University of Udine

Ph.D. Program in

Environmental and Energy Engineering Sciences

STORMWATER CHARACTERIZATION AND MANAGEMENT IN SMALL URBAN CATCHMENTS

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XXIX Cycle

Academic Year 2015/2016

To my family

Spes sibi quisque.

(Virgilio)

Contents

Abstract

THIS thesis is a preliminary study on how stormwater management should be improved also in small urban catchments and rural communities.

The aim of the work is to improve academic knowledge and get new concepts on stormwater, in order to assess environmental risk by modeling and by proposing alternative ways to manage this phenomenon. This paper was written after another thesis on stormwater management, developed in the Master Degree in Environmental Engineering three years ago: the need to investigate on this topic was really crucial, so I was lucky to further deepen it in a Ph.D. program. In this case, a little basin of the High Friulian Plain was studied: in Friuli - Venezia Giulia Region, there is a huge number of little villages, each one with its own wastewater treatment plant and with its own way to discharge stormwater. The selected catchment for the study was Galleriano di Lestizza, the place where I live, so it was my pleasure to understand stormwater fate and the implications of common design strategies of sewer systems. The results of the thesis could help to evaluate possible solutions to reduce first flush discharges and to control the total load of pollutant discharged into the infiltration pond at the end-of-pipe.

This thesis opens a discussion on stormwater management in Friuli - Venezia Giulia Region: surface and groundwaters need to be protected from urban stormwater runoff, and this work allows to start a long and difficult path for an integrated water management and treatment protocol. The last hope of this work is to invite water regulators and water industries to focus on this topic, because they all must feel involved in the improvement of water resources and environmental habitats.

Chapter 1

Introduction

1.1 The water cycle

WATER is a tireless source of life, running from mountains to hills, strolling through plains, forests and soils, resting in lakes and lagoons, and then reaching the sea. Meanwhile, water allows every single natural and anthropic activity. After evaporation, water comes back to the land as rain, and the cycle can start again. This process is called hydrologic cycle and it is potentially endless, according to the power of the sun, which is the fuel and the engine of the entire course of water. The role of gravity is definitely important too.

Water is present everywhere, in various phases and locations during the cycle, but global numbers on water availability give a false sense of security [1], because it is not distributed equally on the Earth. In the oceans we can find out about 97% of total water; freshwater is divided into rivers, lakes, glaciers, ice caps and groundwater (Fig. 1.1).

Water is renewable in quantity, but it still imposes several issues in many regions [3]: available freshwater on Earth comprises only about 3% of the total supply [4]. Unfortunately, water is not uniformly distributed, and for this reason, talking about the hydrologic cycle usually means explaining how water take place in different phases, but mainly from a quantitative point of view.

In spite of this poor availability, population growth and higher living standards will cause ever increasing demands for municipal and industrial water [5]: this issue pushes the need for different approaches to sewage flows management and treatment. Furthermore, sewage flows are commonly affected from stormwater surcharges: urbanization significantly impacts on water environments with increased runoff and water degradation [6]. A qualitative approach is

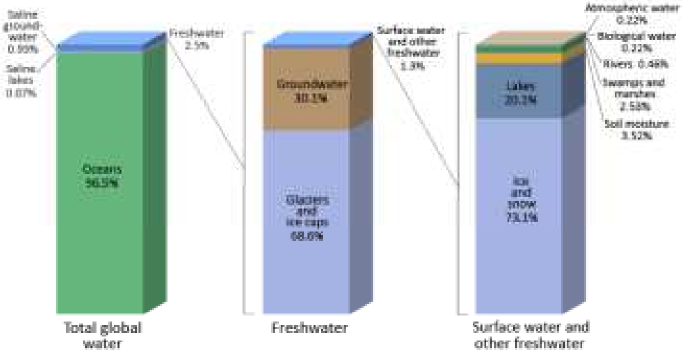


Figure 1.1: Water distribution on Earth [2]

needed in water management.

1.1.1 Water management in ancient times

Water resources were strictly important in ancient times: developments like the implementation of hygienic living standards, advanced hydraulic technologies for water transportation, constructions for flood and sediment control, and sustainable urban water management practices, were a very significant way to improve human habitats, allowing life and growing of knowledge about water relevance [7]. Archaeological studies in the last century revealed remarkable techniques in various fields of water resources management, as found in ancient Greece: groundwater exploitation, water transportation, water supply, drains (Fig. 1.2), stormwater and wastewater systems, etc. [8].

Apart of water supply, water managing was difficult because there were a lot of different types of forcing issues: heavy rains, bad human habits and a lack of good hygienic conditions. It is really common thinking about "water sanitation", but this concept is very far in time, due to hygienic needs. For example, in the Mesopotamian Empires (Assyria, Babylonia, Sumerian, Akkadian), sewerage was made of brick, collecting water-flushed latrines from the houses [10], to keep away bacteria from the city. This kind of excavations were really similar to the ones which nowadays stand in our cities. Similar techniques were founded in the Indus civilization, going on with remarkable knowledge of hydraulics, as we could notice in Rome, a few decades later. Rome was the city with the famous *cloaca maxima*, primarily constructed for removing stormwater from the streets; people used to throw waste and excrement on the street, so each rainfall event was extremely awaited for cleaning the streets [10]. Water harvesting was definitely

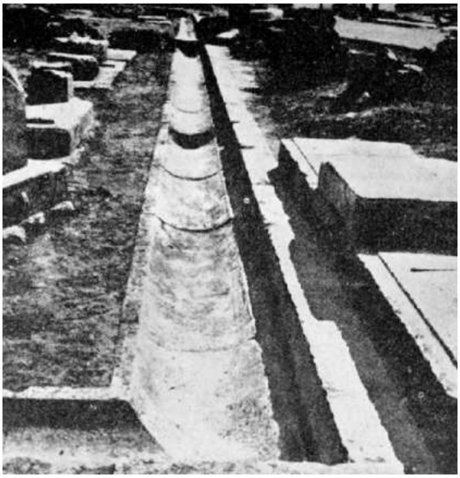


Figure 1.2: Stormwater drain in the agorà of ancient Messene [9]

important too, increasing plant production and potable sources [11]: keeping rain and runoff water in situ was one of the most common practices, as found in a lot of monasteries in Europe (Fig. 1.3).

Figure 1.3: Rain water harvesting at the University "La Sapienza" in Rome which was an old monastery [12]

Capital cities in Europe (and all over the world) became more and more crowded, so the public need of stronger wells in the urban mesh to get potable water was essential; furthermore, stormwater removal and water treatment became more and more crucial for hygienic reasons. In fact, medioeval age was really poor in sanitation, and for this reason a lot of plagues scourged many countries. First laws and regulations about sewer management were published around the end of the 19th century [10] in the European area. Sewers could get both wastewater and stormwater, respecting certain basic rules.

Since ancient times, these issues did not change: water had been a persistent and consistent factor in urban development [13], which imposed a variety of watershed changes [14]. Harvesting, water supply, protection from floods, stormwater management: these are only some of the issues for water professionals, researchers, water regulators and water industries. What about water quality in the environment after human intervention? Abatement of pollution in water was not recognized as a necessity in some industrial countries until the nineteenth century [15], but currently it is one of the most important challenges, according to the lack of potable water in developing countries.

1.1.2 Runoff in the water cycle

The water cycle was roughly represented in Fig. 1.4: each part of the cycle is linked as in a chain. Depending on latitude and climate characteristics of the region, there can be different ratios between evapotranspiration, precipitation, runoff or storage, but the global mass is conserved. When human needs try to modify these ratios, we can see a disturbance of the cycle, which can be positive (sustainable) but it can be also negative (unsustainable). According to Fig. 1.4 the inventory equation of runoff can be written as follow [16]:

$$Beginning\ Storage + Inputs - Outputs = Ending\ Storage$$

and then

$$S_0 + (P + R + B) - (I + T + E + O) = S$$

Certainly, water cycle can be divided in two different and twisted sections: quantity and quality. Surface water represents one of the most important parts of the cycle, and the one which is more affected from human activities. It takes place as rain in the sky, and then it runs on permeable or impervious surfaces reaching streams or filtrating down to the soil.

Depending on the land use (urban, rural or industrial), surfaces can affect in several ways stormwater runoff: this is an important issue in order to understand why managing surface water is the key to improve environmental habitats [17]. Both in the sky or on the earth, human activities modify runoff quality and it could be really difficult to understand "how & when" strong pollution arrives at the outlet.

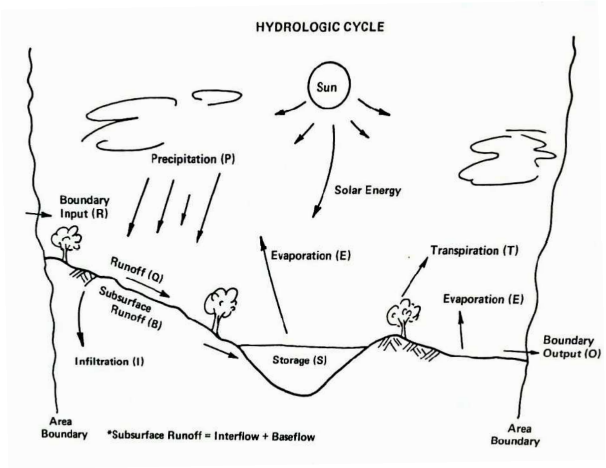


Figure 1.4: The hydrologic water cycle [16]

1.2 Issues and challenges: stormwater in the integrated water cycle

Water research should focus on the entire hydrologic cycle, because each section is important, in order to protect the environment and human society. In this thesis, we will focus on stormwater management, because it is one of the most difficult water to manage, in quantity and quality. It can be located into the *Integrated Water Cycle* (IWC), which is the cycle of water for human needs, regulated by water industries: stormwater provides to recharge groundwater, or to feed rivers and lakes, so it is a source of life which cannot be thrown aside.

Recently, numerous decision support tools have been developed to assist stormwater managers and water industries, in order to understand future scenarios and to devise management strategies [18]: scenarios help stormwater managers to diagnose potential problems that may emerge from strong climate changes and variability, but there is a lot to do in this applied planning science. We can find out great examples of stormwater management plans in some regions of the world, but in Italy there is a lack of this planning culture, without any link between stormwater and land use in watersheds (Fig. 1.5)

The US EPA published a lot of papers on integrated stormwater planning for different situations (e.g. construction sites, industrial activities,...) [20]; the Center for Watershed Protection as well is promoting sustainable stormwater systems on basin scale, focusing on watershed imperviousness and using it as a key-factor for enhancing future quality of many headwater streams [21].

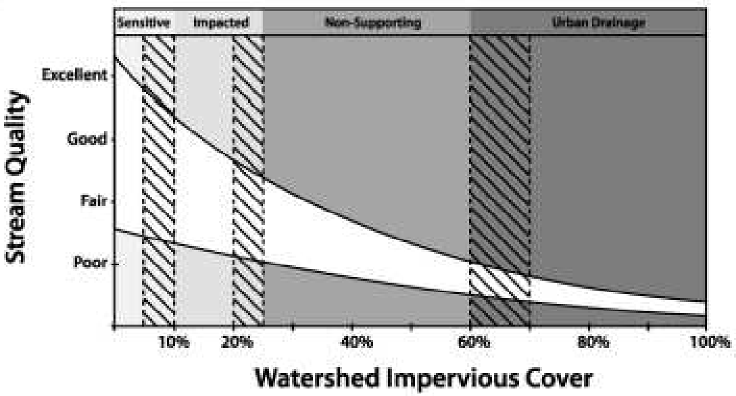


Figure 1.5: Conceptual model illustrating the relationship between impervious cover and stream health [19]

Improving quality of surface and groundwater streams means reacting to common urbanizing activities, according to land use analysis: stormwater strategies must be integrated with urban cores and rural catchments [22], preferring LIDs (Low Impact Development) or BMPs (Best Management Practices) instead of conveying all to the outlet. Furthermore, improving quality of water means getting an opportunity to introduce this goal to the urban society, affecting stakeholders with precious informations on their environment and their network; this could definitely improve water health with structural and non-structural projects [23]. Stormwater education should begin in the schools: many regions in the world applied kids educational programs on stormwater pollution (e.g. Rhode Island Stormwater Solutions [24]). Effective watershed and stormwater education and public involvement programs strive to increase awareness of watersheds and landscape connectivity; also encouraging behavior changes may contribute to solve water quality and quantity problems within a targeted basin [25]. Obviously, these educational programs should be controlled and calibrated on each single watershed, because each one could present many features (i.e. economical or technical constraints could define different scenarios [26]): surveys and audits have to be considered as one of the most important ways to achieve streams and groundwater restoration, providing how effective the education campaign is [27].

Stormwater management (i.e. water management) is a complex topic, which needs to be studied from many points of view. There have been a number of challenges to overcome as transdisciplinary researchers: the first and most important challenge was to understand the different research philosophies and theoretical assumptions behind various natural and social science research methods [28]. As a matter of fact, the integrated water management (Fig. 1.6) is essentially a transdisciplinary science, including politics.

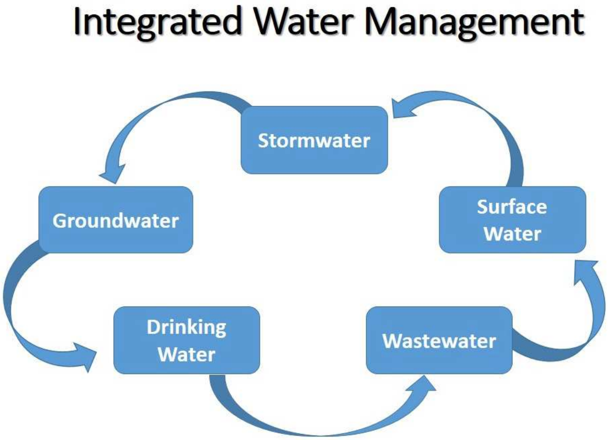


Figure 1.6: The integrated water cycle: renewal of quantity and quality by managing transdisciplinary sciences from different water sources

However, despite significant advances in alternative "integrated urban stormwater management" techniques and processes over the last 30 years, wide-scale implementation has been limited [29]: transdisciplinary approach must break this political inertia, demonstrating that sustainable management is the only way to get a better quality of water and life.

Last but not least, this introduction wants to introduce the reader into regional stormwater management in Friuli - Venezia Giulia Region: the challenge of this thesis is to understand stormwater behaviour in small and suburban catchments, in order to assess possible sustainable managements in quality and quantity. A framework is needed in this Region: according to environmental and geological features, stormwater must be recovered because groundwater is really precious and streams are really short, so it is important to improve water quality for assessing good habitats, and for protecting little urban settlements from water pollution.

Chapter 2

Quality of surface water

SURFACE water quality should approximate the quality of the rainfall, but this does not really happen, because precipitations are always affected by human activities or natural events (i.e. vulcan eruptions). Several papers in literature report a huge amount of data, considering dry and wet season, according to urban, rural or industrial areas as rain catchment [30]. In fact, knowing atmospheric and rain composition in pollutants is really important, in order to understand the role of diffuse pollution on Earth and then surface water quality, as result of runoff [31].

Nonpoint pollution resulting from stormwater runoff has been identified as one of the major causes of receiving water quality deterioration [32]: for this reason, scientific research on this topic must be improved, and a lot of environmental data are required, in order to plan possible solutions.

2.1 Nonpoint source pollution

A lot of papers ascribe bad surface water conditions to stormwater management and CSOs (Combined Sewer Overflow) discharges [33]: certainly, rainfall events can get pollution both from the atmosphere and from impervious surfaces, so every kind of polluted material can be dragged away by runoff transport into receiving bodies.

Nonpoint source pollution means the spreading source of diffuse pollution (i.e. human activities improve gaseous chemical deposition, or flotation in the atmosphere without any rule or spatial limitation), so we can find out chemicals everywhere, depending on various factors.

2.1.1 Rural sources

Agriculture can contribute to water quality deterioration through the release of sediments, pesticides, animal manure, fertilizers and other sources of inorganic matter [34]. Large areas are involved in agriculture, so managing this kind of nonpoint source pollution could be very difficult (Fig. 2.1). This problem is common all over the world, especially in countries with emerging markets, where agriculture is growing day by day (e.g. in China: knowledge about agriculture runoff pollution is pushing for significant legislative and infrastructural changes [35]).

Typical nonpoint sources of pollution from agricultural or rural areas are [34]:

- leaching of nitrogen and phosphorus from arable land;
- leaching of nitrogen and phosphorus due to inappropriate storage of manure from animal production;
- atmospheric emissions of ammonia from manure, due to inappropriate storage and field application;
- leaching of pesticides, due to inappropriate application techniques and storage facilities;
- inadequate treatment of wastewater in rural areas.

In addition, fate of pesticides in streams and groundwater is generally unknown, especially because of their high solubility and absorbability in sediments [37], which can cause possible environmental hazards [38]. Certainly, high variability is expected from rural areas, depending on farms, ground cover, climate, land use, slope and type of cattle.

2.1.2 Urban sources

Pollution coming from urban activities can be really dangerous against environmental habitats. A lot of pollution sources can be found in urban areas, starting from industries, vehicle tires, air-deposited substances, gas emissions, acid rain, street buildup of pollutants: Hazard maps are reported in several papers, in order to improve the knowledge about sustainable urban drainage planning [39]. Runoff hazard for streams is strongly related with precipitation intensity and frequency: higher runoff discharges mean more nutrients and more toxic compounds dragged by solid material [40]. In addition, organic pollutants produce

Figure 2.1: Runoff from farmland near the Santa Maria River (CA-USA): from ditches to the river [36]

a decreasing level of oxygen in streams, so aquatic life can be strongly degraded (Fig. 2.1); toxic effects (cf. Par. 2.4) can be due to heavy metals and polycyclic aromatic hydrocarbons adsorbed in road debris [41]. There are three main type of sources for pollutants in urban area [42]:

- *atmospheric contribution*: pollution in the atmosphere is present as gases (volatile compounds), aerosols (liquid particles, i.e. associated with raindrops and fog) and suspended solid particles (dust). Atmospheric pollution source depends on land use, or industrial activities or daily traffic volume: it is strictly related to the runoff from the roofs, as they are not affected from vehicular traffic or industrial field activities.
- *human land activities*: this source is strictly related to land use, both from stationary sources (industries, houses, urban installation) or mobile sources (automobile traffic) which are probably the most important. Sub traffic related sources are: degradation products from automobile tires and brake pad wear, corrosion products, transported load losses, fuel combustion products, contamination from road surface material and de-icing agents (e.g. road salt);
- *illegal activities*: impervious surfaces may be affected from illegal activities or illegal discharges, so these sources could badly degrade runoff in urban areas.

In addition, daily wastewater flows (in combined sewers) and accumulated sewer

Figure 2.2: Typical runoff from highly polluted street with saturated manhole [43]

solids could be a huge source of pollutants, because when a storm event occurs they could be discharged via CSOs.

2.2 Law and regulations for surface runoff

Surface runoff is one of the most regulated parts of the integrated water cycle. Regulations about surface runoff permit to focus on land management in order to protect urban areas from flooding and surface potable sources.

First of all: flooding. Big urban centers focus on finding new paradigms in order to achieve a sustainable water management in water bodies, which are usually severely hit and impaired by poorly planned urbanization [44]. In the urban context, regulation is changing because climate changes require flooding resilient cities, and there are many projects involved in this kind of approach (e.g. Collaborative research on flood resilience in urban areas - CORFU [45]). *Resilience* is the new term and concept to follow, in order to prevent hazard from extreme events: recognizing the presence of climate impacts is a way to promote adaption of existing cities [46]. Water quantity is one of the most alarming issues: inundations are no longer acceptable, so regulators are improving laws on hydrologic and hydraulic invariance i.e. the require of new lottings not to overload receiving systems because of imperviousness.

Secondly: water pollution control. Surface water conditions are extremely related to nonpoint sources (cf. 2.1), and regulation about this topic is really varied all around the world. In this thesis, european situation will be analyzed; in order to achieve the aim of this work, quality regulations will be examined in depth instead of quality regulations.

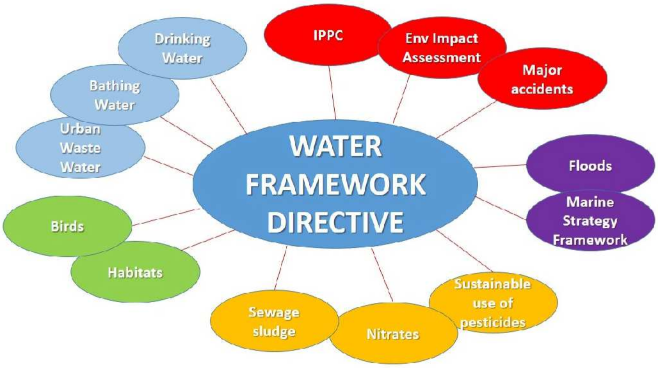


Figure 2.3: The Water Framework Directive conceptual scheme: various regulations are involved in a "good status" target for all waters [49]

2.2.1 European directives

The aims set out in the EU treaties are achieved by several types of legal act [47]. These deeds can bind european states (e.g. commercial agreements) or they can just set some goals to achieve in a certain period of time.

The European Union decided to set objectives in the environmental area, so it gave some *directives* to the States of the Union, especially about water. The most important document of the European Union is the *EU Water Framework Directive* (WTD), which affects 27 countries: it marked an important trend towards an ecosystem-based approach for water policy and water resource management [48].

This directive melted regulations concerning all waters (cf. rivers, lakes, estuaries, coastal water and groundwater, Fig. 2.3), with the aims [49] of:

- protect/enhance all waters (surface, ground and coastal waters);
- achieve "good status" for all water by December 2015;
- manage water bodies based on river basins or catchments;
- involve the public.

This targets were very advanced in the 90s, because water policy was fragmented between states and a unique approach was needed in order to protect the entire environment. The directive was published on 22.12.2000 on the European Journal, and named *Directive 2000/60/EC*. In this document, fundamental statements were reported, and the first is maybe the most important: *"water is not a commercial* *product like any other but, rather, a heritage which must be protected, defended and treated as such"* [50].

The WFD aims to achieve an ecological "good status" for all ground and surface waters according to the following criteria [51]:

- biological quality (fishes, benthic invertebrates, aquatic flora)
- hydromorphological quality (e.g. river bank structure, river continuity or substrate of the river bed))
- physical-chemical quality (e.g. temperature, oxygenation and nutrient conditions)
- chemical quality that refers to environmental quality standards for river basin specific pollutants.

Unfortunately, the only reference about stormwater is located at *Annex II - Art. 2.3*, so some modifications are needed in order to prevent pollution of stormwater in a more mandatory way in all the European Union. Regulation aspects require Member States to ensure their own authorities to solve and regulate many topics, in order to apply the WFD from concepts to actions.

2.2.2 Italian regulation

Water regulations in Italy begun to improve environmental quality in 1976, with the *"Legge Merli"*: for the first time, certain terms and limits were written, according to different pollutants and parameters. That was the first step, but clearly this kind of approach did not investigate on the surface water status. There was a need for a reverse approach, starting from water status, to define the limits which could improve it [52]. In recent years, many laws have been promoted by the Parliament (e.g. *D.Lgs. 152/1999* according to *European Directives 91/271/CEE and 91/676/CEE*) but the last one is the *D.Lgs. 152/2006*, according to the European Union WFD [53].

In the third part of the *D.Lgs. 152/2006* we can find out the rules about pollution protection and prevention in soils and waters. Focusing on stormwater, the article 113 introduces some particular definition, which is the central topic of this thesis. The main issue of this article is a delegation to the Regions of regulation about stormwater:

ART. 113 *(acque meteoriche di dilavamento e acque di prima pioggia)*

1. *Ai fini della prevenzione di rischi idraulici ed ambientali, le regioni, previo parere del (Ministero dell'ambiente e della tutela del territorio e del mare), disciplinano e attuano:*
    - **a)** *le forme di controllo degli scarichi di acque meteoriche di dilavamento provenienti da reti fognarie separate;*
    - **b)** *i casi in cui puo' essere richiesto che le immissioni delle acque meteoriche di dilavamento, effettuate tramite altre condotte separate, siano sottoposte a particolari prescrizioni, ivi compresa l'eventuale autorizzazione.*
2. *Le acque meteoriche non disciplinate ai sensi del comma 1 non sono soggette a vincoli o prescrizioni derivanti dalla parte terza del presente decreto.*
3. *Le regioni disciplinano altresi' i casi in cui puo' essere richiesto che le acque di prima pioggia e di lavaggio delle aree esterne siano convogliate e opportunamente trattate in impianti di depurazione per particolari condizioni nelle quali, in relazione alle attivita' svolte, vi sia il rischio di dilavamento da superfici impermeabili scoperte di sostanze pericolose o di sostanze che creano pregiudizio per il raggiungimento degli obiettivi di qualita' dei corpi idrici.*
4. *E' comunque vietato lo scarico o l'immissione diretta di acque meteoriche nelle acque sotterranee.*

The language of the law is Italian, and it must be interpreted in this language, because there have been a huge number of court cases on this topic, so any translation may be incorrect.

2.2.2.1 Regional regulation

Each Region applied the *D.Lgs. 152/2006* in a different way, according to their own problems or issues as excess of rainfall events, dry periods, urbanization; for this reason, rules about stormwater are very variable; in any case, the main principles of regulators are *"quantity of runoff"* or *"maximum flow"*, so quality of stormwater is usually overshadowed. In this thesis, just a few examples will be listed, because the aim of the thesis is to characterize stormwater in respect of the phenomenon: regulations should be studied separately.

Lombardia Region The Lombardia Region was the first regulator agency on stormwater and risk assessment. The first law was approved in the 1985, [54], probably because the Region was one of the most industrialized of the entire country. In this law, there are two main articles which it is important to report:

ART. 19 *Smaltimento delle acque meteoriche*

1. *I nuovi insediamenti di cui al precedente art. 14 possono recapitare sul suolo o negli strati superficiali del sottosuolo le acque meteoriche, previa separazione delle acque di prima pioggia, individuate ai sensi del successivo art. 20, purché esse vengano convogliate e recapitate con opere di smaltimento indipendenti e tali da consentire il prelevamento di campioni ai fini di quanto disposto dal successivo art. 23.*

2. *Negli insediamenti già esistenti, le opere indipendenti di convogliamento e smaltimento di cui al precedente comma devono essere realizzate entro il termine perentorio di due anni; un termine inferiore può essere stabilito dal sindaco con provvedimento da notificarsi all'interessato, assegnando comunque almeno sei mesi per l'adempimento.*

ART. 20 *Smaltimento delle acque di prima pioggia e di lavaggio*

1. *Previa realizzazione di opere di convogliamento e smaltimento indipendenti, nelle zone non servite da pubbliche fognature e non ubicate in prossimità di corpi d'acqua superficiali, le acque di prima pioggia e quelle di lavaggio delle superfici, quali pavimenti, cortili, piazzali e di qualsiasi altra area interna ed esterna degli insediamenti di cui al precedente art. 14 possono essere recapitate sul suolo o negli strati superficiali del sottosuolo, nel rispetto delle disposizioni di cui alla legge 10 maggio 1976, n. 319 e successive modificazioni, nonché di quelle emanate dal consiglio regionale di cui al successivo terzo comma e di quelle del successivo art. 23.*

2. *Sono considerate* ACQUE DI PRIMA PIOGGIA QUELLE CORRISPONDENTI PER OGNI EVENTO METEORICO AD UNA PRECIPITAZIONE DI 5 MM UNIFORMEMENTE DISTRIBUITA SULL'INTERA SUPERFICIE SCOLANTE SERVITA DALLA RETE DI DRENAGGIO. *Ai fini del calcolo delle portate, si stabilisce che tale valore si verifichi in quindici minuti; i coefficienti di afflusso alla rete si assumono pari ad 1 per le superfici coperte, lastricate od impermeabilizzate e a 0,3 per quelle permeabili di qualsiasi tipo, escludendo dal computo le superfici coltivate.*

3. *Il consiglio regionale individua ai sensi del successivo art. 37 quelli, tra gli insediamenti di cui al precedente art. 14, i cui scarichi siano recapitati sul suolo o negli strati superficiali del sottosuolo, che, in relazione alla tipologia dell'attività svolta, debbono assoggettare a trattamento le acque di prima pioggia, stabilendo gli obiettivi del trattamento e le modalità dello smaltimento, nonché i termini di adeguamento per gli insediamenti esistenti.*

4. *Il sindaco può fissare termini di adeguamento più brevi con provvedimenti da notificarsi agli interessati, assegnando comunque almeno sei mesi per l'adempimento.*

This is the first reference in the Italian regulation: 5 mm of rain, uniformly distributed on the impervious basin area define the *"first flush volume"*. This evaluation was integrated in the italian law: stormwater first flush detention was assumed as important for an environmental improvement. Groundwater recharge with polluted stormwater was essentialy prohibited [53].

Lombardia Region continued its work on stormwater regulation, so in 2003 and then in 2006 the regional parliament approved rule books on stormwater, where we can find the definition of *"rainfall event"* as *"a rain event greater than or equal to 5 mm of rain in 96 hours"* . In this case, stormwater must be stocked or treated [55], without any discharge in the environment from any dangerous catchment (e.g. industries, impervious surfaces greater than 2000 mq, paper mills, foundries, etc.). All the areas in which there is a fouling because of the land use, the surface must be impervious. In this areas, the project manager must provide a tank for the first flush, with a volume of at least $50\,mc/ha_{imperv.}$ (or $5\,mm_{rain}/ha_{imperv}$). The tanks have to be connected with a drainage network which should be able to separate first foul flush from the second part of the rain with automatic devices; no mixing with clean stormwater is acceptable (the law does not approve an abuse of dilution). If the impervious surface is affected from activities which are involving hydrocarbons, first flush stormwater has to be treated continuously, basing on the maximum flow coming from the *rainfall event* defined as explained in this paragraph. Some other instructions are listed into the regional government acts, regulating also the second part of the storm, which is called "second flush" (i.e. *acque di seconda pioggia*) such as DGR 8/2772 - 21/06/2006 and DDG 8056 - 18/07/2007, so the Region was very involved in an improvement of this regulation. Each regional law provided to improve both technical and environmental aspects such as position of the first flush tanks, CSOs design strategies, drainage network planning, etc.; there is no difference between storm events or combined sewer pipes: the first flush volume must be retained.

Veneto Region In the Venetian Region, the most recent rule book was approved in 2012 in an annex of the Regional Plan of Water Protection (i.e. *Piano Regionale di Tutela delle acque*) [56]: at the art. 39, there is an obligation of first flush retention and treatment. Water industry has to treat water coming from industrial areas, chemical plants or any land use which is affected from processing any waste exposed to the rain and settling on the ground, without any cover. Water treatment needs to be composed at least of a sedimentation tank and an oil separation tank (where required). Chemical features of stormwater before the discharge into receiving systems are integrated in this regulation: TSS, COD and Total Hydrocarbons are regulated. The designer is free to provide harvesting systems or to discharge stormwater when first flush effect is passed away, by demonstrating this task with a dedicated calculation report.

Friuli - Venezia Giulia Region The last Region taken as an example is the Region where the case study is located, so this is the most important regulation to keep in mind in this area. Friuli - Venezia Giulia Region approved in 2014 the *Piano Regionale di Tutela delle Acque* [57]: at *Capo II* regulations about stormwater runoff were listed. The first definition of "polluted stormwater runoff" is the *whole* runoff volume on a list of surfaces/land uses:

- activities of the Ann. I D.Lgs. 18.02.2005 n.59 (IPPC Directive);
- tires production;
- logistic platforms and freight yards;
- urban waste treatment plants;
- metal scrap deposits;
- gas and gasoline stations;
- any activity which is working with substances integrated in the Ann. V, tab. 3/A of D.Lgs. 152/2006.

The second definition of "polluted stormwater runoff" is the *first flush* runoff volume on a list of surfaces/land uses:

- activities without environmental integrated authorization needed (e.g. energetic plants, metal factories, mineral factories, chemical industry, paper mills, textile industry, tanneries, meal transformation plants, food processing plants, recycling animal waste activities, impervious surfaces with use of specific toxic compounds, graphite and electric plants);
- repairing garages;
- car body shops;
- vegetable markets;

- ecological sites;
- commercial sites over 5000 mq (leaving out any roof or green area)
- public transport logistic sites;
- shipyards;
- car washes sites.

There are two different definitions of "polluted stormwater runoff" in this regional rule book in case of separated sewer systems. "Rain conveyed in stormwater sewers can be discharged without any treatment", and this may be an unclear part of the regulation because no first flush effect is considered. The very interesting part of the regulation is the need to treat the first flush volume from public areas, so also from streets and park lots: it would be a really difficult task, because in the Region there are a lot of streets connecting separated villages, so it could be hard to intercept all the waters coming from that kind of streets.

First flush volume should be evaluated with a runoff coefficient taken as "1" in 15 minutes of rain. The rain intensity has to be evaluated in respect of short and strong events, depending on the area of interest. Stormwater tanks need to be connected to the sewer network, in order to get $50\,mc/ha$ of volume, or the most suitable part according to total amount of the rain considered in the calculation report. The last observation on this regional law is about CSOs: for the end-of-pipe overflow a dilution fraction of "4" could be used.

2.2.2.2 Regional regulation overview

A few regional regulations were reported, therefore we can make a comparison between them. Each regulation starts with the same concepts, but each one has its own way to define:

- *first flush* definition;
- type of surfaces to consider, in order to evaluate the first flush volume;
- CSOs dilution levels and position into the drainage network;
- first flush tanks features;
- design criteria for improving quality of surface waters;

According to the concepts of each regulation, the designers should improve the regulation knowledge in order to move all around the country, because each one has its own parameters and features.

2.3 The first foul flush phenomenon

The *first foul flush phenomenon* is the abundant quantity of pollutants washed off by stormwater coming to the end-of-pipe of common sewer systems, which are the majority in the area of interest. In the first part of stormwater runoff, high concentration of pollutants may be discharged without any treatment and this happening could be very dangerous for receiving waters. We will understand that the total discharge load is extremely important due to toxicity aspects, so first flush is not the only part to keep in mind when a stormwater management plan needs to be reported.

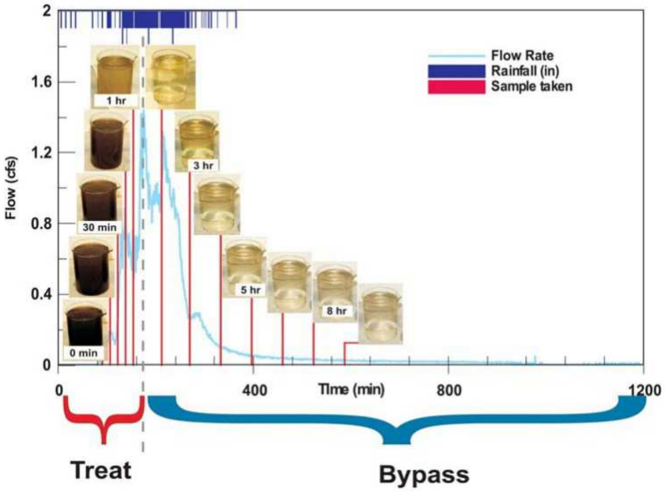


Figure 2.4: The first flush phenomenon: pollutant dilution grows until the washoff contribuition decrease and the dilution effect is greater [58]

Pollutant origins of first flush pollution were already listed in Par. 2.1: atmospheric and ground deposition, according to rain intensity and land use, contribute to make this increase of pollutant concentration greater or lower. In 2005, an interesting publication of the California Department of Transportation Division of Environmental Analysis [58] illustrated the first flush phenomenon in a simple way, just to underline the importance of stormwater treatment (Fig. 2.4). The quantity to treat, graphed in the picture, was commonly assumed as the only one affecting receiving water qualities; nowadays this assumption can not be confirmed, so the paradigm has completely changed. Pollutants affecting stormwater are listed in Tab. 2.1, according to the origin.

The knowledge of pollutants must be improved with the knowledge of

Pollutants	**Anthropic Source**
Total Solids	Asphalts, traffic loads, veichles, tires
Nitrogen	Fertilizers on streets
Phosphorus	Fertilizers on streets
Lead	Combustion fuels, oil, lubricants, worn bearings
Zinc	Tires erosion, zinc roofs, traffic loads
Iron	Vehicle rust, iron infrastructures
Copper	Vehicle corrosion, worn bearings, fungicidal, insecticide
Chromium	Vehicle corrosion, brake wear
Nickel	Diesel and gasoline residuals, oils, vehicle corrosion, brake wear, asphalts
Cyanide	Frost protection compounds
Sodium Chloride	Asphalt frost protection
Hydrocarbons	Lubrificant leakage, asphalts, gasoline and diesel combustion
PCBs	catalysts, road asphalt signs

Table 2.1: List of pollutants with their origin according to most common literature [59]

the order of magnitude of their concentration: this will be underlined at Cap. 4. Pollutants can increase their activity in stormwater runoff because of the imperviousness of surfaces: an interesting study on highway runoff in Austin - Texas [60] reports the influence of impervious areas in respect of pollutants concentration in the first flush (Tab. 2.2).

Copper, nitrites, nitrates, phosphates do not confirm this issue, but for the most important pollutants, this increase is really significant (Fig. 1.5).

2.3.1 Quantity of first flush and total load: M(V) curves

The first flush phenomenon depends essentially on the land use: if the surface is clean, stormwater quality will be the same as it is for rain, but if the surface is dirty, stormwater quality may be very undesirable. A remarkable work of the University of Aberdeen [61] analyzed the influence of total suspended solids, pH and temperature on first flush behavior considering two places far apart (Serbian and Swedish urban catchments). The features of the two catchments were almost the same. The paper analyzed which kind of pollutants could be overlooked, in order to establish a minimum number of parameters to measure: it was a sort of simplification for saving money in laboratory activities. This is a very useful operation, but the correlation between different parameters should be verified.

Parameter \ % Impervious Fraction	5%	30%	50%	70%	90%
BOD5	9	10	14	16	19
COD	26	52	65	66	69
TOC	7	13	14	18	24
Nitrites+Nitrates	0.15	0.71	0.52	0.55	0.67
Ammonia	0.09	0.24	0.38	0.30	0.24
Phosphates	0.04	0.22	0.20	0.20	0.20
Total Solids	80	170	212	220	223
Copper	0.01	0.01	0.01	0.01	0.01
Iron	0.36	0.68	0.48	0.54	0.58
Lead	0.004	0.045	0.03	0.04	0.06
Zinc	0.008	0.060	0.090	0.12	0.17

Table 2.2: Concentration of pollutants in the paper of Barret [60]in some little street catchments in Texas (US) $[\frac{mg}{L}]$

This assumption will be also verified for the experimental campaign in this thesis (Cap. 4).

Considering pollutant variability, with load and flow during a rainfall event is crucial in order to assess stormwater pollution hazard. For this reason, one of the methods to understand the first flush potential (but also in case of medium storm events) in scientific literature are the *mass-volume curves* (also know as *M(V) curves*). Some technical definitions of first flush are based on the analysis of this type of graphs [62].

The first step in order to plot mass-curve graph is plotting common charts of stormwater monitoring campaigns (Fig. 2.5) reporting:

Flow Rate curve: variation of flow in the pipe in respect of time due to a rainfall event or washing activities;

Concentration curve: variation of concentration of one or more pollutants/parameters in respect of time due to washoff of impervious surfaces by rain or washing activities.

Once the common graph is plotted, the next step is to normalize variables according to the whole event, so integrating the curves in respect of time a mass-volume graph is plotted (Fig. 2.6).

If the slope of the M(V) curve is greater than the bisector slope, the first flush intensity is measured from the maximum distance between the two curves in the first part of the graph. The bisector of the chart represent the flow with constant concentration of pollutant, so the transport of some compound is constant during the rainfall event. This is the graphical definition of first flush, or maybe the most immediate reading key of the graph.

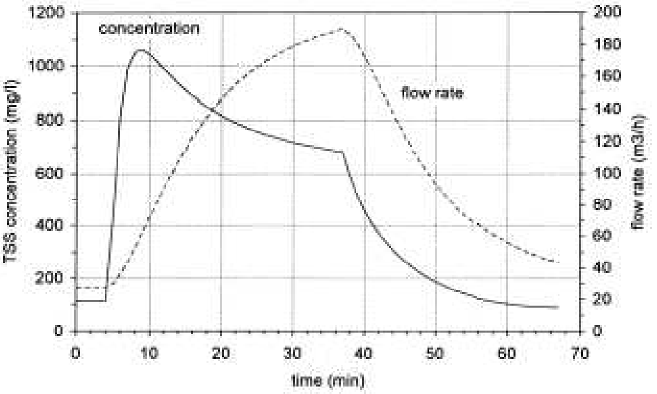


Figure 2.5: Common chart with hydrograph and pollutograph [62]: the curves are drawn as measured or verified in the laboratory. Stormwater quality is strictly connected to time-flow curves.

Plotting M(V) curves means to get the real evidence of first flush, but also to get the total mass load transport of the washoff process; maximizing the load intercepted before discharge for each pollutant means preserving environmental quality and preventing toxicity by huge pollutant loads.

The mathematical process to calculate M(V) curves is reported below. Each pollutant describes this curve:

$$\frac{\sum_{i=1}^{j} C_i Q_i \Delta t_i}{\sum_{i=1}^{N} C_i Q_i \Delta t_i} = f\left(\frac{\sum_{i=1}^{j} Q_i \Delta t_i}{\sum_{i=1}^{N} Q \Delta t_i}\right) = f\left(\frac{\sum_{i=1}^{j} V_i}{\sum_{i=1}^{N} V_i}\right)$$

The curve should represent pollutant washoff during the storm event, giving important information in order to model the washoff process. If the concentration is constant during the storm event (C_0), the curve will be a straight line:

$$\sum C_i Q_i \Delta t_i = C_0 \cdot \sum Q_i \Delta t_i = C_0 \cdot \sum V_i$$

The straight line is plotted in the plane(X, Y): X represents the volume fraction and Y the mass fraction of pollutant. If we consider the straight line as the bisector of the plane (X, Y) so to retain an X fraction of pollutant we should retain an $Y = X$ fraction of volume. When the M(V) curve is above the bisector, if an X fraction of pollutant needs to be retained, so we need to retain an $Y < X$ volume fraction of storm. It will be the opposite if the M(V) curve is below the bisector. In Fig. 2.7 some of possible and common M(V) curves were plotted [62].

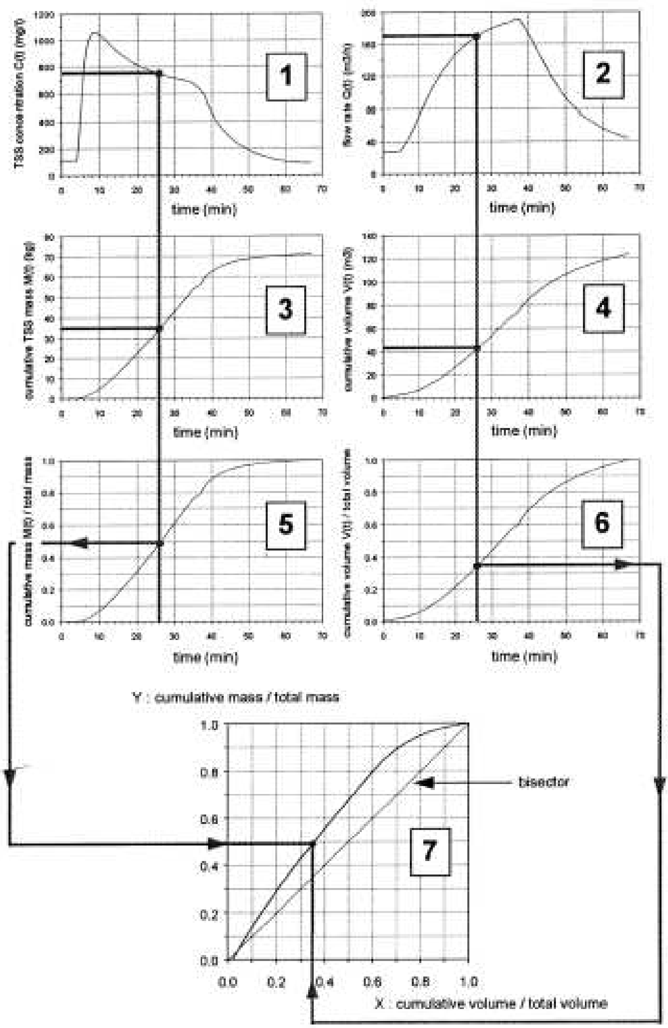


Figure 2.6: Construction of M(V) curves [62]: starting from common graphs (1&2), passing through cumulative curves (3&4) and then drawing normalized mass&volume variables (5&6). At the end of the construction process (7) the M(V) curve can be plotted and compared with the bisector, in order to assess the potentiality of first flush.

Mathematically, the M(V) curves can generally fit by power function:

$$F(X) = X^b$$

where

$$X \epsilon \left[0, 1\right]$$

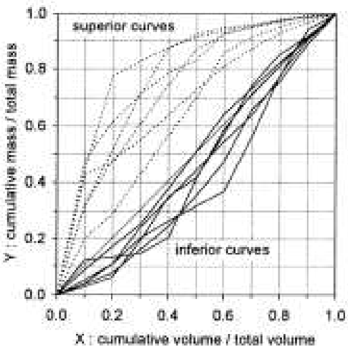


Figure 2.7: Extreme M(V) curves to evaluate the maximum benefit on pollutant total load retention [62]

$$F(0) = 0 \; e \; F(1) = 1$$

and b is the parameter to find to fit the experimental curve. The correlation index is satisfactory when $r^2 \geq 0.9$ [62].

Another definition of first flush occurrence is the $30/80\, first\, flush$: this means that first flush occurs when at least the 80% of the total event load passes in the first 30% of volume.This definition is really useful because:

- it is really easy to use also graphically on the *M(V) curves plan;*
- fitting the curves in the *M(V) curves plan* can be very interesting in order to calculate rapidly the volumes as a first approach to the first flush analysis.

Another precious definition was made by EPA [63] at the beginning of the 90s: based on the concentration of a pollutant before the storm and after it, the V_p (first flush volume) is calculated by the interception of the pollutographs of baseline concentration C_b and storm concentration $C(t)$ (Fig. 2.8).

The last definition may cause two kinds of problems: first of all, if $C(t)$ remains above the baseline concentration, first flush volume may be very big; secondly, if the baseline concentration C_b is very high, the stormwater first flush volume could be very little, so if a CSO is used, a lot of pollution may be discharged without any treatment.

In conclusion, even if the first flush definition could be various, stormwater discharges must be evaluated in respect of receiving systems: first flush is a disputed phenomenon and many researchers are looking for new and innovative methods to assess and quantify its volume [64].

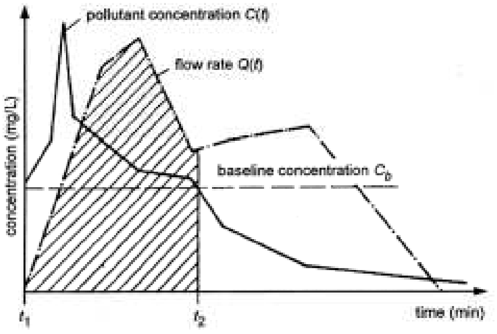


Figure 2.8: V_p is the first flush volume to retain: it has to be calculated from t_1 and t_2 according to EPA definition and depending on baseline concentration C_b [63]

2.3.2 BMPs in urban areas

The key word in sustainable quantity and quality stormwater management seems to be "disconnecting": the main concept on sewers in cities has been changed from several years. Nowadays, the main issue for designers is to disconnect runoff from the sewer system. The sewers should collect only wastewater or the surplus of stormwater runoff. This design strategy is not so easy, because a lot of water industries and sewer managers did not invest time and money on green infrastructure training, BMPs (Best Management Practices), LIDs (Low Impact Developments) or SUDs (Sustainable Urban Developments): this acronyms mean every physical or cultural control to retain quantity and quality of stormwater by planning.

In terms of storwmater facilities, these green infrastructures come in all sizes, shapes and types [65], to achieve various targets ([66], [67]); some authors also ranked them by assessing potential effectiveness [68] or by evaluating economical benefits[69]. Certainly, BMPs can be technically divided in two main categories:

structural BMPs: physical actions or constructions in order to retain flow or pollution into some device which is able to constrain or treat it (e.g. detention basins, first flush tanks);

non-structural BMPs: any cultural or institutional change or watershed management planning which can achieve an awareness of stormwater management problem by citizens (e.g. school programs, modification of the use and disposal practices of household chemicals [70]).

Non-structural BMPs could fill a dedicated paragraph but those prac-

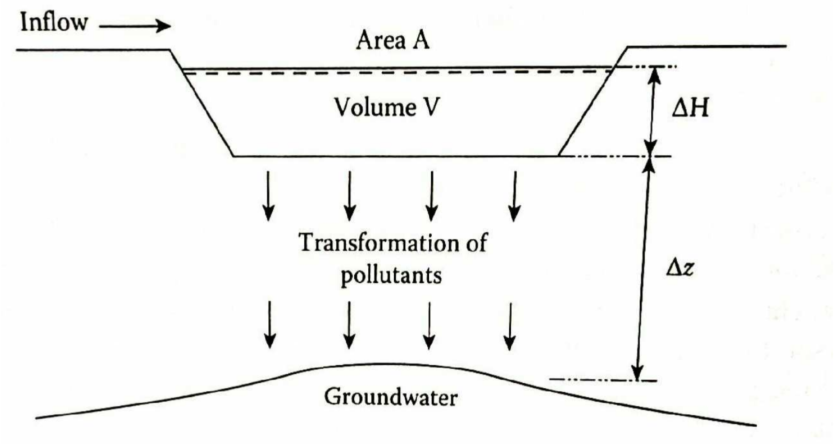


Figure 2.9: Principle of stormwater infiltration from an infiltration pond [42]

tices are not the subject of this thesis; structural BMPs list may be very long (e.g. detention basins, infiltration ponds, wet ponds, constructed wetlands, filters, ditches, swales,...) but we will focus on infiltration basins because they will be the subject of the case study.

Infiltration basins

An infiltration system for stormwater is a BMP where the runoff water is temporarily detained until it is recharged into the ground at the site where it is generated [42]. The concept is to infiltrate stormwater as nature does if there wasn not any urban catchment: water is stored in excavation where runoff percolates into surrounding soils. Filtration, biological transformation and adsorption are the most important processes which can reduce pollutants in stormwater infiltration (Fig. 2.9). However, the main physical process in infiltration ponds is water infiltration, based on the flow theory into porous medias by Darcy:

$$u = -K \cdot \frac{\Delta H + \Delta z}{\Delta z}$$

where:
u = one-dimensional flow velocity (ms^{-1})
K = hydraulic conductivity (ms^{-1})
ΔH = water depth in the pond (m)
Δz = lenght of travel (m)
$\Delta H + \Delta z$ =pressure head or hydraulic head (m)

Runoff water is not pure and sediments can produce pond clogging; filling layer at the bottom of the pond could reduce infiltration rates and the Darcy's law ca be reformulated as follows:

$$u = -K_c \cdot \frac{\Delta H}{\Delta l} = -L_t \Delta H$$

where:
K_c = hydraulic conductivity of the colmation layer (ms^{-1})
Δl = tickness of the colmation layer (m)
$L_t = \frac{K_c}{\Delta l}$ = leakage factor for the colmation layer (s^{-1}). It is the inverse value of hydraulic resistance.

A large number of factors affect infiltration of stormwater (e.g. permeability, clogging, groundwater level distance), and the basins could be designed according to various criteria, based on detention capacity, infiltration in soils and clogging, capacity for accumulation of pollutants or sorption kinetics of selected pollutants. Each criterion focuses on various hypothesis, and a lot of variables play an important role; certainly, pollutant removal could be really difficult to evaluate. Pollutant removal of infiltration ponds found contradicting information in literature: the risk of contamination is not related only to the soluble pollutant fractions, but also can be due to adsorption on the mobile colloidal phase found in the pore water [71]. Potential groundwater contamination can be due to several compounds, depending on their mobility, so infiltration devices must be carefully designed using site specific information [72]. In the case study description (cf. Cap. 3) several features of infiltration ponds in Friuli - Venezia Giulia Region will be reported.

2.4 Toxicity of stormwater

Some concepts about toxicity will be used at the end of this thesis, so an introduction is needed. Environmental toxicology is the study of the impacts of pollutants upon the structure and function of ecological systems [73]. This subject borrows a large number of scientific disciplines (Fig. 2.10).

Stormwater runoff pollutant may be toxic to aquatic organisms, especially for small watersheds in urban street scale, and a lot of works in literature report this big issue ([74], [75], [76]). Several experiments confirmed the importance of hydrocarbons, and fractionation studies indicated that most of the observed toxicity was due to the fraction containing polycyclic aromatic hydrocarbons [74]. This assumption means that magnitude evaluation of urban runoff

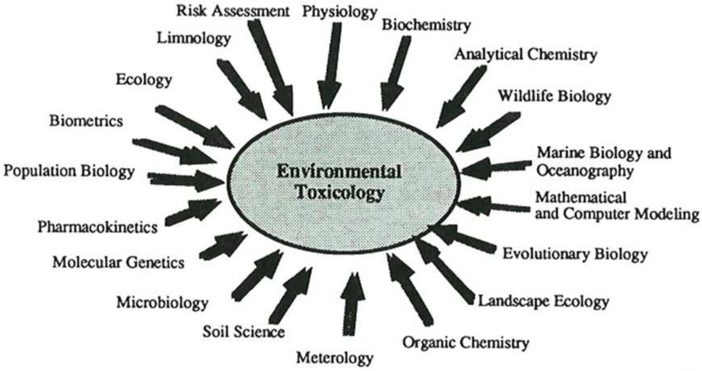


Figure 2.10: The components of environmental toxicology: multidisciplinary approach as the key to assess toxicological risks [73]

toxicity is important for an effective runoff quality management : in fact, toxicity in the first flush may be as high as in the final phase of stormwater discharges [77]. For this reason, toxicity of stormwater have to be analyzed, even if it is not easy: many authors discussed on the difficulties in assessing toxicity of brief pollutant exposures ([78], [79], [80]). Toxicity indicators may be very different and in some cases *toxic units approach* has been widely applied for the assessment of risks originating from chemicals measured in mixture toxicity tests or in environmental samples [81].

Stormwater pollutants drag toxicity from streets and human activities into receiving systems, mainly by sediment adsorption of heavy metals and PAHs [82]; for this reason many papers investigated on sediment toxicity. The variation in stormwater quality over time and the existence of the first flush (Fig. 2.4) means that the sampling results can be influenced by timing of grab samples [83].

Referring to Par. 2.3.2 our interest involves sediment contamination assessment and basic ecotoxicological characterization, according to literature data and QSAR analysis. Retention-detention or infiltration basins are essential for managing urban stormwater effluents, but they can present a few ecotoxicological issues [84]; a lot of papers investigated on acute effects due to short-term high concentration during rain events, because a lot of basins are also areas for recreational purposes ([85], [86]). Toxicity can be very various in the pond in spatial scale, depending on the toxicity indicator used (Fig. 2.11 and 2.12)

Unfortunately, in this thesis a careful toxicity evaluation was not possible because advanced tools were not available. Certainly, QSAR analysis could be a good opportunity to predict potential toxicity: *Quantitative structure-activity rela-*

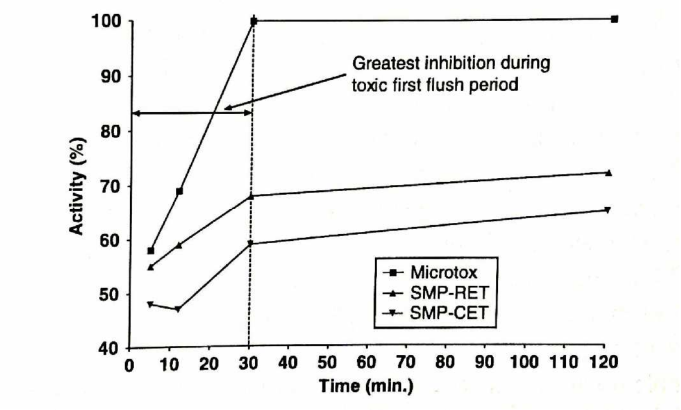


Figure 2.11: Toxic first flush effect exhibited by a highway runoff event and documented by three toxicity tests [83]

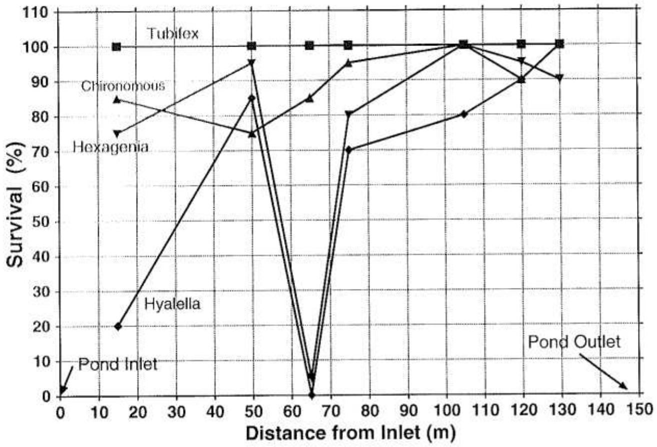


Figure 2.12: Spatial variation in stormwater pond sediment toxicity percent survival of pollution-tolerant species (*Chironomus* and *Tubifex*) and pollution-intolerant species (*Hexagenia* and *Hyalella*) [76]

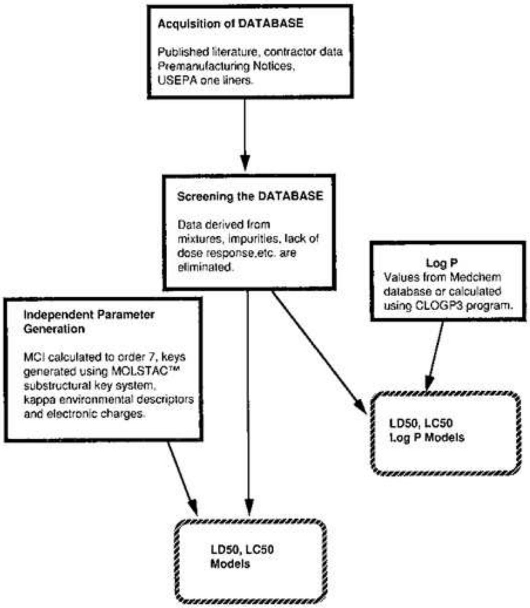


Figure 2.13: The developmental process for the construction of a quantitative structure activity relationship model (QSAR) [73]

tionships (QSARs) are empirical models which predict relative toxicity of a family of chemicals from fundamental and surrogate molecular qualities [87]. QSARs are developed mostly for organic compounds, PPCPs but less developed for metal ions based on metal-ligand binding propensities [88], and their developmental process is not very easy to build up (Fig. 2.13). Some discussion will be reported at the final part of the thesis (cf. 4).

2.5 Impacts

All the information collected in this chapter need to be summarized in order understand how a research study can assess possible risks and evaluate impacts of stormwater discharges. In Fig. 2.14 various levels of toxicity in time and spatial case are represented in order to show how complex is the evaluation of stormwater impacts. They do not depend on chemical pollution: also hydraulic effects and biological changes can degrade water quality and improve bad impacts of stormwater into receiving systems too. This issue is generally related to structural BMPs and CSOs, because when activated they can badly force receiving system quality equilibrium: risk assessment and ecotoxicological approach (i.e. multidisciplinary approach) are the keys to solve stormwater impact according to streams and soils. The solution comes from territorial features knowledge and from characterization of land uses and stormwater quality; then, a rigorous environmental risk assessment (ERA) process could be developed (Fig. 2.15).

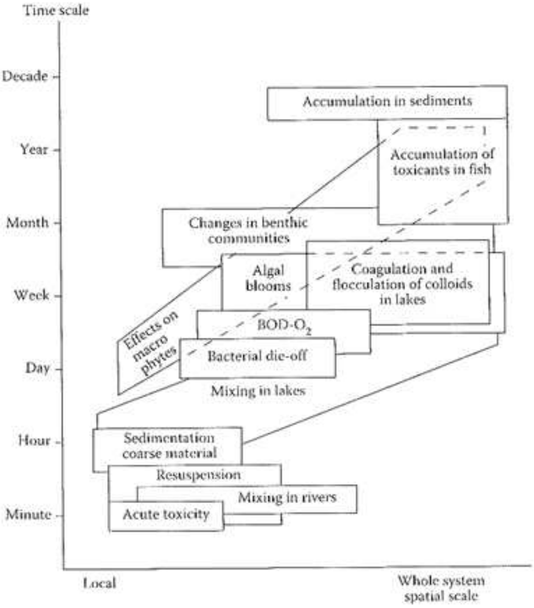


Figure 2.14: Time and spatial scales for receiving water effects (Modified from [89])

Anyway, the evaluation of stormwater impacts do not present a clear procedure: environmental legislation is primarily based on common toxicity analysis and chemical composition values, but there are a lot of alternative methods and studies in scientific literature ([90],[91]). There is a need to develop *in situ* indicator organism in order to define a short-term ecotoxicological criteria: this issue is real, because shifting from laboratory to field scale is not essentially concerned with a real environmental quality assessment. In this wide scientific panorama, biomonitoring approaches seem to gain remarkable results: they can integrate biological response with chemical and physical features of water, based on monitoring some kind of microorganisms in density, richness and community composition [92]. Ecotoxicological criteria for episodic discharges should be evaluate with macroinvertebrate species, which are more sensitive for sediment degradation after storm mobilization: greater flows re-suspend contaminated sed-

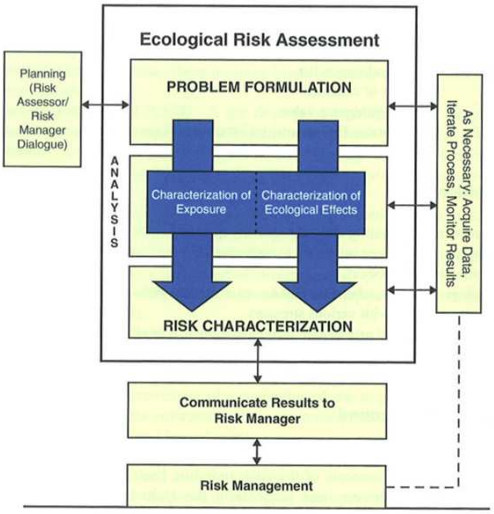


Figure 2.15: General and rigorous scientific process to quantify the magnitude of risk attributable to a single or multiple stressors [93]

iments which can be very toxic for environmental species. Finally, sewer and WWTP designers have to manage their projects regarding only effluent chemical composition: there is the need to evaluate wastewater and stormwater quality discharges with more integrated criteria according to specific receiving system features. This issue will be considered in the case study proposed in this thesis, by characterizing and assessing stormwater infiltration quality.

Chapter 3

Material and methods

First of all, a stormwater management framework must be preceded by a plan of activities and methods. Stormwater should be measured as flow, but stormwater quality is also a really big task: in this preliminary study, only a few pollutants were analyzed, in order to understand first foul flush and its implications. Analysis on stormwater first flush were made at FriuLab srl Laboratory (Udine) and at IRCSS Mario Negri (Milan). Some analysis were made at University of Udine, including sample preparing.

In this chapter, case study, material and methods will be described, in order to introduce some experimental results which will be discussed in the last part of the thesis.

3.1 Site description

In Cap. 1 and Cap. 2 a literature review was reported, in order to understand the importance of stormwater management. All theories and knowledge on stormwater in quantity and quality should be applied to solve territorial problems and pollution in the environment.

Galleriano di Lestizza is a little italian urban catchment in the Friuli - Venezia Giulia Region (Fig. 3.1). In Italy, and also in Europe, there are a lot of little urban catchments or villages, spreading everywhere: this is a feudal heritage. In the last 50 years, urbanization grew up with infrastructures and industries, so the land use of little catchments and cities became more intensive and impervious surfaces became widespread. Harvesting of water became less important then before, so sewers were needed also in little villages: technical knowledge in those years approved combined sewers as a solution for stormwater and wastewater.

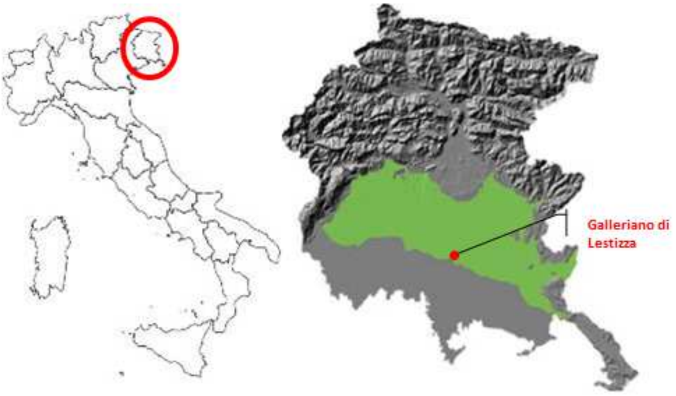


Figure 3.1: Case study: urban catchment of Galleriano di Lestizza (Province of Udine)

Vehicular traffic was not so busy and asphalts or impervious surface were not dirty or covered by huge pollution. For this reason CSOs for wet weather periods were not seen as a big deal for the environment. Stormwater was a problem only for quantity reasons.

Galleriano di Lestizza is located into the *High Plain* of the Friulian Region (the green portion in Fig. 3.1 and 3.2): it is a little village with 615 inhabitants and there are no industries or warning activities. The catchment can be classified as *rural* because it is not covered everywhere: some large areas are pervious, with high permeability, so runoff is not relevant. The runoff becomes important on the streets and from the roofs: asphalt and houses near the street discharge stormwater directly into the sewer. The high permeability of the soil permits to discharge stormwater from isolated roofs into infiltration ditches.

Discharging stormwater in the High Plain means relying on infiltration: in the 60s and 70s this practice was really common because there were no other way to discharge stormwater. The High Plain is an alluvial plain, rich of gravel and sand, with less clay then in the Low Plain, and for this reason the rivers infiltrate into the ground: there is a lack of surface waters, in spite of abundant annual rainfalls (e.g. 1800 mm/y in this area, [94]), for this reason, a lot of rural areas in the middle-region are named *Magredi* (i.e. "poor land") or *Grave* (i.e. "gravel zone"), where infiltration is higher than usual values. Each rural village had its own way to discharge stormwater, mainly with infiltration ponds or infiltration trenches, because no surface waters were available. This infiltration practices were constructed according to low slopes and, in many cases, according to an-

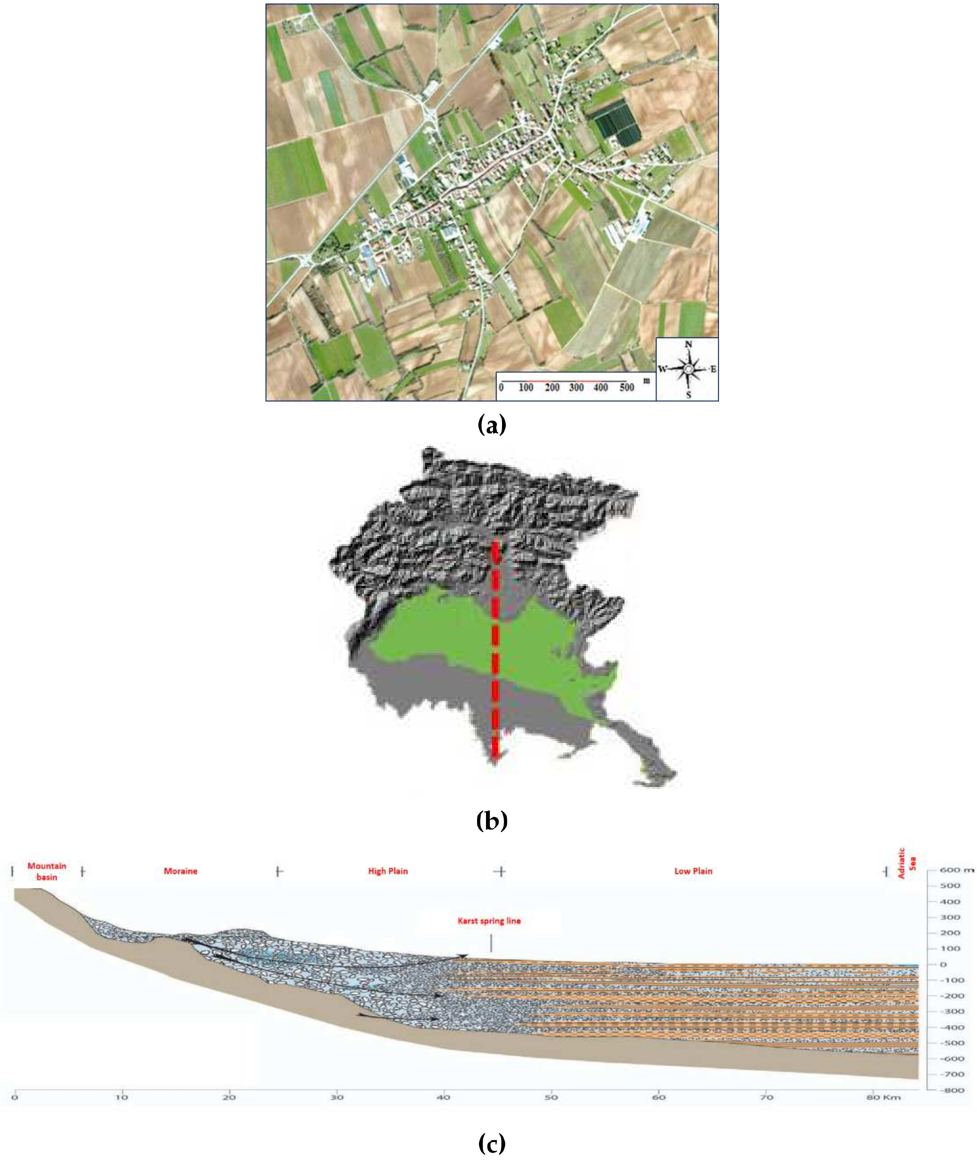


Figure 3.2:
(a) aerial photo from *Google Maps®*
(b) the High Plain of the Friulian Region [94], between the hills and the *karst spring limit*
(c) a geological section with groundwater mobility [95]

Figure 3.3: Infiltration pond position in respect of the village: the main slope of the plain is indicated by the arrows (aerial photo from *Google Maps®*)

cient infiltration ponds of old rivers: in the middle-region there were almost five *Lavie* [96], which were temporary rivers which flooded into the villages and infiltrated into natural ponds or depressions. This areas were used in many cases for stormwater infiltration after waterproofing of rural catchments. Nowadays, those old rivers do not exist anymore, but depressions and infiltration areas remained and are usually used. The description showed the importance of infiltration in the High Plain, so this practice should be adequately studied, in order to protect groundwater from polluted water and from dangerous compounds. In the case of Galleriano di Lestizza, the infiltration pond is located at S-W in respect of the village, and it is an ancient infiltration of a *Lavia River* (i.e. the *Lavia of Galleriano* [96]). Surface waters are really far from the village: Galleriano di Lestizza is bounded from the Corno River (on the West side, 9 km away) and the Cormôr River (on the East side, 5 km away), so the infiltration is the unique way to discharge stormwater according to the minimum slope (Fig. 3.3). In the following paragraphs a lot of information will be reported, in order to understand how various techniques were applied on the case study, according to literature advises.

3.2 Measuring quantity and quality of stormwater

Good quality hydrologic data are required to develop and calibrate simulation models, which are often used to plan, design and upgrade urban stormwater drainage systems [97]. Measuring equipment should fit to data requirements because each kind of academic survey needs its own measuring plan and output; planning a measuring program permits to save a lot of money and to get the needed data without unnecessary sophistication. Furthermore, the cost of urban stormwater investigation constitutes the largest part of the total costs coupled with laboratory analysis. Relying on the economic availability, the research program decided to use a tipping-bucket rain gauge, an area-velocity flow sensor and an automatic sampler: these instruments allowed to get all the information needed for this preliminary study on stormwater quantity and quality in small urban catchments (cf. Cap. 4).

Literature review permits to plan the progress of the thesis work. Measuring quantity and quality of stormwater runoff needs adequate instruments, and continuity of registration. Scheduling the progress of work means also to correctly choose the catchment: in this chapter, all these issues will be reported.

3.2.1 Rain gauge

Tipping bucket rain gauges are widely used in hydrological monitoring, even though it is known they underestimate high intensity rainfall because a great water amount is lost during the tipping movement of the bucket [98]. Rain volume and rain intensity are two important inputs in the system and they have to be measured according to the most available precision. For this reason, tipping bucket pluviometers represent the better cost-effective solution for rainfall monitoring. Data precision for rainfall intensity and runoff rate using tipping bucket technology depends on the bucket volume, the catchment area and the sampling interval [99]; the rainfall affects stormwater characteristics for modeling [100].

Figure 3.4: Rain gauges map in the Friuli - Venezia Giulia Region: each drop represents a rain monitoring station linked to the Civil Protection Agency head office [94] (aerial photo from *Google Maps*®)

In the Friuli - Venezia Giulia Region, the Civil Protection Agency installed a really huge hydrological monitoring network (pluviometers, hydrometers, air thermometers, hygrometers, barometers, wind direction and speed sensors, snow gauges, radiometers and accelerometric boys). Anyway, the rain monitoring network spreads almost homogeneously all around the Region (Fig. 3.4) but the use of data depends obviously on the application needed.

Rainfall precision (volume and intensity) is strictly important in the case study, because the catchment is very little and variability of rainfall intensity could massively influence the rainfall-runoff modeling. According to the monitoring map of the Civil Protection Agency, we notice the long distance between existing pluviometers from the catchment (Fig. 3.5).

For this reason, a on-site rain gauge was needed, so we reported the technical features of the model we used. The model M1-PLUV rain gauge [101] with tipping-cup is a standard precision tool: its cylinder and collector-funnel are made of painted light-alloy and its base is painted thick-aluminum. Rainfall is measured using a stainless steel double-cup balance: collected rain fills one of the two cups, which tips when filled from the funnel. Then, a 10 mL accumulation cup tips the scale placing the opposite collection cup under its funnel and so on. A built-in magnet within the tipping mechanism produces an impulse corresponding to 0.2 mm of precipitation. This impulse can be directly recorded or converted into a 4 to 20 mA signal. Levelling screws under the scale provide

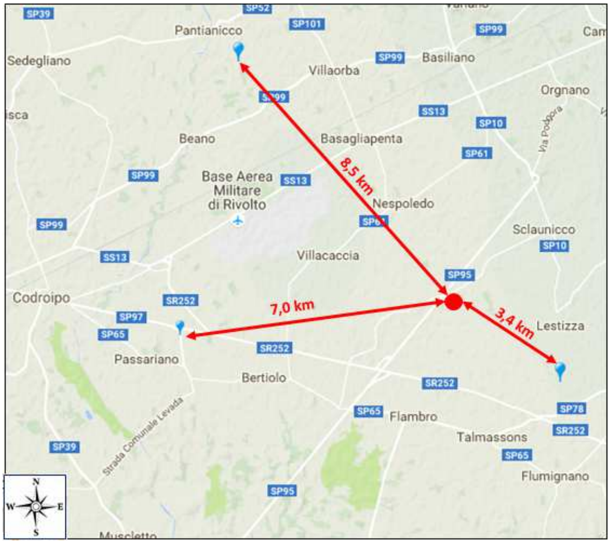


Figure 3.5: Rain gauges map near Galleriano: the distance between the civil network and the catchment is long in respect of the precision needed [94] (aerial photo from *Google Maps®*)

periodical access for calibration. It comes with a ball-pivot and jack screws on its base for a correct set-up. In Tab. 3.1 some features of the device are reported.

Calibration procedures were made at the laboratory at the University of Udine, to set the rain gauge and to permit on-site installation. The rain gauge has to be installed in an open area, without any tree or roof above it: the rain should be intercepted by the funnel also when it is windy, so no obstacles are allowed in order to record valid data. There is a very comfortable site in the middle of the catchment (Fig. 3.6), so the rain gauge needs to be installed there.

3.2.2 Flow meter

Runoff on urban surfaces enters into the sewer network, so the rain is transformed in flow. Accurate and representative precipitation data are due to rain gauge standards, but stormwater flow measures are really crucial for modeling quantity and quality in the sewers. Stormwater flow measures are really difficult to obtain because of the spatial and temporal distribution of precipitation and flows during a storm; furthermore, stormwater flow rates can range over several order of magnitude in a short period [102].

In the catchment of Galleriano di Lestizza, the use of a very flexible instrument is strictly important: variability could be really high, from the baseflow

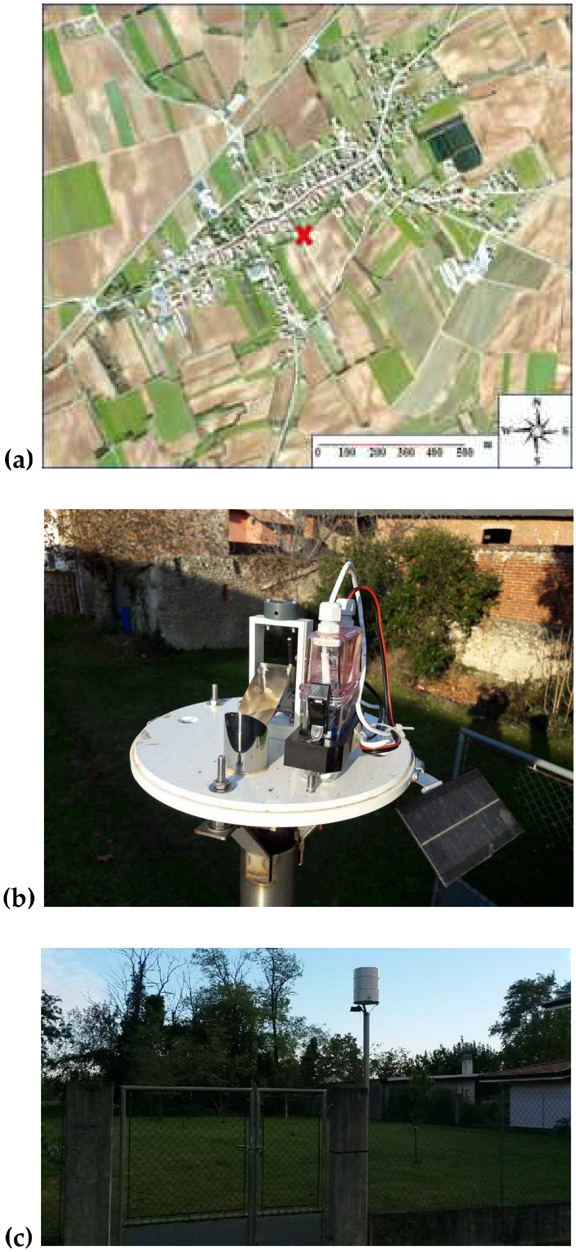


Figure 3.6:
(a) pluviometer position in the catchment of Galleriano (aerial photo from *Google Maps*®)
(b) interal configuration of the pluviometer
(c) model M1-500 PLUV by Tecnopenta installed on site

M1-PLUV 500 - Specifications	
Type of pluviometer	Tipping bucket
Catchment Area	$500\,cm^2$
Material	Alluminium painted RAL 9010
Collection cup	AISI 304 stainless steel
Total height	$340\,mm$
Outside diameter	$256\,mm$
Aperture Area	$500\,cm^2 \pm 0.25\%$
Weight	$3.7\,kg$
Resolution	$0.2\,mm$
Precision	$\pm 2\%\, at\, 1\, L/h$
Measurement range	$0.2\,mm/h\, to\, 200\,mm/h$

Table 3.1: Rain gauge M1-500 PLUV Specifications [101]

SIGMA AV 950	
Type of flow meter	Ultrasonic with data logging
Data Logging	$128\,kB\,of\,RAM$
Submerged sensor accuracy	$\pm 0.1\%\,full\,scale$
Sensor range	$0.01\,to\,1.75\,m$
Operating temperature	$0\,to\,71°C$
Communication ports	$RS232$
Sampler connection	$4-20mA\,analog\,outputs$
Weight	$5\,kg$

Table 3.2: Area Velocity Sigma 950 AV specifications [104]

of a few liters per second up to several hundreds liters per second. For this reason, the area-velocity flow meters should be the best choice in this application case.

The Tab. 3.2 collects all the features of the Sigma Hach 950 AV [103].

3.2.3 Stormwater sampling

Accurate quantification of stormwater pollutant levels is essential for estimating overall contaminant discharge to receiving waters; a huge number of methods have been evaluated in literature, in order to assess better quality to stormwater sampling procedure [105]. Academic approach means to choose the most suitable method, to get the expected quality of data: in this case study we chose to get single samples and to analyze them individually, just to get the information of quality according to stormwater flowing in sewers. Characterization of stormwater quality needs to start with single samples: getting the order of magnitude of single pollutants and getting the variability of the first flush phenomenon is the

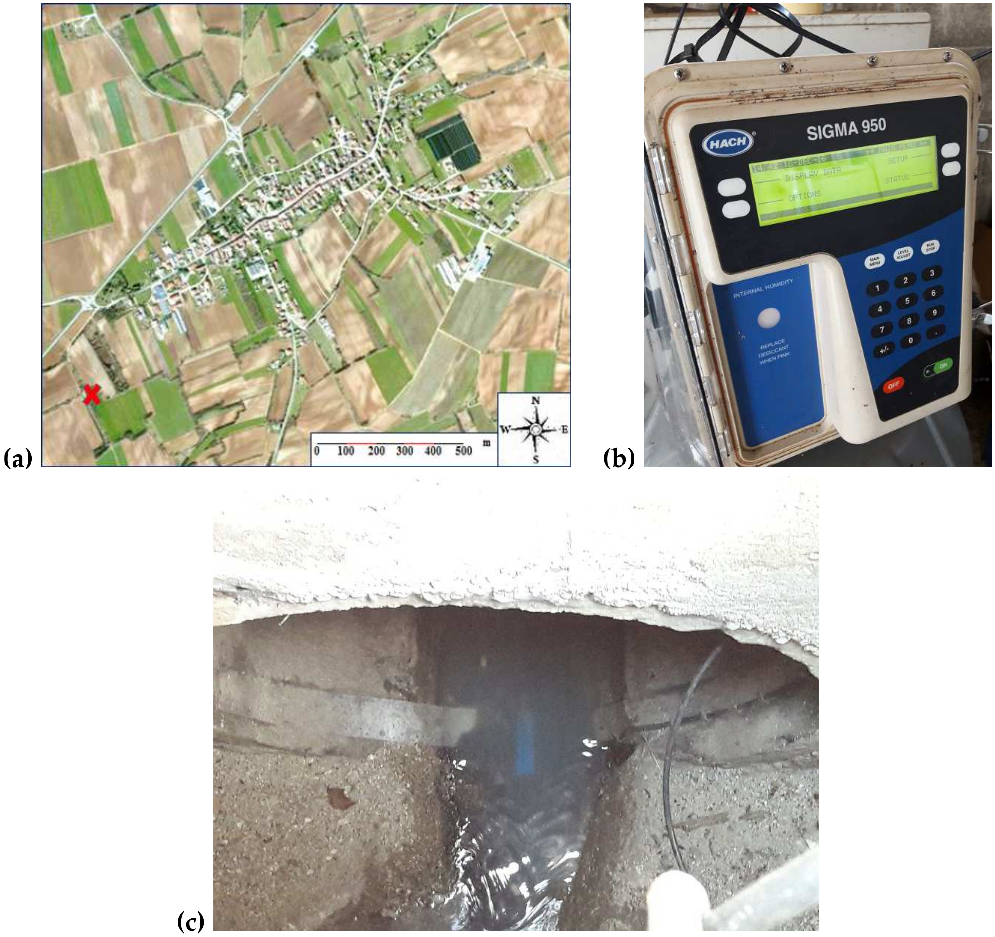


Figure 3.7:
(a) Flow meter installation in the catchment (aerial photo from *Google Maps*®)
(b) model sigma 950AV by HachFlow
(c) the Area-velocity sensor installed at the end-of-pipe

SIGMA SD900 - Automatic Sampler	
Type of sampler	Automatic (24 bottles)
Temperature range	$0 - 60$°C
Strainers	316 stainless steel
Sample intake tubing	$9.5\,mm$ $(\frac{3}{8}in.)$
Power requirements	12 VDC supplied or battery
Pump	Peristaltic high speed, spring mounted rollers
Sample accuracy	$\pm 10\%$ $of\,200\,mL\,sample$
Weight	$15\,kg$
Type of bottles	$1L$ polyethylene bottles

Table 3.3: Automatic Sampler SD900 specifications [106]

first step, in order to understand the catchment behaviour. After this phase of work, it will be possible to install other types of instrument to evaluate pollution washoff (e.g. turbidimeters, passive samplers). Furthermore, this is the first work on stormwater pollution runoff for little catchments in the Friuli - Venezia Giulia Region, so collecting and analyzing single stormwater samples was needed.

The SD900 Automatic Sampler took the samples for the present work of thesis: it is an automatic sampler of the Sigma Sampler Series (cf. Tab. 3.3 for technical specifications).

According to technical difficulties when installing the stormwater sampler inside the manhole, the instrument was left outside: during each rainfall event an operator had to go up to the treatment plant and prepare the SD900 to get the samples, by introducing the tube into the manhole (Fig. 3.8a)

3.3 Laboratory analysis

Laboratory analysis are a fundamental part of the thesis, so some of the analysis made in order to confirm conceptual issues are listed below. Common standard methods were followed for waters ([107] & [108]) and, for advanced sediment analysis, we refer to Par. 3.3.5 (i.e. Mario Negri Institute proper methodology). In this section, an overview of the laboratory procedures is reported (for complete procedures, please follow the references [107] and [108]).

3.3.1 TSS

Total Suspended solids represent a fundamental parameter of stormwater quality ([109], [110], [111]) . TSS is the dry-weight of solids trapped by a filter with pore

Figure 3.8: **(a)** The end-of-pipe manhole and the automatic sampler Sigma SD900 ready to take samples during storm events (the location is the same of the flow meter) and **(b)** bottles and tubes ready to divide samples for the laboratory analysis

diameter of $0.45\mu m$. The principle of the $2540D$ Method [107] is to calculate TSS from the difference between total dissolved solids and total solids.

Procedure Prepare the filters and choose sample volume to yield between 2.5 and 200 mg dried residue; the procedure provides information if any problem occurs with the preparation of the sample. Anyway, the procedure advises to analyze at least the 10% in duplicate. Duplicate determinations should agree within 5% of their average weight. Calculation is quite simple, according to the following formula:

$$mg\, total\, suspended\, solids\,/\,L = \frac{(A-B)\cdot 1000}{sample\, volume, mL}$$

where
A = weight of the filter + dried residue, mg
B = weight of the filter, mg

3.3.2 COD

Chemical oxygen demand (COD) is defined as the amount of a specified oxidant that reacts with the sample under controlled conditions [107]. The quantity of oxidant consumed is expressed as an oxygen equivalence. COD is often used as a measurement of pollutants in wastewater and natural waters; COD is related essentially to other analytical values such as biochemical oxygen demand (BOD), total organic carbon (TOC), and total oxygen demand (TOD). The most common interferent is the chloride ion.

Procedure Samples were collected in test tubes: generally, there was a delay before analysis, so samples were acidified with concentrated H_2SO_4 in order to keep $pH < 2$. Blend all samples containing suspended solids before analysis. Analysis is based on oxidation by a boiling mixture of chromic and sulfuric acids. A sample is refluxed in strongly acid solution with a know excess of potassium dichromate ($K_2Cr_2O_7$); after digestion, the remaining unreduced potassium dichromate is tritrated with ferrous ammonium sulfate, to determine the amount of $K_2Cr_2O_7$ consumed and the oxidizable matter is calculated in terms of oxygen equivalent.

Apparatus consists in digestion vessels, block heather, microburet and ampule sealer (for further details please read reference [107] 5220 C - Titrimetric Method and the 5130 of [108]). Reagents are essentialy a standard potassium dichromate digestion solution ($0.25N$), sulfuric acid reagent (Ag_2SO_4+H_2SO_4), ferroin indicator solution, standard ferrous ammonium sulfate titrant (FAS). After several steps, when the indicator turns from blue-green to reddish brown, the formula is:

$$COD\,(mg_{O_2}/L) = \frac{V_t \cdot N_t \cdot 8000}{V}$$

where
V_t =volume of FAS solution
N_t =normality of FAS solution
V =volume of the sample

3.3.3 Heavy metals

For heavy metals analysis in the samples, the *UNI EN ISO 17294-2:2005* [112] was implemented. This standard method explain the determination of a long list of elements in digests of water, sludges and sediments. The working range typically covers concentrations between several pg/L to mg/L.

This method uses the inductively coupled plasma mass spectrometry (ICP-MS). This type of mass spectrometry detect metals and several non-metals by ionizing the sample with inductively coupled plasma. The ions are then separated and quantified by a mass spectrometer. Comparing to other techinques, ICP-MS has greater speed, precision and is more sensitive: for this reason it is really common in water analysis. The apparatus for these type of analysis is made by an ICP source and a spectrometer.

3.3.4 Hydrocarbons

For total hydrocarbons $5520C$ of [107] (or the equivalent $5160B2$ of [108]) was followed. The principle of this method is related to the use of trichlorotrifluoroethane as extraction solvent, which allows absorbance of the carbon-hydrogen bond in the infrared. The elimination of the evaporation step permits infrared detection of many relatively volatile hydrocarbons. Samples have to be collected into clean glass bottles.

Infrared measures are due to calibration curves, so the total hydrocarbon quantity is determined by the following:

$$TH = \frac{A \cdot f}{V}$$

where
TH =total hydrocarbons (mg/L)
A =quantity of TH in mg from the calibration curve

chromatography column	Atlantis T3, 150x2.1mm, $3\mu m$ (Waters) and Xterra MS C_{18}100x2 mm, $3.5\mu m$ (Waters)
eluent A	formic acid 0.1% (positive ion modality) and ammonium acetate $5mM$ (negative ion modality)
eluent B	acetronile
flow	$200\mu L/min$
gradient	from 1% to 99% of B in 24 minutes
injection volume	$4\mu L$
ionization source	ESI in positive or negative ion mode
acquisition mode	complete scan (MS)

Table 3.4: Apparatus and instrument conditions for pesticides and atrazine compounds advanced analysis

f = dilution factor
V =volume of the sample (L)

3.3.5 Advanced analysis on sediments

Advanced sediment analysis were made by the Mario Negri Institute (Milan - Italy), at the Department of Environment and Health. These analysis were mandatory in order to assess contaminants in the infiltration pond: pesticides, atrazine compounds, heavy metals and hydrocarbons.

Pesticides and related compounds Sediment sample must be sifted in order to remove rocks; then heat and weight the dry part. Add $1\,ng$ of atrazine-D5 per g of dry weight in each sample. Then, $10g$ of sediment were extracted with acetone/hexane 2:1 in Soxhlet for $8h$. The extraction product was concentrated with rotavapor until $4mL$; then, $0.5mL$ of the extraction product was dried and renewed in $50\mu L$ of methanol with ultrasound agitator for $10min$. After spin-dry the solution was finally analyzed with HPLC-HRMS.

Extraction products were analyzed with high resolution mass spectrometer LTQ Orbitrap XL Plus (Thermo Fisher) coupled with liquid chromatography Agilent 1200 (cf. Tab. 3.4). The orbitrap is an ion trap mass analyzer: an outer barrel-like electrode and a coaxial spindle-like electrode trap ions in orbital motion around the spindle. The image from trapped ions is converted to a mass spectrum by the Fourier transform of the frequency signal. This is a really high resolution instrument. Two different methods were applied: A and B. *Method A* is the positive-ion modality with isotropic dilution with the standard atrazine-D5 as internal standard and fixed solution of the substances collected in Tab. 3.5. Values below $0.01ng/g$ are not detected by the method. *Method B* permits to search compounds basing on exact mass, isotropic profile or fragmentation spectrum. In case of determined peak, a peak-standard ratio was calculated referring to singular compounds. This method is a raw estimation of the mass, but it is a valid method for thesis proposal.

Hydrocarbons Hydrocarbons were detected in sediments only to have a qualitative screening of major compounds in samples. Gas chromatography-mass spectrum (GC-MS) is an analytical method that permits to identify different substances from a test sample. GC-MS have been widely applied in order to search trace of elements and permits to identify unknown samples.

Heavy metals Heavy metals detection was made by ICP-AES and ICP-MS with *3050B method by EPA*. Alternative methods are present in scientific literature. Samples need to be digested according to the procedure: details can be found directly in [113]. This method is not a total digestion technique for most samples, but it is a really strong acid digestion that will dissolve almost all elements that could become environmentally available. For digestion samples, a representative 1 or 2 gram sample is digested with repeated additions of nitric acid HNO_3 and hydrogen peroxide H_2O_2.

3.4 Catchment modeling

There are a lot of modeling software, some of them are open-source, some of them are commercial. In this thesis we used the Environmental Protection Agency Stormwater Management Model 5.1.011 (i.e. EPA-SWMM 5.1.011) [114] for hydraulic and pollutant transport modeling. The choice of the software is fundamental in order to achieve academic and research targets. Treatment and infiltration of stormwater were not modeled because several data and measure campaigns are missing at present time: we are looking forward to continue this study, in order to achieve also that target.

3.4.1 SWMM

Stormwater Management Model is a dynamic rainfall-runoff simulation model used for single event or long-term (continuous) simulation of runoff quantity and quality from primarily urban areas [115]. SWMM operates through a system of pipes, channels, storage devices, pumps and regulators with a tool for water

Method A
desetil-desisopropil-atrazina (DACT)
desisopropil-atrazina (DIA)
desetil-atrazina (DEA)
desetil-terbutilazina (DET)
atrazina (ATZ)
simazina (SMZ)
terbutilazina (TBZ)

Method B		
imidacloprid	Flufenacet	Piperonyl butoxyde
2-Hydroxyatrazine	Linuron	Thiophanate methyl (Frumidor)
2-Hydroxyterbutylazine	Metolachlor	Cyanuric acid
Carbendazim	Metolachlor ESA	Oxadiazon (Ronstan)
DEET (N,N-diethyl-m-toluamide)	Metribuzin	Triallate
Diazinon	Nicosulfuron	Triclosan

Table 3.5: Quantitative analysis methods for sediments for different compounds (Mario Negri Institute)

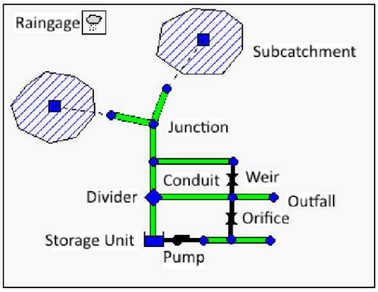


Figure 3.9: SWMM's conceptual model of a stormwater drainage system [115]

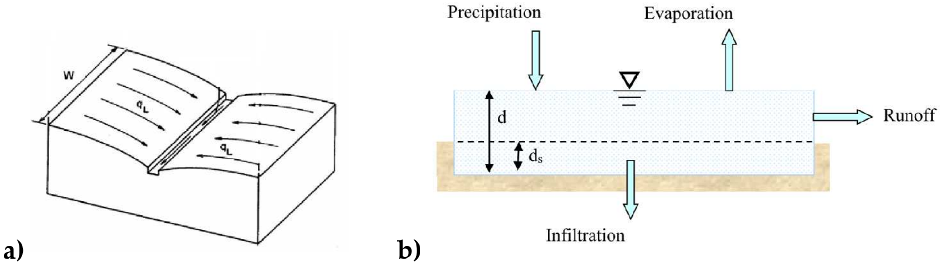


Figure 3.10: **(a)** Idealized representation of a subcatchment and **(b)** nonlinear reservoir model of a subcatchment in SWMM [115]

quality too (Fig. 3.9). SWMM was used also for similar works and papers in scientific literature (e.g. [116], [117], [118]), because it is user-friendly, it is a free software and it is quite simple to use.

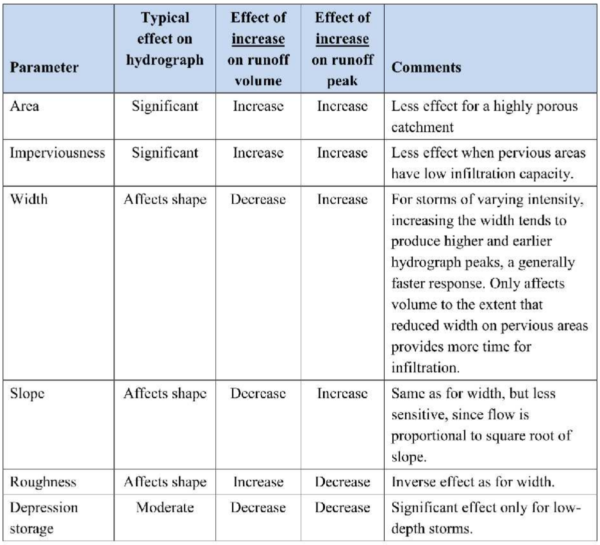
The simulation model is a distributed discrete model, and it computes new values over a sequence of time steps: as its state variables are updated, other output variables of interest are computed and reported.

SWMM model computes a lot of hydrologic and hydraulic issues but we will focus on runoff modeling and stormwater quality, so we will report just this information to introduce these features. SWMM uses a nonlinear reservoir model to estimate surface runoff from rainfall over a subcatchment, which is a rectangular surface with uniform slope S and width W that drains to a single outlet channel (Fig. 3.10).

According to Fig. 3.10, where the net excess ponds atop the subcatchment surface to a depth d, the expression for the runoff volumetric flow rate Q is:

$$Q = \frac{1}{n} W S^{\frac{1}{2}} (d - d_s)^{\frac{5}{3}}$$

Runoff volume can be significantly varied by a lot of parameters: sen-



Parameter	Typical effect on hydrograph	Effect of increase on runoff volume	Effect of increase on runoff peak	Comments
Area	Significant	Increase	Increase	Less effect for a highly porous catchment
Imperviousness	Significant	Increase	Increase	Less effect when pervious areas have low infiltration capacity.
Width	Affects shape	Decrease	Increase	For storms of varying intensity, increasing the width tends to produce higher and earlier hydrograph peaks, a generally faster response. Only affects volume to the extent that reduced width on pervious areas provides more time for infiltration.
Slope	Affects shape	Decrease	Increase	Same as for width, but less sensitive, since flow is proportional to square root of slope.
Roughness	Affects shape	Increase	Decrease	Inverse effect as for width.
Depression storage	Moderate	Decrease	Decrease	Significant effect only for low-depth storms.

Figure 3.11: Sensitivity of runoff volume and peak flow to surface runoff parameters [115]

sitivity of runoff can be very high (Fig. 3.11), so the calibration may be affected from a large number of factors.

Water Quality SWMM can consider several types of pollutants sources, as well as reported in Cap. 2, in order to assess wastewater and stormwater quality (e.g. precipitation, surface runoff, dry weather flow, groundwater flow, inflow & infiltration, external inflows). The model represents water quality through a *Pollutant* object with *co-pollutants* (e.g. really useful for representing adsorbed heavy metals, or nutrients). Another important object is the *Land Use*, which contains the features of development activities or land surfaces assigned to subcatchments [119].

Governing equations of a stormwater quality model are buildup and washoff functions: they are typically nonlinear [120]. The buildup function is not proper for each pollutant, but each land use can provide different data sets of functions according to its features; several types of function are generally used, but in this thesis we will use the *exponential buildup* because it is the most common function for little and rural catchments in literature. This function follows an exponential growth curve:

$$b = B_{max}(1 - e^{-K_B t})$$

where

b =Buildup (mass per area)
t =buildup time interval, days
B_{max} =maximum buildup possible
K_B =buildup rate constant

Parameter estimation is not a single choice: there are no universal parameters and variability is really high, influencing washoff modeling too ([121], [122]).

Washoff is the process of erosion or dissolving of constituents from a subcatchment surface during a runoff period [119]. Several works underlined the difficulty of washoff modeling and calibrating (e.g. [123], [124]). The most oft-cited result for pollutant washoff behaviour is the exponential washoff, which is governed by the following equation in SWMM:

$$w = K_W q^{N_W} m_B$$

where
w =washoff rate (mass per hour)
K_W =washoff coefficient
q =runoff rate over the subcatchment
N_W =washoff exponent
m_B =buildup rate at the time

Buildup and washoff equations will be used in order to calibrate the drainage system in quantity and quality.

3.4.2 Catchment features

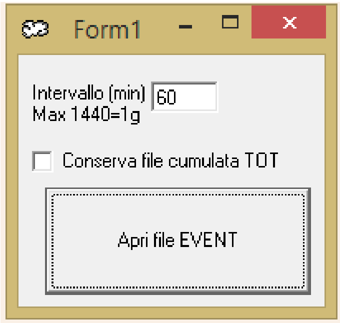
Installed instruments completely monitored the catchment for 6 months (from January to June 2016): due to technical issues, it was not possible to continue with sampling and flow monitoring after the summer. Furthermore, summer season in 2016 was one of the hottest and driest of the last 136 years [125], so a large number of rain events miss at the measuring campaign. Despite this inconvenience, measured data provide the opportunity to get a lot of information.

Runoff modeling is strictly related to a detailed survey of the sewers, made by camera inspections and direct survey (Fig. 3.12)

3.4.3 Rainfall events and sample history

Rainfall events were collected via SD card by the rain gauge TecnoPenta M1-500 PLUV in a *.txt* file. The SD card collected each step of the tipping-cup, so to

Figure 3.12: Some pictures about the survey of the sewers, a fundamental step in order to model the sewer and hydraulics of runoff and the end-of-pipe section



Intervallo (min) Max 1440=1g: 60

☐ Conserva file cumulata TOT

Figure 3.13: The application for rainfall data conversion *Pluviometro*

get the rain intensity, a conversion is needed. This conversion was made by a simple application called *Pluviometro* (by Tecnopenta, Fig. 3.13): the catchment is quite little so rain should be measured each minute in order to detail flow measurements, due to rapid rain variations. Rainfall events used for calibration in the model are essentially two; 05/19/2016 and 05/29/2016. During these rainfall events, the sampler got several samples: after laboratory analysis, we will be able to graph and to model flow and stormwater quality. Rainfall were measured in this period because all the instruments were available.

3.4.4 Runoff modeling

Runoff modeling could be really difficult in little catchments because of several reasons. First of all, combined sewer overflow drags a huge quantity of solids during dry weather flow, so the area-velocity sensor can be blocked by solids due to low velocities: this issue can be very dangerous for the next stormwater flow data. If the blockage is permanent, stormwater flow could be not measured, so the registration will be lost. This inconvenience happened sometimes during the monitoring campaign. Secondly, in little rural basins a lot of solid material can reach the drains and ti could be dragged into the sewers: this solid material (e.g. little rocks, branches) can beat on the sensor or block it.

One of the biggest difficulties when modeling little rural catchments is related to runoff coefficients and subcatchments definition: a lot of roofs and parking lots drain directly into infiltration wells (according to high permeability of soils). There is a quite recent regional regulation on the prohibition of roofs runoff discharge into the sewer is quite recent, so it is really difficult to understand the real discharging configuration in the village. For this reason, literature coefficients have to be used and the subcatchments in SWMM can be roughly de-

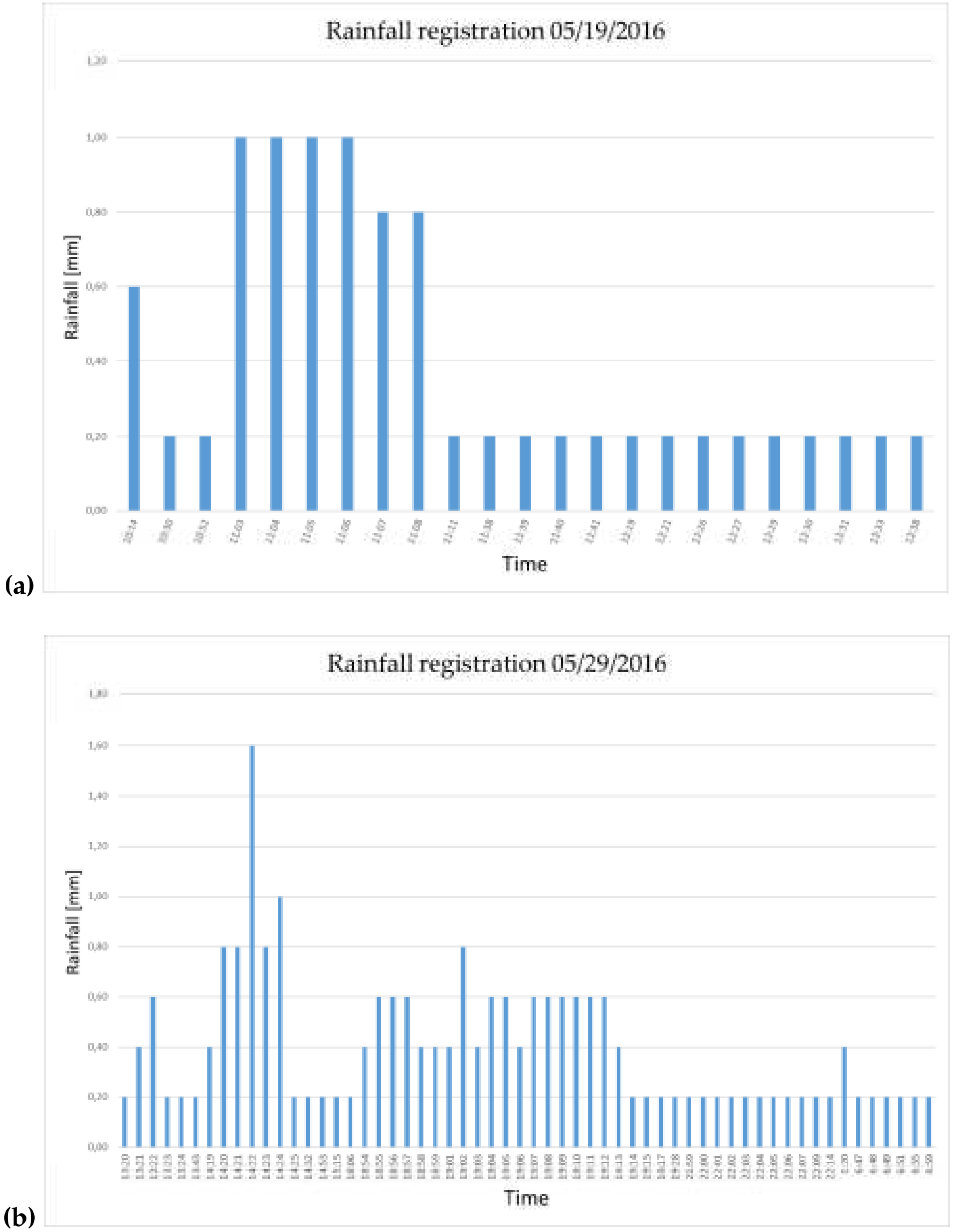


Figure 3.14: **(a)** rainfall event registration (05/19/2016) and **(b)** rainfall event registration (05/29/2016)

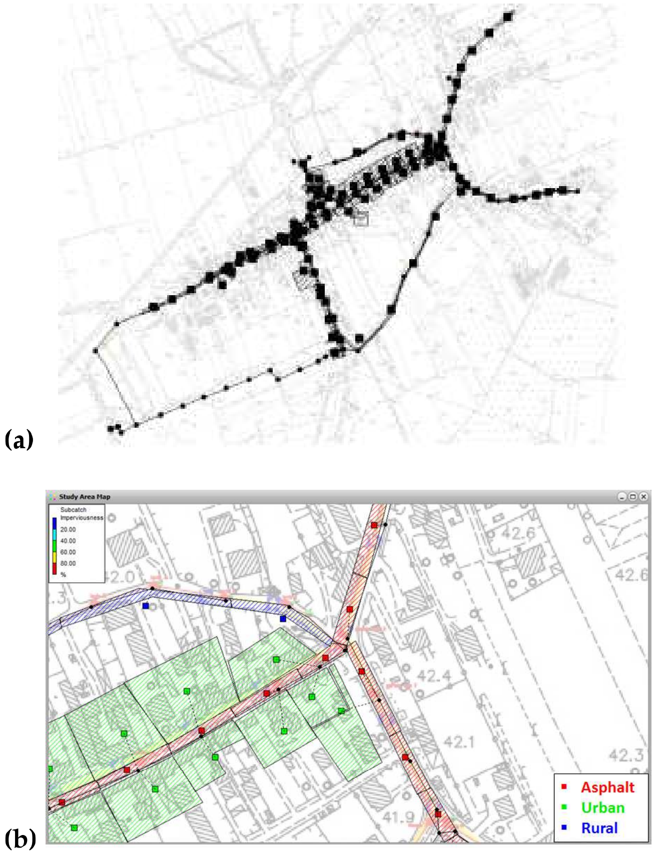


Figure 3.15:
(a) catchment map overview in SWMM
(b) subcatchment partition in *asphalt, urban and rural*

fined. This operation can be simpler in large urban catchments, where impervious areas discharging into the sewer are sharply defined.

Data were collected by instruments located into the catchment; the catchment modeled map in SWMM is reported in Fig. 3.15a.

The model in SWMM presents three different subcatchments: rural, urban and asphalt (Fig. 3.15b): large areas of the entire basin were not modeled because they do not discharge stormwater into the sewers. Infiltration wells for roofs runoff are really common outside the center of the village (residential areas). First attempt coefficients and features for the three types of subcatchment are collected in Tab. 3.6.

	Rural	**Urban**	**Asphalt**
$\% slope$	1.5	0.5	1.5
$\% imperv$	15	50	90
$N - imperv$	0.012	0.015	0.010
$N - perv$	0.100	0.100	0.100

Table 3.6: Subcatchment features and coefficients for the SWMM model

Data collection According to the problems listed in Par. 3.4.4, in Fig. 3.16 some issues are reported from the Insight software provided by [103].

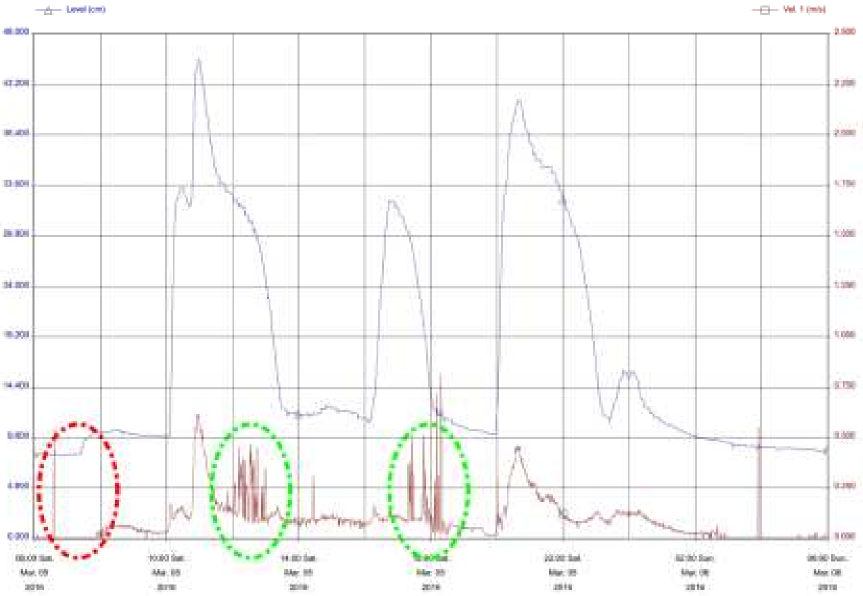
3.4.5 Washoff modeling and analysis

Washoff and stormwater quality modeling is a particular goal in the scientific literature ([126], [127], [128]) and its implications are quite important, in order to assess optimum stormwater volumes to treat. Modeling is quite difficult because a lot of occurrences influence the four parameters of the exponential functions which were described in Par. 3.4.1.

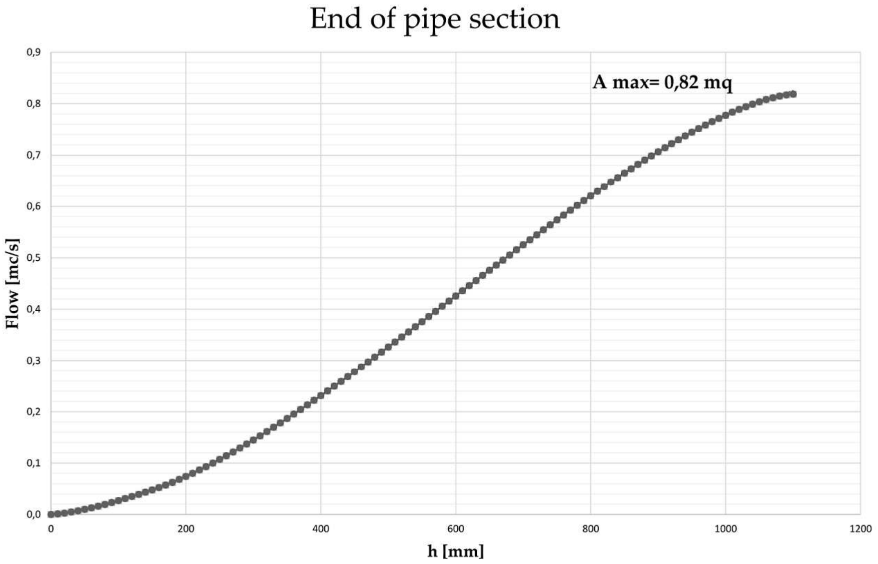
Obviously, all the laboratory analysis will give back a value (or a concentration) of a compound, but it is not possible to model each of them and, finally it does not make sense. In this thesis, the subject of the stormwater quality modeling will be the *TSS* parameter, because of several reasons. First of all, a *TSS-COD*, *TSS-Hydrocarbons* and *TSS-heavy metals* relations were quite clear after the laboratory analysis, so modeling TSS could mean modeling also COD and other several metals. Secondly, TSS and COD are fundamental parameters in order to assess clogging or treating stormwater. Initial parameters of the SWMM functions are collected in Tab. 3.7, referring to the equations of Par. 3.4.1. The catchment was modeled in SWMM with a total area (the sum of each subcatchment) of $5.25ha$. The land use set as *asphalt* is the only one with buildup and washoff function defined on it.

Buildup		***Washoff***	
B_{max}	K_B	K_W	N_W
5	0.5	0.25	1.2

Table 3.7: Buildup and washoff functions for TSS in SWMM model for *asphalt* land use



(a)



(b) **(c)**

$$A = -8 \cdot 10^{-10} h^3 + 2 \cdot 10^{-6} h^2 + 1 \cdot 10^{-4} h$$

Figure 3.16: **(a)** Common issues during flow monitoring: in the red circle something blocked the velocity sensor (velocity is zero); in the green circles the signal is disturbed by turbulences due to solid material at the bottom like paper or branches. **(b)** end-of-pipe section of the catchment and area rating curve ($[A] = mq$ and $[h] = mm$)

Chapter 4

Results and discussion

THE case study reported at Cap. 3 produced some interesting results, both from hydrologic-hydraulic simulations and from laboratory analysis.

4.1 Hydrologic-hydraulic results

In the catchment, hydrologic and hydraulic simulations are affected by rainfall registrations: several papers in literature report on poor accuracy of tipping-bucket ([129], [130]), especially during heavy rain events. In the case study, several intense events were collected. SWMM permits to overlap directly measured data with simulated data, so one event will be chosen for calibration and one for validation (i.e. all the other storms will not be reported in this thesis).

The first rainfall event of the 05/31/2016 was used in terms of calibration; the second event of the same day was used in terms of validation. Validation parameters are shown in Tab. 4.1.

	Rural	**Urban**	**Asphalt**
$\% slope$	1.5	1.5	1.5
$\% imperv$	10	40	90
$N - imperv$	0.010	0.013	0.010
$N - perv$	0.100	0.100	0.100

Table 4.1: Subcatchment features and coefficients for SWMM model validation

4.2 Stormwater characterization and washoff results

Stormwater sampling and sample analysis permitted to characterize stormwater pollution intensity. First of all, before to start this thesis and studying stormwater pollution, a preventive sampling was set in July 2015. This sampling was interesting for several reasons. First of all, rainfall event came after 25 dry weather days, so a lot of pollutants could be settled on impervious surfaces; secondly, no one had an idea of pollutant concentration and first flush behavior of little catchment like the one which is the subject of the thesis when a huge storm occurs. On 25th July 2015, a heavy rain was expected, so the sampler was set to get the first flush each 2 minutes during the discharge into the pond. Unfortunately, no rain gauge or flow meter was installed in the catchment.

Results of the analysis were comforting: concentration of pollutants was really high and a first flush effect was observed (Fig. 4.2, 4.3, 4.4, 4.5). A lot of pollutant concentrations exceed regulation values, proving the uncontrolled discharge in terms of quality (Tab. 4.2). A comparison with literature values were reported in Tab. 4.6.

Unfortunately, there was a lack of pollution data in other storm events and samples were got only during 05/19/2016 and 05/29/2016 storm events (which are the only ones taken as reference in this thesis). Sampling during storm event is not always comfortable: suction strainer can be blocked by solid material or it can be pushed on water surface without getting a complete sample. In the first storm event (05/19/2016) samples were analyzed as the ones of 07/25/2016; in the 05/29/2016 event, the samples were analyzed also after filtration, in order to understand the percentage of pollutant on solid particles or in aqueous phase.

4.2.1 Rain event 05/19/2016

The rain event of 05/19/2016 was quite short, despite of what we expected after 5 dry weather days. Anyway, we got the samples from the manhole and then we analyzed as shown in Cap. 3. Data analysis were collected in Tab. 4.4 and Fig. 4.6.

4.2.2 Rain event 05/29/2016

The rain event of 05/29/2016 was a good event, after 5 dry weather days. Data analysis were collected in Tab. 4.5 and Fig. 4.8.

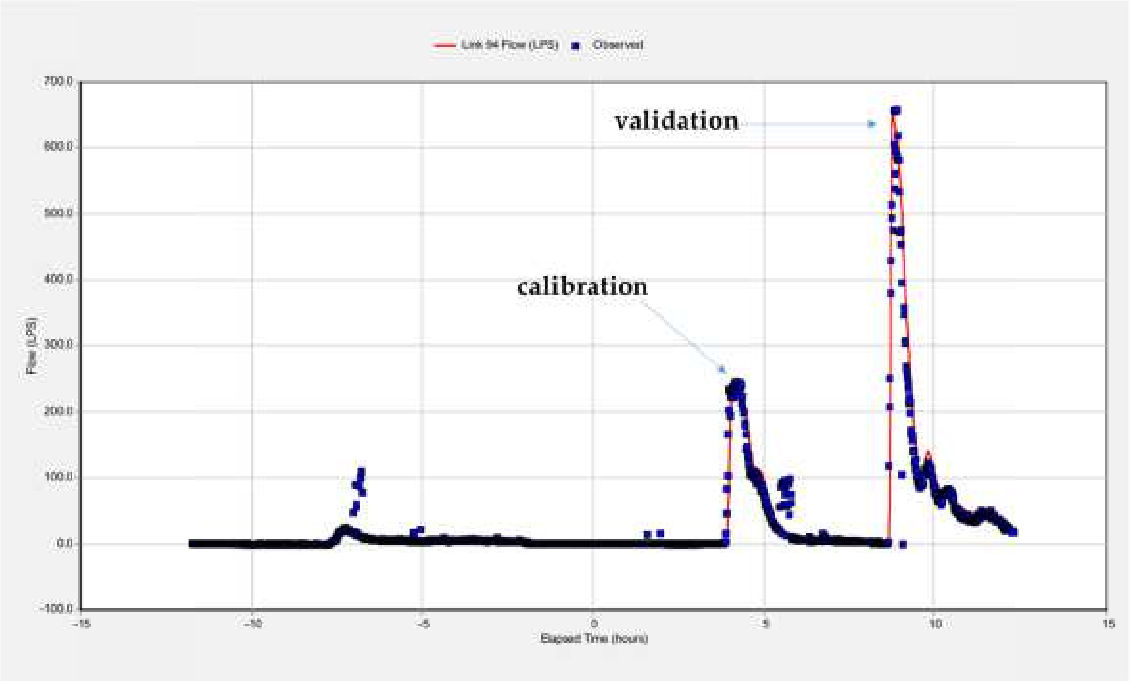


Figure 4.1: The two hydrographs refer to different and separated rainfall events. The first one was used in order to calibrate parameters; the second one was used to validate the model.

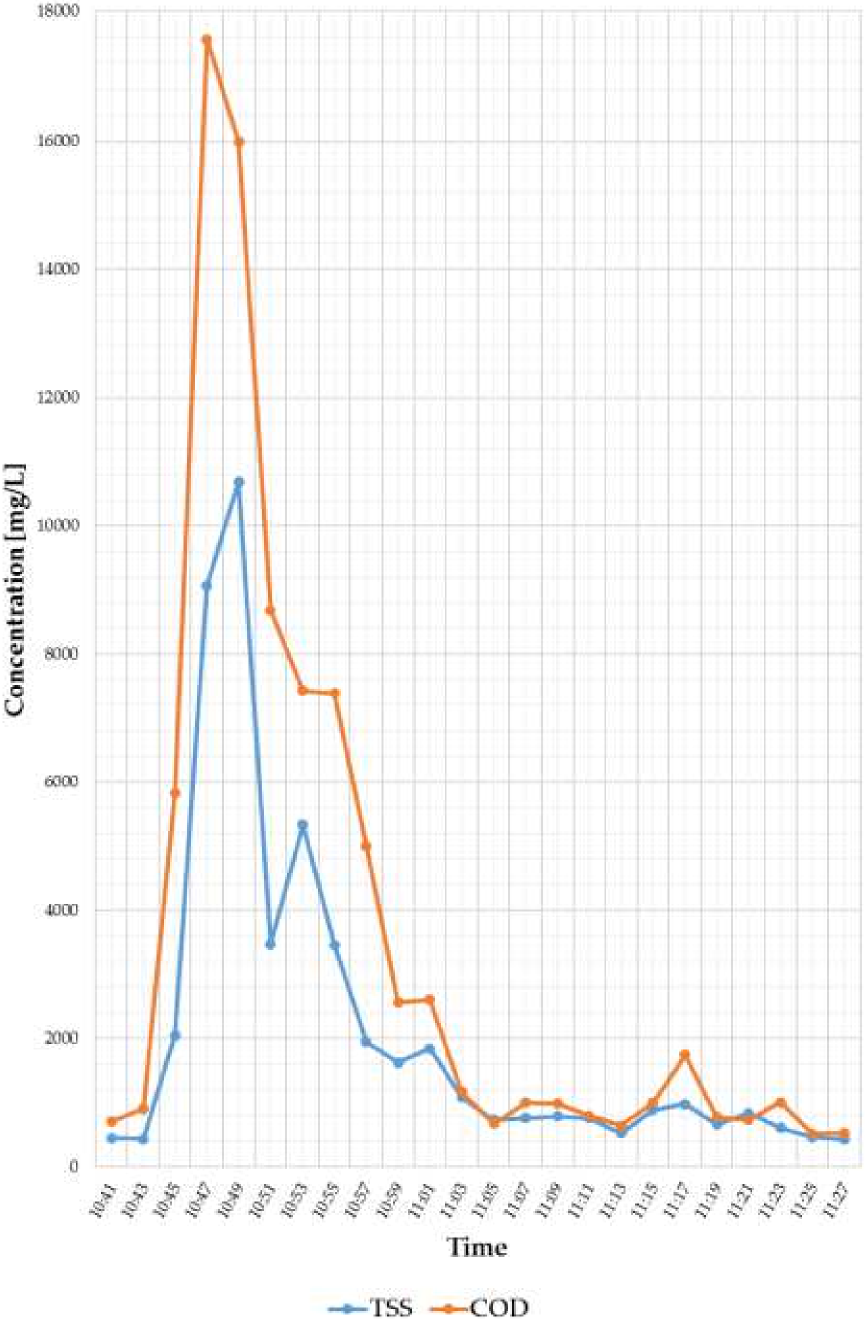


Figure 4.2: TSS and COD - First flush of 07/25/2015 storm event

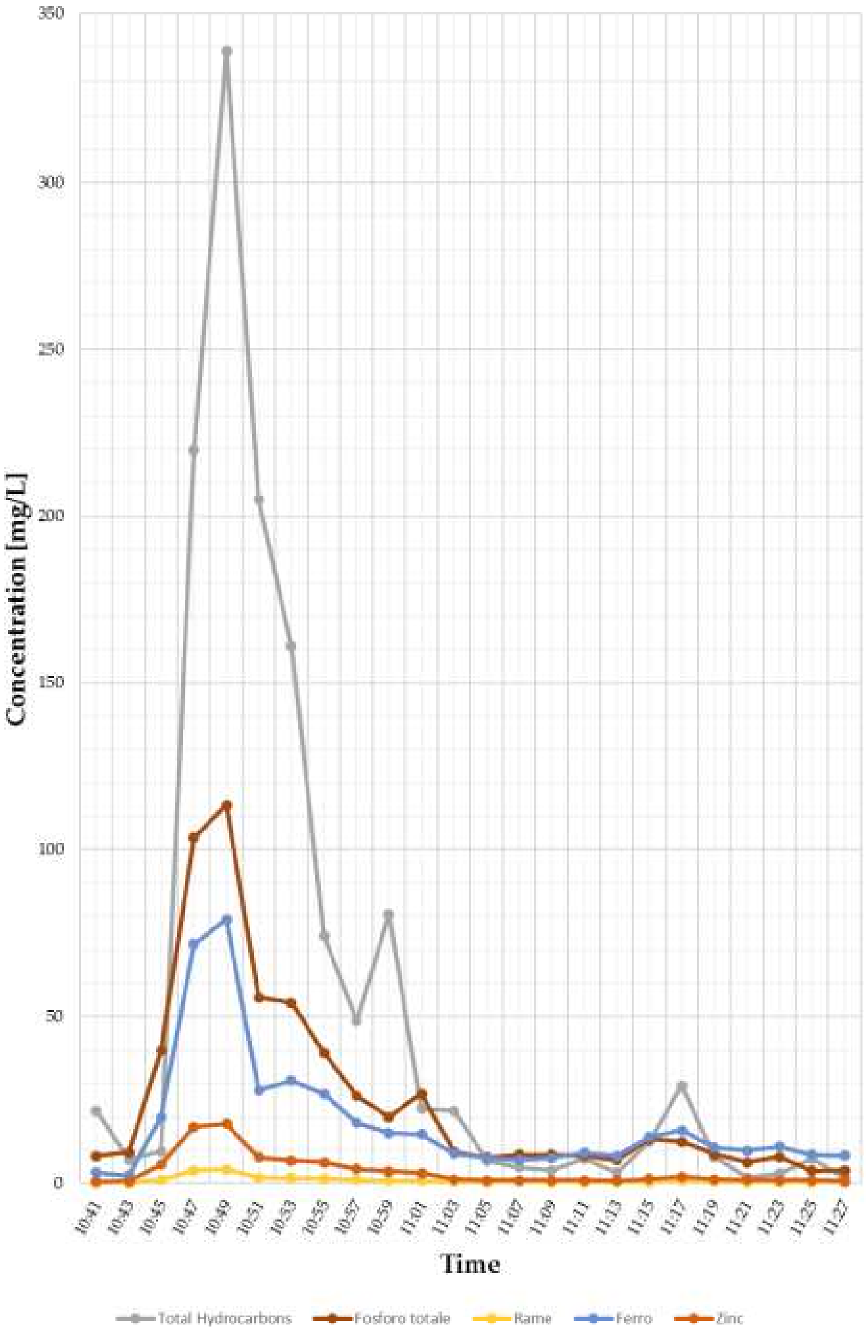


Figure 4.3: Most significant heavy metals and total hydrocarbons - First flush of 07/25/2015 storm event

		C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18	C19	C20	C21	C22	C23	C24
	Parametro	**10:41**	**10:43**	**10:45**	**10:47**	**10:49**	**10:51**	**10:53**	**10:55**	**10:57**	**10:59**	**11:01**	**11:03**	**11:05**	**11:07**	**11:09**	**11:11**	**11:13**	**11:15**	**11:17**	**11:19**	**11:21**	**11:23**	**11:25**	**11:27**
mg/l	**TSS**	450	436	2050	9070	10690	3470	5330	3460	1950	1620	1840	1080	736	764	792	764	528	888	980	664	840	608	464	428
mg/l	**COD**	704	908	5826	17560	16000	8680	7420	7380	5000	2560	2604	1169	678	1002	988	796	646	999	1740	776	736	1004	522	523
mg/l	**Barium**	0,1	0,1	0,46	1,52	1,6	1,22	0,68	0,79	0,46	0,34	0,35	0,18	0,15	0,17	0,21	0,23	0,16	0,24	0,24	0,2	0,15	0,16	0,13	0,14
mg/l	**Boron**	0,08	0,08	0,2	0,28	0,27	0,13	0,17	0,28	0,2	0,33	0,16	0,11	0,09	0,15	0,12	0,11	0,13	0,38	0,12	0,14	0,11	0,09	0,11	0,1
mg/l	**Cadmium**	0	0	0	0,013	0,014	0	0,007	0,005	0,012	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
mg/l	**Total Chromium**	0,05	0,05	0,09	0,29	0,31	0,11	0,15	0,15	0,13	0,1	0,1	0,06	0,05	0,05	0,05	0,05	0,04	0,06	0,09	0,06	0,06	0,06	0,06	0,05
mg/l	**Total Phosphorus**	8,1	9,2	39,9	103,5	113,3	55,8	54,2	39,2	26,2	20	26,9	9,4	7,7	8,6	8,6	8,3	6,9	13,3	12,4	8,7	6,3	7,9	3,7	3,9
mg/l	**Manganese**	0,16	0,14	0,46	1,42	1,54	0,87	0,81	0,75	0,56	0,46	0,53	0,37	0,32	0,35	0,35	0,39	0,32	51	0,48	0,34	0,35	0,37	0,33	0,29
mg/l	**Nickel**	0,11	0,11	0,14	0,29	0,34	0,13	0,19	0,17	0,14	0,1	0,1	0,07	0,06	0,04	0,05	0,06	0,05	0,06	0,09	0,06	0,06	0,07	0,06	0,05
mg/l	**Lead**	0,03	0,03	0,17	0,52	0,55	0,25	0,23	0,21	0,16	0,12	0,1	0,06	0,05	0,11	0,05	0,06	0,05	0,06	0,11	0,07	0,06	0,07	0,05	0,05
mg/l	**Selenium**	0	0	0	0,02	13,3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
microg/l	**Silver**	0	0	8	28	31	95	12	12	9	9	6	0	0	0	0	7	0	0	8	6	0	34	195	0
mg/l	**Arsenic**	0	0	0,01	0,04	0,04	0,01	0,02	0,02	0,01	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
mg/l	**Alluminium**	2,91	2,44	20,32	75,14	78,12	27,38	32,12	28,72	20,49	17,64	16,35	10,08	8,58	8,47	10,02	10,38	8,61	11,37	17,51	12,39	112,29	13,97	11,15	10,55
mg/l	**Copper**	0,14	0,14	1,12	3,91	4,09	1,69	1,56	1,46	1,07	0,85	0,81	0,49	0,39	0,49	0,33	0,37	0,45	0,4	0,93	0,48	0,37	0,46	0,41	0,26
mg/l	**Iron**	3,23	2,42	19,99	71,75	79,11	27,92	30,79	26,94	18,22	15,06	14,76	8,84	7,66	6,93	7,61	9,16	8,22	13,87	15,97	10,67	9,79	10,95	8,61	8,29
mg/l	**Sodium**	58	55	4	58	61	35	31	25	21	18	21	13	9	11	9	9	4	7	14	6	5	5	4	5
mg/l	**Tin**	0,01	0,06	0,1	0,31	0,33	0,13	0,12	0,12	0,09	0,06	0,05	0,03	0,02	0,02	0,02	0,09	0,03	0,03	0,05	0,04	0,03	0,04	0,03	0,03
mg/l	**Zinc**	0,55	0,64	5,67	16,94	17,88	7,82	6,89	6,28	4,28	3,57	3,04	1,25	0,96	0,93	0,93	0,95	0,81	1,39	2,07	1,26	1,1	0,95	0,88	0,61
mg/l	**Total Hydrocarbons**	21,75	7,16	9,5	219,7	338,9	205,1	161	74,2	48,76	80,68	22,43	21,82	6,77	4,81	3,91	7,32	3,2	12,5	29,3	7,9	1,8	2,9	7,3	1,6

	Law Limit	Max	Min	Mean		Law Limit	Max	Min	Mean
TSS	25	10690	428	2079,250	**Selenium**	0,002	13,3	0	0,555
COD	100	17560	522	3592,542	**Silver**	-	195	0	19,167
Barium	10	1,6	0,1	0,416	**Arsenic**	0,05	0,04	0	0,006
Boron	0,5	0,38	0,08	0,164	**Alluminium**	1	112,29	2,44	23,625
Cadmium	-	0,014	0	0,002	**Copper**	0,1	4,09	0,14	0,945
Total Chromium	1	0,31	0,04	0,095	**Iron**	2	79,11	2,42	18,198
Total Phosphorus	2	113,3	3,7	25,083	**Sodium**	-	61	4	20,333
Manganese	0,2	51	0,14	2,623	**Tin**	3	0,33	0,01	0,077
Nickel	0,2	0,34	0,04	0,108	**Zinc**	0,5	17,88	0,55	3,652
Lead	0,1	0,55	0,03	0,134	**Total Hydrocarbons***	5	338,9	1,6	54,180

Table 4.2: **(a)** First flush event on 07/25/2015: in the table all the values are collected and the red color paint irregular discharging values. **(b)** law limits in Italy for discharge on soils [53] (*law limit for surface water discharge)

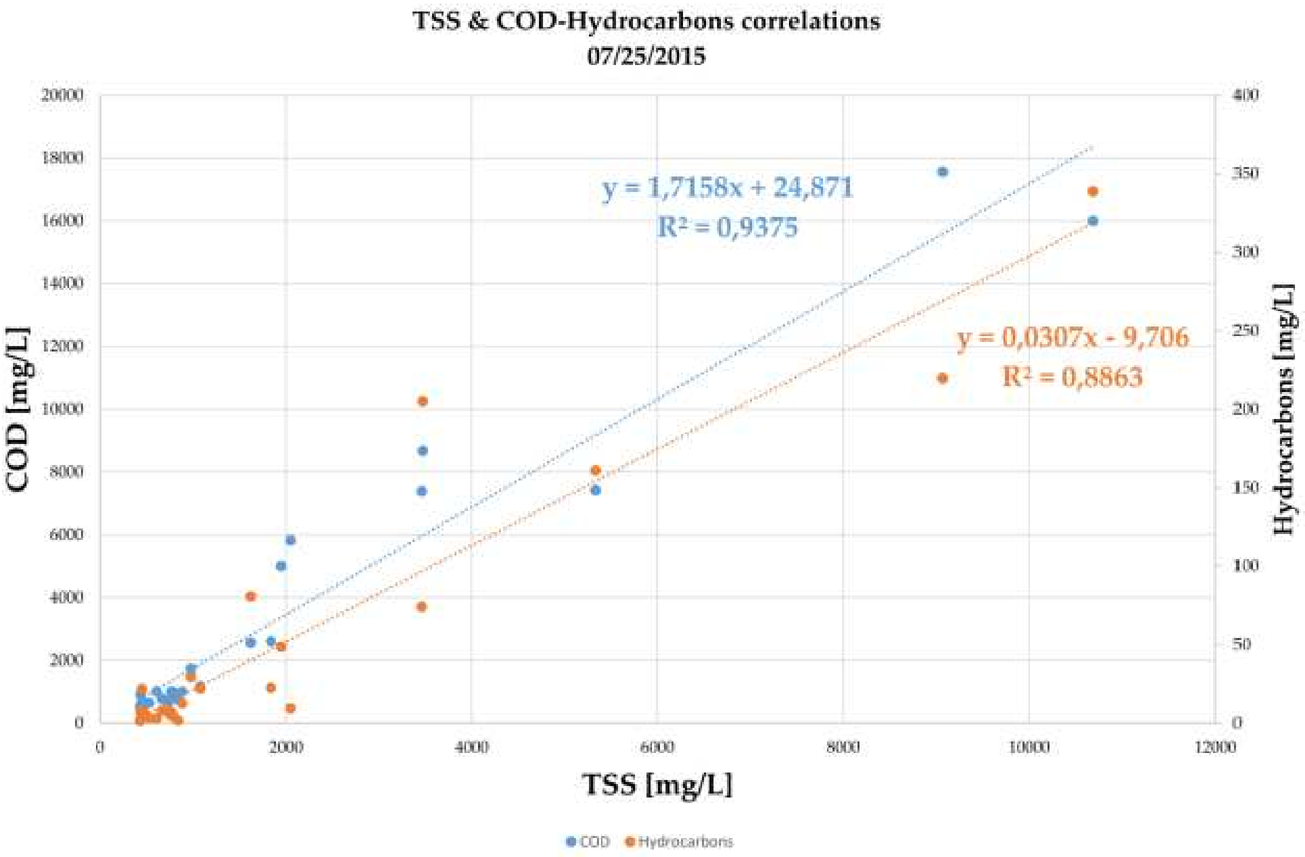


Figure 4.4: TSS&COD-TotalHydrocarbons correlations - First flush of 07/25/2015 storm event

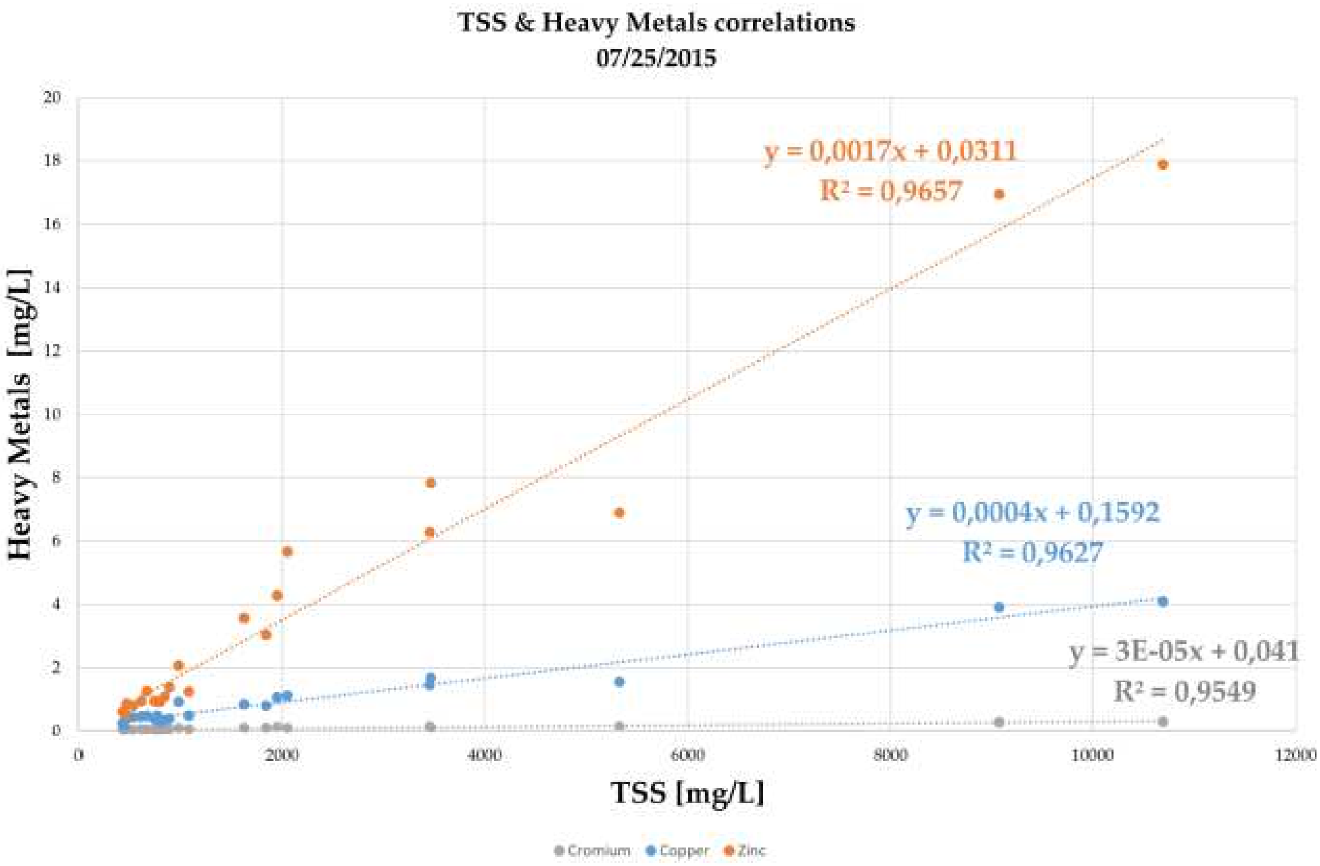


Figure 4.5: TSS & Heavy Metals correlations - First flush of 07/25/2015 storm event

4.2.3 Buildup and Washoff parameters

Uncertainty on TSS measures in samples means uncertainty in buildup and washoff coefficients, of course. According to literature values, calibration values of buildup and washoff exponential functions are listed in Tab. 4.3. In order to get more statistical-based values for calibration, a quite huge number of analysis is needed: calibration needs more data and more registrations, but unfortunately in this thesis no more of two sampled events were collected.

Buildup		***Washoff***	
B_{max}	K_B	K_W	N_W
0.1	0.08	0.18	1.75

Table 4.3: Buildup and washoff functions for TSS to calibrate the SWMM model for *asphalt* land use

		C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18	C19	C20	C21	C22	C23	C24
	Parametro	**11:55**	**11:57**	**11:59**	**12:01**	**12:03**	**12:05**	**12:07**	**12:09**	**12:11**	**12:13**	**12:15**	**12:17**	**12:19**	**12:21**	**12:23**	**12:25**	**12:27**	**12:29**	**12:31**	**12:33**	**12:35**	**12:37**	**12:39**	**12:41**
mg/l	**TSS**	1964	520	352	592	704	680	712	600	1056	584	516	512	540	416	552	508	576	872	660	516	548	704	592	604
mg/l	**COD**	382						181				131	177	466	185	100	296	290	153	123	362	388	616	77	85
mg/l	**Bario**	0,2	0,14	0,06	0,04	0,09			0,07			0,07	0,07	0,06	0,03	0,06		0,06	0,11	0,1	0,05		0,06	0,02	0,03
mg/l	**Boro**	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05			< 0.05			< 0.05	< 0.05	< 0.05	< 0.05	< 0.05		< 0.05	< 0.05	< 0.05	< 0.05		< 0.05	< 0.05	< 0.05
mg/l	**Cadmio**	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005			< 0.005			< 0.005	< 0.005	< 0.005	< 0.005	< 0.005		< 0.005	< 0.005	< 0.005	< 0.005		< 0.005	< 0.005	< 0.005
mg/l	**Cromo totale**	0,03	< 0.02	< 0.02	< 0.02	< 0.02			< 0.02			< 0.02	< 0.02	< 0.02	< 0.02	< 0.02		< 0.02	0,02	0,02	< 0.02		< 0.02	< 0.02	< 0.02
mg/l	**Fosforo totale**	5,4						2,8				2,2	2,4	3,6	2	1,3	2,6	2,6	2,6	1,8	3	2,8	3,8	1,6	1,4
mg/l	**Manganese**	0,55	0,3	0,29	0,21	0,31			0,27			0,26	0,25	0,25	0,15	0,28		0,25	0,38	0,36	0,21		0,24	0,14	0,16
mg/l	**Nichel**	0,03	< 0.02	< 0.02	< 0.02	< 0.02			< 0.02			< 0.02	< 0.02	< 0.02	< 0.02	< 0.02		< 0.02	< 0.02	< 0.02	< 0.02		< 0.02	< 0.02	< 0.02
mg/l	**Piombo**	0,07	0,03	0,02	0,02	0,03			0,03			0,03	0,02	0,02	0,01	0,02		0,02	0,06	0,07	0,02		0,02	< 0.01	< 0.01
mg/l	**Selenio**	0,0024	0,001	0,001	0,0009	0,0012			0,0016			0,0008	0,0006	0,0012	0,0009	0,0006		0,0012	0,0016	0,0021	0,0011		0,0009	0,001	0,0008
mg/l	**Arsenico**	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01			< 0.01			< 0.01	< 0.01	< 0.01	< 0.01	< 0.01		< 0.01	< 0.01	< 0.01	< 0.01		< 0.01	< 0.01	< 0.01
mg/l	**Alluminio**	12,14	6,69	5,25	3,41	7,22			6,05			5,8	5,73	5,92	2,89	5,66		5,07	8,19	9,22	4,49		5,54	2,29	2,49
mg/l	**Rame**	0,29	0,12	0,08	0,07	0,18			0,18			0,12	0,1	0,08	0,05	0,08		0,07	0,17	0,18	0,07		0,1	0,03	0,03
mg/l	**Ferro**	9,79	4,82	3,76	2,38	5,29			4,91			4,29	3,62	3,6	1,89	4,03		3,77	6,61	6,49	3,21		4,29	1,62	1,76
mg/l	**Sodio**	10	6	5	8	8			6			6	7	5	5	4		6	9	8	9		9	10	9
mg/l	**Stagno**	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02			< 0.02			< 0.02	< 0.02	< 0.02	< 0.02	< 0.02		< 0.02	< 0.02	< 0.02	< 0.02		< 0.02	< 0.02	< 0.02
mg/l	**Zinco**	1,98	0,84	0,59	0,48	0,39			0,72			0,98	0,73	1,16	0,86	0,76		1,23	0,96	3,08	0,54		0,91	0,46	0,53
mg/l	**Idrocarburi totali**	22,31	< 0.05	< 0.05	1,36	1,48	< 0.05	< 0.05	0,51	< 0.05	< 0.05	< 0.05	2,17	2,24	2,07	2,4	1,73	3,35	3,86	5,4	2,78	2,58	2,88	3,27	1,92

Table 4.4: First flush event on 05/19/2016: in the table all the values are collected and the red color paint irregular discharging values

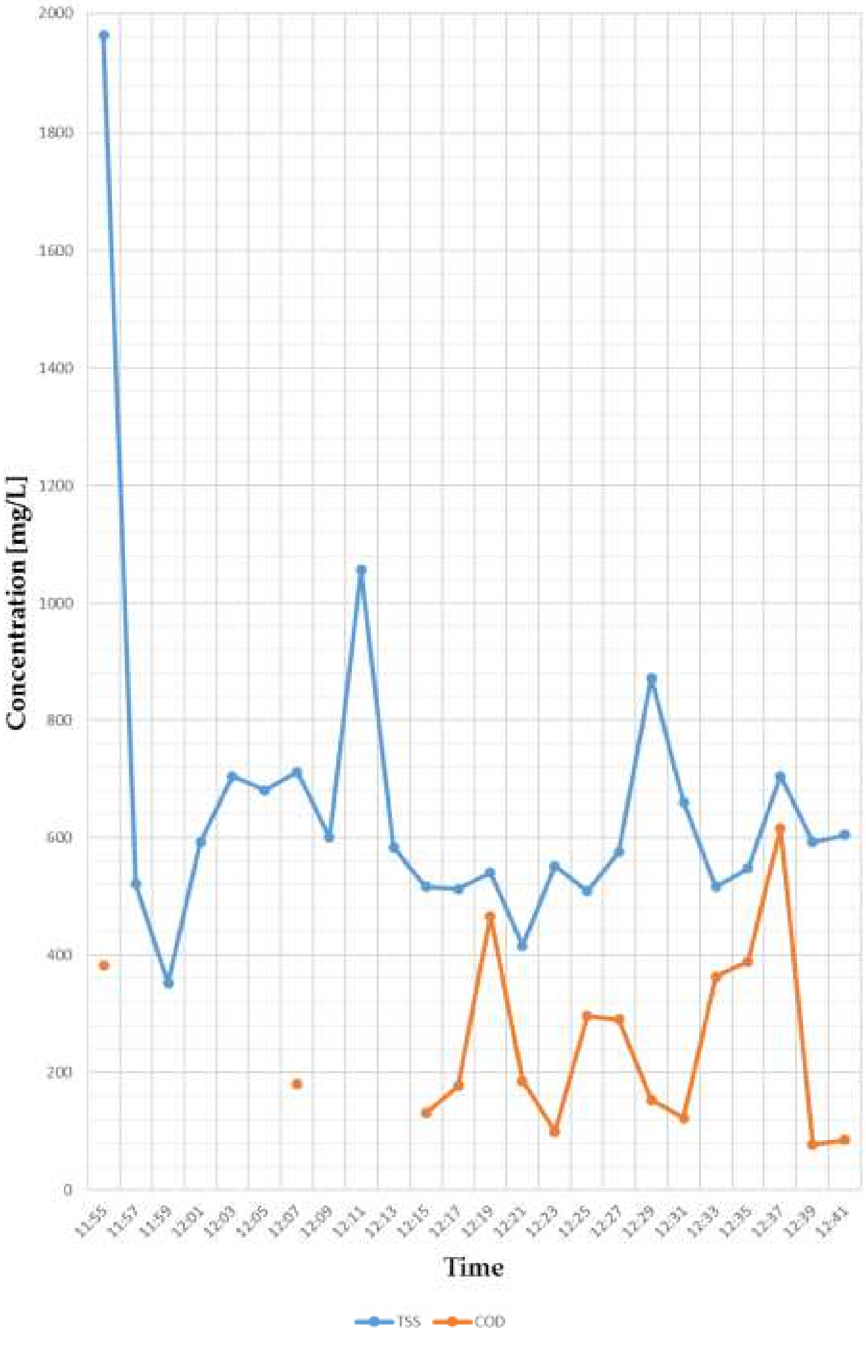


Figure 4.6: TSS and COD - First flush of 05/19/2016 storm event

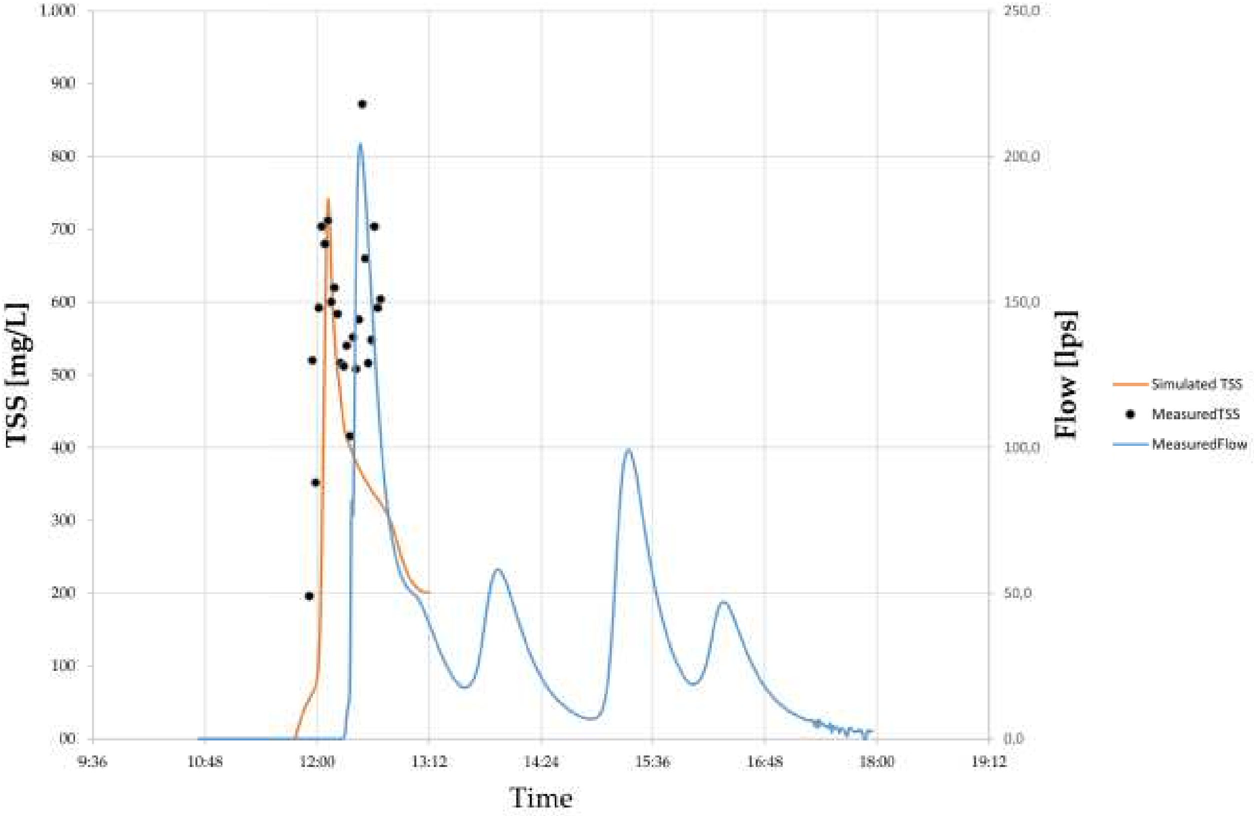


Figure 4.7: Simulated TSS for the 05/19/2016 storm event with SWMM

		C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18	C19	C20	C21	C22	C23	C24
	Parametro	15:31	15:33	15:35	15:37	15:39	15:41	15:43	15:45	15:47	15:49	15:51	15:53	15:55	15:57	15:59	16:01	16:03	16:05	16:07	16:09	16:11	16:13	16:15	16:17
mg/l	**TSS**	1092	6890	1596	848	1064	1132	840	868	704	792	728	988	872	744	616	544	584	576	492	576	456	368	320	284
mg/l	**COD**	5010	9180	5010	530	740	608	654	682	604	374	1030	1180	564	414	366	302	319	303	250	352	309	198	178	153
mg/l	**Bario**	0,21	1,09	0,26	0,11	0,16	0,14	0,15	0,15	0,17	0,13	0,15	0,15	0,15	0,13	0,1	0,11	0,12	0,09	0,08	0,1	0,07	0,06	0,06	0,05
mg/l	**Boro**	0,1	0,16	0,06	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05
mg/l	**Cadmio**	< 0.005	0,007	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005
mg/l	**Cromo totale**	0,07	0,18	0,08	< 0.02	0,03	0,03	0,03	0,03	0,03	0,03	0,02	0,03	0,03	0,02	0,02	0,03	0,03	0,02	0,02	0,02	0,02	< 0.02	< 0.02	< 0.02
mg/l	**Fosforo totale**	11,2	47	8,4	3	4,8	4,5	4,1	4,8	3,4	3,3	5,3	4,4	4	3,2	2,6	2,1	2,3	2,2	1,8	2,4	1,8	1,5	1,6	1,3
mg/l	**Manganese**	0,36	1,2	0,57	0,35	0,39	0,4	0,39	0,41	0,45	0,47	0,43	0,43	0,43	0,41	0,37	0,4	0,35	0,33	0,34	0,3	0,27	0,23	0,23	0,2
mg/l	**Nichel**	0,04	0,14	0,05	< 0.02	0,02	0,02	0,02	0,02	0,02	0,03	0,02	0,02	0,02	0,02	0,02	0,02	0,02	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02
mg/l	**Piombo**	0,05	0,31	0,08	0,03	0,05	0,05	0,05	0,06	0,04	0,04	0,05	0,06	0,06	0,05	0,04	0,04	0,04	0,03	0,03	0,03	0,03	0,02	0,02	0,02
mg/l	**Selenio**	0,015	0,027	0,0125	0,0013	0,0017	0,0018	0,002	0,0018	0,0011	0,0011	0,0017	0,002	0,0017	0,0014	0,0012	0,0016	0,0014	0,0011	0,0009	0,0011	0,0012	0,0006	0,0009	0,001
mg/l	**Arsenico**	< 0.01	0,02	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
mg/l	**Alluminio**	13,27	60,59	24,56	12,11	13,99	13,2	14,28	13,92	13,71	14,33	12,72	13,47	12,8	12,09	11,58	11,53	11,82	11,24	10,41	10,1	8,65	7,15	7,38	6,29
mg/l	**Rame**	0,56	3,79	0,8	0,22	0,32	0,29	0,22	0,27	0,23	0,19	0,22	0,29	0,24	0,21	0,17	0,18	0,2	0,21	0,19	0,18	0,17	0,12	0,12	0,12
mg/l	**Ferro**	9,42	35,89	14,98	7,71	9,25	8,23	8,55	9,02	10,08	10,26	9,18	8,81	9,42	8,9	8,28	7,84	8,27	7,79	7,55	7,12	5,94	4,76	4,94	4,13
mg/l	**Sodio**	33	32	11	5	8	9	5	13	4	4	8	5	5	5	3	4	3	3	4	3	3	3	3	3
mg/l	**Stagno**	0,03	0,16	0,03	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02
mg/l	**Zinco**	2,15	9,28	2,27	1,26	2	1,42	0,97	1,62	1,42	0,95	1,59	1,71	1,84	1,21	1,23	1,16	1,21	0,92	1,12	0,92	0,8	0,9	0,92	0,56
mg/l	**Idrocarburi totali**	13,66	84,11	5,08	< 0.05	3,66	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	3,21	0,46	0,32	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05

Table 4.5: First flush event on 05/29/2016: in the table all the values are collected and the red color paint irregular discharging values

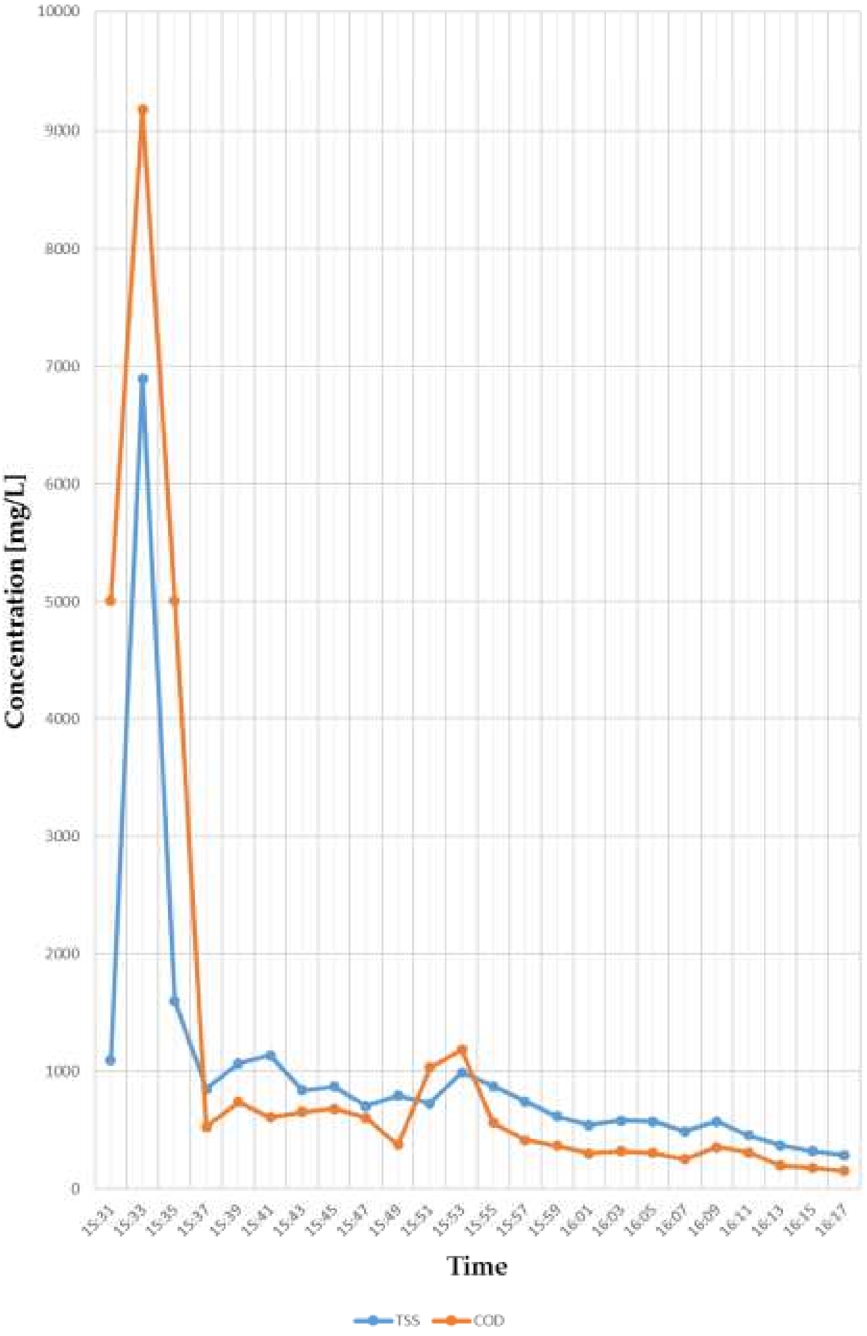


Figure 4.8: TSS and COD - First flush of 05/29/2016 storm event

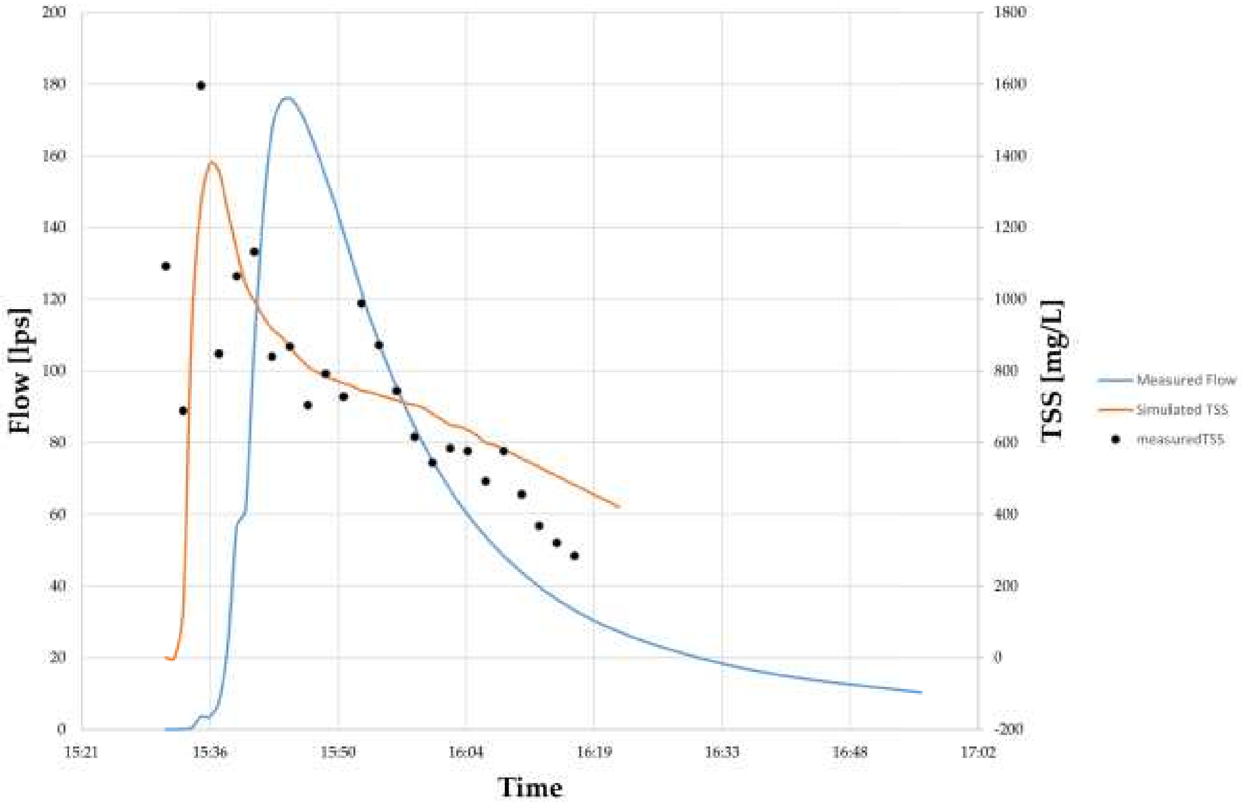


Figure 4.9: Simulated TSS for the 05/29/2016 storm event with SWMM

	Ref.	**Cd**	**Cr**	**Cu**	**Pb**	**Zn**
Italy	[131]	0.2-4.2	11-146		14-188	104-1544
Canada	[132]	ND-1.5	0.28-17	3.4	1.2-20	6.1-130
Korea	[133]	0.3-0.39	0.19-4.45	1.02-3.76	0.06-0.39	4-10
Singapore	[134]	ND-1.79	ND-5.97	1.6-76	ND-21.2	4.9-183
USA	[135]	ND-5	ND-42	ND-53	ND-112	13-908
UK	[136]	ND-2.3	0.1-27.6	ND-25.6	ND-6.1	4.0-79.5
UK	[137]	0.3-9.6	0.5-9.5	1.6-75.4	1.5-92	2.5-632
Summary		**ND-9.6**	**ND-146**	**ND-76**	**ND-112**	**2.5-1544**
Case Study		ND-7	ND-180	30-560	10-310	510-3860

Table 4.6: Comparison between literature values for heavy metals in stormwater from highway and streets ($\mu g/l$) with values of 05/19/2016 and 05/29/2016 in the catchment of Galleriano. (ND = below detection limits)

4.3 Sediment analysis

Sediment analysis is the last and final investigation on stormwater in this thesis. The laboratory of Mario Negri Institute (Milan) made the analysis on 4 samples of sediments collected from different points of the infiltration pond (Fig. 4.10); furthermore, a blank sample was collected outside the pond.

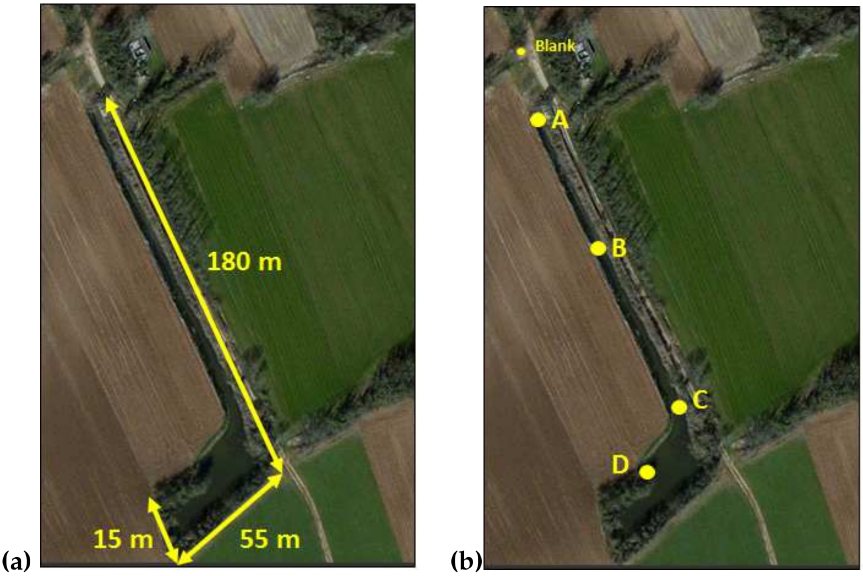


Figure 4.10: **(a)** infiltration pond dimensions and **(b)** Collecting position of samples from the infiltration pond in Galleriano di Lestizza (aerial photo from *Google Maps®*)

Unfortunately, it was not possible to collect a sample at the center of the pond due to an excess of sediments (Fig. 4.12): probably that sample could present higher concentrations than the others, because of the huge solid deposition in that area. Analysis spread from advanced analysis to heavy metals. Advanced analysis were made in order to find particular compounds (e.g. pesticides, PPCPs and others) into the infiltration pond, for the first time in the Friuli - Venezia Giulia Region. Referring to 4.3, the results are reported in Tab. 4.8 and Fig. 4.11).

In order to assess the presence of other compounds, qualitative analysis on hydrocarbons produced the results collected in Tab. 4.9. Furthermore, heavy metal analysis are reported in Tab. 4.10.

	DACT	DIA	DEA	DET	ATZ	SMZ	TBZ
Blank	0.07	0.17	0.18	1.10	0.34	0.13	3.60
A	< 0.01	< 0.01	< 0.01	< 0.01	0.01	< 0.01	0.40
B	< 0.01	< 0.01	< 0.01	0.08	0.01	< 0.01	0.26
C	< 0.01	< 0.01	< 0.01	0.59	0.11	0.03	68.00
D	< 0.01	< 0.01	< 0.01	0.14	0.01	< 0.01	0.75

Table 4.7: Quantitative Analysis with internal standard atrazine-D5 ($1\,ng/g$) and positive ion modality.

	Imidacloprid	DEET	Diazinon	Metolachlor	Triclosan*	Triclocarban*
Blank	0.44	3.29	0.82	2.94	0.03	0.01
A	< 0.01	1.94	1.12	0.36	24.74	15.01
B	< 0.01	3.31	1.14	0.51	16.52	7.99
C	0.03	17.81	0.66	2.17	80.22	45.07
D	0.03	5.11	0.91	1.41	48.97	35.55

Table 4.8: Area-peak ratios analyte/atrazine-D5 ($1\,ng/g$) with positive ion modality. For the other compounds listed at Par. 4.3 the ratio was lower than 0.01. (*negative ion modality)

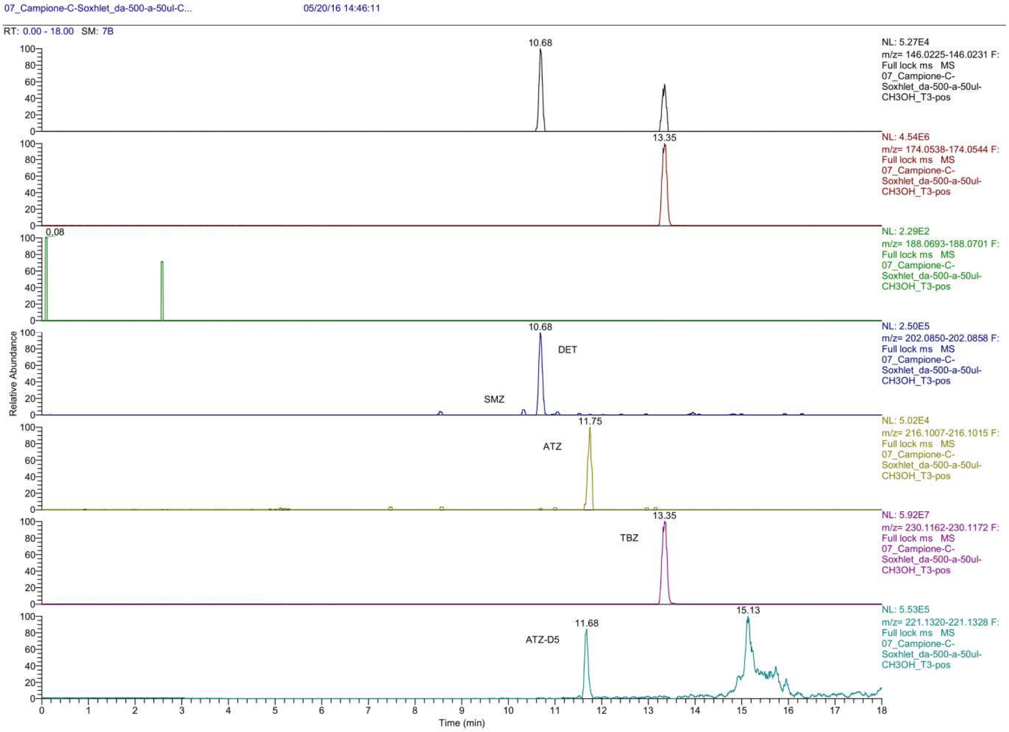


Figure 4.11: Triazine and metabolites in Sample **C** of the infiltration pond (GC-MS)

A	**B**	**C**	**D**
perylene	cholestanol	cholestanol	cholestanol
benzo(e)pirene	cholestan-3one(5-beta)	cholestan-3one(5-beta)	cholestan-3one(5-beta)
benzo(A)antracene	pirene	benzene (1-buthylheptyl)	benzene (1-pentylheptyl)
naphthacene	fluorantene	benzene (1-pentylheptyl)	pirene
pirene	antracene	pirene	fluorantene
fluorantene		fluorantene	antracene
antracene		antracene	
dibutyl phthalate		dibutyl phthalate	
		10,18bisnorabieta-5,7,9(10),11,13 pentaene	

Table 4.9: Qualitative analysis for hydrocarbons in sediment samples of the infiltration pond

	Co	**Cu**	**V**	**Mn**	**Ni**	**Pb**	**Cr**
Blank	4.07	12.34	54.81	587.48	22.54	11.77	135.09
A	1.59	24.03	11.55	134.88	11.2	12.81	20.91
B	1.89	55.08	12.79	126.62	7.32	3.88	18.81
C	3.89	193.26	76.05	192.47	30.90	27.57	61.07
D	5.28	169.99	60.45	165.67	40.45	30.18	115.09

	Cd	**Sn**	**Tl**	**As**	**Zn**	**Sb**	**Hg**
Blank	0.02	2.99	0.25	13.45	84.05	1.16	0.05
A	0.04	1.87	<0.01	0.95	78.16	0.58	0.04
B	0.06	1.14	0.05	1.4	73.68	2.48	0.11
C	0.09	4.10	0.13	4.91	177.54	2.98	0.30
D	0.02	2.92	0.12	5.23	195.54	3.66	0.39

Table 4.10: Quantitative analysis for heavy metals in sediment samples of the infiltration pond $[\mu g/g]$

4.4 Discussion

The results showed some interesting issues despite of poor data availability.

Firstly, a critical point was scarcity of rainfall events in 2016: there was a lack of precipitations, so hydraulic database is not as large as needed. Despite of this issue, hydraulic model could be assessed as valid for our purposes. In fact, the purpose was to combine stormwater characterization with hydraulic peaks, and volumes, according to sampled storm events: this was the first attempt to deeply characterize stormwater in this kind of catchments in the Friuli - Venezia Giulia Region.

Time of concentration of the basin is around 25 minutes, and this is a good parameter to underline the importance of first flush effect depending on the time of concentration [138]. Hydraulic peaks shown a very impulsive behavior: in case of huge rain events, flow could be higher than $0.6\,mc/s$ (cf. validation graphs). For this reason, pollutant load may be quite huge in the first flush phenomenon: the 07/25/2015 event represents a shining example. Pollutant load generally reaches the infiltration pond quite easily: the overflow activates at $30\,l/s$ (10 times the dry weather flow), so a static control is not possible in this sewer configuration. Another interesting aspect is the calculation of the first flush volume: according to total catchment surface ($7.69\,ha$), impervious surface is about $3.8\,ha$ ($\phi_{mean} = 0.49$). Regional regulation advises first flush tanks for a $5mm$ of rain on the impervious part of the catchment, so $V_{FF} \simeq 190mc$. If we consider the 05/29/2016 event, TSS present quite high values during almost one hour: the first flush is passed by, but solid material continue dragging several compounds and there is the need to retain them. According to this interesting event, $V_{FF,model} \simeq 250mc$ (but it could be higher). Both the volumes are quite easily to handle: the most important issue is to calibrate gates, in order to guarantee a complete separation between first flush and the second part of the rain.

Washoff analysis probably gave the most important results: despite of literature values, in this small urban catchment concentrations may be very high. Furthermore, the total load of a short event can be considerable and all the volume goes into the infiltration pond. A lot of heavy metals were found in stormwater, also toxic ones: further analysis are needed. Direct correlations between TSS and Hydrocarbons or COD have to be considered as two important evidences: first of all, TSS can be correlated with turbidity as well, so turbidimeter (i.e. instrument for turbidity measurement) may be a comfortable way to measure TSS and indirectly COD. Secondly, turbidimeter is really cheaper than sampling. For other similar catchments, stormwater first flush determination could be made by these kind of instruments. Washoff modeling depend on a huge quantity of data, so turbidimeters or continuum quality sensors could be the right choice in order to get stormwater quality during the whole rain event.

Sediment analysis provided interesting data from different points of view. Heavy metals are present into the pond in a huge amount (some values are many times higher than regulation limits for remediation of soils). Bad discharges of first flush induce the increasing of heavy metals in soil. Unfortunately, we did not got deeper samples, in order to assess mobility. Despite this, a deeper discussion of the results could be made, according to literature data for infiltration ponds or wetlands all over the world. In Tab. 4.11 several literature values were reported. Quite high values were detected for Cr, Cu and Zn. This issue could be explained because of the massive use of zinc roofs or metal roofs. Case study sediment analysis are quite interesting because instead of a little catchment we can find out high values as near highways or big cities (cf. cited literature in Tab. 4.11). This is another evidence on how stormwater management is important also in rural and suburban catchments. Another interesting issue to understand is the role of the *blank* sample: in chemical analysis, getting a blank sample mean to get a sample *"zero"* without any interference. In some cases, the blank sample returned higher values in respect of the samples (A, B, C, D). This was unexpected, so we need to understand the reasons of these results. The blank was unique, so probably it makes no statistical evidence and we were a little unlucky when digging it out. Higher values of Cr outside the pond are probably due to an old garbage dump set right near the pond, so maybe the blank was affected by this historical heritage.

Qualitative analysis of hydrocarbons just confirmed their presence as in stormwater quality analysis.

Advanced analysis provide quite worrying data: some of the compounds are banned in the United States (i.e. are going to be banned from 2017; e.g. triclosan & triclocarban), so their presence means a huge toxicity into the environment, which is threatening groundwater with heavy metals. Further investigation are needed in order to assess possible direct implications in groundwater quality. Mario Negri analysis confirmed some issues for the blank sample: some of the atrazine-based analysis revealed higher values for the blank sample so a discussion is needed also in this case. Atrazine was one of the most used compounds in the past as a pesticide, and unfortunately it is really persistent in the environment.

In conclusion, analysis on stormwater and pond sediments revealed a strong pollution, according to the area of the catchment. The comparison between the case study values with literature values permitted to consider the analyzed

	Ref.	**Cd**	**Cr**	**Cu**	**Mn**	**Ni**	**Pb**	**Zn**
Italy	[139]	0.4	50				280	313
Italy	[131]	0.25-1.7		20-260		170-540	110-3510	
Japan	[140]	1.3-3.0	68-110	140-340	720-950		110-250	770-1500
Canada	[132]	0.75-2.9	22-150	35-300	420-910	12-39	22-160	140-1070
Norway	[141]	0.02-11.1					9-675	51-4670
UK	[137]	3.0-9.6	3-167	17-178		17-178	38-350	21-830
UK	[142]	5.8-44.4		5.8-41.5			24.5-95.5	59.5-240
Summary		**0.02-44.4**	**3-167**	**5.8-340**	**420-950**	**12-540**	**9-3510**	**21-4670**
Case Study		0.02-0.09	18.81-115.09	24.03-193.26	134.88-192.47	7.32-40.45	3.88-30.18	73.68-195.54

Table 4.11: Comparison between literature values for heavy metals in sediments from wetland or infiltration ponds receiving stormwater from highway and streets ($\mu g/kg$ of dry weight) (ND = below detection limits)

Figure 4.12: Digging out some samples from the pond (March 2016)

samples as reliable for scientific proposals. Further investigations are needed in order to assess the degree of contamination in the pond, especially because of the high permeability of the soils.

Chapter 5

Conclusions

In this thesis, various topics have been underlined: hydrology and hydraulics of little urban catchments, buildup and washoff modeling, sediment analysis and infiltration pond critical issues. It is time to draw some conclusions, in order to critically evaluate the results and to open the way for further studies on this topic.

Certainly, this work is not complete as the authors wanted, but it prompt several evidences on how actual stormwater management is running in the Friuli - Venezia Giulia Region. In fact, in the High Plain, quality groundwater recharge by stormwater must be improved: stormwater washoff analysis and sediment contamination assessment underlined the need to get the first flush load and to treat it.

Secondly, a more detailed studied has to be promoted, in order to get some possible treatment strategies for the remaining part of the washoff. This issues should be integrated into a more comprehensive study for a better management of stormwater and wastewater too. As a matter of fact, there is a huge plan to restore and centralize wastewater treatment plants (Fig. 5.1) in all the Friuli - Venezia Giulia Region [143]. Unfortunately, there is no clear reference to stormwater management and treatment, so this thesis might represent an effort and a proposal for future integration on this topic.

The research on stormwater management produced interesting results because it opened a wide view on the importance of stormwater infiltration in the Region. Furthermore, the results improved the knowledge on stormwater runoff quality in little urban catchments, so these data should be evaluated by designers and planners in order to amend common design strategies. This assumption becomes even more important if we take a look to the number of the infiltration ponds in the High Friulian Plain (almost 150, including secondary CSOs in ponds and trenches). Secondly, if we keep in mind the importance of the karst spring area in the Region and the preciosity of that kind of water (i.e. karst ecosystems and habitats) a reflection should be improved, and a solution must be found, hopefully.

Collected data permit to evaluate possible solution according to the BAT and to increase efficiency in water treatment and management: three different scenarios can be hypothesized.

Scenario 1: continuum treatment of stormwater

There are a lot of commercial devices able to continuously treat stormwater: this kind of devices are mostly used in parking lots or in little impervious areas (e.g. gas stations). They are sectional tanks with sedimentation and oil separation filters. These prefabricated devices are really convenient because they present a very compact design and they are ready-to-use after several connections at the end-of-pipe. In addition, there is no overflow from the treatment system.

On the contrary, the catchment saw in Cap. 3 is quite big, and the attitude of these kind of catchments is not the one from a single lot or a single impervious area: hydraulic behavior is completely different and flow may be higher than expected (e.g. high intensity storm events, climate changes), coming in different periods during the rain event; generally, these devices work in the range $30 \div 300\, L/s$. Furthermore, there is a huge contribution of solid material, so a serious management plan of the sediment section should be adopted. In this little communities, management actions must be reduced as much as possible, so this application may be really demanding. Finally, there are several contaminants which can pass through sedimentation and oil separation: in the first flush a lot of metals are dissolved so this solution may not be totally efficient. For these reasons, the continuum treatment of stormwater should be avoided in this catchment.

Scenario 2: first flush tanks and direct overflow

The second option for stormwater management in the little catchment can be the first flush tank. First flush tank volume has been evaluated in Cap. 4, responding to the Regional Law of Friuli - Venezia Giulia (or even more). This solution might be a good answer to the problem, because it can intercept a huge load of pollutants. First flush volume can be pumped to the centralized treatment plant by the same dry-weather pumps, and the volume can be formed into the existing

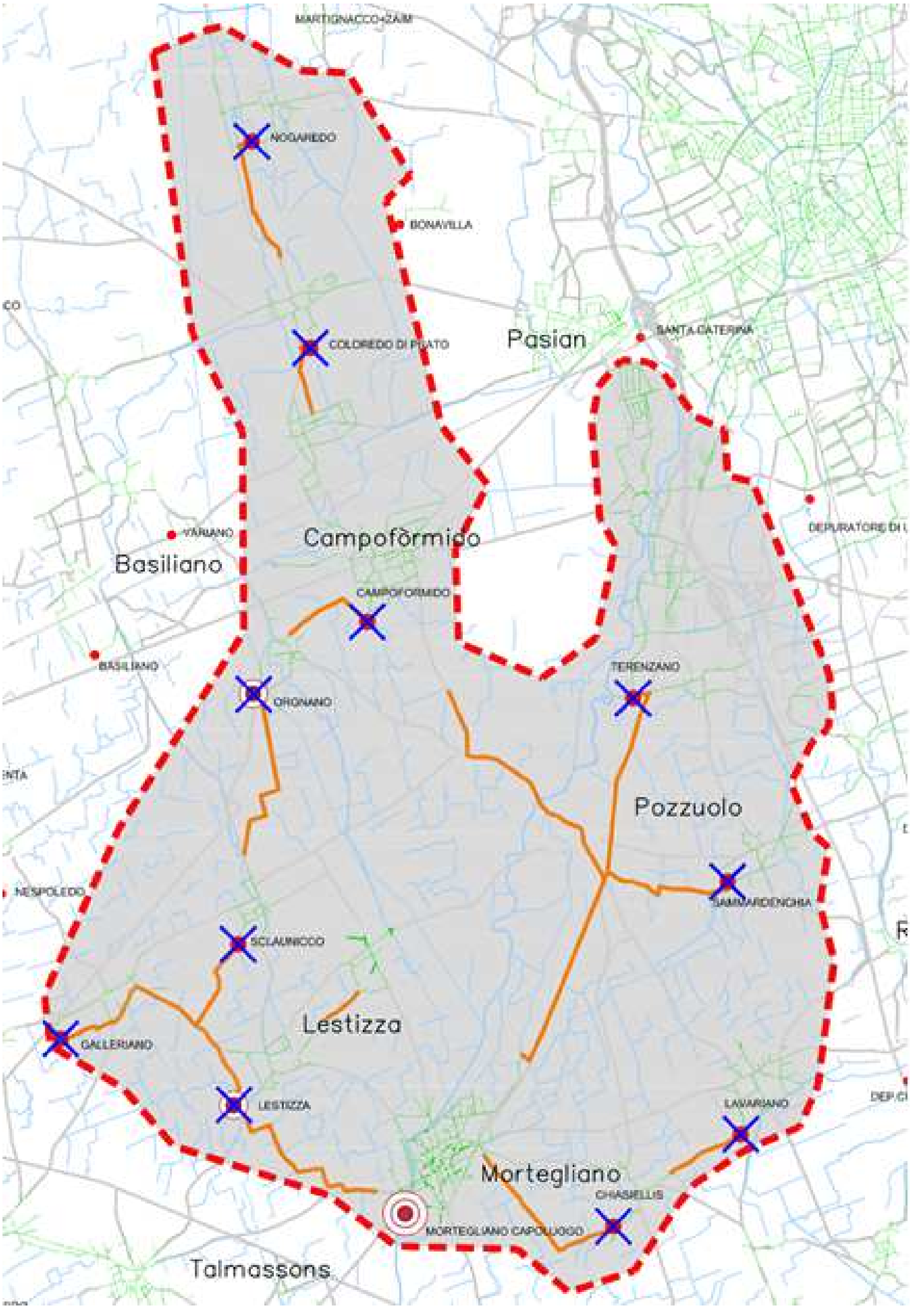


Figure 5.1: Map of sewer district of Mortegliano (Province of Udine) [143]

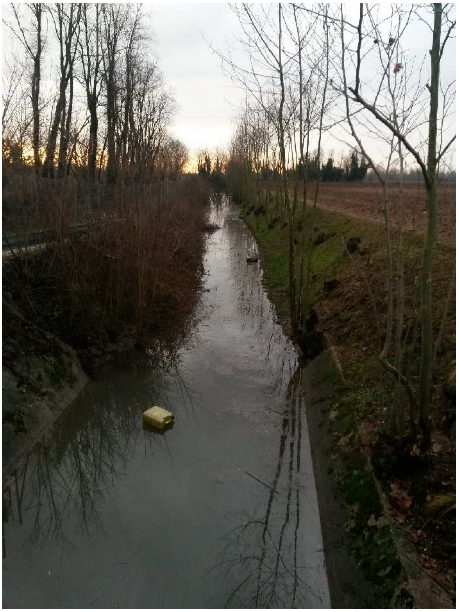


Figure 5.2: Trench channel after a huge storm event (October 2016) : according to depth level, a big volume can be stored in it

channel (Fig.). Overflow volume will be directly discharged in the infiltration pond without any other treatment, via bypass.

This solution could be great to get the first flush load and it can function in this catchment with this hydraulic behaviour: another rural or suburban catchment may have different features in stormwater quantity and quality. In this case, the remaining part of stormwater could be rich in pollutant load during the total event, even if the concentration is lower than the first flush. In addition, combined sewer overflow may discharge priority and toxic pollutants (cfr. Par. 2.4 and Par. 4.3). Finally, this configuration presents several risks in case of a breakdown, a second intensive flush or a floodgate block: there is the need to preserve infiltration from this happenings.

Scenario 3: first flush tanks and secondary treatment

Last but not least, the more comprehensive scenario is the configuration with a first flush tank and a secondary treatment by phytoremediation or by a set of treatment block as saw in the first scenario. Certainly, the treatment of the first flush volume will be demanded to a centralized wastewater treatment plant. The target of secondary treatment (i.e. phytoremediation) is to catch toxic compounds by filtrating into the soil and absorption by plants: this solution permits to save a lot of energy and management action. Even if the efficiency of stormwater load retention is demanded to the tank, secondary treatment ensures another filter before discharging stormwater into the infiltration pond. Considering this solution means to occupy the same area as before, but infiltration could be improved in terms of quality as much as possible ([144], [145]).

Coming next

In conclusion this thesis opens a narrow path to awareness of artificial stormwater infiltration in the Friuli - Venezia Giulia Region. Laboratory analysis and stormwater modeling showed interesting results in order to improve quality of infiltration, but there is still a lot to do.

First of all, quantity measuring campaign should be integrated with intense events: the hyetograph reported did not get all the information about stormwater volume because of the scarcity of rainfall events. This problem may be quickly solved, so this is not the main issue in order to continue and finish this work. Furthermore, groundwater sampling is needed: characterization of pollutants in groundwater nearby the infiltration pond could be helpful to a more comprehensive modeling of groundwater layer. Tracer tests will be useful for this target, and the hope is to evaluate the fate of pollutants in groundwater streams.

Secondly, the fate of pollutants must be evaluated as an ecotoxicological risk for the environment: a huge quantity of this groundwater comes out below the karst spring line, so a scientific analysis of this issue must be developed. Laboratory analysis should also improve the knowledge about phytoremediation proposed in the third scenario: assessing the efficiency of the system could be an optimum way to promote this best management practice in all the sewer district for a complete and integrated solution.

Laboratory analysis, field observation and measurements will permit an hazard identification and risk characterization: a development of regulatory options will be done by the scientific awareness of storwmater issues. Water industries, social communities, scientific and academic worlds must work together with water regulators, because water is a public resource and a human right which must be preserved.

List of Figures

List of Tables

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Conferences and Publications

This Ph.D. program was really helpful for participating at International Conferences and for publishing proposals. Several works and data are needed in order to continue this work and to get some other scientific results to share with the scientific and technical community.

Publications

- M.Trigatti, D. Goi, "**Sustainable stormwater management: an analysis of the industrial area of Buja & Osoppo (Udine)**", Gjornâl Furlan des Siencis (Friulian Journal of Science), (2012-13), 17:19-28. (preparatory study for PhD and Master Degree)

- M.Trigatti, R. Perin, M. Nicolini, D. Goi, "**Stormwater quantity and quality for sustainable management of runoff in an industrial district. Preliminary analysis and modelling of first foul flush effect**", Journal of Multidisciplinary Engineering Science and Technology (JMEST), Vol. 3 Issue 7, July – 2016; ISSN: 2458-9403. (http://www.jmest.org/vol-3-issue-7-july-2016/)

Poster sessions

- M. Trigatti , R. Perin , M. Nicolini , D. Goi, "**Preliminary Analysis of stormwater runoff and pollutant washoff in an industrial district**", Prooceedings of 13th Specialized Conference on Watershed and River Basin Management, 9-12 September 2014, San Francisco (USA).

- M. Trigatti , R. Perin , M. Nicolini , D. Goi, "**Quality stormwater modeling in small suburban catchments: a case study**" Prooceedings of International Conference on Sustainable Water Management; 29 November to 3 December 2015 at Murdoch University, Perth, Western Australia.

- Poster award at the "**Premia il Poster**" organized by the University of Udine for the "PhD Expo UniUd 2016". The poster "**Ingegneria della pioggia. Approccio multidisciplinare per l'analisi dell'impatto ecotossicologico e la gestione sostenibile delle acque meteoriche di dilavamento**" was the most voted in the technical-scientific area of research.

Oral presentations at conferences

- M. Trigatti , R. Perin , M. Nicolini , D. Goi, "**Using EPA-SWMM in quality stormwater modeling: calibration and design strategies**". In: M.R. Boni, P. Sirini, A. Chiavola, A. Polettini, R. Pomi, P. Viotti, A. Rossi. Book of Abstracts, (2016), X International Symposium on Sanitary and Environmental Engineering, SIDISA 2016. Rome, 19-23/06/2016, 145, ISBN: 978-88-496-391-1.

- M. Trigatti, R. Perin, M. Nicolini, D. Goi "**Infiltration ponds in small urban catchments: stormwater modeling and sediment contamination assessment**". Proceedings of IWA Regional Conference on Diffuse Pollution and Catchment Management - Book of Abstracts (2016) DCU Water Institute (Dublin) - 23rd-27th October 2016.

Teaching activities

- Seminar lecture on "**Sustainable management of runoff**" at the Corp of Engineers of Udine during the "Innovative solutions for water infrastructure design", April-June 2015.

- Seminar lecture on "**Stormwater management in rural communities**" at IRES FVG in an educational training for Carniacque SpA & Poiana SpA, November 2015

- Seminar lecture on "**Modeling stormwater in quantity and quality: first flush assessment**" at the Corp of Engineers of Udine during the"Innovative solutions for water infrastructure design", April-June 2016.

- Seminar lecture at the University of Udine **for the students of Sanitary Engineering class**, June 2016

Attended Workshops&Seminars

2014

- SAIE fair in Bologna - October 2014 - seminar "**Sistemi idraulici urbani: tra sostenibilità ambientale e cambiamenti climatici**" organized by CSDU (Centro Studi Deflussi Urbani)

2015

- Corp of Engineers of Milan - September 2015 - workshop "**La progettazione e la gestione degli impianti MBR**"
- EcoMondo fair in Rimini - November 2015 - seminars "**Pompaggio nei sistemi di fognatura**" and "**Controllo in tempo reale delle fognature**" organized by CSDU (Centro Studi Deflussi Urbani)

2016

- FAST srl in Milan - January 2016 - seminar "**Acqua potabile, problemi emergenti**"
- FAST srl in Milan - February 2016 - seminar "**Impianti di depurazione avanzata**"
- FAST srl in Milan - February 2016 - seminar "**Verifica e collaudo impianto di depurazione**"
- University of Pavia - - May 2016 - Summer school attended at the Villa del Grumello Foundation in Como "**S**ustainable **W**ater-Energy-**C**entric **C**ommunities (**SWEC**)"
- SAIE fair in Bologna - October 2016 - seminar "**Il controllo degli scarichi nelle fognature**" organized by CSDU (Centro Studi Deflussi Urbani)
- DHI Group in Genova - November 2016 - practical workshop "**Advanced Modelling of WWTP with WEST**"
- EcoMondo fair in Rimini - November 2016 - seminars "**Gestione degli scarichi e tutela della balneazione**" and "**Gestione Acque Meteoriche in ambito urbano: situazione attuale e prospettive**"

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