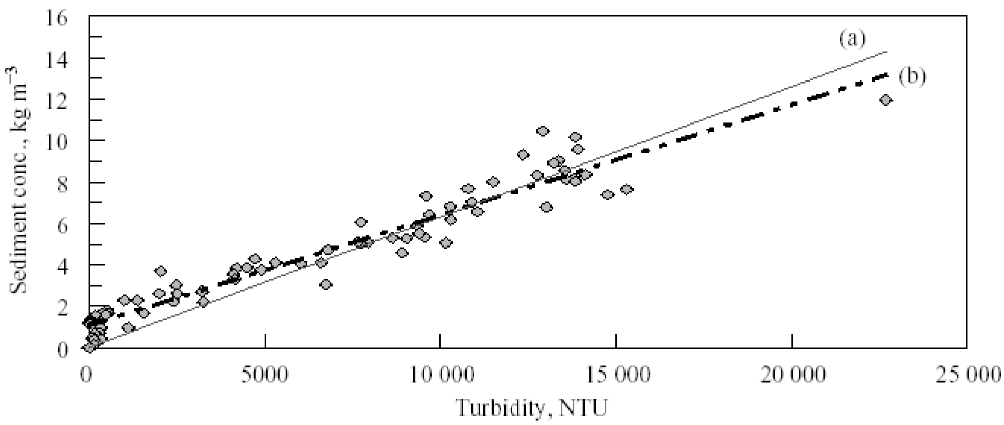


Figure 4.18 - Plot of SSC in kg/m^3 versus turbidity in NTU (Pavanelli and Pagliarini, 2002)

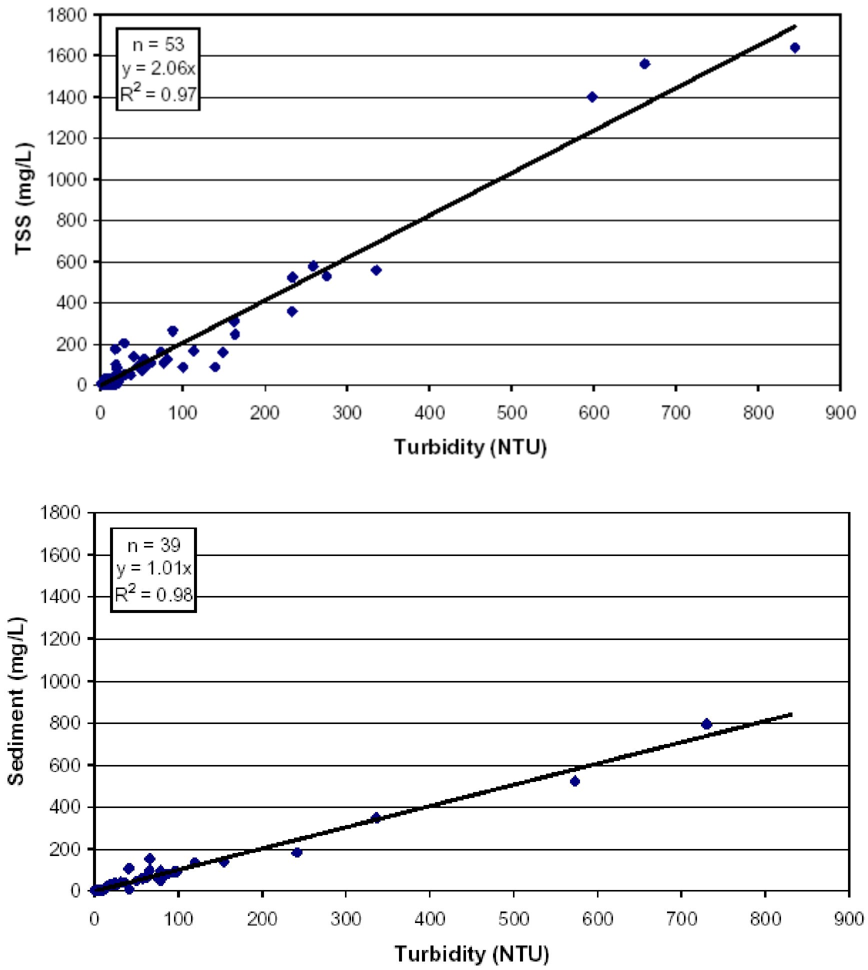


Figure 4.19 - Turbidity – suspended sediment concentration rating curves found by Fink (2005) at the USGS station (up) and at the North Branch site in Baird Creek (down)

Ying and Sansalone (2008) investigated particulate matter (PM) granulometry delivered in source area runoff as a function of hydrologic transport, in a completely paved area in Baton Rouge, LA. During the eight collected run-off events, turbidity was measured and for each event at least 30 samples sets were taken manually. The hydrographs were divided in two different types of behavior: Flow-Limited events (FL), characterized by low volume and low runoff intensity, they did not produce a mass or concentration "first-flush"; Mass-Limited events (ML), which typically generated high runoff volume. Relationships between turbidity and SSC were examined for the two behaviors. For ML events, the relation between SSC and turbidity is higher than for the FL events; this is probably due to the influence of settleable and sediment particles, while for the FL events case the relationship was predominately influenced by suspended particles. In both cases relationships between SSC and turbidity could be explained to a significant degree by a linear relationship:

SSC [mg/l]=2.83·(NTU) Mass-Limited event (4.22)

SSC [mg/l]=1.23·(NTU) Flow-Limited event (4.23)

Desmond (2009) investigated the impact of urbanization on runoff, sediment and stormwater quality in two residential catchments in Singapore (Jurong West and Ang Mo Kio), carrying out a sampling campaign of 20 months. Among the objectives of his research, there was also the investigation of suspended sediment concentrations and turbidity during storm events. He developed a linear relationship for the first site and a polynomial rating curve for the second one; both rating curves showed a moderately significant relationship with R^2 values of 0.5305 and 0.7443, respectively (Figure 4.21). Samples of 850 ml were collected with an auto sampler every five minutes.

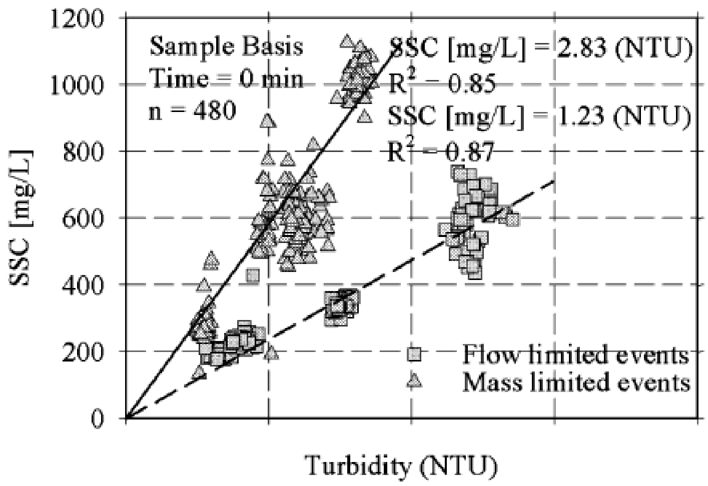
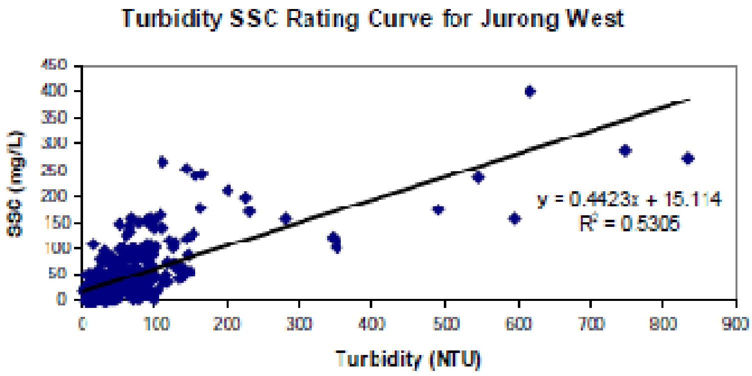


Figure 4.20 - Differentiation of the constitutive relationship between turbidity and suspended sediment concentration (SSC) considering flow and mass limited events (Ying and Sansalone, 2008)



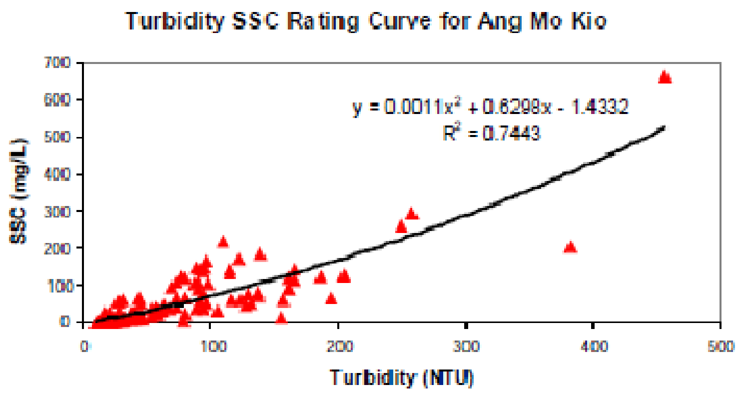


Figure 4.21 - Turbidity – suspended sediment concentration rating curves found by Desmond (2009)

4.12. Methodology and instruments

4.12.1. Turbidity

"Turbidity can be defined as a decrease in the transparency of a solution due to the presence of suspended and some dissolved substances, which causes incident light to be scattered, reflected, and attenuated rather than transmitted in straight lines" (Ziegler 2002). Turbidity is typically determined by shining a light beam into the solution and then measuring the light that is scattered off of the particles which are present. For turbidity systems capable of field deployment, the usual light source is a light emitting diode (LED) which produces radiation in the near infrared region of the spectrum. The detector is usually a photodiode of high sensitivity; the angle between the emitted and detected light varies (usually between 90 and 180 degrees) depending on the probe used. The International Standards Organization (ISO) recommends the use of a light source with a wavelength between 830 and 890 nm and an angle of 90 degrees between the emitted and detected radiation (ISO 7027). The most widely used measurement unit for turbidity is the FTU (Formazin Turbidity Unit). ISO refers to its units as FNU (Formazin Nephelometric Units). The units of turbidity from a calibrated nephelometer are called Nephelometric Turbidity Units (NTU). To some extent, how much light reflects for a given amount of particulates is dependent upon properties of the particles like their shape, color, and reflectivity. For this reason a correlation between turbidity and suspended solids is somewhat unique for each location or situation.

The turbidity system used for the experiments is a YSI 600 OMS probe, which is a multi parameter water quality monitoring device equipped with 6136 Turbidity Sensor for accurate, in-situ measurement of turbidity; the output of the sonde turbidity sensor is processed via the sonde software to provide readings in NTUs. The OMS also incorporates sensors for the measurement of conductivity and temperature. It has a built-in memory that can store the data it records and data stored in the YSI are downloaded after each run. Temperature is an important variable, since it can affect turbidity measurement. A schematic of a YSI turbidity sensor is shown in the following picture.

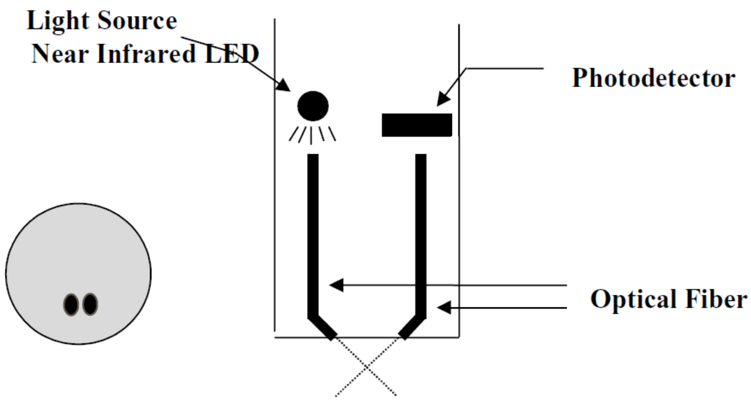


Figure 4.22 - Schematic of a YSI turbidity sensor

The probe has been installed at the unit outlet, as shown in figure 4.23; the YSI is programmed before every run with field details and calibrated to start logging data each 5 seconds. After each run the data are uploaded from the YSI with the data acquisition notebook computer which has been installed with Eco Watch, a PC software interface for YSI.

Figure 4.23 - YSI 600 OMS probes installed at the outlet of the clarifier

4.12.2. SSC measurement

The measured turbidity values have been compared with the discrete SSC values. Analytical methods to obtain solid-phase concentrations include the suspended sediment concentration (SSC) method (ASTM, 1997) and the total suspended solids (TSS) method (APHA, 1995). The SSC method is considered to be a better analysis for stormwater runoff than the TSS method for several reasons (Gray et al., 2000):

- The SSC method uses standardized procedures that process the entire sample; these procedures include evaporation, filtration or wet sieving of the whole sample volume.
- The TSS method requires analysis of a subsample extracted from the original sample. The subsample volume is 100 mL, unless more than 200 mg of residue is expected to collect on the filter, in which case a smaller volume is extracted.

Sub sampling procedures appear not to obtain an aliquot that is representative of the sediment concentration and particle size distribution of the original sample. As a result, the subsample is usually deficient in sand size particles.

- The percentage of sand-size and finer material can be determined by the SSC method, but not by the TSS method.
- The TSS method originated as an analytical method for wastewater, presumably for samples collected after a settling step at a wastewater treatment facility. It is considered fundamentally unreliable for the analysis of natural water samples.

The TSS method of analysis was found to produce concentration data that are negatively biased (i.e. tend to underestimate) by 25 to 34% with respect to the SSC method. Discrepancies between the two methods were attributed to the procedures in the TSS method to obtain aliquots or sub samples, particularly if very fine sands and larger particles are present (Gray et al., 2000). The TSS method provided unbiased results when less than 25% of the sample material was finer than 62 μm.

For the purpose of this study, the SSC analytical method has been selected as the basis of determining the concentration of suspended solids, measured according the protocol ASTM D 3977 (ASTM, 2002). Before any experimental run, microfiber filters have been pre-cleaned with distilled water, dried in the oven (105°C) and weighted. Once collected the samples, the volume of the water has been measured with a graduated cylinder, and then poured within the filter holder; the vacuum pump draws the water and the PM remains trapped on the microfiber filter, which is then dried at 105°C overnight and weighted. The difference between the two filter weight (before and after the SSC measure) is the PM weight, which divided by the water volume provides the concentration value. Discrete duplicate samples have been taken manually across the entire cross section at the unit outflow. After each run, sampling bottles have been brought to the laboratory to perform SSC measurements; an event mean SSC measure has been generated from averaging the two individual measurements.

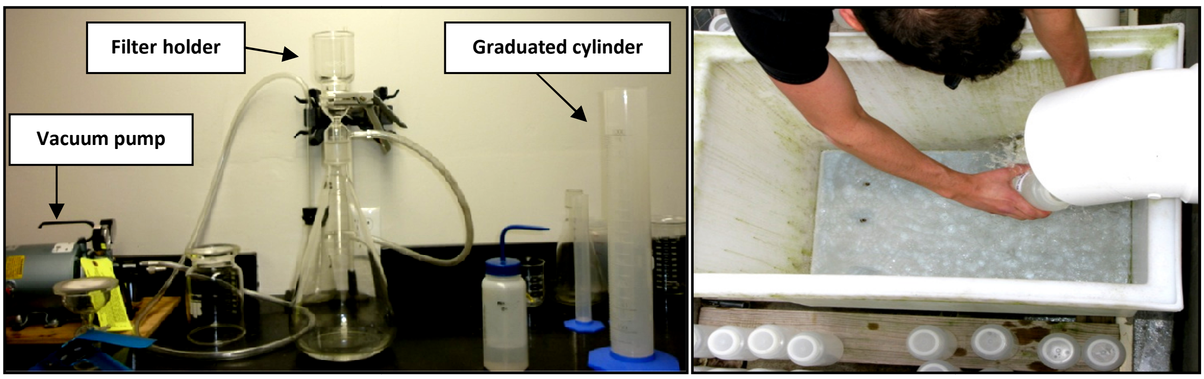


Figure 4.24 - Equipment for the measure of SSC (left); collecting samples (right)

4.13. Results and discussion

In order to try to find a relationship between turbidity and suspended sediments concentration, for every run, each data point was obtained by pairing every SSC value against turbidity values recorded by the YSI sonde at the same time, as plotted in figures 4.25. It is possible to notice how there is a strong relation between turbidity and sediment solids concentration (R^2 included between 0.83 and 0.95) except for the runs three for both configurations. The hydrograph of these experiments is characterized by having a sharp flow rate peak. Learning from previous experiences (Artina et al., 2007) when a high flow rate peak occurs, the turbidimeter response can be no longer able reasonable. In fact for runs 3, if only the rising part of the hydrograph is considered, there is a linear relation between NTU and SSC. For the crenulated configuration a constant value (equal to 17 NTU) corresponds to different value of SSC; this is probably due to a malfunctioning of the instrument.

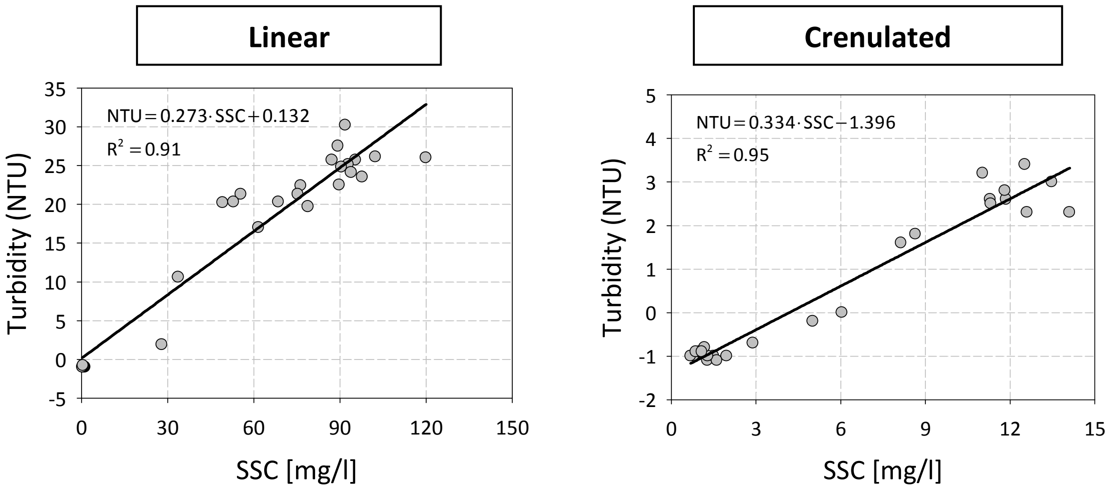


Figure 4.25 - Run 1: Comparison between NTU and SSC

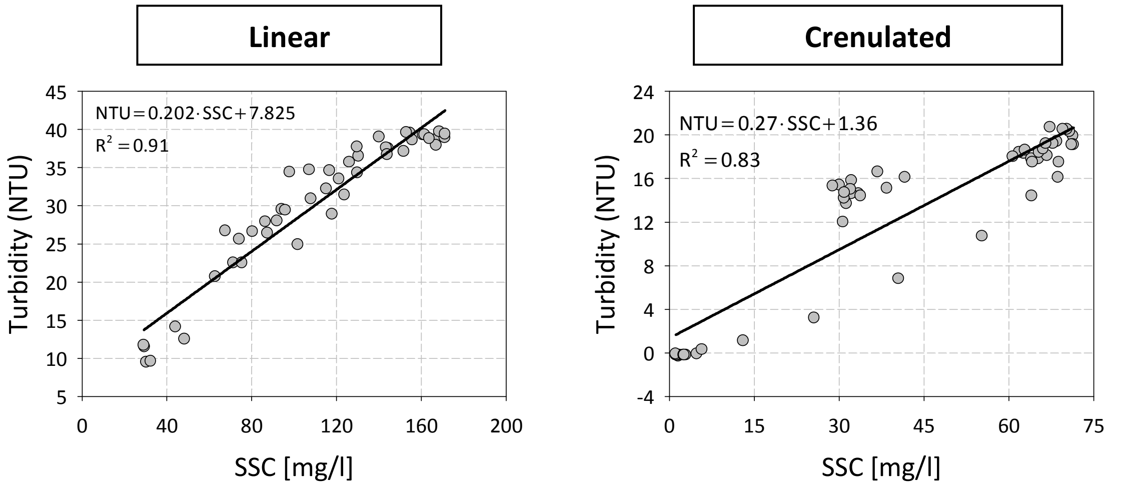


Figure 4.26 - Run 2: Comparison between NTU and SSC

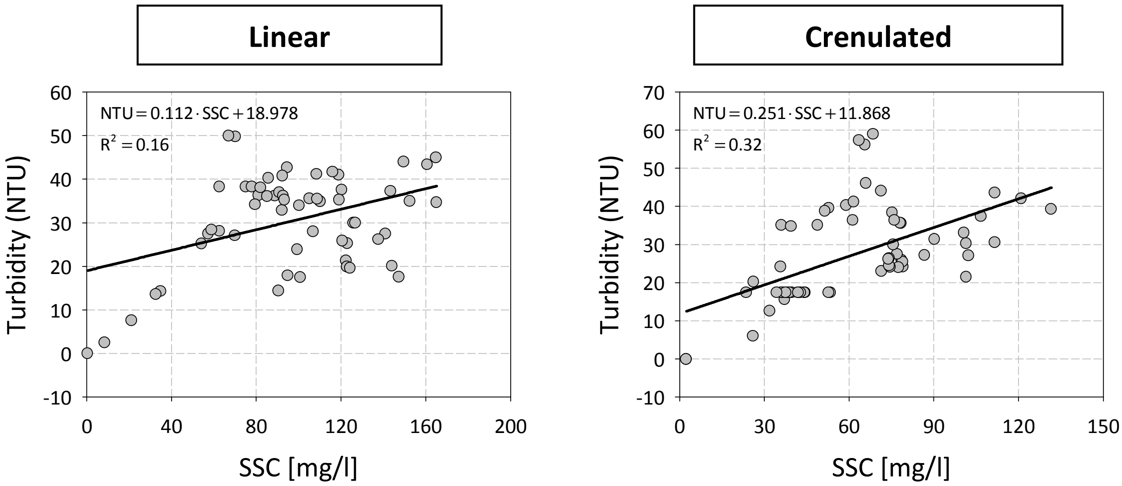


Figure 4.27 - Run 3: Comparison between NTU and SSC

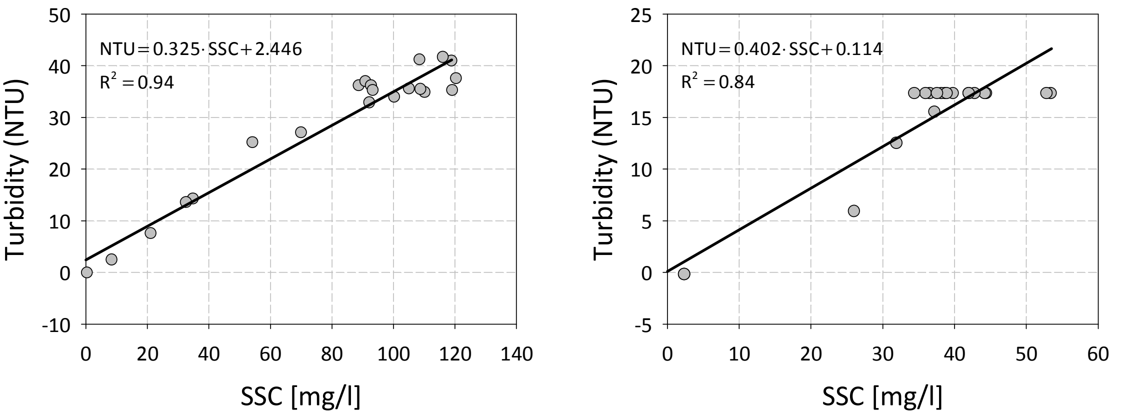
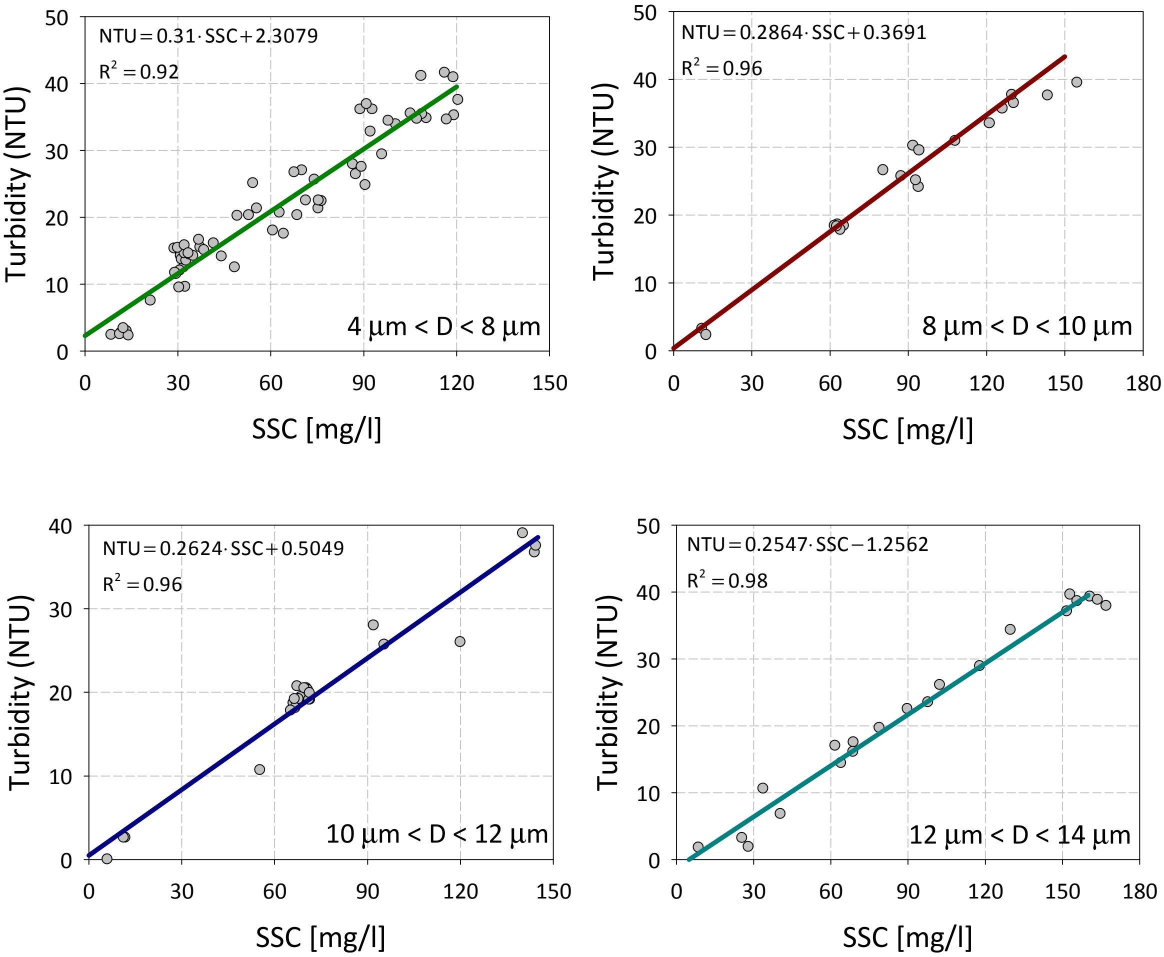


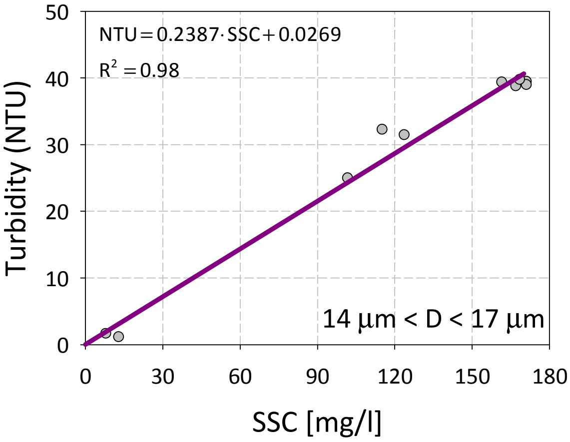
Figure 4.28 - Run 3: Comparison between NTU and SSC for the linear (left) and the crenulated (right) configuration, for the first rising part of the hydrograph

Since previous studies showed how turbidity is affected by temperature and particle size, some considerations have been taken into account. For the six tests executed the temperature has been variable between 10 and 29°C, due to the different time of the day, when each experiment was performed. Considering the linear regression NTU-SSC with the change in temperature, not a significant influence has been observed; indeed the slope seems not to be considerably affected by difference in temperature.

Concerning to the influence of particle size, Foster et al. (1992) found that with the increasing in particle size, the slope of the linear regression NTU-SSC decreases. In their studied they decided to produce 5 particle size bands (< 4 µm, 4-8 µm, 8-16 µm, 16-32 µm and 32-63 µm) and they found for each band a decreasing slope with the increasing in particles dimension. Thanks to the PSD analysis performed on each sample, in this study it has been possible to associate a mean particle diameter (D_{50}) to each values of suspended solid concentration and turbidity. Five bands of particle diameters have been taken into account (4-8 µm, 8-10 µm, 10-12 µm, 12-14 µm, 14-17 µm), considering the D_{50} of each sample (data of runs 3, both configurations, have been only partially included); it is possible to notice that a decrease in linear regression slope corresponds to an increment in sample mean diameter (Figure 4.29), in agreement with Foster's study.

Considering the whole database (expect the samples concerning runs 3, linear and crenulated configuration, for the descending part of the hydrograph), it is possible to see how data are included between two linear regression, as shown on figure 4.30. With the increment in the sediments concentration, data appear to be more spread and it is more complex to find a correlation to associate to a turbidity measure a sediments concentration value.





D_{50} µm	a	b	R^2
4-8	0.310	+2.308	0.92
8-10	0.286	+0.369	0.96
10-12	0.262	+0.505	0.96
12-14	0.255	-1.256	0.98
14-17	0.239	+0.267	0.98

Figure 4.29 - Linear regression turbidity-sediment concentration, with increasing particle size

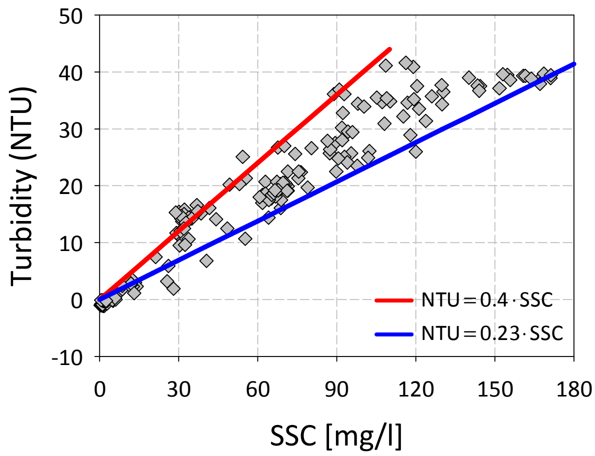


Figure 4.30 - Linear regressions turbidity-sediment concentration

The research of a correlation between turbidity measurements and SSC keeps on being an important goal in the urban drainage and in other hydraulic branches (such as river hydraulics), since it allows to obtain continuous measures of sediments concentration, and then of the amount of sediments discharged, without the necessity to grab samples and perform SSC analyses. Different studies have shown that relation between SSC and turbidity is typically nearly linear, but unfortunately it depends on several factors (particle size, temperature, …) and therefore it appears difficult to establish a relation to determine the suspended sediments concentration from turbidity data.

4.14. Conclusions

Three tests have been performed under unsteady conditions on two different configurations of a clarifier; the purpose of these tests is to evaluate the device efficiency in terms of solid material retained during the simulation of a storm event and to compare the performances of the two configurations. The experimental runs have been conducted using as loaded PM samples of very fine sand at constant concentration. During each test, samples have been taken at the outlet of the unit, and SSC measures and PSD analyses have been performed on each sample, in order to check the functioning of the device during the change of influent flow rate. The importance of the tests is the choice to perform them under unsteady conditions, studying the efficiency of the unit in conditions similar to those that occur during a rainfall event; in addition testing the two configuration for the same conditions allows to have a direct comparison of their effectiveness in PM removal. The experimental results obtained in terms of percentage of solids retained show that the crenulated configuration has a better efficiency since it retains a greater amount of sediments and it reduces the maximum value of SSC at the outlet. Moreover the PSD analyses on the trapped material exhibit that this configuration is able to capture finer particle, to which are commonly attached pollutants such as heavy metals. The two configurations, linear and crenulated, are characterized by having the same foot print; however the different way to use the same volume has shown that it is possible to achieve to higher value of efficiency.

Experimental data have been compared with those obtained by the application of literature formulations to determine the efficiency of devices that works with gravity (SOR model). The efficiencies have been therefore calculated assuming various formulations of the settling velocity (Newton's law, Stokes' law and Cheng's formulation) and different values of the coefficient of short-circuiting according to Hazen. For both configuration the SOR model has provide unsatisfactory results; so it is possible to state that a more complex model is needed to replicate the functioning of these two configurations. Eventually experimental data can be used as calibration values for computational fluid dynamics models.

Turbidity data recorded at the outlet section have been compared to suspended sediments concentration measured for the discrete samples grabbed at the same section during the experimental runs. The comparison shows a linear correlation between NTU and SSC, which is not unique since it is different from one experiment to the other. All the collected data SSC-NTU has been correlated to obtain two regression lines, which include all the data; anyway it has not been possible to find a unique correlation.

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4.15. References

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4.16. Appendix of US Silica sand product data

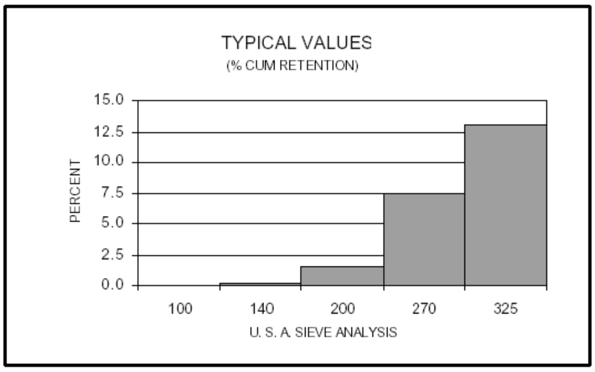
U.S. SILICA®
Sands of Time

PRODUCT DATA

SIL-CO-SIL® 75

GROUND SILICA

PLANT: MILL CREEK, OKLAHOMA



USA STD SIEVE SIZE		TYPICAL VALUES		
		% RETAINED		% PASSING
MESH	MICRONS	INDIVIDUAL	CUMULATIVE	CUMULATIVE
100	150	0.0	0.0	100.0
140	106	0.2	0.2	99.8
200	75	1.3	1.5	98.5
270	53	5.9	7.4	92.6
325	45	5.6	13.0	87.0

TYPICAL PHYSICAL PROPERTIES

HARDNESS (Mohs) 7
MELTING POINT (Degrees F) 3100
MINERAL .... QUARTZ
pH 7
REFLECTANCE (%) 89.5
YELLOWNESS INDEX 3.42
SPECIFIC GRAVITY 2.65

TYPICAL CHEMICAL ANALYSIS, %

SiO_2 (Silicon Dioxide) 99.7
Fe_2O_3 (Iron Oxide) 0.016
Al_2O_3 (Aluminum Oxide) 0.135
TiO_2 (Titanium Dioxide) .... <0.01
CaO (Calcium Oxide) .... <0.01
MgO (Magnesium Oxide) .... <0.01
Na_2O (Sodium Oxide) .... <0.01
K_2O (Potassium Oxide) 0.02
LOI (Loss On Ignition) 0.2

May 29, 1998

WARNING: The product contains crystalline silica - quartz, which can cause silicosis (an occupational lung disease) and lung cancer. **For detailed information on the potential health effect of crystalline silica - quartz, see the U.S. Silica Company Material Safety Data Sheet.**

U.S. Silica Company **P.O. Box 187, Berkeley Springs, WV 25411-0187** **(304) 258-2500**

Conclusions

Several studies have identified sediments as one of the most widely pollutant occuring in waters. Sediment deposits in storm sewers can cause hydraulic problems, such as reduction in flow cross section and increase in bed roughness. Concerning to waterbodies, suspended sediments cause the water to become cloudy or muddy; this increased turbidity damages the aquatic environment and put in danger acquatic wildlife. Moreover many pollutants, such as nutrients, hydrocarbons, metals, and others, are attached to particles. For these reasons most stormwater treatment efforts involve the physical removal of particulates. To better understand the functioning of sedimentation stormwater treatment devices, laboratory tests have been performed on three different units: a roadside gully pot; an hydrodynamic separator and two configuration of a clarifier. The main aim of the work was the experimental determination of the capability of these devices to trap the solid material (efficiency). Then tests' results have been compared to efficiency determined through analytical formulation, to understand if it was possible to apply simple formulas to estimate the amount of particulate matter trapped within a particular device.

All tests performed on the gully pot, with different samples, have shown that the efficiency is inversely proportional to flow rate (steady) and directly proportional to the particle size and specific gravity. Experimental results have been compared to efficiency obtained applying an overflow rate model (SOR model); since settling velocity is a fundamental parameter, different settling rate formulations have been applied (Newton's law, Stokes' law, Zanke, Dietrich, Cheng, Ahrens, Ferguson and Church, Camenen). Efficiency calculated adopting a modification of Stokes' law, as proposed by Butler, gives the best result for mono-disperse tests; the coefficient introduced by Butler probably helps to reduce the error due to turbulence effects, that the overflow rate model does not reproduce. For hetero-disperse tests comparable results have been obtained with all the settling velocity formulations, except for Stokes' law. It is possible to state that results of this study do not contradict those obtained by previous studies, but usefully extend their substantial validity also to contexts and conditions for which they had not been directly verified (hetero-disperse PM). Results show how the influent flow rate affect the efficiency of the unit both in terms of PM removal and reduction of the maximum sediments concentration at the discharge. Therefore the knowledge of the hydraulic conditions is very important to determinate the effectiveness of the unit, as well as the characteristics of the inlet PM (size and specific gravity). The measured efficiency has been compared with efficiency obtained by the application of non-ideal overflow rate model, considering different settling velocity formulations (Newton's law, Stokes' law and Cheng's formulation) and different values of the coefficient of short-circuiting according to Hazen. The comparison with the results achieved in the gully pot study, attributes to the HS excellent performance in terms of capacity to retain solids. The innovation of these tests is the use of unsteady hydrographs, which allows to verify the device performance in conditions similar to those that occur during a rainfall event (previous experiments carried out on similar units have been performed under steady conditions). Moreover several tracer tests have been carried out in order to determinate the experimental determination of the residence time distribution (RTD) for different values of the influent flow. The results have shown the complexity of the unit behavior, which strongly depends on the hydraulic conditions; the RTD curves, indeed, have an exponential decay for high and medium flow rate, while for low flow rate the curve is more spread. These experimental data can be used as calibration values for computational fluid dynamics models.

Two different configurations of a clarifier (a linear and a crenulated one) have been tested under unsteady conditions, using as loaded PM samples of very fine sand at constant concentration. Comparing two configuration for the same conditions has allowed to have a direct comparison of their effectiveness in PM removal. Experimentally measured efficiency shows that the crenulated configuration has higher performances; in fact it retains a greater amount of sediments and it reduces the maximum value of SSC at the outlet. Moreover the PSD analyses on the trapped material exhibit that this configuration is able to capture finer particle, to which are commonly attached pollutants. The two configurations, linear and crenulated, are characterized by having the same foot print; however the different way to use the same volume has shown that it is possible to achieve to higher value of efficiency. Experimental data have been compared with those obtained by the application of a SOR models, assuming various formulations of the settling velocity (Newton's law, Stokes' law and Cheng's formulation) and different values of the coefficient of short-circuiting according to Hazen: for both configuration the SOR model has provided unsatisfactory results; a more complex model is needed to replicate the functioning of these two configurations. SSC measurements and turbidity data recorded at the outlet section have been compared; a linear correlation between NTU and SSC has been observed, slightly different from one experiment to the other. All the collected data SSC-NTU has been correlated to obtain two regression lines, which include all the data; anyway it has not been possible to find a unique correlation.

Real applications of proposed and verified formulas for the different devices are possible if associated to road solids build-up data, rainfall data, characteristics of the particles accumulated on the urban surface and to an appropriate runoff model. It could be then possible to formulate hypotheses on the characteristics of solids not trapped and directly delivered to the sewer system or to the waterbodies, providing a useful support to the maintenance strategies, in terms of both hydraulic and environmental efficiency. Eventually experimental data can be used as calibration values for more complex models, such as computational fluid dynamics models.

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