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# Comparison of Different Scenarios of Suspended Solids Production in a Combined Sewer System Using an Adapted Hydrodynamic Model

**par**

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# Abstract

Despite their disappointing performance, urban stormwater quality models are still considered to be a potentially efficient decision making tool to control combined sewer overflows (CSOs) and thus are receiving ongoing investments to improve their quality. In this respect, in-sewer sediments are now widely recognized for their preponderant contribution to the pollution of CSOs assigning therefore a particular importance to mastering sewer processes module when refining these models. Recent studies conducted on in-sewer sediments in one of the extensively investigated urban catchments in Paris, Le Marais, highlighted new elements that could be helpful when addressing this module: (1) the existence of quasi-steady sewer grits deforming sewer characteristics and thus suspected to modify sewer flow conditions; (2) the identification of the potentially eroded sediment type during wet weather that is formed at the upstream parts of the Marais main trunks, the organic layer, that showed a cohesive like characteristic during in-situ flushing experiments. A site specific model for the Marais catchment is developed in this thesis adopting a semi-distributed configuration to examine the effect of integrating these field observations in its structure on the simulation of outfall discharges' quality.

In the first part, an evaluation of the impact of considering the sewer grits in the hydrodynamic module on the solid production and transfer processes in sewer system was carried out. To do so, a special modelling tool was necessary in order to handle sewer flow over a complex bathymetry. So, a well-balanced Godunov numerical scheme was developed and verified against some reference test cases before being extended to the Marais sewer scale. Results showed a significant impact of these coarse deposits on the hydraulic parameters. Solid production was demonstrated to be more sensible to this impact than the transfer processes.

In the second place, previous findings obtained on combined sewer systems having no organic layer and high sewer contribution along with those obtained on the Marais were deeply investigated to identify the real role of this organic layer in sewer wet weather production. Results showed that this latter is only a minor source for wet weather erosion. To identify the major source, a quality module based on Skipworth erosion formulation and simple advection equation was used to test several scenarios of sewer sediment localization. The benchmark confirmed that the organic layer is not the major source of sewer production and that another source is preponderant and that can be located at the upstream branches as well as along the principal collectors with more probability of the former case.





# Résumé

Malgré leurs mauvaises performances, les modèles de calcul de flux polluants (MCFP) dans les rejets urbains de temps de pluie (RUTP) continuent à susciter de l'intérêt du fait du fort potentiel qu'ils présentent pour prédire et contrôler ces RUTP. La contribution des sédiments à la pollution des RUTP est aujourd'hui largement reconnue comme prépondérante ; en conséquence, une modélisation idoine des processus en réseau apparait comme un élément clé pour améliorer la qualité de ces modèles. Dans ce contexte, plusieurs éléments ont été révélés par des études récentes menées sur les dépôts de réseaux d'assainissement unitaires, notamment sur « Le Marais » : (1) la présence d'une quantité importante de dépôts grossiers quasi-stationnaires qui modifient les caractéristiques du réseau ainsi que les conditions d'écoulement ; (2) l'identification d'un dépôt organique cohésif sur le Marais, la couche organique, capable d'expliquer la contribution du réseau à la pollution de RUTP et qui se constitue dans les parties amonts des collecteurs principaux. L'objectif de cette thèse est d'examiner l'effet de l'intégration de ces observations dans un MCFP de type semi-distribué, en prenant comme cas d'étude le site expérimental du Marais.

Dans la première partie, on a travaillé à la prise en compte des dépôts grossiers dans le modèle hydrodynamique, puis on a évalué l'impact de cet ajout sur les processus de transport solide dans les réseaux. Pour y parvenir, un outil de modélisation capable de gérer l'écoulement sur une bathymétrie complexe était nécessaire. Ainsi, un schéma numérique conservatif de type Godounov a été développé et validé par rapport à certains cas de référence, avant de l'appliquer à l'échelle du réseau du Marais. Les résultats ont démontré un effet significatif de ces dépôts grossiers sur l'hydraulique du réseau, qui ensuite influence la production des particules et, dans une moindre mesure, le processus de transfert.

Dans la deuxième partie, des données acquises récemment sur plusieurs sites avec des contributions de dépôts aux RUTP comparables et d'états d'encrassement différents (notamment pour la couche organique) ont été analysées dans le but d'identifier le vrai rôle de cette couche organique vis-à-vis de la production en réseau par temps de pluie. Les résultats ont montré que la couche organique ne représente qu'une source mineure vis-à-vis de la production en réseau. Afin d'identifier la source majeure, le modèle hydraulique développé dans la première partie a été couplé avec le modèle d'érosion de Skipworth et le modèle d'advection simple pour tester différents scenarii de localisation de dépôts. Les résultats de ce banc d'essai sont cohérents avec ce qui précède concernant la contribution de la couche organique ; il en ressort par ailleurs que les localisations les plus vraisemblables de la source prépondérante sont, dans l'ordre, le réseau amont et les collecteurs principaux.





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# General Introduction

## General context

Combined sewer networks are water drainage systems designed to convey towards treatment plants foul wastewater during dry weather and a mixture of foul wastewater and stormwater during wet weather. When input volumes into these plants surpass their capacity, usually limited to 2.5-3 times the maximum dry weather flow rate, excess amounts are directly discharged into the watercourses without any treatment through Combined Sewer Overflow (CSO) devices. During the last few decades the high rate of urbanization increased the wastewater and stormwater volumes and consequently the risk of treatment plants saturation during wet weather conditions and thus the frequency of CSOs. The pollution of these discharges has become widely acknowledged among researchers, urban sewer managers, and governments that established legal framework to control the quality of these point discharges.

So, several management policies were enacted around the world: European directive 2000/60/CE, LEMA in France (Loi sur l'Eau et les Milieux Aquatiques) 2006… that require the consideration of these risks in all strategies of water management. It became urgent in order to respond to these challenges to acquire more knowledge about the quantities, sources, impacts and mechanism of the CSOs. This was the origin of a number of research programs that were conducted worldwide to provide all necessary elements to estimate and control this pollution: NURP (1978-1983), French campaigns (1980-1982), QASTOR (Saget, 1994), OPUR (1994-), OTHU (1999-), ONEVU (2006-)…

These studies shed light on the importance of the pollution of CSOs with the majority of contaminants found to be transported by the suspended solid vector. Investigations on the origin of these particles demonstrated the major role of sewer deposits and thus the importance of mastering in-sewer processes in order to reduce the release of pollutants from sewer system. This has driven researchers to scrutinize all aspects concerning sewer deposits to construct a considerable body of detailed data on their characteristics, their contribution to CSOs, the mechanism of their sedimentation and erosion all being employed to propose practical measures to manage this source. This objective has often been linked to the development of sewer sediment transport model intended to be applied on a wide scale to efficiently and economically achieve this goal.

Numerous mathematical tools were therefore developed by researchers since the 1970 to calculate the pollutographs during storm events at combined sewer outfalls. These models are composed of two joint modules: hydrological-hydraulic module and sediment and quality module. The first approaches adopted were almost purely conceptual. Then, with the advance





in scientific knowledge about mechanisms governing sediment production and transport as well as increasing computing capacities, enabling solving complex hydrodynamic equation and modellers tended to include them in the model formulation. However, since the rate of quality module improvement wasn't in pace with the quantity one, most researchers' efforts were focused on the former module. The description of quality processes in these models is however still not far from those adopted in the pioneer approaches due to several reasons: (1) complexity of processes governing water quality processes, (2) difficulty of carrying extensive measurements to determine all necessary information on sediment characteristics, (3) the huge spatial and temporal variability of all aspects of phenomenon of sewer processes. So, latest investments in this field were made in the calibration procedures used to optimize these models. Advanced calibration techniques were thus implemented to analyse the performance of these conceptual models, assess their sensitivity to their parameters, evaluate the uncertainty associated to their parameters' estimations, and evaluate their predictive capacity. Although these techniques showed to be robust and efficient in optimizing the model parameters and improving their mathematical structure, the modelling results were still unsatisfactory (Kanso, 2004; Métadier, 2010).

## Thesis framework

As said before, most attempts of improving these models have concentrated on refining and calibrating the quality module considering that the hydraulic one is satisfactory. However, this hydraulic model was designed and evaluated based on the good agreement between measured and simulated hydrographs at sewer outfall. This approach does not guarantee a good representation along the whole sewer network of the hydraulic parameters that are determinant for solid transport processes (flow depth, flow velocity, shear stress). Moreover, the presence of coarse deposits substantially modifies the profile and cross section of the sewer collectors and thus impacts the hydraulic parameters quoted here above. This effect is seldom accounted for in the available models since this requires robust numerical schemes capable of handling the variability of collectors' characteristics which demand high computational time.

Parallel to these modelling efforts, field studies were continuing to exploit new techniques of data acquisition and constructing a rich detailed database not only on the outfall discharges but also on sewer deposits characteristics and mechanism that opens new perspectives in the modelling arena. Results obtained confirm the importance of the erosion of deposits during wet weather in the combined sewer systems, but diverge concerning the nature and location of this source. For instance, the role of the organic layer observed on the Marais catchment is still ambiguous.

Based on all these elements, the thesis work aims at three following objectives:





1. Evaluate the interest of a distributed hydrodynamic model specifically adapted to collectors of highly varying slope and sections and assess the spatial resolution of data required to efficiently operate this model
2. Exploit the database acquired in the two observatories OPUR and OTHU in order to obtain a coherent vision concerning the contribution of different possible sources of suspended solids to wet weather pollution discharges in combined sewers
3. Develop a solid transport model relying on a suitable hydrodynamic model and apply it on a well-documented catchment in order to assess whether available knowledge is sufficient for predicting wet weather pollutographs, with some assumptions to fill the gaps.

## Thesis structure

The thesis dissertation is structured in three parts:

The first part presents a state of the art about the knowledge and models of the source and processes implied in wet weather pollution in combined sewers. A focus is made on the Marais catchment for which many investigations and data acquisition were performed.

In the second part a new numerical method is developed for solving the shallow water equation for a better handling of highly varying collector geometric characteristics, especially those induced by high coarse sediment levels. This hydraulic model is then coupled with an adapted solid transport module in order to evaluate its interest for our specific application.

In the third part the data available in several catchments in SOERE URBIS database were thoroughly analysed to consolidate assumptions on SS sources. Then a water quality model is built on the basis of the improved hydraulic representation made in Part I and of Skipworth solid production model, and different scenarios of in-sewer suspended solid sources are tested.







# PART I

## STATE OF THE ART

## &

## DATASET PRESENTATION



# Chapter 1
# State of the art

## 1. Pollution of Urban Wet Weather Discharges (UWWD)

Urban drainage problems have been long restricted to public health and flood protection (Chocat et al., 2007). Only in recent times with the growing rate of urbanization, a scientific awareness has arisen on the substantial stress these urban drainage systems have on their surrounding environment (Freni et al., 2008). The huge expansion of urban development entailing more imperviousness (Paul and Meyer, 2001) led to a faster process of stormwater drainage with a significant increase in the discharged volume and peak flow (Schueler, 1994; Booth and Jackson, 1997; DeFries and Eshleman, 2004). A large part of runoff water is conveyed to underground sewer systems where, in the case of combined sewer systems, it is mixed with the wastewater generated by domestic, commercial, and industrial sectors. During severe storm episodes, the drainage capacity of sewer infrastructures is not sufficient to convey the combined sewer flow to downstream treatment plants and thus excess water is released through overflow facilities directly into the receiving water bodies without or with partial treatment. These discharges called combined sewer overflows (CSOs) (Butler and Davies, 2004) were studied by numerous research projects realized in different countries in which extensive experimental campaigns were conducted to observe, identify and evaluate the pollutants loads, characteristics and impact on receiving water bodies: QASTOR (Saget, 1994), Generation and transport of the pollution of UWWD in combined sewer system (Chebbo et al., 2006), OTHU (1994-), OPUR (2001-). Results of these studies highlighted the following points:

**Pollution loads:** high levels of contaminants mass and concentration: organic, microbiological, organic and mineral micropollutants, nutrients (particularly phosphorus), and pathogenic microorganisms (Seager and Abrahams, 1990; Chambers et al., 1997; Suarez and Puertas, 2005; Gasperi et al., 2008; Phillips and Chalmers, 2009; Weyrauch et al., 2010; Zgheib et al., 2011; Phillips et al., 2012; Madoux-Humery et al., 2013).

**Pollutant characteristics:** a dominant particulate nature for the majority of the analysed pollutants (Chebbo and Bachoc, 1992; Aalderink et al., 1990). The Total Suspended Solids (TSS) was then considered to be the major vector of most of the contaminants released in the receiving water bodies. Table 1-1 gives the particulate proportion of several types of contaminants measured in wet weather effluents in the sewer of several urban catchments. As an average, more than 80% of organic materials and between 40% and 99% of metals are transported in particulate form. For other sites, the reader is referred to (Kafi-Benyahia, 2006).

Table 1-2 provides an order of magnitude of the Event Mean Concentration (EMC) of TSS observed in sampling campaigns conducted in some countries. Values obtained show high contamination levels of suspended solids with remarkable variability between sites and between rainfall events on the same site.

| % Pollution linked to particles | COD | $BOD_5$ | Cd | Cu | Pb | Zn |
|---|---|---|---|---|---|---|
| Marais (1) | 64-94 (82) | 59-95 (80) | 90-100 (99) | 87-99 (96) | 91-99 (86) | 38-99 (88) |
| Clichy (2) | - | - | 49-86 (73) | 83-98 (91) | 66-97 (87) | 65-90 (80) |
| Boudonville (3) | - | - | - | (95) | (98.5) | (97) |
| Collector 13 (4) | 83-92 | 83-91 | - | - | 82-99 | - |

(1) Gromaire (1998), (2) Saget (1994), (3) LHRSP and Laurensot (1998), (4) Chebbo (1992)

*min-max (mean)*

***Table 1-1:*** *Percentage of pollution carried by particles of urban discharges as an average on rainfall event*

| Catchment | | EMC (mg/l) | Catchment | | EMC (mg/l) |
|---|---|---|---|---|---|
| 1 | Sweden | 5;857 (152) | 10 | Quais, Paris | 186 – 356 [265] |
| 2 | United States | (305) | 11 | Clichy centre, Paris | 187 – 320 [250] |
| 3 | Munich-Harlaching | (163) | 12 | Coteaux aval, Paris | 277 – 401 [381] |
| 4 | Stuttgard-Busnau | (177) | 13 | Clichy aval, Paris | 203 – 297 [259] |
| 5 | Base "QASTOR" | (240) – (670) | 14 | BBW site, Korea | 656 |
| 6 | Coteux channel, Paris | 118;508 (260) | 15 | YMW site, Korea | 74 |
| 7 | Lelystad, Netherlands | (39.5) | 16 | MSW site, Korea | 1021 |
| 8 | Marais, Paris | 121 – 519 [221] | 17 | Santiago de Compostela, Spain | 281;394 (309) |
| 9 | Sebastopol, Paris | 263 – 409 [322] | 18 | Ecully, Lyon | 13;1433 (260) |

1,2 (Hoghland et al., 1984); 3,4 (Geiger, 1986); 5 (Saget and Chebbo, 1996); 6 (Philippe and Ranchet, 1987); 7 (Aalderink et al., 1990); 8 (Gromaire, 1998); 9,10,11,12,13 (Kafi-Benyahia, 2006); 14,15,16 (Lee and Bang, 2000); 17 (Diaz-Fierros et al., 2002); 18 (Métadier, 2011)

(x): (mean) [x]: [$d_{50}$] $x_1 – x_2$: $d_{10}$-$d_{90}$ $x_1;x_2$: min;max

***Table 1-2:*** *Order of magnitude of EMC of TSS in combined flow at sewer outfall*

**Impact on receiving waters:** the major role of wet weather discharges in downgrading the urban surface streams quality by modifying the ecological functioning and increasing the concentration of dangerous substances (Mulliss et al., 1997; Even et al., 2004; Blumensaat et al., 2011; Passerat et al., 2011; Gosset et al., 2016). Many types of impacts have been identified: decrease in the oxygen concentration (Harremoës, 1982; Hvitved-Jacobsen, 1982; Paul and Meyer, 2001), the toxicity effects on phytoplankton from heavy metals (Seidl et al., 1998), the impact on the microbiological water quality (Armstrong et al., 1980; Passerat et al., 2011), endocrine disruptions due to some micropollutants (Cladière et al., 2011), and the possible

impacts on fish mortality of hypoxia and un-ionized ammonia (Magaud et al., 1997; Boët et al., 1994).

∴ Being highly loaded with pollutants, Combined Sewer Overflows (CSOs) are considered a serious danger on the quality of urban watercourses whose protection starts by controlling these discharges. A major part of the pollution in these CSOs was found in particulate form (TSS).

## 2. Origin of pollution in Urban Wet Weather Discharges

In an attempt to limit the impacts of these discharges, a legislative framework was established demanding stringent regulations of the CSOs to ensure the ecological restoration of all surface waters: Water Framework Directive EU/2000/60/EC (European Council, 2000), Directive 91/271/CE on treatment of residual urban water, Urban Pollution Management Manual (FWR, 1998), Swiss STORM method (VSA, 2007), ATV German standards (ATV, 1992), and France regulatory guidelines (CERTU, 2003)…

This has prompted research initiatives to investigate different aspects of these discharges and provide helpful elements for the development of efficient control strategies. In this respect, a key factor after the evaluation of the pollutants loads in these outflows is the identification of the different origins and their relative contribution. So, many studies (e.g. Gromaire et al., 2001) were carried out to determine and quantify the sources producing these pollutants based on field work along with some hypotheses that were sometimes questionable and other times valid. Results of these studies are summarized in table 1-3 below.

On urban catchments, we can distinguish between three sources of solid particles:

1. Particles' load washed from different urban surfaces (roads, roofs and courtyards)
2. Particles' load transported by the dry weather flow in the sewer system
3. Particles' load mobilized from in-sewer sediments by wet weather flow

Krejci et al. (1987) evaluated the contribution of different sources on 4 rainfall events in a 12.5 ha catchment area of Zurich which is a fully developed and urbanized residential area having 5.3 ha covered by roofs and roads. The sewer slope varies between 0.5% and 10% with circular sewer channels of diameter varying between 30cm and 90cm. The hypotheses made were:

- The mass of pollutants attributed to wastewater was evaluated by TSS flux measured in dry weather.
- The mass of pollutants produced by runoff flow is estimated from the annual mean concentration of TSS measured 10 years earlier in a stormwater network.
- A distinction was made between 2 types of sewer deposits: sediments and biofilms, where the mass of sediments eroded was estimated from experimental flushing during dry weather period, and those susceptible to be generated from biofilms were evaluated from the surface of biofilms observed and analysed on another site.

Chebbo (1992) computed the contribution of each source on annual scale based on a simulation made on a theoretical catchment where certain hypotheses were made:

- The total load of contaminants conveyed by wet weather flow to the outfall of combined sewer system was calculated from annual mean concentration of wet weather effluents measured on 4 combined sewers.
- The pollutants mass in wastewater was evaluated from effluents measured during dry weather at the outfall of the same sites.
- The pollutants' mass produced by the runoff flow was calculated from total volume transported by wet weather flow to the outfall of combined sewer systems and a mean annual concentration established from measures made at the downstream of seven storm sewers.

Another estimation of the contributions of the three predefined sources to SS mass and organic matter was carried out by (Bachoc, 1992) on the watershed 13 in Marseille (average slope = 5%, impervious coefficient = 87%) during two rainfall events of high intensity preceded by long dry weather period. The hypotheses made were also strong considering that:

*For mass balance:*

- Production of suspended solids from wastewater is considered negligible for these two rainfall events.
- Contribution of sewer deposits is less than or equal to the average calculated on some Parisian sewers (≤44%).
- Runoff water contribution for these 2 rainfall events is greater than the mean annual contribution calculated by (Chebbo, 1992).

*For VM balance:*

- VM content in the TSS coming from the runoff water is between 17% (maximum value found during rainfall events at the outfall of 4 stormwater networks) and 35 % (double the previous value to take into account that the watershed 13 is situated in the downtown and thus the organic content of runoff water should be higher).
- VM content in the TSS coming from sewer deposits is less than the VM content in particles of dry weather wastewater (≤80%).

Much more reliable evaluations of different sources quotas were later carried on in the framework of OPUR project that sought to investigate the source, characteristics, and mechanism of generation and transport of pollutants in sewer system. In its first phase, Gromaire (1998) assessed the sewer deposits' contribution on the 42 ha watershed of "Le Marais" by the means of mass balance of pollutants entering and exiting the sewer network. The originality of this study was the important number of rainfall events considered with respect to the preceding studies (31 rainfall events of intensities varying between 1.1 mm/h

and 35.5 mm/h) along with the evaluations based on values measured on the same site and for the same rainfall events. Once again, some assumptions that smear the results with uncertainties were indispensable for the calculations:

- Transposition of wastewater concentration measured in dry weather conditions to calculate its contribution during rainfall events.
- Extrapolating the TSS concentration measured for runoff flow on certain surfaces to other areas with same surface type for the whole watershed
- The mass of pollutants carried by runoff water is measured at the inlet point of the sewer and assigned to this source (runoff) at the outfall point, not considering the possible deposition of solids between these 2 points.

In the second phase of OPUR, further studies were carried out to find out whether the contribution results obtained on "Le Marais" are specific to this site or can be generalized to the whole sewer system of Paris. Thus, six watersheds of growing size and comparable land use were outfitted with experimental observatories in the thesis of (Kafi-Benyahia, 2006) in order to quantify the contribution of the different sources to pollutants' transport rate at their outfalls during 5 to 16 rainfall events using the same method of mass balance used in (Gromaire, 1998).

On the two sites: Clichy in Paris and Ecully in Lyon having different sewer characteristics, (Hannouche et al., 2014) assessed the contribution of each of the three sources of pollutants (wastewater, runoff water, and sewer deposits) to the pollutants' mass of a rainfall event. The originality of this study resides in two main points: the size of database used, the new techniques (continuous monitoring) used to acquire this big database. Similar to its previous matches, this study called for some hypotheses in its calculation procedure:

- The relation used to transform the continuous measurements of turbidity to concentration on Clichy site wasn't established on the same studied site, but taken from another site
- Considering wastewater concentration measured in dry weather the same as that during rainfall events (as all previous authors). The impact of this hypothesis was tested in (Hannouche, 2012) who estimated the TSS mass generated from wastewater and that won't settle in wet weather flow conditions. Results show that the hypothesis made on wastewater in the mass balance calculations does not induce more than 10% overestimation on the sewer deposit contribution and consequently an equal underestimation of that of wastewater.
- Attributing values of TSS concentration of runoff water taken from measurements on "Le Marais" site and from literature data to the runoff water on Clichy and Ecully site respectively.





| Reference | Watershed | Rainfall events | WWC (%) | SRC (%) | SDC (%) |
|---|---|---|---|---|---|
| (Krejci et al., 1987) | Pilot basin in Zurich | 4 | (6) | (35) | (59) |
| (Bachoc, 1992) | Catchment 13, Marseille | 2 | <15 | >56 | 30-44 |
| (Gromaire, 1998) | Marais | 31 | 4-43* [21] | 9-25* [15] | 40-81* [64] |
| (Kafi-Benyahia, 2006; Gasperi et al., 2010) | Marais | 14 | 9-39* (21) | 3-18* (9) | 54-82* (70) |
| | Sébastopol | 3 | 23-47* (30) | 5-7* (6) | 46-72* (64) |
| | Quais | 4 | 23-58* (32) | 4-12* (16) | 38-61* (56) |
| | Clichy center | 13 | 29-68* (42) | 5-13* (9) | 22-60* (49) |
| | Coteaux downstream | 8 | 16-45* (24) | 6-12* (11) | 48-70* (65) |
| | Clichy downstream | 7 | 24-69* (37) | 5-16* (12) | 24-60* (51) |
| (Hannouche et al., 2014) | Clichy | 88 | 32-48** [41] | 7-13** [11] | 42-57** [50] |
| | Ecully | 239 | 11-43** [24] | 11-32** [22] | 30-62** [48] |

WWC: Wastewater Contribution
SRC: Surface Runoff Contribution
SDC: Sewer Deposits Contribution
[$d_{50}$] (Mean) * : $d_{10}$-$d_{90}$ ** : $d_{25}$-$d_{75}$

***Table 1-3:*** *Contribution of three sources (wastewater, surface runoff, sewer deposit) to TSS load at sewer outfalls*

∴ All the studies cited above converge in their ranking of the relative contribution of the three sources, coming in the following decreasing order of importance: exchange with the deposits, wastewater, and runoff. In general, a large portion of TSS is produced by the sewer deposits; a moderate to important percentage comes from the wastewater, and a weak contribution of runoff except for Krejci et al. (1987) and Bachoc (1992) where the evaluations were based on annual scale measurements taken on another site drained by storm sewer. So, control of CSOs pollution discharge can be attained to a big extent by controlling the sewer sediments production.

# 3. Sewer deposits

Pollutants in CSOs were shown to be basically produced from erosion of in-sewer sediments by wet weather flow although no clear relationship between pollutant loads and the characteristics of rainfall events and those of the watershed (Gromaire, 1998). This has oriented research concerns towards this "big player" that once mastered might help reduce the impact of these CSOs. The objective was to examine the characteristics, composition, and mechanism of these deposits in different flow conditions to understand and possibly control their contribution.

## *3.1. Composition and Characteristics*

All field surveys on sewer sediments have reported that these sediments can't be considered as unique entity but a compound structure typically formed of three distinct components:

(1) Sewer grits accumulated on the channel bed and are predominantly mineral that are sometimes consolidated and other times loose depending on the hydraulic conditions and deposits' age
(2) Organic pipe wall slimes and zoogloeal biofilms formed around the mean flow level
(3) Organic near bed materials

### 3.1.1. Sewer grits

The first type was identified by almost all researchers (Crabtree, 1989; Bachoc, 1992; Verbanck, 1992; Ristenpart, 1995) who realized detailed fieldwork programs on sewer deposits and noticed the prevalence of coarse mineral materials accumulated on the bottom of sewer channels. This stock is found to be formed of the granular particles washed from the surface by runoff flow and entering through gully pots into the sewer system that, due to their high density, can't be hold suspended for long distances especially in the slow flow zones and thus settle down early after joining the sewer system. So, they are found in significant amounts at the upstream of the sewer channels and are cohesive and consolidated and thus difficult to erode. The table 1-4 below shows some order of magnitude of density, organic content, and metallic content of this type of deposits.

| Watershed (reference) | Dundee (Crabtree, 1989) | Marseille channel 13 (Bachoc, 1992) | Bruxelles (Verbanck, 1992) | Hildesheim (Ristenpart et al., 1995) | Marais (Ahyerre, 1999) and for metals (Garnaud, 1999) |
|---|---|---|---|---|---|
| MVS/TSS (%) | 2.77 – 27.69 (7) | 2 – 17.6 (7.7) | 2 – 6 | 3.6 – 11.8 (7.6) | 3 – 13* (4) |
| COD/TSS ($gO_2/g$) | 0.006 – 0.079 (0.023) | – | – | 0.014 – 0.269 (0.069) | 0.06 – 0.22* (0.16) |
| $BOD_5$/TSS ($gO_2/g$) | 0.001 – 0.04 (0.005) | – | – | 0.003 – 0.089 (0.014) | 0.01 – 0.058* (0.017) |
| Density ($kg/m^3$) | (1720) | 2510 – 2700 (2630) | 1510 | 1350 – 1820 (1560) | 2418 – 2800* (2593) |
| Cd (mg/kg) | - | - | - | - | 1.64 – 5.73* (3.9) |
| Cu (mg/kg) | - | - | - | - | 470 – 1230* (870) |
| Pb (mg/kg) | - | - | - | - | 1210 – 2280* (1870) |
| Zn (mg/kg) | - | - | - | - | 2461 – 5750* (4047) |

Min – max (mean)
* d10 – d90 (d50)
Grey shaded cells: Type A < 400 µm

***Table 1-4:*** *Characteristics of sewer grits on different combined sewer systems*

### 3.1.2.Biofilms

The biofilms are constituted of colonies of Zooglea formed intermittently on the sewer wall and have a filamentous and rough surface with a few millimeters thickness (Flemming, 1995). It was identified by many researchers (Crabtree, 1989; Krejci et al., 1987; Michelbach, 1995, Ahyerre, 1999; Garnaud, 1999; Oms, 2003) who observed the formation of this type of deposits on the sewer section walls. The constitution of this layer basically occurs during dry weather depending on the hydraulic conditions and the walls' roughness. It was found to be the most concentrated type of the deposits in terms of pollutants (Crabtree, 1989) with high organic content and high concentration of heavy metals and micro-pollutants (Ahyerre, 1999). However, as the wall slimes are intermittent and difficult to sample, little attention has been given to them (Ashley and Crabtree, 1992). Organic and metallic content obtained when analysing this type of deposits are represented in table 1-5 below.

| Reference | MVS/TSS (%) | COD/TSS ($gO_2/g$) | $BOD_5$/TSS ($gO_2/g$) | Cd (mg/kg) | Cu (mg/kg) | Pb (mg/kg) | Zn (mg/kg) |
|---|---|---|---|---|---|---|---|
| Krejci et al. (1987) | - | (0.8) | - | - | - | - | - |
| Ahyerre (1999) | 39 – 81 (71) | 1 – 1.7 (1.4) | 0.26 – 0.62 (0.37) | - | - | - | - |
| Garnaud (1999) | - | - | - | 3 – 92 (13) | 500 – 15500 (2900) | 1300 – 29900 (3900) | 7000 – 157000 (21000) |

d10 – d90 (d50)
Grey shaded cells: Type A < 400 µm

***Table 1-5:*** *Characteristics of biofilms on different combined sewer systems*

### 3.1.3.Organic near bed sediment

This type of deposits has been the subject of long discussions among researchers who haven't yet reached a consensus in defining the identity of this interface in terms of composition, origin, build-up, transport and mobility. Chebbo et al. (2003) reviewed the different studies carried out on this sediment type on different sites: Belgium (Verbanck, 1995), Germany (Ristenpart, 1995), UK (Arthur, 1996), France (Ahyerre et al., 2000) in order to understand and establish a coherent overview on the different results obtained in these studies. It was reported that there is a general agreement on the organic nature of this sediment type but not on its transport mode. The divergence concerning this latter was attributed to the different ambient flow conditions between the studied sites and the different experimental methods used to sample/observe this sediment type. According to their composition and behaviour observed during different campaigns, this interface was given different denominations (Table 1-6).

| Denomination | Watershed | Reference |
|---|---|---|
| **Type C deposit** | Several sites, UK | Crabtree (1989) |
| **Near Bed Solids (NBS)** | Dundee, UK | Arthur et al. (1996) |
| **Organic layer** | Marais, Paris, France | Ahyerre (1999), Oms (2003) |
| **Fluid sediment:** | | |
| Organic near bed fluid sediment | Dundee, UK | Arthur et al. (1996) |
| | Hildesheim, Germany | Ristenpart et al. (1995) |
| Dense undercurrent | Brussels, Belgium | Verbanck (1995) |
| Dense layer | Nantes, France | Hemmerle (2014) |

***Table 1-6:*** *Different denominations of the fluid sediment organic solids*

#### *3.1.3.1. Type C deposit*

In his five-fold classification system of deposits (A-E) established on a number of sewers in UK, Crabtree (1989) described the interface between the sewer flow and the coarse deposits (Type A) by a mobile fine-grained deposits formed in slack flow zones, either in isolation or above coarse deposits. The rheological characterization revealed the weak cohesion of this thin layer that makes it easily erodible in a bed-load fashion during small storms event under the influence of small bed shears. It was also identified as being potentially important for polluting watercourses due to its strongest pollution concentration (Table 1-7) (Crabtree, 1989; Ashley et al., 1990; Ashley et al., 1992; Ashley and Crabtree, 1992). Samples analysed in these studies were all collected using a silt trap built inside the in-situ flume.

| Watershed (Reference) | Volatile content (%) | COD/TSS ($gO_2/g$) |
|---|---|---|
| Dundee sewers (Crabtree, 1989) | 50 | 0.076 |
| Dundee interceptor sewer (Ashley et al., 1990; Ashley et al., 1992) | 76 | 1.691 |

***Table 1-7:*** *Pollutants' content in Type C deposits on different sewer systems*

#### 3.1.3.2. Near Bed Solids

Near bed solids are defined by Arthur (1996) as all solid particles transported at the flow bed regardless of their physical and chemical characteristics. Three field data collection programs were conducted on Dundee site to study sewer sediments and pertaining processes between June 1992 and August 1995 on three different points of the sewer: one in a trunk sewer, another at the head of an interceptor sewer, and the other at the downstream end of the same interceptor sewer. Samples of the near bed solids were collected using a sediment trap compartmentalized into five to six rectangular containers fixed on the bottom of a PVC conduit installed on each site. The characteristics of the samples taken were so variable from one site to another and represent a variable volatile solid content at the same point and among the three points (Table 1-8).

| Catchment (Reference) | Site | Volatile content (%) |
|---|---|---|
| Dundee (Arthur et al., 1996) | Trunk | 1.0 – 61.8 |
| | Interceptor upstream | 12.5 – 83.9 |
| | Interceptor downstream | 55.6 – 87.6 |

***Table 1-8:*** *Pollutants' content (volatile matter) in the Near Bed Solids of Dundee sewer system*

#### 3.1.3.3. Organic layer

On the Marais sewer system, Ahyerre et al. (2000) developed a new observational system and another sampling one that permit to minimize the effect of the experimental procedures on in-situ observations and sediment sampling results:

- *The sampling system* comprised a PVC parallelepiped box (1.2m long x 50 cm wide x 55 cm high) open at both ends where two PVC watertight panels can be slid down to stop water from flowing into the box. The device is pushed down into the deposits with its length put along the flow direction, the panels are slid down, the sewage inside the box is pumped out until reaching the deposits surface that is sampled using a small shovel until reaching the coarse deposits. This method permits to take samples of the near bed organic sediments without influencing the structure of the deposits and thus to obtain

undisturbed samples that would be more representative than those taken by the multi-depth sampler where aspiration might occur blindly.

- *The observation system* is made up of a PVC box (1.5 m long x 55cm high x 11 cm wide) bevelled on the sides so as not to disturb the flow when pushed down the deposits and fixed against the side wall. Its front side is made up of glass and at the bottom there is a mirror inclined at 45° so that to reflect an image of the sewer sediments for a top viewer. This system was later improved by Oms (2003) who embedded the box into the side wall and installed an automatic camera system to capture photos reflected by the inclined mirror at a fixed time step (15 minutes). Oms (2003) employed another advanced technique to observe these deposits, i.e. the endoscope which is easily transportable and allows observing sediments without disturbing them.

| Catchment (Reference) | Number of samples | Sampling method | Volatile content (%) | | | COD content (g/g) | | | $BOD_5$ content (g/g) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | $d_{10}$ | $d_{50}$ | $d_{90}$ | $d_{10}$ | $d_{50}$ | $d_{90}$ | $d_{10}$ | $d_{50}$ | $d_{90}$ |
| Marais (Ahyerre et al., 2000) | 40-10-10 samples in the 3 main trunks | Pump | 58 | 64 | 74 | 1.40 | 1.60 | 2.10 | 0.26 | 0.28 | 0.54 |
| Marais (Ahyerre et al., 2000) | 5 samples on 2 points of VdT upstream | Sampling box | 60 | 68 | 76 | 0.90 | 1.15 | 1.43 | 0.19 | 0.30 | 0.362 |
| Marais (Oms, 2003) | 6 samples On 2 points of SG upstream | Sampling box | 51 | 76 | 82 | 0.63 | 1.55 | 1.88 | 0.20 | 0.40 | 0.60 |

***Table 1-9:*** *Pollutants' content in organic layer on the Marais catchment*

Ahyerre (1999) started his field investigations of this sewer type by sampling it using a multidepth sampler on a 50m space step along the three main collectors of the Marais sewer and then analysing 40 samples for the volatile content, 10 samples for the COD content, and 10 for the $BOD_5$ content (Table 1-9). Results obtained of these analyses showed similar characteristics to the fluid sediment observed on other sites. But when some difficulty was encountered in the mass balance closure on the sewer scale between eroded particles and this sediment layer, a more local investigation was conducted (Ahyerre, 1999). So, observations were then made by the PVC box (Ahyerre et al., 2000) installed in a pipe where the sampling analysis showed a highly organic sediment layer (upstream on Vieille du Temple). These observations showed a stratified structure of deposits with a well delimited immobile layer formed on top of the coarse deposits (Table 1-9) with a thickness varying between 1.5 cm and 7 cm. Samples taken by the sampling box of this immobile layer revealed similar characteristics to the fluid sediment observed on the whole sewer scale and thus this latter was supposed to be only an aspiration of the organic immobile layer. These results were then confirmed by the endoscope observations realised between December 2000 and January 2001 along the 3 main

collectors of the Marais site by Oms (2003) where the organic layer was detected at the points where the concentration profiles established in Ahyerre (1999) exceeds the 700 mg/l near the bed. Based on the endoscope results, Oms (2003) chose two points in the sewer to sample and analyse for their physical and chemical characteristics. Analysis results converged with previous ones where a high organic content concentration was obtained in this layer (Table 1-9).

Using a cyclic flush Hydrass gate, Laplace et al. (2003) generated increased water flow in a 120m long trunk in Marseille's combined sewer system where an organic layer similar to the one observed on the Marais sewer system was detected over a 10 m length using the endoscope. The trunk has an egg-shaped form of 1.7 m high and a slope of 0.02% over the first half (60 m) and 0.03% on the second half (60 m) and the average dry weather velocity ranges between 0.35-0.40 m/s. The comparison of the pollutants' content of eroded particles and those stored in the coarse deposits and the organic layer (Table 1-10) showed that the origin of eroded particles is the organic layer and the moveable particles of the coarse deposits (<400µm) especially that after the flushing experiments the endoscope indicated the absence of the organic layer.

| | COD/SS (g/g) | Zn/SS (mg/kg) | Pb/SS (mg/kg) |
|---|---|---|---|
| Particles eroded by first flush (Laplace et al., 2003) | 0.45-1.5 | 1.17 | 208 |
| Particles eroded by second flush (Laplace et al., 2003) | 0.26-1.4 | 850 | 254 |
| Coarse deposits (<400 µm) (Ahyerre, 1999) | 0.28-0.56 | 2.46-570 | 400-10000 |
| Organic layer (Ahyerre, 1999) | 0.9-1.4 | 970-1550 | 197-335 |

***Table 1-10:*** *Pollutants' content in organic layer on the Marais and the particles eroded by the flushing experiments in Marseille trunk of Rue Tobelem*

#### *3.1.3.4. Fluid sediment*

A different technique was implemented to study this kind of sediments where a SS concentration profile in the dry sewer flow was established using a multi-depth sediment sampler designed to sample the sewer flow at different levels. Two different methods of this sampling technique were employed: the pump creates void in several bottles each connected to a sampling tube placed at different level (Ristenpart, 1995; Ahyerre, 1999), or the pump is connected successively to several rigid tubes to sample at different levels (Verbanck, 1995). All the studies employing this technique observed a sharp increase in the dry weather suspended load concentration in the immediate proximity of bed deposits that goes up to 5g/l (Chebbo et al., 2003) with a high volatile solid content.

On an interceptor sewer in Germany (Hildesheim), Ristenpart et al. (1995) analysed the vertical distribution of SS in a water column. The SS concentration profile measured during dry weather periods revealed a remarkable gradient near the bed with the concentration at points just above the bed exceeding by one order of magnitude those measured in the sewage flow body. During wet weather flow, the gradient was less pronounced than in dry weather flow especially at the rising limb of the storm event during which the SS content was doubled in the sewage flow and halved in the fluid sediment layer indicating the suspension of the latter into the former which does not only erode this layer but also swirl up a part of the underlying sediment bed. The term employed to describe this sediment type is "organic near bed fluid sediment".

In order to avoid any confusion between the bed-load used in the fluvial hydraulics field and the highly organic material transported at the bed in some sewers under certain flow conditions, Arthur et al. (1996) considered the term "organic near bed fluid sediment" to be the most exact description of this component of the system combining the chemical properties (organic) with position (near bed) and physical nature or mobility (fluid sediment).

Verbanck (1995) noticed a steep gradient of solid concentration near the bed (at ≈ 15 cm) marking out two distinct regions of suspended particles along the water column with each region displaying different type of particles and polluting strength. Particles transported in the lower region were found to be highly organic (90% volatile content) and remain in suspension for a limited range of hydraulic conditions and are ready to leave their zone to join the upper one at the slightest modification in these conditions. The integrity and stability of this zone were referred to the: (1) physical concepts set up by Bagnold (1973) which state that the immersed weight of particles at such low elevations can be supported by the flowing medium; (2) complex abrasion process created by the near-bed motion of granular bed load particles; (3) the steep velocity gradient near the bed which introduces a pressure difference and thus creates a lifting force that reestablishes the equilibrium between hindered settling and turbulent diffusion. Having particles maintained in suspension and moving at a lower longitudinal velocity than the upper region, this interface was denoted by the "dense undercurrent".

In his monitoring campaigns of in-sewer sediments on the collector of "L'Allée de l'Erdre", Hemmerle (2014) realized a systematic occurrence of a jump in the vertical profile of TSS concentration near the deposits' bed determined by a UB-mud device based on the Doppler Effect principle. The analysis of the samples taken at this level of water column showed fine ($d_{20}$ = 0.08 mm), organic (VM > 80%), and mobile (longitudinal movement) nature and was thus denoted by "dense layer".





### 3.1.4. Comparison of pollutants' load in eroded particles with those of different sewer sediments

In order to identify which type of deposits contributes to wet weather flow pollution, a comparison between the different sediments characteristics and those of wet weather flow was carried by previous researches.

In Brussels' main trunk, Verbanck (1992) noticed that the particles transported in suspension during rainfall events are of different nature than those of type A deposits.

For 4 rainfall events on Zurich catchment, Krejci et al. (1987) estimated that 20% of suspended load and 23% of COD load is due to the erosion of biofilms whereas the other types of sediments contribute by 39% of the total TSS load and 35% of the COD load.

The fluid sediment identified in Ashley et al. (1994) in the Dundee sewer was found to be highly concentrated with COD (87.5-193 g/l) and was believed to contribute significantly to any foul flush. Ristenpart et al. (1995) realized a clear interaction between the sewage flow and the fluid sediment layer in Hildsheim interceptor at the beginning of the rainfall event where the COD concentrations in the wet weather flow were similar to those in the fluid sediment layer just after the rising limb of the rainfall event. This layer was considered to be responsible of the marked increase in the pollutants' load transported with the sewage, the famous phenomenon of "first foul flush". Verbanck (1995) also highlighted the role of his dense undercurrent in the "foul flush" phenomenon in combined sewers.

Ahyerre (1999) carried out an extensive analysis of the mass and characteristics of sewer deposits and compared them to the eroded particles on both sewer scale and pipe scale. He noticed that the only sewer sediment whose mass and characteristics are of the same order of magnitude as those of the eroded particles in wet weather flow is the organic layer. Type A was found to be more mineral than the erode particles and the biofilms presented much higher metallic content than those in the eroded particles (Table 1-11).

| Type of particles | | VM/TSS (%) | COD/TSS (g/g) | $BOD_5$/TSS (g/g) | Cd/TSS (mg/kg) | Cu/TSS (mg/kg) | Pb/TSS (mg/kg) | Zn/TSS (mg/kg) |
|---|---|---|---|---|---|---|---|---|
| Eroded particles | Catchment scale (Gromaire, 1998) | 58-76 | 0.77-1.5 | 0.29-0.66 | - | - | - | - |
| | Pipe scale (Ahyerre, 1999; Garnaud, 1999) | 61-86 | 1.1-1.5 | 0.31-0.45 | 2.5 | 207 | 213 | 1239 |
| Deposits (Ahyerre, 1999; Garnaud, 1999) | Type A | 3-13 | 0.06-0.22 | 0.01-0.06 | 2.8 | 555 | 1304 | 3238 |
| | Biofilms | 39-81 | 1-1.7 | 0.26-0.62 | 6 | 1273 | 2589 | 12484 |
| | Organic layer | 60-76 | 0.9-1.43 | 0.19-0.36 | 0.84 | 212 | 212 | 1457 |

***Table 1-11:*** *Pollutants' load of eroded solids and of different types of deposits in combined sewer systems*

There is a clear consensus on the considerable pollution potential of this organic near bed sediment and its major role in the wet weather erosion. However, various results were obtained concerning the nature of this near bed sediment. This might be attributed to the different sampling method implemented and different characteristics of the studied sites. Table 1-12 below summarizes the different field studies found in the literature with the different techniques used and the nature and characteristics of this sediment layer observed.

| Sites | Dundee trunk | Dundee Interceptor upstream | Dundee Interceptor downstream | Hildesheim | Nantes | Marais | Brussels |
|---|---|---|---|---|---|---|---|
| Surface | 236 ha | 245 ha | 340 ha | 739 ha | 100 ha | 42 ha | 3 520 ha |
| Population | 9 500 | 13 300 | 18 100 | 100 000 | - | 12 500 | 380 000 |
| Sewer section | Egg-shaped | circular | Egg-shaped | Circular | Egg-shaped | Rectangular | Rectangular |
| Slope | 4.6% | < 0.1% | 0.06% | 0.056% | 0.12 % | 0.09 % | 0.03 % |
| Dry flow speed | 0.4-0.75 m/s | 0.3-0.46 m/s | 0.09-0.29 m/s | 0.25 m/s | 0.13 m/s | 0.16 m/s | 0.5 m/s |
| Dry flow depth | - | - | - | 0.3 m | 0.45 m | 0.1 m | - |
| Coarse deposits | No | - | No | Yes | Yes | Yes | - |
| Sampling method | Bed traps | Bed traps | Bed traps | Multi-depth sampler | UB-mud device | Observational box and endoscope | Multi-depth sampler |
| Organic near bed sediment | Near bed solids (NBS) | | | Organic near bed fluid sediment | Dense layer | Organic layer | Dense undercurrent |
| Nature of near bed sediment | Organic Mobile | | | Organic Mobile | Organic Mobile | Organic Immobile | Organic Mobile |

***Table 1-12:*** *Characteristics of different sites and sampling methods used to investigate the organic near bed sediments*

It is remarkable that the type of the organic near bed sediment is tightly linked to the sampling technique used to identify and characterize it. On sites where bed traps were used (Dundee 1, 2, and 3), this sediment layer was supposed to be composed of organic particles moving near the bed that were called "Near Bed Solids". On other sites where a multidepth sampler was used (Hildsheim, Brussels), a fluid sediment is observed. Even on the Marais catchment, when Ahyerre (1999) determined the vertical profile of SS concentration using the multidepth sampler, the near bed concentrated area was supposed to be the fluid sediment observed on other sites. However, when Ahyerre (1999) then installed his observational box at the same points where this fluid sediment layer was identified, he found that this fluid sediment is only a result of the aspiration of particles from the immobile organic layer at the

bottom and not from the overlying flow. So, a new investigation of the other sites was performed by Oms (2003) using the endoscope device in Dundee, Hildesheim, Marseille, and Yorshire. Particles of organic nature floating on the surface of the coarse deposit layer were seen by the endoscope in Dundee and Hildesheim which correspond to the NBS and organic near bed fluid sediment detected before by Arthur (1996) and Ristenpart et al. (1995) respectively. The agreement of field observations between different sampling methods lowers the probability of the sampling technique being involved in the sediment deposit identification.

So, other factors related to the site characteristics were suspected. The collectors in which the organic layer was found can be classified in an upstream level compared to the collectors sampled on the other sites where fluid sediment or NBS were detected. The similar chemical composition of the different kinds identified for this near bed sediment suggests that all are of the same origin and made up of the same material but take different forms according to the hydraulic conditions dominating their occurrence position.

On the very upstream trunks of the sewer that are very close to the input sources and have very low flow velocity, these organic materials that are not still decomposed will settle down and will be specially trapped inside the coarse sediment cavities forming the immobile organic layer. The organic particles that fail to settle at these parts will be transported further downstream and decompose along its way forming near bed solids that due to the high flow velocity in downstream zones will remain in suspension or move by silting, sliding, and rolling. These particles could sometimes occur in a continuous layer moving near the bed or separate particles moving as a bed load. The distinction between these two forms is complicated. The deposits observed in Dundee by Arthur et al. (1996) and supposed to be near bed solids were also called organic near bed fluid sediment in the same article to avoid any confusion with the traditional definition of the bed-load given by Ackers et al. (1994) cited in Arthur et al. (1996) i.e. “The part of the sediment load which travels by rolling, or sliding, along the sewer invert, or deposited bed, or by saltating”. The same observations made in Dundee of sewer sediments were also studied in Ashley et al. (1994) who called it fluid sediment since as stated therein: “Despite the evidence to support the use of term “bed load” to describe the sediment collected in the trap studies in Dundee, there is some disagreement as to whether material moving close to the bed of a sewer is strictly bed-load…layering of this material has been detected giving problems for echo-sounding.”. So, the debate about the adequate descriptive term of the prevailing highly organic material near the bed in combined sewer is still raging.

However between the organic layer and the NBS/fluid sediment, the current knowledge does not permit to decide whether both exist simultaneously (immobile layer with an upper layer composed of particles detached from this immobile layer but are still heavy to be carried

in suspension and thus move near the bed) as seen by Hemmerle (2014) or each form exist individually depending on the hydraulic conditions as explained before.

On other sewers with steeper invert slope as in Ecully (Lyon) (average bed slope = 2.7%), the sewage flows at higher velocity leaving no chance for these organic materials to develop in its trunks in neither an immobile organic layer nor a fluid sediment or near bed solids.

## 3.2. Dynamics of sewer sediments

After observing and characterizing the different deposit types formed inside combined sewers, researchers were interested in studying the dynamics of these sediments to understand the processes occurring during dry and wet weather conditions.

### *3.2.1.Accumulation of sewer grits*

Although their characteristics were different from the wet weather effluents and thus are unlikely to contribute to discharges pollution, sewer grits have made the subject of extensive field studies as they were believed to influence the morphodynamic and hydraulic properties of sewer channels.

A two year survey of in-sewer sediment in collector 13 in Marseille (Laplace, 1991) provided useful elements for the comprehension of the dynamic of in-sewer coarse sediments during dry and wet weather periods. The majority of the studied events generated an increase in the deposits volume in collector 13. The author explained this phenomenon by the low energy of water flow and thus the transport capacity in this part of the sewer favouring deposition of the particles eroded during the same rainfall event from the upstream parts of the sewer system. It was demonstrated through the measurements of the evolution of deposits profile with time that sewer flow tends to distribute the deposit particles along the collector according to a decreasing depth from the upstream to the downstream thus steepening progressively the invert slope of the collector (from 0.001 m/m to 0.0035 m/m). Rainfall events disrupt the regularity of this profile by abrupt lateral inflows through junctions and gully pots provoking local erosion at these points. Then, the successive dry weather flow corrects these irregularities and smoothes the grade line by filling up these depressions. This phenomenon of progressive steepening of invert bed towards an equilibrium slope was explained by the increase of the average flow velocity due to the increase in bed slope and thus to an increase of transport capacity that will consequently prevent further accumulation in the parts previously favourable for deposition.

In their long term monitoring of sewer sediments in the Lacassange sewer (from 2000 to 2004), Bertrand Krajewski et al. (2006) found an asymptotic increase of both sediment mass

and longitudinal slope (Figure 1-1) with time corroborating the results of Laplace (1991). This tendency was explained by the associated increase in flow energy capable of transporting more particles or by the balance occurring between erosion and sedimentation processes.

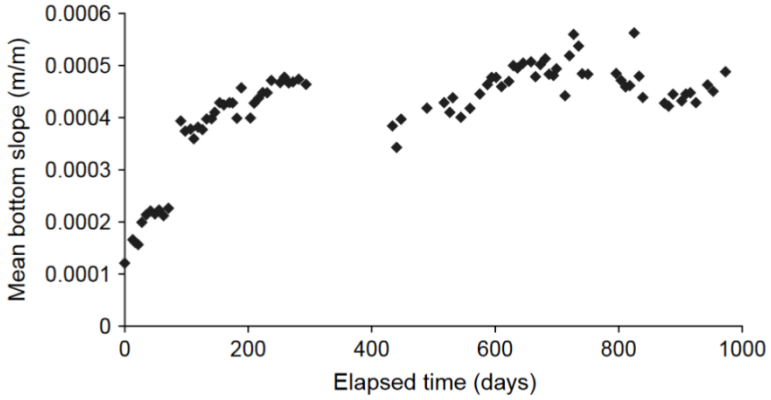



***Figure 1-1:*** Asymptotic variation of the mean bottom slope in Lacassange sewer (Bertrand Krajewski et al., 2006)

### *3.2.2.Erosion of organic near bed materials*

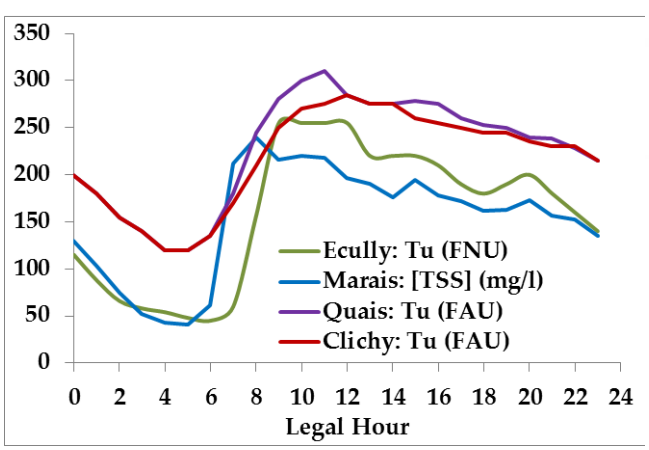
From a theoretical point of view, the erosion of a deposited particle is mainly due to the transfer of mean and turbulent kinetic energy of water flow to particles on the flow bottom (Mehta et al., 1989; Hérouin, 1998) by means of lift and drag forces. Lift forces are caused by pressure and viscous skin friction and is proportional to the square of the flow speed, while drag forces are caused by the velocity gradient in the flow (shear effect) and by the spinning motion of the particle (Magnus effect) which is considered to be in viscous flow and turbulent flow proportional to the flow speed and to its vertical gradient (Van Rijn, 1984). In the in-sewer sediment case, the cohesion property of these organic deposits induces an opposing force to these forces, and thus particles motion does not start before the destabilizing forces exceed the sediments' cohesive resistance. Current knowledge of the mechanism of these organic deposits including the erosion process and its rate and the cohesive resistance is limited to the few experimental studies conducted in sewer systems either in real conditions (dry and wet) or in artificial context (flushing experiments). The scarcity of such studies is related to the onerous procedures necessary in field investigations when working in the hostile hardly controllable and heterogeneous environment of sewer systems.

#### 3.2.2.1. Investigations in real sewer flow conditions (dry/wet)

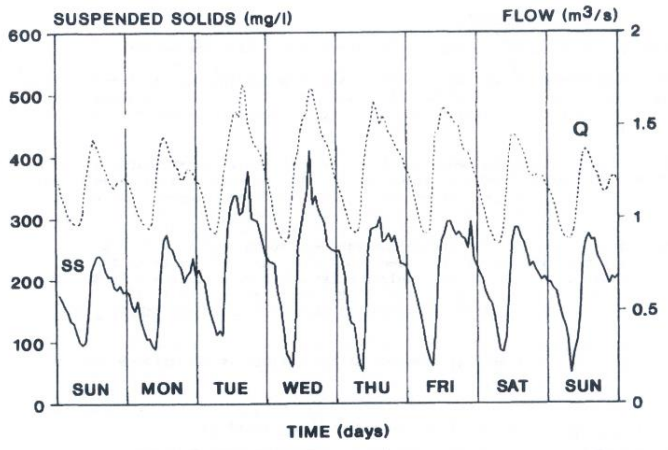
Measurements on several combined sewer systems (Brussels main trunk (Verbanck, 1990), Marais (Gromaire, 1998), Quais and Clichy (Lacour, 2009), Ecully (Métadier, 2011)) show a daily cycle of both flow rate and TSS concentration (Figure 1-2). When the cycle of the flow rate seems logical due to the fluctuations of water consumption during the day, the cycle of

the TSS concentration is more surprising. This evolution of TSS concentration was exhaustively investigated in (Gromaire, 1998) by analysing the data acquired in all the dry weather measurement campaigns. It was found that the increase of TSS concentration is accompanied by an increase of the discharge flow due to the increase of the transport capacity of the flow regime that triggers particles' erosion more than being a result of dilution by clean water. This was concluded from several elements observed during the measurements at the peak flow moment: increase in particulate proportion with wastewater flow, decrease in the organic content, decrease in the biodegradability of the effluents, and sharp increase in the ratio TSS/CODd along with a break in the relation between TSS transport rate and wastewater flow rate.

The temporal monitoring of the "dense layer" during dry weather periods as a function of hydrodynamic conditions of sewage flow, Hemmerle (2014) noticed that the build-up of this layer starts at the moment following the morning peak flow after being eroded by this latter, where in more general expression, a flow speed > 0.13 m/s corresponding to a shear stress of 0.055 N/m² is sufficient to initiate the suspension of this layer.




(1-2a)




(1-2b)

***Figure 1-2:*** *Daily cycle of wastewater TSS concentration at sewer outfalls during dry weather on: (1-2a) Ecully, Marais, Quais, and Clichy, (1-2b) Brussels main trunk*

Gromaire (1998) has studied the variation of the contribution of the sewer deposits inside the storm event and showed that this contribution occurs along the whole duration of the event but with a highly variable proportion from one moment to another. It's maximum at the moment of peak flow rate and in the following 30 minutes due to the erosion process. In events having several flow peaks, a net decrease in the TSS production is observed between the consecutive peaks demonstrating a progressive decrease of the sediment stock available for erosion, possibly related to an erosional strength of the contributing deposits increasing with depth. The organic content of the particles issued from the deposits erosion was high

throughout the whole rainfall event even at the moment of the flow peak which signifies that even when the flow energy increases no (or little) erosion of the mineral deposits takes place. The maximum concentration of volatile matter was generally observed at the beginning of the rainfall event whereas the minimum values were obtained at the end of the rainfall event.

Another study conducted by (Ristenpart et al., 1995) based on the comparison of the vertical SS concentration profiles between dry weather flow and wet weather flow indicated that the interaction of the organic near bed fluid and the overlying flow is the phenomenon responsible for organic particles production during wet weather. For an extensively monitored storm event on Hildesheim, the well-marked SS concentration gradient at the beginning of the rainfall event decreased significantly during the rise of the water level to become fairly homogeneous where the SS content was doubled in the sewage flow and halved in the fluid sediment indicating a suspension of the fluid sediment into the water column. A few minutes later just at the moment of the flow velocity peak, a short time scale increase in the SS concentration was noticed due to rapid erosion not only of the fluid sediment layer but also of the sediment bed itself as the deposits bed decreased.

#### 3.2.2.2. Investigations in controlled flushing experiments

A flushing experiment was carried out on the low-sloped Brussels main trunk by Verbanck (1995) as an alternative approach to the heavy experimental campaign made during real rainfall event on the sewage flow and sediments layer to compare their properties and identify their interaction mechanism. An artificial change in the hydraulic conditions (flow rate and shear stress) due to the water release from the vane of a cleaning trolley displayed a marked increase in the SS concentration determined at mid-depth of the flow section. The shear stress induced by this experiment was between 1.1-1.2 $N/m^2$ at the mid-depth giving a local shear value of 1 $N/m^2$ at the level of the dense undercurrent layer. Such low value affirms that the eroded layer is looser than the coarse granular deposits that need high shear stresses to be scoured.

The experimental study realised by Gendreau et al. (1993) on the impact of flood waves on the removal of a deposit in a sewer showed that the first part of the wave is the most efficient where erosion initiation is related more to the change in the hydraulic conditions than to the hydraulic conditions themselves. They concluded that it is better for scouring sewer sediments to release small volume of water at high frequency than bigger volume at a lower frequency. This was also confirmed by field experiments carried in Heldesheim combined sewer (Ristenpart, 1997).

In order to examine the solid transport processes, 14 flushing experiments under controlled conditions were realised in two combined sewers in Heldesheim during normal

operation (Ristenpart, 1997). The behaviour of the bed deposits was found to correspond well to the transport in suspension where erosion of sediment bed (decrease in its depth) coincided with the SS peaks. However, the analysis of the characteristics of both the suspended particles and the bed deposits revealed that the peaks of SS concentration were mainly produced by an increase in the organic solid fraction rather than the mineral fraction that constitutes the principle component of the bed deposits. Thus, the material remobilized out of the sediment bed wasn't entirely suspended in the wastewater column. However, a major part of it must have been transported as bed load and the organic fraction is the one being released in the wastewater column and constituted the observed SS.

Several in-situ hydraulic flush experiments were realised in the Marais site (Ahyerre, 1999; Oms, 2003) to measure the erosion rate of the organic layer detected as the potential source of pollution in wet weather effluents as a function of the hydraulic parameters (discharge flow rate and boundary shear stress). The field tests were carried on a discrete length of sewer pipe (150 m) with no lateral inputs on the upstream of Vieille du Temple (Ahyerre, 1999) and Saint Gilles (Oms, 2003) by injecting clean water from fire hydrant found at street level. The behaviour of sediments in these experiments were studied by measuring TSS concentrations at the downstream end of the test pipe and by observations made using the visual monitoring system installed at studied points. An increase in the TSS load was observed at each flow rate increase signifying the sensitivity of the organic layer to the slightest change in the hydraulic conditions (starting from a shear stress of 0.03 $N/m^2$). The decrease of measured pollutograph peak from one flow injection to another consecutive (whether with the same magnitude or higher) reflects the layered structure of the erodible layer whose strength increases with depth. In addition, a better correspondence was obtained between the shear stress evolution and the eroded load than between the flow rate and the eroded load. This supposes that the shear stress is a better parameter to explain deposits' erosion than flow rate. Concerning the formation of the organic layer, upstream hydraulic conditions (low shear stress < 0.03-0.1$N/m^2$ and low flow velocity < 0.1 m/s during dry weather) seem to be suitable for this phenomenon to occur. This organic layer was found to have a quasi-stable state reaching a height of 15 cm, where cavities formed occasionally by erosion are rapidly filled up by the NBS trapped in these irregularities while moving near the bed surface. Images taken during artificial injection of water flow show that the erosion occurring in this layer is not uniform along the whole pipe, where two explanations arise: either due to the heterogeneity of surface resistance to erosion or decrease in the transport capacity of the flow when loaded with sediment particles from upstream erosion.

∴ Studies on sewer sediments' composition showed that these sediments can't be treated as one block when addressing sewer contribution to the pollution of CSOs. A considerable advance in the knowledge of each type of sewer sediments has been made thanks to some field surveys that were conducted in a perspective to understand their mechanism to be able in the next step to replicate it in a modeling framework needed to test the control strategies of CSOs.



# 4. Modelling sewer processes

The main objective of all the research work done on CSOs (especially on the sources and their proper production processes) is to provide all necessary information to quantify these discharges (occurrence, loads, and rate) in order to conceive, design and evaluate sustainable control strategies that could efficiently limit their detrimental impact on receiving water bodies. Among these control strategies are rehabilitation and replacement of CSOs structures, construction of retention basins, application of Best Management Practices to limit runoff inflows into sewers, and setting up of real time control systems to make the best use of available transfer and storage capacities…. So, the acquired knowledge on the major contributor (the in-sewer sediments and specifically the near bed organic layer) had to be translated into mathematical formulations to be used to quantify the magnitude and variations of the produced loads. As discussed earlier (§3.2.2), to estimate the production of SS from these sewer sediments, we need to determine the instantaneous active force and the instantaneous resistive force and then transfer the produced quantity by the water vector in the sewer network.

## 4.1. Modelling in-sewer sediment erosion

Current sewer quality models use sediment transport rate formulae that were developed for application in fluvial environment (De Sutter et al., 2000). Most of these formulae are based on an energetic approach supposing that erosion occurs whenever the transport capacity exceeds the suspended mass transported in the flow and deposition occurs when the latter is superior. Some models use the same transport capacity for both processes (erosion and deposition) while others consider that an intermediate state exists between the two erosional and depositional limits in which no exchange with the sediments occur. However, there is no consensus among researchers on the definition of the transport capacity that was approached using different analytical and empirical derivations: gravitational power approach (e.g. Velikanov, 1954), power balance approach (e.g. Pacheco-Ceballos, 1989), probabilistic approach (e.g. Einstein, 1950), regression approach (e.g. Karim and Kennedy, 1990), unit stream power approach (e.g. Yang, 1972; Yang, 1973), stream power approach (e.g. Bagnold, 1966; Engelund and Hansen, 1972; Ackers and White, 1973; Ackers, 1994). These approaches finally ended up establishing the transport rate formulae using only a couple of hydraulic parameters: shear stress ($\tau$), stream power (shear stress x flow velocity: $\tau V$), and unit stream power (flow velocity x energy slope: VS). Many of these formulas have been employed on SS production from in sewer sediments (table 1-13) with various degrees of complexity (distinction between deposition and erosion in terms of motive threshold parameter, distinction between different transport modes: bed load, suspended load…). However, none of the existing models stands out for its acceptable performance where all simulation results gave low precision and high uncertainties vis-à-vis the observations (references in the Table 1-

13 below). Although these models were coupled with other modules of pollution generation and transport on subcatchments surface and that might have participated in their weak performance, it's more likely that the contribution of these models to the final results exceeds other modules' regarding the weight of the treated source and the relevance of such models in the sewer conditions.

| Model | Reference | Sewer production model |
|---|---|---|
| HYPOCRAS | (Bertrand-Krajewski, 1993) | Exponential model function of flow rate |
| MOUSE TRAP | (Mark et al., 1993) | • Ackers-white (Total load)<br>• Engelund-Hansen (Total load)<br>• Engelund-Fredsoe (Bed + Suspended)<br>• Van-Rijn (Bed + Suspended) |
| STSim | (Schlutter, 1999) | Erosion: exponential model function of flow rate<br>Deposition: exponential model function of excess shear stress |
| Detailed model | (Kanso, 2004) | Velikanov model |
| WSD | (Yoshida et al., 2007) | Exponential model function of excess flow rate |
| MOSQITO | (Moys et al., 1988) | Ackers and White |
| HYSRAD/Extran | (Borovsky and Scholz, 1996) | Ackers and White coupled with Wotherspoon model (1994) |
| Flupol | (Bujon, 1988) | Velikanov model |
| SewSim | (Ruan and Wiggers, 1997) | Exponential erosion as a function of flow rate |
| HORUS | (Zug et al., 1998) | Velikanov model |

***Table 1-13:*** *Sewer sediment production model in urban drainage models*

The transposition of the results and relations obtained for fluvial hydraulics to urban hydrology especially sewer systems is not straightforward. It's even questionable regarding the different conditions between the two studied environments: sewer particles are smaller and more variable, and sewer sediments are cohesive due to their organic fraction. It was noted out by many authors that if reliable predictions of suspended solid production from sewer deposits are to be made (De Sutter et al., 2000), the effect of cohesion on the erosion process must be taken into consideration by selecting appropriate value of motion threshold and well representing the erosion rate. For that reason, significant research programs have been undertaken in the late 1980s and 1990s on laboratory flumes with free surface flow and cohesive particles either taken from estuaries, or prepared by a mixture of sand and cohesive materials, or taken directly from the sewer to reproduce as closely as possible the real conditions in the sewer systems (Parthéniades, 1965; Ariathurai and Arulanandan, 1978; Mehta et al., 1989; Kleijwegt, 1992; Nalluri and Alvarez, 1992; Perrusquia, 1992). Table 1-14 displays some formulas established to describe the erosion from cohesive sediments. For the most suitable driving force to consider, the International Workshop on origin, occurrence and

behaviour of sediments in sewer systems unanimously considered that the bed shear stress was the most appropriate parameter for defining erosive and deposition criteria (Verbanck et al., 1994).

| Equation | Reference | Erosion rate |
|---|---|---|
| 1-1 | Parthéniades (1965)<br>Kandiah (1974)<br>Ariathurai and Arulanandan (1978) | $E = M.\left(\frac{\tau_b - \tau_c}{\tau_c}\right)$ |
| 1-2 | Skipworth et al. (1999) | $E = M.\left(\frac{\tau_b - \tau_c}{\tau_c}\right)$<br>$\tau_c = \tau_{cs} + \left(\frac{d^{1/b}(\tau_{cu} - \tau_{cs})}{d'^{1/b}}\right)$ |
| 1-3 | Parchure and Mehta (1985) | $E = E_f e^{\alpha(\tau_b - \tau_c)^{1/2}}$ |
| 1-4 | Lick (1982) | $E = M.\left(\frac{\tau_b - \tau_c}{\tau_c}\right)^n$ |
| 1-5 | Izumi and Parker (2000) | $E = \beta_e \left(\frac{u}{V_c} - 1\right)^\gamma$<br>E=0 for $u \leq V_c$ |
| 1-6 | Wotherspoon (1994) | $d_e = d_s \left[1 - \left(\frac{\rho_f}{\zeta \overline{\rho_0}} \frac{1 + \left(\frac{\tau_b}{e^{18.386}}\right)^{\frac{1}{-3.168}}}{1 + \frac{\rho_f}{\rho}\left(\frac{\tau_b}{e^{18.386}}\right)^{\frac{1}{-3.168}}}\right)^{-\frac{1}{\xi}}\right]$ |
| $E$ is the erosion rate (M.L$^{-2}$.T$^{-1}$), $\tau_c$ is the critical bed shear strength at the point of erosion (P), $\tau_b$ is the applied shear stress (P), $\tau_{cs}$ is the erosional strength at weak layer surface (P), $\tau_{cu}$ is the erosional strength of the uniform layer underlying the weak layer (P), $d'$ is the weak layer depth (L), $b$ is the exponent describing the evolution of erosional strength with depth in the weak layer (unitless), $M, E_f, \alpha$ are calibration parameters, $n$ is an exponent that is generally unity, $\beta_e$ is an entrainment coefficient, $\gamma$ is an exponent (typically between 1 and 2), and $V_c$ is the threshold entertainment flow velocity (L.T$^{-1}$), $u$ is the flow velocity (L.T$^{-1}$), $d_e$ is the eroded deposit depth (L), $d_s$ is initial deposit depth (L), $\rho_f$ is the sediment mass density (M.L$^{-3}$), $\overline{\rho_0}$ is the initial average bed density (M.L$^{-3}$), $\xi, \zeta$ are dimensionless coefficients. | | |

***Table 1-14:*** *Erosion rate formulas of cohesive sediments*

Partheniades (1965) carried out flume experiments on erosion and deposition of fine estuarine cohesive sediments with bed material taken from San Francisco Bay mud and water at ocean salinity and constant depth. Critical shear stresses were found between 0.48 N/m$^2$ and 1.34 N/m$^2$. Partheniades (1965) realised that two modes of erosion take place: erosion of small clusters of particles and layer erosion. It was found that the surface erosion rates depend strongly on the excess of the applied shear stress over the critical shear stress and that the erosion rates are not affected by the concentration of suspended sediments. Kandiah (1974) and Ariathurai and Arulanandan (1978) parameterized Partheniades' equation (Winterwerp

et al., 2012).This formula was then generalized (Lick, 1982) by introducing a coefficient to the excess shear stress.

Lambermont and Lebon (1978) cited in Alvarez-Hernandez (1990) studied the erosion of soft cohesive soils using experimental data from Partheniades (1965). They derived an expression for the density distribution in sediment layers found to be dependent on the whole previous deposition and erosion history. They also formulated a differential equation of cohesive sediment bed under some assumptions (parabolic density distribution, constant coefficients of diffusion and sedimentation, temperature gradient in the bed neglected…), where the analytical solution was shown to agree very well with the erosion experiments of Partheniades (1965).

Thorn (1981) performed experiments on soft cohesive sediments and demonstrated that the critical shear stress is a function of the bed density.

Parchure and Mehta (1985) studied the erosion of the top active layer of the estuarine beds through laboratory experiments on circular flumes with soft cohesive sediments subjected to an increasing magnitude of shear stress. It was found that the erosion rate is proportional to the square root of the excess of applied shear stress over the shear strength of the bed

Wotherspoon (1994) used the empirical relationship established between sediment strength and liquid content by Wotherspoon and Ashley (1992) (Equation 1-7) and the density-depth relationship derived for estuarine cohesive sediments by Mehta and Partheniades (1982) (Equation 1-8) to determine his erosion model (Equation 1-6) that predicts the erosion onset as well as the amount of material that will be released by the sediment bed during the erosion process.

$$\tau_y = e^{18.386}.m^{-3.1682} \quad (1\text{-}7)$$

$$\frac{\rho_d}{\overline{\rho_d}} = \zeta \left(\frac{z}{d_s}\right)^{-\xi} \quad (1\text{-}8)$$

| | |
|---|---|
| $\tau_y$ | = Sediment strength (N/m²) |
| $m$ | = Sediment liquid content (%) |
| $\rho_d$ | = Density at height z (M.L$^{-3}$) |
| $\overline{\rho_d}$ | = Average dry density (M.L$^{-3}$) |
| $d_s$ | = Sediment layer thickness (L) |
| $z$ | = Height above sewer invert (L) |
| $\zeta$ | = Dimensionless coefficient |
| $\xi$ | = Dimensionless coefficient |

Skipworth et al. (1999) conceptualized the in-sewer sediments structure by a weak layer of increasing resistance with depth and a more cohesive underlying layer with a constant resistance where the erosion rate is determined by the relationship inspired from the model proposed by Parchure and Mehta (1985) to describe the erosion of estuarine mud (Figure 1-3).

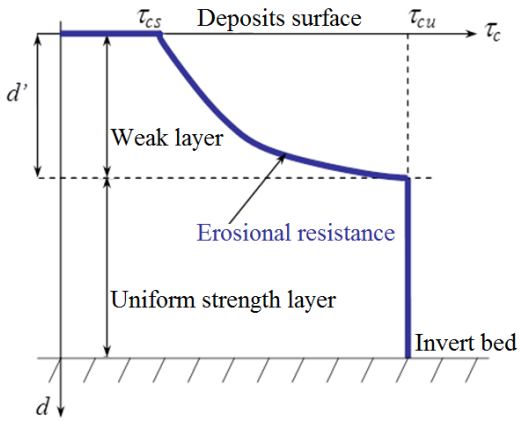



***Figure 1-3:*** *Variation of the erosional resistance of in-sewer sediments as described by (Skipworth et al., 1999)*

## 4.2. Modelling suspended solid transfer in sewer system

Once the particles mass eroded from the sewer sediments, it will join the SS produced by other sources (wastewater and surface runoff) to be transferred by the sewage flow to the sewer outfall. In the existing urban quality models, two levels of complexity are usually used to model the transfer process: conceptual approach and physical approach. The conceptual model is represented by the linear reservoir model as in HYPOCRAS (Bertrand-Krajewski, 1993). The physical one is made by the advection dispersion equation (Butler and Davies, 2004).

The linear reservoir model is based on the lumped form of the continuity equation of the SS load ignoring the spatial but considering the temporal variations in the system.

$$\frac{\Delta M}{\Delta t} = \varphi_{in}(t) - \varphi_{out}(t) \qquad where \qquad M = K_s \,.\, \varphi_{out}(t) \qquad (1\text{-}9)$$

| | |
|---|---|
| $M$ | = TSS load storage in the reservoir (M) |
| $\varphi_{in}$ | = Input TSS rate ($M.T^{-1}$) |
| $\varphi_{out}$ | = Output TSS rate ($M.T^{-1}$) |
| $K_s$ | = Reservoir constant which represents the speed at which the reservoir drains (T) |

The advection dispersion equation represents physically the solid transfer within the fluid matrix considering both: advection by the mean flow velocity and dispersion by turbulence. It is expressed by the following equation:

$$\frac{\partial(AC_s)}{\partial t} + \frac{\partial(QC_s)}{\partial x} - \frac{\partial}{\partial x}\left(DA.\frac{\partial C_s}{\partial x}\right) = q_s \qquad (1\text{-}10)$$

| | |
|---|---|
| $A$ | = Wetted cross-sectional area for channel flow ($L^2$) |
| $Q$ | = Discharge flow rate ($L^3.T^{-1}$) |
| $C_s$ | = Suspended load sediment concentration ($M.L^{-3}$) |
| $D$ | = Longitudinal dispersion coefficient ($L^2.T^{-1}$) |
| $q_s$ | = Source/sink term of suspended load produced/removed from wastewater, runoff, and sewer deposits |

∴ Modelling the processes governing sewer sediment can be broken down into two instantaneously consecutive steps:

Production: There has been a scientific preference for shear stress as the main parameter defining the flow transporting power. One of the most studied formulations of sewer sediment erosion flux is a relationship with the excess shear stress with reference to a (fixed or variable) threshold value.

Transfer: For suspended solid transfer, two options are available: a conceptual (linear reservoir) and a physical (advection-dispersion equation) model each adapted to a distinct level of sewer system description (lumped and distributed respectively).

## 5. Modelling hydraulics in sewer systems

It was shown that all the active forces governing the solid transport processes in sewer systems (both production and transfer) are driven by the hydraulic parameters of combined flow (shear stress and flow velocity respectively) that can't be determined except by a hydrodynamic model. That's why all urban stormwater quality models have a water quantity module to describe overland and sewer flow during a rainfall event whose results are then exported to the water quality module to calculate the pollutants' loads. So, the accuracy of the latter strongly depends on the former. A wide spectrum of approaches has been used in the literature to model water flow on urban catchments. The selection of the most suitable model for a certain application depends on the relative weight attributed to each of the following factor:

- Degree of the spatially distributed representation needed in the application
- Model accuracy vs the accuracy required in the application must be coherent with the measurement accuracy
- Availability of required data
- Computational cost of the model

If spatial variation of hydraulic flow is not sought, the simple methods (storage routing models and level pool reservoir models) can be used although their assumptions are not physically correct and some effort is to be made on calibrating their parameters. On the other hand, when spatial description of the flow is desired, simple routing or complex routing models are applicable. When information about the hydraulic parameters other than the flow rate is needed i.e. (flow velocity and flow depth), the complex routing models are inevitable since unlike the simple routing models they represent physically the channel routing process.

### 5.1. Simple hydraulic models

In order to encompass most of the simplified routing models, a unified coefficient routing model was developed that helps better understand the similarities and differences between the different models (Fread, 1983a). The model has the following form:

$$q_{out}(t+\Delta t) = C_1 q_{in}(t) + C_2 q_{in}(t+\Delta t) + C_3 q_{out}(t) + C_4 \qquad (1\text{-}11)$$

where $C_1$, $C_2$, $C_3$, and $C_4$ are the routing coefficients that are either determined empirically or evaluated from the hydraulics characteristics of the channel reach:

$$C_1 = \frac{(1-\theta)\,\tilde{a} + X}{C_0} \qquad C_2 = \frac{\theta\,\tilde{a} - X}{C_0} \qquad C_3 = \frac{1-(1-\theta)\,\tilde{a} - X}{C_0} \qquad C_4 = \overline{q}\frac{\Delta x.\,\tilde{a}}{C_0}$$

$$C_0 = 1 + \theta\,\tilde{a} - X \qquad \tilde{a} = c\frac{\Delta t}{\Delta x} \qquad \overline{q} = \frac{q_i(t) + q_i(t+\Delta t)}{2}$$

where c is the wave celerity (L.T$^{-1}$)

The various simple routing models can be obtained from this general equation by assigning particular values for the parameters $(\theta, \tilde{a}, X)$ in the coefficients ($C_0$, $C_1$, $C_2$, $C_3$, and $C_4$) as presented in the table below:

| Model | $\theta$ | $\tilde{a}$ | $X$ |
|---|---|---|---|
| Linear reservoir | 1/2 | $\Delta t/K_s$ | 0 |
| Muskingum | 1/2 | $\Delta t/K_s$ | [0,1/2] |
| Muskingum-Cunge | 1/2 | $c.\Delta t/\Delta x$ | $1/2(1 - q_0/(c\Delta x S_0))$ |
| SSAR | 1/2 | $\Delta t/T_s$ | 0 |
| Kalinin-Miljukov | 1/2 | $\Delta t/T_{prop}$ | 0 |
| Lag and K | 1/2 | $\Delta t/K_s$ | 0 |
| Kinematic | [1/2,1] | $c.\Delta t/\Delta x$ | [0,1/2] |
| $K_s$ = Reservoir constant (T) ; $c$ = Kinematic wave celerity (L.T$^{-1}$); $T_s$ = Storage time (T); $q_i(t)$ = Lateral discharge flow per unit length at $x_i$ and time t (L$^2$.T$^{-1}$); $T_{prop}$ = Time of propagation of a given discharge (T); $q_0$ = Unit width discharge (L$^2$.T$^{-1}$); $S_0$ = Channel bottom slope (m/m). | | | |

***Table 1-15:*** *Coefficients of the hydrologic models*

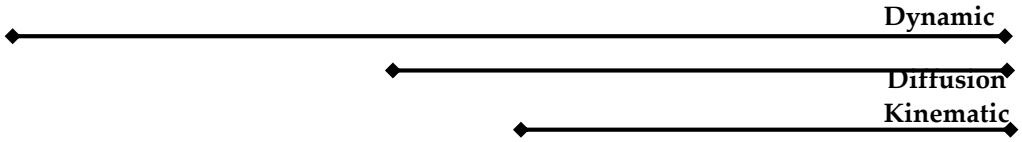
## 5.2. Complex hydraulic models

Complex hydraulic models are deterministic models based on distributed description of the modelled system in both dimensions: space and time the property that allows the application of the physical conservation laws governing fluid behaviour. Their mathematical basis was laid by Henri Navier and George Stockes with the contribution of Barré de Saint-Venant who formulated the one-dimensional analysis of flood wave propagation known now by the Saint Venant Equations or Shallow Water Equations (SWEs) (Chow, 1959; Abbott and Basco, 1989; Cunge et al., 1980). This model is used in varying degrees of simplification (dynamic, diffusive, and kinematic wave models) depending on the geometrical and flow complexities and the dominant processes. The conservation laws generally considered are the mass and momentum conservation with a closure equation for the friction parameter. The model is driven under the assumption of incompressible fluid, negligible vertical acceleration, flow velocity independent of depth, and weak bed slope.

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q \qquad (1\text{-}12)$$

$$\frac{\partial Q}{\partial t} + \frac{1}{A}\frac{\partial (Q^2/A)}{\partial x} + g\frac{\partial h}{\partial x} = gI_2 + gAS_0 - gAS_f + qQ/A \quad (1\text{-}13)$$

| Local acceleration term | Convective acceleration term | Pressure force term | Lateral pressure force term | Gravity force term | Friction force term | Lateral inflow term |
|---|---|---|---|---|---|---|




| Accounts for | Kinematic wave | Diffusion wave | Dynamic wave |
|---|---|---|---|
| Wave translation | Yes | Yes | Yes |
| Backwater | No | Yes | Yes |
| Wave attenuation | No | Yes | Yes |
| Flow acceleration | No | No | Yes |

***Table 1-16:*** *Applications of simplified Saint-Venant equations after Butler and Davies (2004)*

### 5.3. Numerical schemes of Shallow Water Equations

The mathematical formulation of the SWEs model constitutes a set of non-linear hyperbolic system of conservation laws that can be expressed in terms of 3 variable groups: flow variable $U$, flux variable $F$, and source term variable $S$.

$$\frac{\partial U}{\partial t} + \frac{\partial F(U)}{\partial x} = S \quad (1\text{-}14)$$

$$U = \begin{pmatrix} A \\ Q \end{pmatrix} \quad ; \quad F = \begin{pmatrix} Q \\ \frac{Q^2}{A} \end{pmatrix} \quad ; \quad S = \begin{pmatrix} q \\ gA(S_0 - S_f) + g\left(I_2 - \frac{\partial h}{\partial x}\right) + qQ/A \end{pmatrix} \quad (1\text{-}15)$$

When developing a numerical scheme to solve these equations, two difficulties arise: those related to the flow nature (steady/transient flow, transcritical flow/hydraulic jump) that may exist even in simplest conditions, and those related to the geometrical characteristics of the flow domain (irregular flow section, non-prismatic flow section, variable bed topography). The first difficulty comes from the discretization of the flux term which if not carefully made might produce discontinuities in the solution. The second difficulty resides in the discretization of the source term and its delicate interaction with the flux terms. In sewer system application, both difficulties are badly present due to the highly variable nature of the sewage flow in time and space. Invert irregularities due to invert counter slope, manhole drop, offset junctions, and especially the non-uniform invert accretion due to sediment deposition might significantly increase local spatial variability in the channel flow inducing in certain cases hydraulic jump or transcritical flow.

### *5.3.1.Flux term discretization*

The first difficulty where only the homogeneous part of the system is involved (Tseng, 2004) to describe cases with probable shock occurrence was quite intricate to overcome by the simple finite difference method that assumes the derivability of solutions and thus breaks down at discontinuities. This method used in the big majority, if not all, sewer drainage models (Table 1-17) will thus yield numerical instabilities when these discontinuities arise (Sod, 1978; Engquist and Sjogreen, 1998; LeVeque, 2004).

***Table 1-17:*** *Channel routing methods used in some urban quality modelling approaches*

| Model | Reference | Sewer routing | Numerical scheme |
|---|---|---|---|
| **HYPOCRAS** | (Bertrand-Krajewski, 1993) | Linear reservoir | - |
| **FLUPOL** | (Bujon, 1988) | Muskingum model | - |
| **SIMPOL** | (Clifforde and Tyson, 1993) | Nonlinear reservoir | - |
| **SewSim** | (Ruan and Wiggers, 1997) | Double linear reservoir | - |
| **MOSQITO** | (Moys et al., 1988) | • Muskingum-Cunge storage routing<br>• Free-Surface backwater routing<br>• Surcharge routing | - |
| **HORUS** | (Zug et al., 1998) | Muskingum model | - |
| CANOE | (Insavalor-Sogreah, 1997) | Dynamic model | Holly-Preissmann method |
| SWMM | (James et al., 2010) | Dynamic model | Explicit finite difference and modified Euler |
| MOUSE TRAP | (Crabtree et al., 1995) | Dynamic model | Implicit finite difference |
| MIKE11 | (DHI, 1992) | Dynamic model | Implicit finite difference |
| DOSMO | (Hvitved-Jacobsen and Schaarup-Jensen, 1992) | Dynamic model | Implicit finite difference |
| STSim | (Schlutter, 1999) | Dynamic model | Implicit finite difference |

So, a new generation of methods was needed. With the advances made in computational fluid dynamics in the field of aerodynamics, numerical schemes developed to solve Euler equation were transposed to hydrodynamics to solve the SWEs as the two models are mathematically analogic (Hirsch, 1988; Tseng et al., 2001; Kim et al., 2008). These schemes, called shock-capturing methods or Riemann-problem (RP) based methods, are numerical techniques that transform the discretized channel flow into a series of local RPs, each representing a jump between two neighbouring cell units. The first to introduce a discontinuous solution for the flux between these two adjacent cells was Godunov (1959) based on the exact formulation of the RP. Then, numerous Riemann solvers were developed to calculate either the approximate solution of the exact RP (Glaister, 1988), or the exact

solution of the simplified RP (Toro, 1997), among which are Lax-Wendroff (1960), MacCormack (1969), and Lax-Friedrich (1973) solvers. A more efficient solver was later introduced by Roe (1981) who transformed the exact RP into a linearized problem that was later on refined by (Roe and Pike, 1984). Nevertheless, all these methods hadn't been able to cleanly capture the hydraulic jump before Harten (1983) introduced the new class of numerical schemes called Total Variation Diminishing schemes (TVD) that achieve second-order accurate and oscillation-free solutions by reverting to the first order at local extremes to ensure the total variation of the solution is a non-increasing function in time. Harten (1983) presented his HLL-Riemann solver that solves the exact RP by assuming the solution's configuration consisting of three constant states separated by the two fastest and slowest waves ignoring all other intermediate waves. More recently Davis (1988) and Einfeldt (1988) have assessed these ideas while proposing wave-speed estimates and found that the tested algorithm is efficient, robust and very simple to implement. Despite its efficient performance, no single case has been reported in the literature of an urban drainage model employing this method in its channel routing module.

### *5.3.2.Source term discretization*

Concerning the other difficulty related to the source term, two construction methods are commonly used in the literature to solve the inhomogeneous form of the model: the fractional time-splitting algorithm (Yang et al., 1994; Tseng et al., 2001), and the eigenvector-projection technique (Roe, 1981; Glaister, 1993).

First method consists of solving the homogeneous part of the equation using any scheme and then based on the obtained solution solves an ordinary differential equation with the source term (Hu et al., 2000; Kim et al., 2004). This method has been employed in all urban drainage models. The efficiency of this method was proven in many flow cases variable in time and space and without any limitations on channel section. However, a necessary condition for this method to remain applicable was having smoothly variable channel section and/or bed topography which when not fulfilled lead to incorrect results.

In the case where the invert level is to be permanently modified according to the sediment deposits, this method breaks down. This is due to the hyperbolic formulation of the SWEs essential for the development of numerical schemes. In order to generate this formulation starting from the Navier Stockes' equation, an artificial splitting of the pressure term into a **flux** gradient and a source variable is necessary. But since the classical schemes of solving this system proceed in two consecutive steps: the first one deals with the **flux** flow between discretized cells to solve the inviscid form of the equation, and the second one treats the source term to take it into account in the solution using different method for each step, a numerical instability emerges if no balance is assured for the term split between the flux and the source

variable (Rogers et al., 2003). Figure 1-4 illustrates how the numerical scheme will perceive the discretized workspace and the flow variables in each cell if the gravitational force effect (found in the source term) is not incorporated in the flux term. It will be interpreted as additional flux instead of bed level difference and will therefore neutralize its effect by following the bed topography instead of imposing a horizontal water surface. This imbalance appears when the variation of the bed elevation becomes comparable to water depth.

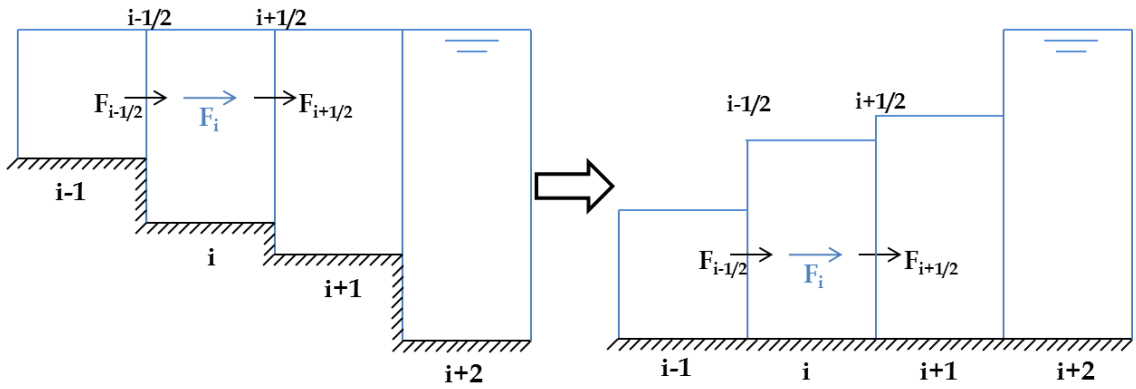



***Figure 1-4:*** *Illustration of the flow variables perceived by a non-well balanced scheme*

This aspect has been extensively studied in the literature where several studies showed that classical numerical schemes fail to replicate flow over highly variable bathymetry. So, to avoid the potential instabilities, either a mesh size small enough should be considered so that the bed elevation difference between adjacent cells reduces significantly, or another more efficient technique (especially in terms of time) should be implemented. Several ways are proposed in the literature for balancing the flux gradient and source terms either in the numerical method or in the mathematical formulation directly.

In the numerical method

It started with Roe (1986) who built the upwind strategy of source term discretization by the characteristic decomposition of this term on the proper eigenvectors of the Jacobian of flux term relative to flow variables. It was developed for problems having constant rectangular sections with variable bed level using flux-splitting techniques. It was later on extended by several researches to apply on more common real cases having more complex source term, or to apply with more numerical schemes: Bermudez and Vazquez (1994) to schemes using flux-splitting techniques, Vazquez-Cendon (1999) to cases having variable section breadth, Garcia-Navarro and Vazquez-Cendon (2000) to cases involving non-rectangular cross section, Hubbard and Garcia-Navarro (2000) to techniques using higher order TVD Roe's scheme.

Then, a new generation of numerical schemes that preserve this balance was introduced and called well-balanced schemes after the pioneer work of Greenberg and Leroux (1996). A

number of these methods have been reported in the literature. Among these, the quasi-steady wave-propagation algorithm of LeVeque (1998) who introduced a new discontinuity at the center of each grid cell and thus an additional Riemann problem in each cell that wasn't actually solved but introduced to assure the balance with bed level source terms. Papalexandris et al. (1997) designed the efficient un-split algorithm that follows the same concept of the method of characteristics by tracing the invariant paths but in this case for the whole system including the source term contribution. He proposed a modification of the flow variables by extracting the pressure force term from the flux to achieve compatibility with the discretized form of the bed slope term. Another efficient one was developed by Zhou et al. (2001) and called the surface gradient method (SGM) based on replacing the water depth by the water surface in the data reconstruction, which was later on extended to the flux-limiting TVD schemes in Tseng (2004). On the other side, Nujic (1995) treated this problem using non-oscillatory high-resolution Lax-Freidrich solver applied on prismatic rectangular channel flow. LeVeque (1998) developed his quasi-steady wave-propagation algorithm by introducing a new discontinuity at the center of each grid cell and thus an additional Riemann problem in each cell that wasn't actually solved but introduced to assure the balance with bed level source terms. Not only was it applicable in a restricted class of problems (rectangular section with a constant width), but also it fails in unsteady states and even transcritical steady states. Catella et al. (2008) proposed a predictor-corrector finite volume method in which the flux between cells is being upwinded for the discharge flow, while for the wetted cross section is calculated based on the Froude number of inter-cell flow. It was tested against a benchmark of different theoretical and real cases and was proven to be accurate and conservative. Zhou et al. (2001) have developed the surface gradient method (SGM) within the slope-limiting high-order finite volume scheme through using the water surface instead of water depth in the data reconstruction, which was later on extended to the flux-limiting TVD schemes in Tseng (2004).

In the mathematical formulation

Other researches chose to derive pre-balance SWEs before solving it by any numerical method. Among these, Rogers et al. (2003) developed a method to construct the deviatoric form of the SWE by subtracting the equilibrium condition which was later extended to encapsulate wetting-drying processes by Liang and Borthwick (2009). Lai and Khan (2012) combined the pressure effect with the breadth variation effect in order to avoid the unphysical flow attributed to improper treatment of the source term. This approach is more attractive as it can be generalized and does not need specific numerical algorithm to be implemented. Their method was proven to work for different section geometry and channel bathymetry. However, the scheme applied is the high order RKDG finite element method which is an accurate method yet not without an additional cost of computational effort. Gascon and Corberan (2001) have presented the transformation of the inhomogeneous problem to homogeneous form through the definition of a new flux formed by the physical flux and the primitive of the source terms.

Most of the aforementioned schemes were basically established for flows in channels with rectangular cross sections (e.g. Vazquez Cendon, 1999; Tseng, 2004) especially when having the flow represented in 2D (e.g. Liang and Borthwick, 2009; Guinot and Soares, 2006) where the section geometry does not appear in the problem's description due to the transversal flow accounted in the equations. Others have neglected certain source terms (e.g. Liang and Marche, 2009; Liang and Borthwick, 2009) that are commonly encountered in real application, or have implemented their source treatment with a certain degree of complexity either in the flux calculation (e.g. Garcia Navarro and Vazquez-Cendon, 2000) or in the workspace discretization (Lai and Khan, 2012). However, in urban drainage models, the hydrodynamic model applied on the sewer scale needs a numerical scheme that combines simplicity of implementation with the capacity of considering all possible conditions (non-rectangular sections, variable section breadth, irregular bed topography) in engineering applications.

∴ Hydraulic modeling constitutes a fundamental step in the models of sewer flow quality based on physical processes as it determines all the driving forces of sediment production (shear) and transfer (velocity). It can be modeled by simple conceptual methods valid only under restricted conditions or by complex physical methods based on the Shallow Water Equations (SWEs). The complete version of this model seems to be the most suitable for sewer application and that isn't possible except by numerical methods.

Numerical methods are all constructed on the basis of the hyperbolic formulation of the SWEs model and thus have two terms to be carefully handled especially when sewer systems are represented with their semi-permanent sewer grits:

Flux term: two categories of schemes were developed to treat this term: finite difference methods used in the majority of urban drainage models and have several shortcomings especially when critical flow arises, and finite volume methods representing interesting features regarding the efficiency, simplicity, shock-capturing but that is still not used in this type of models.

Source term: To avoid any kind of instabilities in the model solution, the discretization of this term must be compatible with that of the flux term. This was done either in the numerical scheme used or directly in the reformulation of the governing equations, where the latter being way simpler. However, none of the existing approaches take into account all the sewer conditions (non-rectangular & non-prismatic flow section and irregular bed topography) except with more complex discretization techniques (RKDG).

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# Chapter 2
# Presentation of experimental and modelling investigations of the Marais site

## 1. Choice of the study site

The study site of this work is the "Marais" urban catchment. The selection of this site was completely based on the criteria that serve our modelling objectives and requirements:

| Site characteristic | Interest in terms of modelling |
|---|---|
| Mixed residential and commercial site | Typical site of urban residential area |
| Small catchment area | Permits better investigation of the catchment features<br>Facilitates the understanding of catchment response in dry and wet weather periods<br>Allows finer description of the system |
| Well-demarcated watershed no input from other catchments and a single outlet | Helps to better define the contributing surface and buildings to water flow and pollutants' production |
| Drained by a dendritic network | Defines the flow direction anywhere in the sewer network |
| Drained by a man entry sewer | Helps to easily visit the sewer channels and carry in-situ measurement campaigns |
| The sewer system is combined and built on low-sloped gradients on which important amount of deposits were observed | Favourable for in-sewer deposits accumulations and thus presents a typical site to study deposits erosion and deposition processes |
| The site was the subject of extensive experimental campaigns of water and pollutants flow on several points of the catchment, with a particular attention on measurement techniques and uncertainties associated (Gromaire, 1998; Ahyerre, 1999; Garnaud, 1999; Gonzalez, 2001; Oms, 2003) | Provides the necessary database on qualitative and quantitative characteristics needed for to define the input variables and to validate the model results |
| The site was the subject of several modelling attempts (Schlutter, 1999; Kanso, 2004; Tait et al., 2006) | Provides useful elements at different stages of modelling:<br>A guiding cursor for model selection in terms of spatial description and level of complexity based on the degree of success of previously tested model<br>Provides prior information on parameters definition for retained models<br>Provides information on others model performance useful for comparison and model assessment |

***Table 2-1:*** *Interesting and distinctive features in the Marais site for modelling objectives*

## 2. Site description

The "Marais" site is located in the centre of Paris covering a part of the 3rd and 4th arrondissement, which is a highly urbanized area. It extends over 42 ha with 90% impervious area and a population density of 295 inhabitants per hectare. It's basically a residential area with many small shops, offices and very few industrial activities, which is representative of old downtown areas. These activities are almost uniformly spread over the whole site surface with more concentration along the main circulation axes: Rivoli Street, Saint-Antoine Street, Francs Bourgeois Street, Vieille du Temple Street, and Turenne Street. The traffic is intense (between 24000 and 28000 vehicles/day) and superior to the average in Paris.

### *2.1. Surface description*

For the surface types covering the catchment area, we can distinguish three categories:

- Pavements occupying 9.7 ha (23.2%)
- Roofs occupying 22.8 ha (54.4%)
- Gardens & playgrounds occupying 9.4 ha (22.4%)

The runoff coefficient of the whole surface is around 78% estimated in (Gromaire, 1998) by values cited in (Bourrier, 1991) for flat land surfaces. The average road slope on the whole watershed (calculated as arithmetic mean weighted by longitudinal length) is around 0.84% with 90% of the roads having a slope inferior to 1.5%.

### *2.2. Sewer system description*

The Marais watershed is drained by a combined sewer system of a branched layout that is man-entry and located at the very upstream of the Paris sewer system. It is composed of 3 main channels: *Saint-Gilles* channel and *Vieille du Temple* channel that discharge their water into the *Rivoli* channel. These channels drain around 50 secondary sewer lines. The characteristics of the three main channels and the secondary sewer lines are represented in the table below.

| Sewer channel | Length (m) | Average slope (%) | Typical section (figure 2-2 and 2-3) |
|---|---|---|---|
| Rivoli | 430 | 0.09 | Riv |
| Saint Gilles | 798 | 0.04 | SG |
| Vieille du Temple | 596 | 0.06 | VdT |
| Secondary lines | 5800 | 0.83 | SL |

***Table 2-2:*** *Geometrical characteristics of Marais sewer system*

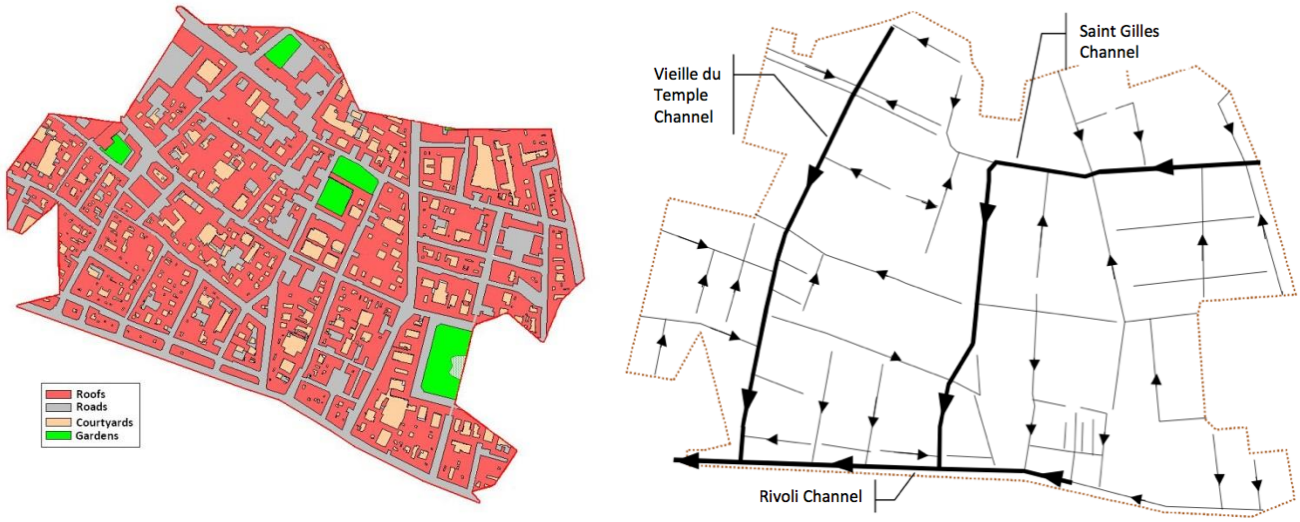



***Figure 2-1:*** *(Left) Surface distribution of the Marais site between roads, roofs, and courtyards; (Right) Principal and secondary channels in the Marais sewer system*

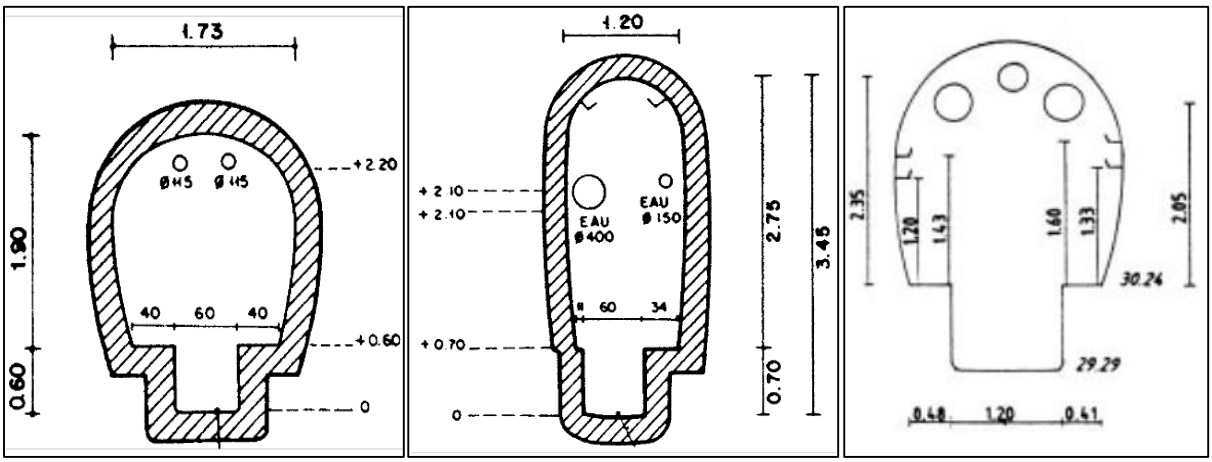



***Figure 2-2:*** *Typical sections of the main channels: (Left)* ***SG****, (Middle)* ***VdT****, (Right)* ***Riv***

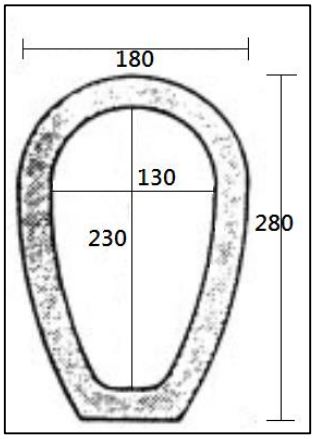



***Figure 2-3:*** *Typical section of secondary channels* ***SL*** *(upstream sewer)*

## 3. Database presentation

As said before, one of the main advantages of this site is being the subject of previous research programs in which several issues with various scale levels have been addressed through extensive in-situ investigations. This led to the construction of a rich experimental database useful for further research studies on the hydrologic behaviour of the system. Besides all the data collected on the topography of the surface and sewer system, many measurements have been taken for:

| Measured database | | | From | To | Comments |
|---|---|---|---|---|---|
| Precipitation data | | | 15 May 1996 | 3 April 1999 | 225 events |
| Outfall (Wet weather) | Discharge flow rate (Flow speed and flow depth) | | 2 April 1996 | 15 March 1999 | Time step = 2 min |
| | Mean concentration on TSS, VM, COD, $BOD_5$ | | 15 May 1996 | 10 October 1997 | 67 events |
| | Mean concentration on metals (Cd, Cu, Pb, Zn) | | | | 20 events |
| | Average concentration of hydrocarbons | | | | 12 events |
| | Pollutograph of concentration of TSS, VM, COD, $BOD_5$ | | | | 41 events<br>Time step = 10 min |
| Outfall (Dry weather) | Discharge flow rate (Flow velocity and flow depth) | | 2 April 1996 | 15 March 1999 | Time step = 2 min |
| | Pollutograph of concentration of TSS, VM, COD, $BOD_5$ | | 15 July 1996 | 27 July 1996 | 3 to 7 days per campaign<br>24 hourly mean samples<br>Time step = 6 min |
| | | | 22 July 1997 | 3 August 1997 | |
| | | | 6 January 1997 | 14 January 1997 | |
| | | | 8 mars 1997 | 1 April 1997 | |
| | Pollutograph of concentration of Cd, Cu, Pb, Zn, Hc | | 6 January 1997 | 14 January 1997 | |
| | | | 8 mars 1997 | 1 April 1997 | |
| | TSS settling velocity | | 8 mars 1997 | 1 April 1997 | |
| | | | 22 July 1997 | 3 August 1997 | |
| | $NH_4^+$ | | 22 July 1997 | 3 August 1997 | |
| Runoff flow | Rooftops (4 initial sites & 7 complementary sites) | Average concentration TSS, VM, COD, $BOD_5$ | 15 May 1996 | 10 October 1997 | 39 to 52 events on 4 rooftops<br>7 to 15 events on 7 rooftops |
| | | Average concentration Cd, Cu, Pb, Zn | | | 16 to 20 events on 4 rooftops<br>4 to 7 events on 7 rooftops |
| | | Average concentration Hydrocarbons | | | 10 to 12 events on 4 rooftops<br>2 to 8 events on 7 rooftops |
| | 3 Courtyards & 6 Roads | Average concentration TSS, VM, COD, $BOD_5$ | 15 May 1996 | 10 October 1997 | 8 to 25 events |
| | | Average concentration Cd, Cu, Pb, Zn | | | 4 to 9 events |
| | | Average concentration Hydrocarbons | | | 5 to 7 events |
| | 6 Roads | Pollutograph of concentration of TSS, VM, COD, $BOD_5$ | 15 May 1996 | 10 October 1997 | 10 events<br>Time step = 10 min |

***Table 2-3:*** *Recapitulative of all measurements made on the Marais site*

## 3.1. Precipitation data and rainfall events characteristics

The precipitation data were collected by the means of 2 rain gauges of tipping buckets installed on the site between 15 May 1996 and 3 April 1999. Then, to identify the rainfall events on this site, a thorough treatment of these data was carried by (Gromaire, 1998) in her thesis where two principal criteria were adopted to filter the registered data:

- The precipitation height > 1mm;
- The duration between 2 successive rainfall events > the concentration time of the Marais watershed (30 min).

This treatment yielded 225 rainfall events during the whole period of measurement.

## 3.2. Dry weather flow data

For dry weather period, no experimental campaigns were carried out to characterize the wastewater flow at the inlet points of the sewer system. Only the sewer outfall was outfitted - during the first phase of OPUR - (Gromaire, 1998) with the suitable equipment to measure water flow and pollutants' concentration in the wastewater outflow. For the latter, we will not talk about all the quality parameters measured and analysed. Only the TSS concentration measurements will be presented.

### 3.2.1. Discharge flow rate

The database of the discharge flow rate at the outfall (during both dry and wet weather) was constructed on the basis of continuous measurements made by a flowmeter Ultraflux installed at the outfall located 80m after the intersection between Rivoli channel and Vieille du Temple channel. It is composed of a velocity ultrasound sensor with 2 water depth sensors: an aerial ultrasound and a pressure sensor. The flow measurements were recorded at a time step of 2 minutes for the period extending between April 1996 and March 1999.

*Average flow rate and its variability*

The average flow rate of wastewater at the outfall of the sewer was 0.048-0.07 $m^3/s$ (338-549 l/head/day) which is considered as rather high and can be partly explained by the intensive street sweeping (of the order of 60 l/head/day). The variability of the average dry weather flow with days of the week and seasons was also studied in (Gromaire, 1998). It was found that the variability between the weekdays is quite low whereas the average flow rate on Sundays is slightly inferior to other days (difference < 7%). This inter-day variability is way inferior to that between seasons. This latter was imputed to the difference of the clear water quantities

entering the sewer from flushing tank system and potable network leakage and to the evolution of wastewater production along the year related to the vacation in summer, and absence of street sweeping in winter.

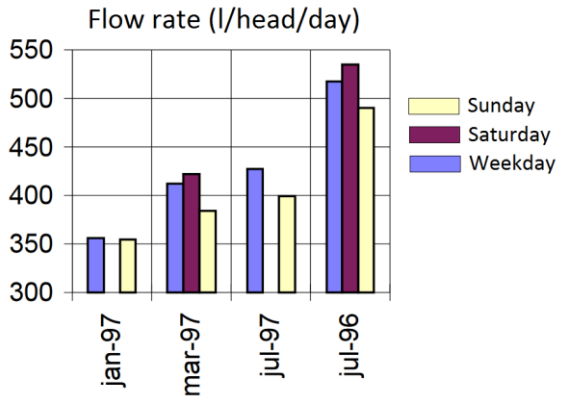



***Figure 2-4:*** *Comparison of average flow rate of dry weather flow at Marais sewer outfall between weekdays and weekends measured during 4 campaigns*

*Flow rate evolution inside the day and its variability*

Concerning the variation of wastewater flow production inside the day, measurements show a clear typical daily cycle attaining its maximum between 8 and 11 AM and its minimum between 3 and 6 AM, with a rapid increase in the morning and a progressive decrease in the afternoon. Similar to the average value observations, the variation of this cycle with the days of the week is minimal, whereas the effect of season on this cycle is more pronounced. So, in defining the dry weather pattern input hydrographs in our model, we will consider only the seasonal and annual variability (shown in the figure below).

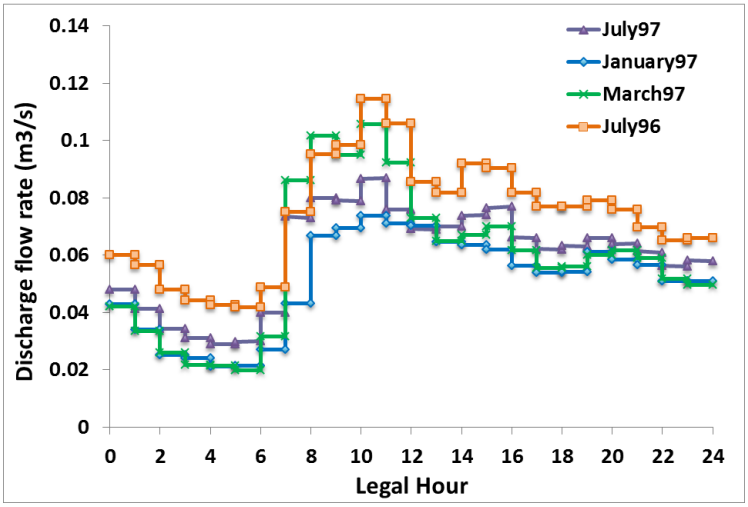



***Figure 2-5:*** *Daily cycle of dry weather flow at Marais sewer outfall measured during 4 campaigns*

### 3.2.2.TSS concentration

Unlike the water flow rate, measurements of the concentration of the pollution parameters weren't possible by continuous means. So, two automatic samplers (one with multi-flask and the other with a mono-flask) were used to take some discrete samples of the outflow discharge:

- Discrete in space (longitudinally w.r.t. the sewer length and vertically w.r.t. the flow section)
- Discrete in time also (at a frequency limited by the capacity of the sampler)

For dry weather flow, four campaigns were realized, for each of which 3 to 7 days were sampled. For each day, 24 hourly mean measurements were recorded. Each measurement is made by the average of 10 samples of 260 ml taken at a 6 minute time step.

The uncertainty induced by this method is principally related to the error of sampling on a fixed time step. But since the dry weather flow rate varies relatively little on a one hour interval, the mean samples constituted by fixed time sampling seems to provide a good estimation of the mean hour concentration. This was verified in (Gromaire, 1998) by specific sampling campaign carried out on different periods of the day.

*Average TSS concentration and its variability*

The average TSS concentration measured on the 4 campaigns is 111-194 mg/l (48-77 g/head/day) which is equivalent to other values found in the literature (e.g. Coteaux Channel for which the average daily transport rate of TSS was found to be 31-71 g/head/day (Philippe and Ranchet, 1987)). The variability of TSS transport rate as a function of day was low as shown in the figure below. For all campaigns except that of January 1997, a decrease of the average TSS concentration by 14 to 25% is observed from weekdays to weekends. This is more remarkable on July 1997 due to the massive depart of inhabitants in summer. Seasonal variations were also low. Vacation periods are distinguished by the lower pollutants' load than other periods of the year. The measurements taken in March 1997 are considered representative of the normal activity on the studied catchment. The campaign of January 1997 is particular due to the absence of street sweeping.

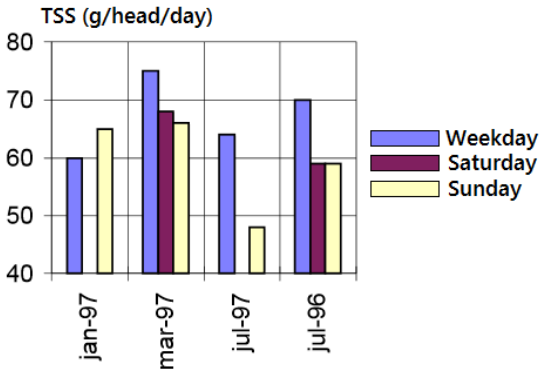



***Figure 2-6:*** *Comparison of average TSS concentration of dry weather flow at Marais sewer outfall between weekdays and weekends measured during 4 campaigns*

*TSS concentration evolution inside the day and its variability*

Dry weather measurements show that not only wastewater flow follows a regular daily cycle, but also TSS concentration daily profile exhibit a periodic evolution analogous to the former cycle. However, if the flow one is intuitive, the concentration one wasn't expected and if it reflects anything, it is the erosion during morning peak where the transport capacity of flow increases, and sedimentation process occurring when flow decreases. The comparison of the TSS concentration daily profile between the 4 campaigns shows important variability between seasons but not between days. A late peak flow was systematically observed for the weekend profiles relative to weekdays ones.

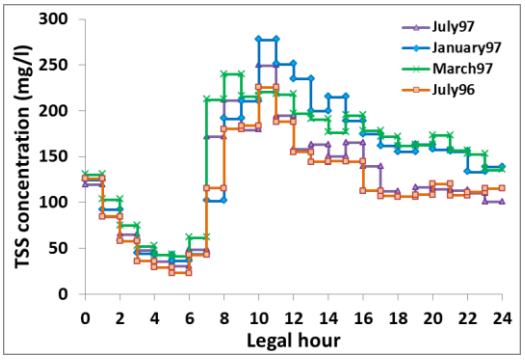



***Figure 2-7:*** *Daily cycle of dry weather TSS concentration at Marais sewer outfall measured during 4 campaigns*

### *3.3. Wet weather flow data*

A more comprehensive characterization of the wet weather flow relative to the dry weather one was carried out on this site where both inlets (not all) and the outfall of the system were sampled. The same equipment used at the outfall during dry weather days was used to measure the quantity and quality of wet weather outflow, whereas other apparatus were installed at the inlet points to measure the inflow quantity and quality.

### 3.3.1.Runoff flow

- Runoff from four rooftops (supplemented with other seven complementary sites) were collected in 100L barrels and then sampled and analysed for its pollutants' concentration, whereas runoff volume was calculated from the precipitation depth multiplied by a theoretical runoff coefficient.
- Runoff from three interior courtyards was measured by an automatic sampler to determine the quality parameters, whereas the volume was also determined from the precipitation depth multiplied by a theoretical runoff coefficient.
- Unlike rooftops and courtyards, both discharge flow and pollutants' concentration were measured for the street runoff on six sites using respectively tipping buckets of 20L and two automatic samplers (Buhler-PBMOS).

The measurement campaigns were made between 15 May 1996 and 10 October 1997 as shown in the figure below.

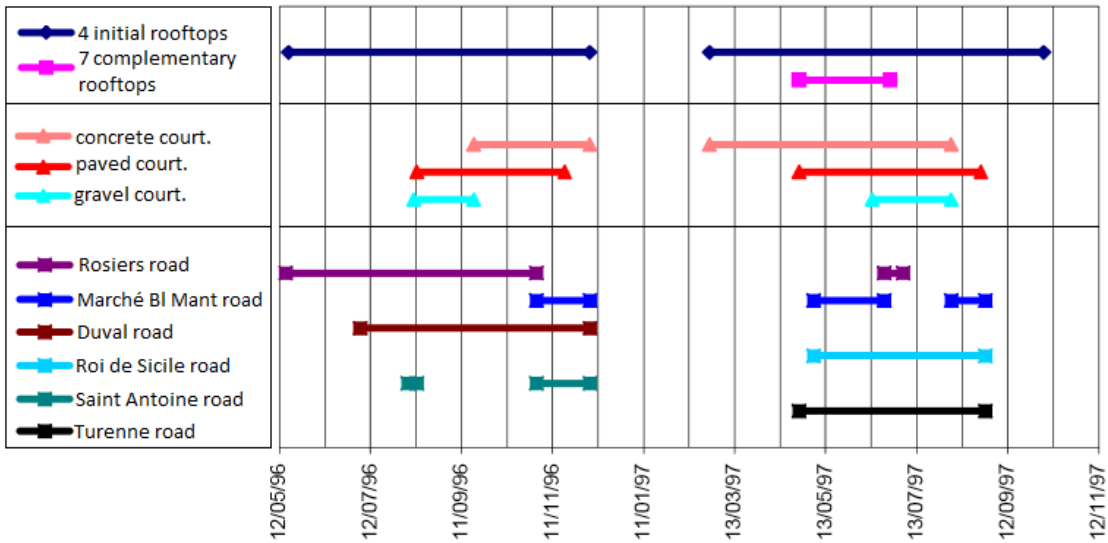



***Figure 2-8:*** *Periods of runoff flow measurements on the rooftops, courtyards, and roads on the Marias site*

*Average TSS concentration and its variability*

The table below presents the order of magnitude of the EMC of the TSS measured in the runoff flow on each surface type.

| Parameter | Surface type | $d_{10}$ | $d_{50}$ | $d_{90}$ |
|---|---|---|---|---|
| TSS concentration (mg/l) | Rooftops | 6 | 17 | 74 |
| | Courtyards | 13 | 40 | 152 |
| | Roads | 53 | 97 | 276 |
| TSS transport rate (kg/ha/event) | Rooftops | 0.18 | 0.74 | 3.8 |
| | Courtyards | 0.26 | 1.59 | 6.95 |
| | Roads | 1.91 | 4.41 | 11.51 |

***Table 2-4:*** *Statistical characteristics of event mean TSS concentration and transport rate on the three sampled surface types of the Marais site*

We notice from the average concentrations that the road surface produces the highest concentration of TSS in the runoff flow with a median value of 97mg/l that is 2.5 times that of the courtyards and 6 times that of the rooftops. The comparison of the EMC between different sites on each of the three surface types uncovered some statistically significant differences between sites, where tile roofs were found to be more polluting than zinc and slate that weren't as much different. For the road surface, runoff from Rosiers was more loaded with TSS than Saint Antoine which was more contaminated than all the other equally polluted roads. This difference was linked more to the pedestrian passage - that is higher on Rosiers road than Saint Antoine - than to the traffic flux - that is higher on Saint Antoine than the Rosiers road where circulation is difficult and frequently blocked due to the delivery vehicles and narrowness of the road and that could have also contributed to the pollution emission. The variability of the concentration of each surface runoff as a function of rainfall events was also studied in (Gromaire, 1998). For rooftops, the best (but still very weak) correlation was found with the average intensity and the ADWP. For roads runoff, weak to moderate correlations were obtained between average TSS concentration and rainfall characteristics that were different from one site to another.

*TSS concentration evolution inside the rainfall event and its variability*

The analysis of pollutographs measured on the six roads revealed high variability inside the rainfall event attaining a factor of 10 on events characterized by high rainfall intensity. The shape of the pollutographs was found to depend on the characteristic of the rainfall event. For those having low intensity, the TSS dynamics produced can be generally described by a maximum concentration at the beginning of the rainfall event and then a progressive decrease

till the end of the event. For others having a well-marked high intensity, the pollutographs present a peak concomitant or slightly preceding the flow rate peak. The observations made on successive discharge peaks show that if two peaks are produced in the same rainfall event, an abatement of the TSS concentration occurs for the second peak which does not applies for the case of two successive rainfall events giving more weight for the instant discharge than the antecedent events characteristics in explaining the wash-off load.

### 3.3.2.Sewer outflow

From the continuous measurements taken by the Ultraflux flowmeter between April 1996 and March 1999, 159 rainfall events were detected. However, only 67 events were analysed in terms of pollution concentration (average and/or pollutograph). The comparison between the 67 events set and the total set of rainfall events shows that both event sets cover the same range of variability of precipitation depth, intensity, ADWP, with a little overestimation of the occurrence frequency of events with small precipitation depth and maximum intensity in the studied set with respect to the whole one. This set was considered globally representative of the whole events' sample.

Wet weather pollutographs of TSS concentration were obtained by an automatic sampling process starting with the water depth surpassing the maximum depth of dry weather flow (31 cm) and recurring with a frequency proportional to the outflow volume. These criteria adopted to determine the beginning and the end of the rainfall event induces an error on the calculation of the event mean concentration estimated by (Gromaire, 1998) to be less than 10% of measured concentration in excess of the real concentration. This uncertainty together with that of the analysis and sampling methods add up to 18±18% of measured w.r.t to real average concentration.

*Average TSS concentration and its variability*

The event mean concentration (EMC) on TSS was determined on the 67 rainfall events. The order of magnitude of the average TSS concentration and transport rate obtained on the event scale is comparable to those obtained on other combined sewer systems (Table 1-1).

| Parameter | $d_{10}$ | $d_{50}$ | $d_{90}$ |
|---|---|---|---|
| TSS concentration (mg/l) | 121 | 221 | 519 |
| TSS transport rate (kg/ha) | 6.4 | 12.7 | 25.8 |

***Table 2-5:*** *Statistical characteristics of event mean TSS concentration and transport rate of wet weather outflow of the Marais site*

The EMC of TSS obtained for each rainfall event did not show (Gromaire, 1998) any correlation with the rainfall event characteristics (neither rainfall characteristic nor sewer flow characteristic). The total event mass of TSS present better relation with the rainfall depth and the maximum intensity that weren't able to explain but a weak part of the observed variability.

| (67 events) | H (mm) | $I_m$ (mm/h) | $I_{max}$ (mm/h) | $I_{max\ 5}$ (mm/h) | $I_{max\ 20}$ (mm/h) | D (hr :min) | ADWP (days) |
|---|---|---|---|---|---|---|---|
| Minimum | 1.3 | 0.7 | 1.2 | 1.2 | 1 | 00 :06 | 0.02 |
| Median | 5.9 | 3.7 | 20.6 | 89.6 | 47.6 | 1 :45 | 0.9 |
| Maximum | 20.8 | 42 | 240 | 12 | 5.9 | 07 :27 | 50.5 |

*H: precipitation depth, $I_m$: average rainfall intensity, $I_{max}$: maximum intensity, $I_{max\ 5}$: maximum intensity during 5 minutes, $I_{max\ 20}$: maximum intensity during 20 minutes, D: rainfall event duration, ADWP: antecedent dry weather period*

***Table 2-6:** Characteristics of the 67 rainfall events*

*TSS concentration evolution inside the rainfall event and its variability*

Out of these 67 events, only the TSS pollutograph was determined for 40 whose characteristics also cover the whole variation of the complete set with a majority of weak rainfall events (table 2-7).

| (40 events) | H (mm) | $I_m$ (mm/h) | $I_{max}$ (mm/h) | $I_{max\ 5}$ (mm/h) | $I_{max\ 20}$ (mm/h) | D (hr :min) | ADWP (days) |
|---|---|---|---|---|---|---|---|
| Minimum | 0.98 | 0.45 | 1.15 | 1.15 | 1 | 00 :10 | 0.02 |
| Median | 6.5 | 2.16 | 16.14 | 11.05 | 6.225 | 02 :34 | 0.57 |
| Maximum | 30 | 34.8 | 240 | 89.6 | 37.5 | 12 :32 | 37 |

*H: precipitation depth, $I_m$: average rainfall intensity, $I_{max}$: maximum intensity, $I_{max\ 5}$: maximum intensity during 5 minutes, $I_{max\ 20}$: maximum intensity during 20 minutes, D: rainfall event duration, ADWP: antecedent dry weather period*

***Table 2-7:** Characteristics of the 40 rainfall events*

The shape of the pollutograph at the outfall of the sewer system is complicated so that it seems so difficult to assign a characteristics pollutograph to the sewer system as many factors intervene in determining it. The analysis made in (Gromaire, 1998) showed that this shape depends basically on 2 important factors: the instant at which the rainfall event occurs during the day, and the intensity of the rainfall event. In those happening at daytime, the concentration peak is synchronous with the flow peak when the rainfall intensity is high, but precedes the flow peak for low intensity events. However, for nocturnal events, the concentration peak always precedes that of the discharge flow. So, in most cases, the concentration peak occurs before or at the same time as the discharge flow peak. For only 30%

of the sampled rainfall events the TSS concentration peak comes after the discharge peak. The analysis of successive peaks belonging to the same event or to a series of events showed a clear attenuation of the TSS transport rate during the next peak only for the former case. This observation reflects: first the rapid reconstitution of the erodible deposits between rainfall events, and second the increasingly resistive nature of the mobilized stock contributing to total TSS transport rate at the outfall.

## *3.4. In-sewer deposits characteristics*

In an attempt to identify which type of in-sewer sediments contributes to the pollution of combined sewer outflow on the Marais site and how the erosion mechanism takes place, a comprehensive experimental survey was conducted (Ahyerre, 1999; Oms, 2003) on the whole sewer system' deposits from which several conclusions can be drawn regarding: type of deposits, localization, physical and chemical nature.

### 3.4.1. Type of deposits

As mentioned before, one of the interesting features of the Marais site is the important fouling in its low sloped channels. In the sampling campaigns and the observation systems installed in the sewer, three types of deposits were identified:

- Coarse granular deposits (Type A according to the classification of Crabtree (1989))
- Biofilms
- Organic layer

### 3.4.2. Localization and topography of sewer deposits

Ahyerre (1999) sampled on different spatial scales each of the three deposit types. Deposits cartographies were later verified by Oms (2003) by sweeping the three main channels with an endoscope at 50 m space step. Results of these campaigns are presented in the figures below.

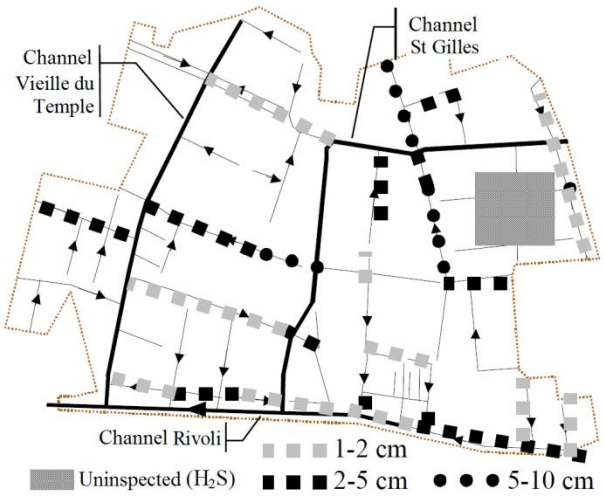



***Figure 2-9:*** *Coarse granular deposits observed on the upstream sewer of the Marais site*

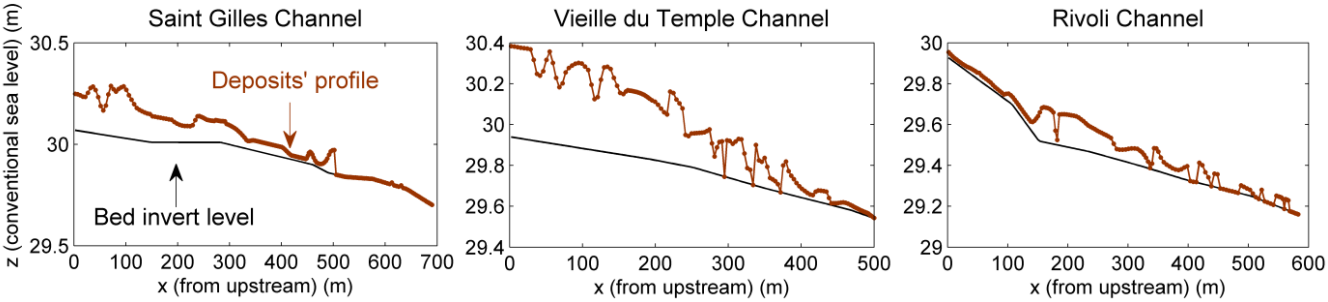



***Figure 2-10:*** *Bed invert level and coarse granular deposits profile on the three main channels of Marais catchment*

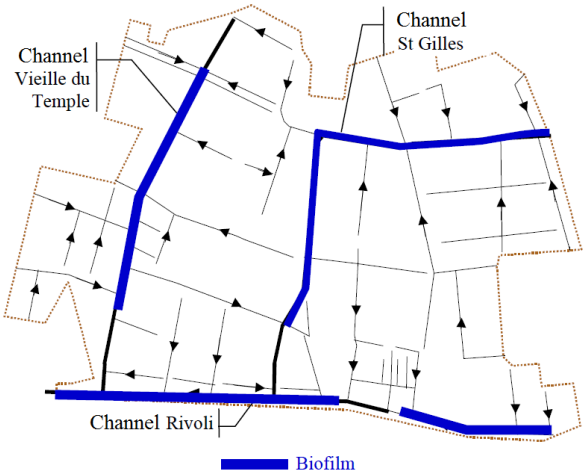



***Figure 2-11:*** *Biofilm observed in the main channels of the Marais catchment*

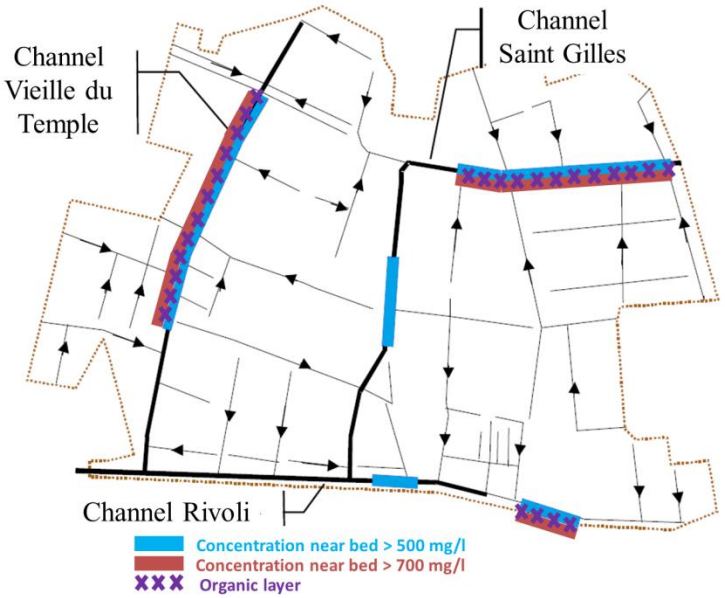



***Figure 2-12:*** *Organic layer cartographies obtained by Ahyerre (1999) (concentration near bed > 500 mg/l), and by Oms (2003) (using the endoscope)*

### 3.4.3.Pollutants' content

Analysis of the pollutants' content for each type of deposits was realized by (Ahyerre, 1999; Oms, 2003). The table below summarizes the results of these analyses.

| Sewer type | MVS/TSS (%) | COD/TSS ($gO_2/g$) | $BOD_5$/TSS ($gO_2/g$) | Cd (µg/g) | Cu (µg/g) | Pb (µg/g) | Zn (µg/g) |
|---|---|---|---|---|---|---|---|
| **Coarse granular deposits (<400µm)** | 13 – 22 (17) | 0.28 – 0.56 (0.43) | 0.019 – 0.059 (0.037) | 1.64 – 5.73 (3.9) | 470 – 1230 (870) | 1210 – 2280 (1870) | 2461 – 5750 (4047) |
| **Biofilms** | 39 – 81 (71) | 1 – 1.7 (1.4) | 0.26 – 0.62 (0.37) | 3 – 92 (13) | 500 – 15500 (2900) | 1300 – 29900 (3900) | 7000 – 157000 (21000) |
| **Organic layer** | 60 – 75 (68) | 1.04 – 1.375 (1.16) | 0.149 – 0.354 (0.25) | 0.82 – 2.93 (0.97) | 103 – 221 (131) | 197 – 335 (214) | 970 – 1550 (1270) |
| **Eroded particles** | 58 – 76 (67) | 0.77 – 1.5 (1.1) | 0.29 – 0.66 (0.42) | 1.4 – 3.5 (2.7) | 170 – 300 (280) | 50 – 400 (200) | 500 – 1500 (1100) |

***Table 2-8:*** *Pollutants' content of the three types of sewer deposits identified on the Marais sewer presented as* $d_{10} – d_{90}$ ($d_{50}$)

The comparison of the characteristics of each of these deposits with those of the eroded particles observed at the sewer outfall during wet weather conditions showed that the former is probably the origin of the latter.

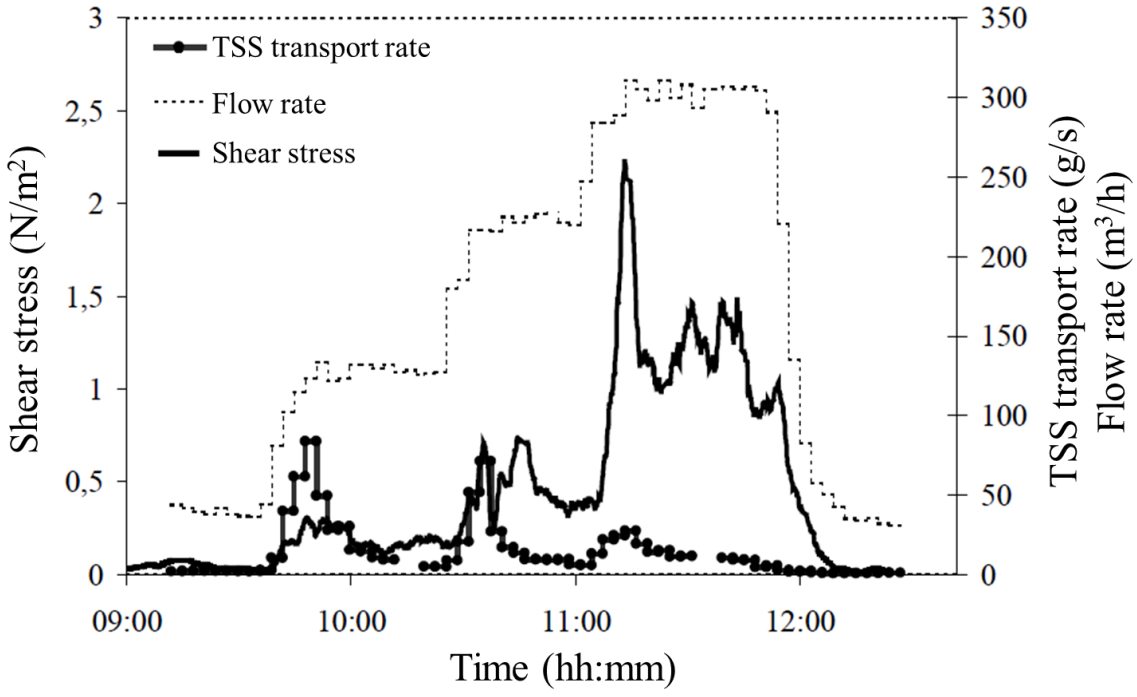
#### 3.4.3.1. *Experimental results of the dynamics of the organic layer*

##### 3.4.3.1.1. *Controlled flushing experiments*

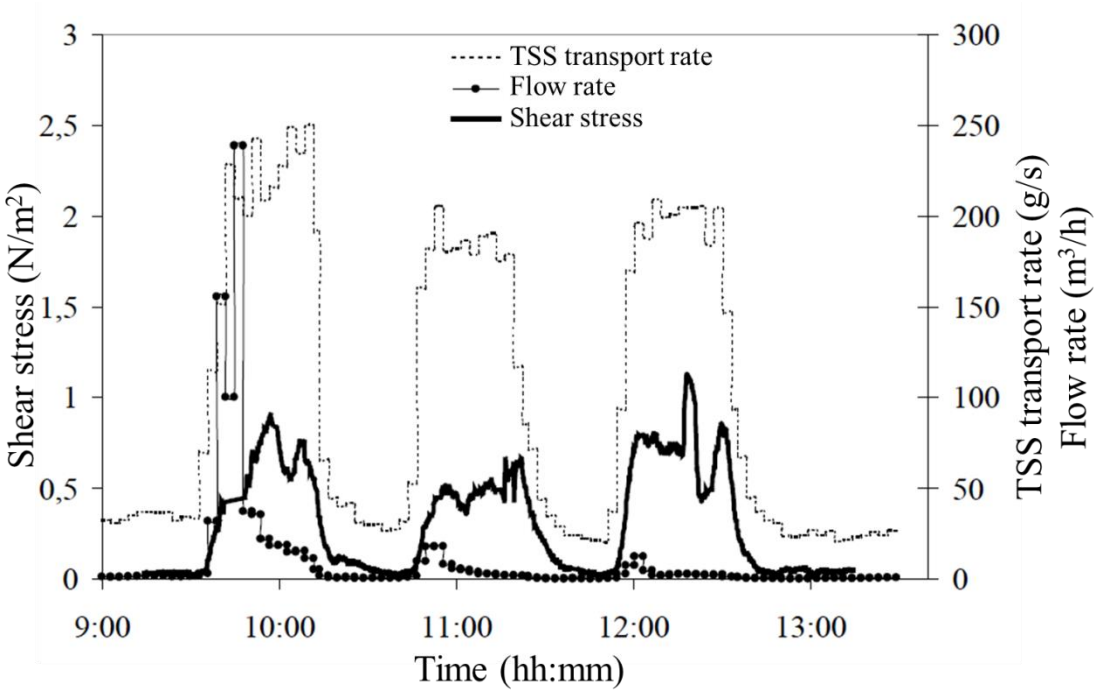
Several in-situ hydraulic flushing experiments were realized to study the dynamics of the organic layer as a function of the hydraulic parameters (discharge flow rate and boundary shear stress). The field tests were carried out on a discrete length of the upstream of Vieille du Temple (150m) (Ahyerre, 1999) and Saint Gilles (100m) (Oms, 2003) with no lateral inflow by injecting clean water from fire hydrant found at the street level. The behaviour of sediments in these experiments was studied by measuring quality parameters at the downstream end of the test pipe.

The quantity and quality of inputs are well known since the scheme of flow injection is totally under control and the used source is clean water with zero sediment loads. Outputs are also known being restricted to the particles eroded from the sediment deposits and any sediment moving into the test section from the upstream by the low dry weather flow. This was estimated during previous periods of dry weather and was found to be at least one order of magnitude lower than the sediment contribution.

Two experiments were performed. The first one included three successive steady levels with increasing discharge values (fig. 2-13 a) and the the second one three steady levels with the same discharge value separated by equal periods without any discharge (fig. 2-13 b).




(2-13 a)




(2-13 b)

***Figure 2-13:*** *Variations of TSS transport rate (g/s), flow rate (m3/h), and shear stress (N/m2) (measured by ADV) at the downstream of the experimental segment studied in Vieille du Temple channel in 02/12/1998 and 05/11/1998*

Results of these experiments showed that the nature of the eroded particles at channel scale is similar to those eroded at sewer scale and thus constitute a source being eroded during wet weather conditions. The physical properties of this layer revealed by these tests can be summarized in:

- The increase of measured TSS transport rate at each flow rate increase indicates that the organic layer is sensitive to every change in hydraulic conditions even at low shear stress (0.03 N/m²)
- The decrease of measured pollutograph peak from one flow injection to another consecutive (whether with the same magnitude (figure 2-13 b) or higher (figure 2-13 a)) reflects the layered structure of the erodible layer whose strength increases with depth
- The increase of the TSS transport rate with each discharge pulse although the discharge value remains the same suggests that the erosion process is more related to the transient character of the flow rather than the flow magnitude

#### 3.4.3.1.2. Observational system

Ahyerre (1999) installed an observational box in the Vieille du Temple collector in order to visualize the evolution of the organic layer during dry weather periods. He found that this layer is almost stable with a depth varying between 1.5 and 7 cm during the studied period. This observational system was later upgraded by Oms (2003) to limit its impact on the hydraulic conditions and outfit it with an integrated automatic camera system. It was installed on another point of the sewer system having organic layer that is at the upstream of the Saint Gilles collector. New observations corroborated the previous ones. They showed that the organic layer is characterized by quasi stable state reaching a height of 15 cm, where cavities formed occasionally by erosion are rapidly filled up by the NBS trapped in these irregularities while moving near the bed surface. Images taken by this system during artificial injection of water flow show that the erosion occurring in this layer is not uniform along the whole pipe, where two explanations arise: either due to the heterogeneity of surface resistance to erosion and local variations of the hydraulic conditions, or decrease in the transport capacity of the flow when loaded with sediment particles. Measures of shear stress coupled with cartographies of organic layer showed that this organic layer is most probably formed in zone with low shear stress (<0.03-0.1N/m²) and flow speed (<0.1 m/s) that make the flow incapable of transporting the solid particles entering the sewer collectors further downstream.

### 3.4.3.2. Results of modelling the dynamics of the organic layer

Several modelling approaches (Tait et al., 2003; Kanso et al., 2005) were later carried out to simulate the erosion of the organic layer to reproduce the pollutographs measured at the pipe scale during the hydraulic flushing experiments realized by Ahyerre (1999). As the observations show, the most remarkable feature of this layer was its rapid reactivity to the variations of the hydraulic conditions and the erosion rate decreasing with time. So, the erosion was modelled using the excess shear stress formula (Parchure and Mehta, 1985) while describing the structure of the organic layer by an increasing resistant layer with depth according to the Skipworth formula (Skipworth et al., 1999). The adjustment of the model parameters was made by different calibration procedures: the genetic algorithm (Tait et al., 2003) and the Markov Chain Monte Carlo (MCMC) algorithm (Kanso et al., 2005). With the genetic algorithm several optimization criteria were tested (mean absolute error, weighted absolute error, standard deviation), and with the MCMC method the normal likelihood function was expressed in terms of TSS concentration.

Both studies demonstrated that the hypothesis describing the variation of the resistance to erosion is suitable to simulate the erosion process under the effect of shear stress. It permits to emulate the behaviour highlighted by site observations which other models developed on non-cohesive sediments do not permit to represent. Results of the calibrated pollutographs of

the experiment of 02/12/1998 using genetic algorithm to minimize the absolute mean error on the suspended solid transport rate (Tait et al., 2003) and using MCMC method to maximize the likelihood function on suspended solid concentration (Kanso et al., 2005) are illustrated in figures 2-14 and 2-15 respectively. They show a good capacity of the model to reproduce erosion as a direct response to the increase in the shear stress where an excellent fit between measured and modelled pollutographs were obtained. Similar performance was obtained for the other experiment.

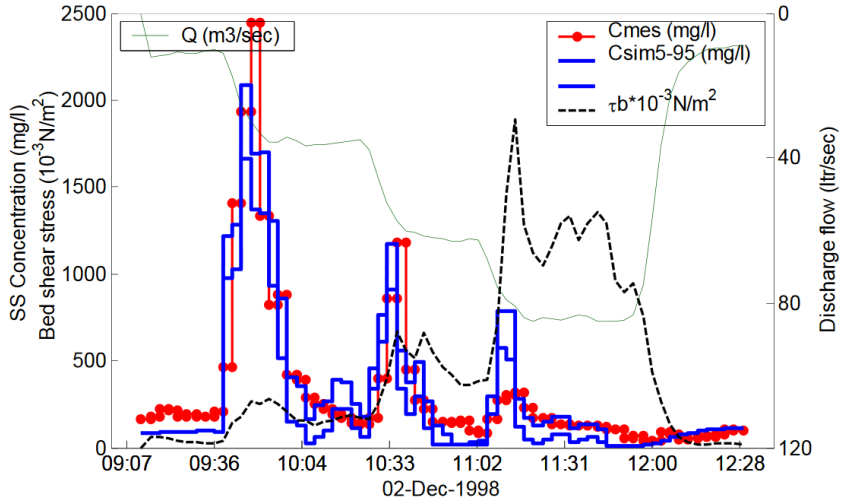



***Figure 2-14:*** *Measured and modelled suspended solid concentration versus time with 5-95% prediction interval obtained by MCMC calibration for the experiment of 02/12/1998 (Kanso et al., 2005)*

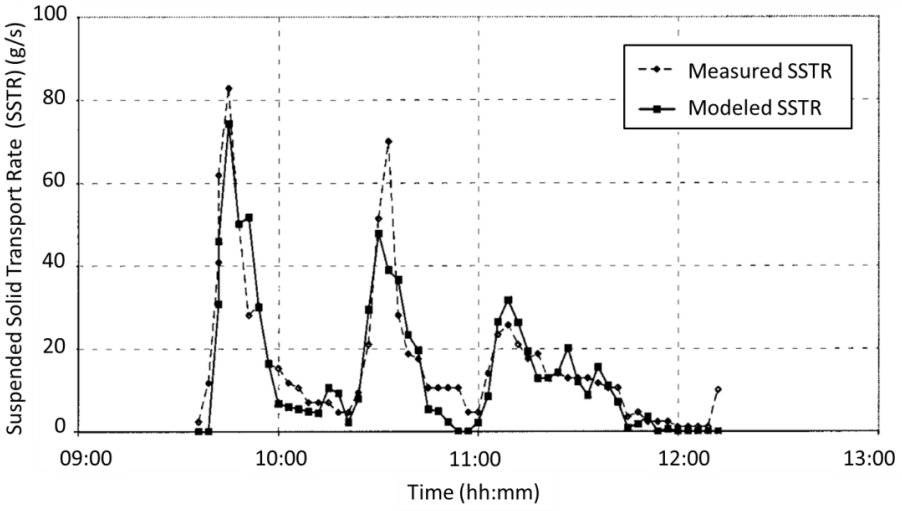



***Figure 2-15:*** *Measured and modelled suspended solid transport rate versus time for the deposits' parameters optimized using genetic algorithm to minimize the mean absolute error for the experiment of 02/12/1998 (Tait et al., 2003)*

Yet Tait et al. (2003) pinpointed the necessity of extensive field data for a complete appropriate calibration of the model's parameters. This was demonstrated by the large uncertainties on the estimation of the maximum resistance and the thickness of the weak layer (Kanso et al., 2005) which were explained by the insufficiency of the dataset taken for calibration (issued from the in-situ experiments and that are not representative of real rainfall event). More precisely, since the model describes the erodible bed as stratified layer with increasing strength at the upper layer and a constant strength in the underlying one, the dataset required for calibration should cover all possible cases of sediment erosion particularly those during which the underlying layer is exposed.

Moreover, the test of several objective criteria in the calibration procedure (Tait et al., 2003) demonstrated the dependence of the latter on the former and the standard deviation on the errors on transport rate seemed to be the best optimization criterion. Results also highlighted the importance of precisely evaluating the shear stress for a good representation of the erosion process (Kanso et al., 2005).

Table 2-9 below summarizes the optimal combination of Skipworth parameters obtained by different optimization approaches. We notice the difference of the optimal values obtained between different calibration methods and different optimization criteria. Two simplified versions of the Skipworth model were tested in (Kanso, 2004): the first neglected the presence of an underlying layer having uniform resistance to erosion; and the other considers in addition to the previous simplification, a linear evolution of this resistance with depth. The results obtained showed that a simplified model can perform as well as the original model.

Increasing stair step flow injection scheme (experiment in Vieille du Temple carried out in 02/12/98)





| Model parameters & calibration method | Tait et al. (2003) | Kanso et al. (2005) |
|---|---|---|
| Optimization algorithm | Genetic algorithm | MCMC |
| Minimization criteria | Mean Absolute Error (MAE) | Likelihood function |
| $\boldsymbol{\tau_{cu}(N/m^2)}$ | 50 | 21 |
| $\boldsymbol{d'(m)}$ | 0.0054 | 0.001 |
| $\boldsymbol{b}$ | 0.3 | 0.27 |
| $\boldsymbol{M_c(mg/m^2)}$ | 171 | 900 |
| $\boldsymbol{\tau_{cs}(N/m^2)}$ | Dry weather shear stress | Dry weather shear stress |
| $\boldsymbol{\tau(N/m^2)}$ | Measured by ADV | Measured by ADV |

| Square signal flow injection scheme (experiment in Vieille du Temple carried out in 05/11/98) | | | | |
|---|---|---|---|---|
| Model parameters & calibration method | Tait et al. (2003) | | | Kanso et al. (2005) |
| Optimization algorithm | Genetic algorithm | | | MCMC |
| Minimization criteria | MAE | Weighted MAE | Standard deviation | Likelihood function |
| $\tau_{cu}(N/m^2)$ | 50 | 0.21 | 50 | NA |
| $d'(m)$ | 0.0054 | 0.00092 | 0.0011 | |
| $b$ | 0.3 | 0.00145 | 0.06 | |
| $M_c(mg/m^2)$ | 171 | 115.8 | 86.5 | |
| $\tau_{cs}(N/m^2)$ | Dry weather shear stress | | | Dry weather shear stress |
| $\tau(N/m^2)$ | Measured by ADV | | | Measured by ADV |

***Table 2-9:*** *Optimal combination of Skipworth parameters determined on 2hydraulic flush experiments using two calibration methods*

**Conclusion:**

The Marais site located in the 3rd and 4th arrondissement in the city of Paris was chosen for our study that aims at modeling water quality on urban catchment. It gathers the maximum number of elements necessary to realize a complete model, starting with its small area (42 ha) very well characterized (surface topography and sewer geometry) on which an extensive database was constructed in previous researches (Gromaire, 1998; Ahyerre, 1999) on the quantity and quality of

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# PART II

# THE INTEREST OF A DISTRIBUTED HYDRODYNAMIC MODEL SPECIFICALLY ADAPTED TO COLLECTORS OF HIGHLY VARYING BED SLOPE AND CROSS-SECTIONS







A key factor in modelling sediment processes in sewer systems is the accurate estimation of the motor forces governing them. These processes are dependent on the strength of the flow vector and the momentum transferred from the fluid particles to the solid ones either lying on the bed or hold in the flow body. Big particles will be transported as bed-load, while small ones as suspended load. The major portion of the solid matrix contributing to pollution in wet weather discharges was found to be constituted of fine fraction transported in suspension. As the model objective is to replicate the quality of the outfall discharges during rainfall events, only this transport mode will be addressed in our study. It will be conceptualized using two mechanisms: production by erosion of fine particles from sediment layer to the suspended load and their transfer by the flow vector. The studied fraction of particles being unlikely to sediment due to its fine size and the flow energy during wet weather, the sedimentation process will not be considered in the model. Erosion of cohesive deposits has been studied in the literature on sediments from different origins (estuarine and sewers) where almost all studies agreed that the flow shear stress is the driving factor of this phenomenon. The transfer of suspended solids has always been expressed physically in terms of advection where the flow velocity is the driving parameter. Both parameters (shear stress and flow velocity) necessary to represent sediment behaviour in sewers can't be determined except using a sewer flow quantity model.

On the Marais urban catchment, the organic layer suspected to be the erodible in-sewer sediment was detected at the upstream parts of the main collectors. So, modelling the production from this source necessitates local information of the hydraulic conditions prevailing in these parts of the sewer. For that reason, a distributed hydraulic model based on the SWEs is needed that explicitly describes the main collectors.

However, several defects were identified in the hydraulic models currently used in the urban water quality models. First, these hydraulic models have always been evaluated with respect to the hydrograph at the outfall of sewer catchments. This can be achieved by calibrating the Manning coefficient of sewer lines that permits to adjust the celerity and friction and compensates a relatively imprecise description of sewer collectors. This approach is however not adapted to solid transport modelling as it does not guarantee the good representation of hydraulic parameters inside the sewer network (shear and velocity) particularly in the presence of coarse deposits. These deposits constitute the second key point that has always been lightly considered in the hydraulic representation is solid transport models. The analysis of the deposits' profiles in many combined sewer networks showed a massive quasi-steady but non-uniform stock that deforms completely the collectors' characteristics especially the bed slope which governs the primary forces driving the sewer flow, i.e. the gravitational forces. Therefore, ignoring their presence should have definitely induced erroneous estimations of the interior hydraulic parameters. In our case, these deposits were observed over extensive length of the upstream parts of the Marais sewer due to its low

bed gradients. So, a distributed hydraulic model that takes into account these deposits seems to be of high importance.

A major difficulty in such an approach is the numerical instabilities that an irregular bed might induce when applying the dynamic wave model. The classical numerical schemes used in commercial modelling software interpret the highly variable bed profile as an additional source/sink of water flux instead of a natural bed evolution. So, if these deposits are to be considered, a special numerical scheme capable of well integrating this feature in the model resolution is necessary.

Another difficulty to correctly model the hydraulic parameters over such irregular bed is the detailed dataset needed on the coarse deposits. The acquisition of this type of dataset is difficult and expensive. Thus it's crucial to assess the minimum spatial resolution necessary to achieve this objective of modelling.

So, in this part of the thesis, we will explain how these two points (numerical scheme and necessary dataset) were addressed. In the first chapter, the development of a numerical scheme adapted to complex conditions encountered in case deposits are considered is carried out. This scheme was validated on challenging reference cases having analytical solution documented in the literature. In the second chapter, we applied this numerical scheme on the Marais catchment where an extensive database is available on the coarse sewer deposits. Then, we coupled it with an adapted transport solid module in order to evaluate the difference of sediment production and transfer between deposited and deposits-free configuration. The sensitivity of this assessment to the parameters of production model was also studied. Finally, these results were compared with output of more classical schemes applied to simplified dataset to test the applicability of this approach to operational conditions.





# Chapter 3

# A Simple Finite Volume Method for 1D Naturally Balanced Shallow Water Equations

## 1. Abstract

The application of the Shallow Water Equations model (SWEs) on real cases involving complex source term has driven a plethora of methods to cope with this term and integrate it in the existing numerical schemes without generating unphysical perturbations. However, the validity of these methods was restricted to certain problem conditions and their implementation does not suit engineering applications. However, with naturally conservative SWEs adapted to wide range of real problems, any numerical method could be applied without a particular treatment of the source term. In this paper, a simple numerical scheme was chosen to solve the intrinsically well-balanced SWEs formulated by combining the hydrostatic pressure forces found in the convective flux term with the lateral pressure forces found in the source term. The scheme used to solve the model is based on a finite volume discretization that computes the mass and momentum fluxes using Harten, Lax & VanLeer (HLL) Riemann solver. An exhaustive benchmarking was then conducted to evaluate the performance of the scheme whose results showed excellent fit with reference solutions proving that the new formulation of SWEs with the accurate resolution method implemented provides a better alternative of all the recently developed methods of source term treatment.

**Keywords:** Shallow Water Equations, Godunov scheme, well balanced, non-rectangular, non-prismatic, source term







# Chapter 4

# Sensitivity of Hydrodynamic Models and Solid Transport to the Description of Silted Collectors

*This Chapter was submitted to Journal of Hydrology in June 2016*

## 1. Abstract

The dynamic wave model might have contrary to common belief been contributing to the poor performance of water quality models such as being implemented. The massive quasi-steady coarse deposits observed by sewer investigations weren't considered in classical approaches when describing sewer collectors due to lack of data and incapacity of numerical schemes used to solve the dynamic wave model. This work uses the extensive data on the Marais catchment to assess the potential repercussions that this practice could have on the solid transport modelling by comparing spatially distributed parameters of solid production and transfer between different deposited bed profiles' configurations and different numerical schemes. Results show that the error made in the hydraulics simulation due to ignoring coarse deposits tends to underestimate the production quantity and to slow down the pollutants' advection with a negligible effect of the coarse deposits' profile resolution and a moderate impact of the numerical scheme.

**Keywords:** Stormwater quality model, sewer sediment, shallow water equations, numerical scheme, erosion, advection



# PART III

# IN-SEWER SUSPENDED SOLIDS SOURCES AND SOLID TRANSPORT MODELLING







Based on the hydraulic modelling and its refinements made in the previous part with respect to classical approaches, a quality model will be constructed in this part that focuses mainly on the sediment processes in the sewer system.

Before that a critical point arises from site observations (URBIS) about the identity of sources to involve in the development of this model.

With all the progress made in field investigations on the identification of the in-sewer sediments eroded during wet weather conditions and contributing to outfall discharges, discrepancies between the observations made on different sewer systems seem to keep the initial question on the identity of this source open. An organic layer observed only the Marais catchment was firstly thought as being the main contributor to the outfall discharges' pollution. Observations on other sewer networks (e.g. Ecully in Lyon) did not show any trace of such source while mass balance calculations of in-sewer contributions to the pollution of its outfall discharges was found to be comparable. These findings imply that the combined sewer contribution to wet weather discharge pollution can be (principally/totally) imputed to another source than the organic layer detected in the Marais sewer. Moreover the actual role of this latter can be questioned.

The different number and characteristics of rain events used for mass balance calculation on each site may have masked an important difference between the contributions of different sources. So, in the first chapter of this part, a detailed analysis of the previous results on sewer deposits contribution will be carried out between sites having different deposited states in an attempt to conclude on the possible erodible sediment sources.

Then, in the second chapter, a water quality model adapted to our experimental site (Marais) is built on the basis of the improved hydraulic representation made in Part I and of Skipworth solid production model. The integration of different possible sources in the model was benchmarked. The performance of different versions of this improved model is assessed on a validation set of rain events. The opportunity of a single or a twin source for representing SS production processes is discussed and a comparison with a simple operational model is performed.



# Chapter 5

# Do storm events samples bias the comparison between sewers deposits contribution?

*This Chapter is considered for publication in Water Science and Technology in June 2016*

## 1. Abstract

Previous researches demonstrated the occurrence of unique in-sewer sediment, the organic layer, on the Marais site in Paris capable of explaining the entire wet weather sewer production of suspended particles. Other studies on other sites, Clichy in Paris and Ecully in Lyon, demonstrated a comparable wet weather sewer deposits contribution (SDC) to effluents pollution between this site and others having no similar organic sediment casting therefore doubts on the implication of the organic layer to the outlet discharges pollution. So, an in-depth comparative investigation of the different sites' means SDC was carried out to confirm or refute the major role of this layer vis-à-vis sewer production. The size and characteristics of the events' sample used to calculate the SDC were analyzed to find whether a statistical bias may have masked a difference that would be more coherent with field observations. After homogenizing these elements, the organic layer regained some of its previously alleged participation in sewer contribution (a maximum of 36% of the total SDC) but another unknown source was still dominant. This suggests that sewer production during wet weather is a result of multiple sediment erosion: the organic layer and another major source not yet identified.

**Keywords:** Sediment; effluents pollution; organic layer; combined sewer; number of events; events' characteristics



# Chapter 6
# Development and Benchmarking of Solid Transport Models with Different Scenarios for In-sewer Sources of Suspended Solids

## 1. Introduction

In-sewer sediments are widely recognized for disrupting the combined sewers performance. From one side, they reduce the hydraulic capacity and increase therefore the flooding risk. From the other side they retain a significant pollution stock that when mobilized by wet weather flow aggravates the pollution levels in combined sewer overflows (CSOs) (Ashley et al., 1994; Arthur and Ashley, 1998; Ahyerre, 1999; Butler et al., 2003). These security and environmental issues have raised the governmental and operational concerns to address these risks and optimize the drainage systems operation. Therefore, concerted research programs have been launched in the last three decades to investigate all aspects of in-sewer sediments and provide useful elements to predict and control the impact of these sediments: in UK (Crabtree et al., 1991; Ashley and Crabtree, 1992), in Belgium (Verbanck, 1992; Torfs, 1995), in France (Bachoc, 1992; Laplace, 1991; Ahyerre, 1999), in Germany and Scandinavia (Ristenpart, 1995). Despite all the advances in knowledge about sediment characteristics and behaviour made through the extensive field surveys conducted within these programs, no model is currently able to predict SS pollutograph during rainfall events (Kanso, 2004, Métadier, 2010). This might be a result of the usually made simplifications in these models due to the lack of the full necessary knowledge on SS sources and processes along with the methods and tools necessary to account for them.

First, an ambiguity is still shadowing the real identity of the source responsible for wet weather suspended solid production. In-situ experimental campaigns revealed that in-sewer sediments are made up of a composite structure: sewer grits, organic deposits, and biofilms having different chemical and physical characteristics where only the organic deposits have shown similar characteristics to the eroded particles collected at sewer outfalls (Crabtree, 1989; Verbanck, 1990; Verbanck and Ashley, 1993). On the Marais sewer system, (Ahyerre and Chebbo, 2002) suggested that the observed organic layer on the upstream parts of the main

collectors can explain the entire sewer production of suspended solids in terms of both mass and chemical composition. However, on other sewers, namely Ecully in Lyon and Clichy in Paris, no similar organic layer was detected in their main collectors while having sewer deposits contribution to particulates pollution discharge comparable with that on the Marais. In an attempt to establish a coherence between these results concerning the erodible source identity, specifically on the Marais site, an in-depth statistical comparison was carried out (Rammal et al., submitted) to find out that the Marais sewer production cannot be explained by the organic layer alone. Its contribution is secondary or might be negligible and hence another unidentified stock should be standing behind the sewer production.

Second, the mathematical processing of the full Shallow Water Equations (SWEs) in the available models is usually fairly crude (for reducing calculation time). If these methods succeed to model the hydrographs at the catchments' outfall, it is not necessarily the case for the hydraulic parameters inside the sewer collectors especially those governing solid transport processes. This is especially true when the longitudinal and transversal profiles of channel bed are deformed by the presence of silt deposits. To deal with this concern, a specific method was developed to solve the SWEs model (Chapter 3) which provides a good representation of the parameters governing production and transfer of SS in main sewers and takes into the account the effect of heavily silted sewers.

Third, concerning the modelling of suspended solids production and transport, a common approach to describe the erosion rate of materials from cohesive sediments was inspired from the excess shear stress relationship proposed by Parchure and Mehta (1985). The cohesive property of the organic sediments and the importance of considering its effect on their strength when modelling their erosion process are still under question (De Sutter et al., 2000). To deal with it, Skipworth (1996) described the critical bed strength by an increasing function with depth reaching a maximum value at the underlying layer whose strength is supposed uniform along the whole depth. The performance and applicability of this model are reported in many laboratory (Skipworth et al., 1999; Rushforth, 2001) and field studies (Tait et al., 2003; Kanso et al., 2005) but an extensive application to a whole catchment is still missing.

This chapter is thus dedicated to test if all these knowledge and tools in both water and solid flow modelling put together and benchmarked in different sewer source scenarios can help us better replicate TSS pollutograph at sewer outfall and hence identify the sewer SS source. From the water flow side, the tested models will benefit from the tool developed in Chapter 3 based on a detailed hydrodynamic description of sewer flow while considering the coarse deposits profile. From the solid transport side, the tested models will consider an appropriate characterization of deposits structure and erodibility using Skipworth model. The difference between the tested models is made in the number of sewer SS sources, their location and nature, and in some cases in the degree of spatial description of these sources

(lumped/distributed). This benchmark permits us to understand the role of organic layer and get more insight of the identity of the major source contributing to sewer-borne discharge at the outfall.

The chapter will be organized in the following way: in the following section, the modelling approach developed for our benchmark is discussed in details. In the next section, the database used for calibrating and validating the model is presented. Then the calibration procedure and the performance criteria used to evaluate the applied model are presented. In the last section, the results of the benchmark made for different sewer sources are illustrated and discussed. Some perspectives of this work for an operational context are outlined before more general conclusions are proposed.

## 2. Conclusion

Whereas the knowledge on sewer deposits characteristics and contribution to the pollution of combined sewer effluents has been significantly advanced, modelling their mechanism during wet weather is still unsatisfactory. In this chapter, a modelling approach is built to model sewer sediment processes considering all the previous knowledge and methods developed to represent the driving forces (hydraulic parameters modelled by Godunov scheme considering the coarse deposit profile), cohesive sediment erosion (Parchure and Mehta (1985) relationship), and cohesive sediment structure (Skipworth (1996) description). Concerning the TSS source that is not yet identified by field investigations, a benchmark of the potential sources suggested by these investigations was realized and is summarized in the following table.

| Scenario | Number of sources | Source(s) location | Skipworth model description | Number of Skipworth parameters calibrated | Spatiotemporal scale of calibration | Objective variable of calibration |
|---|---|---|---|---|---|---|
| $1_{pipe}$ | Single source | Organic layer on the upstream of main trunks | Distributed | 4 parameters* | Calibrated on flushing experiments carried on the Marais site on a pipe scale | TSS transport rate at the downstream on the considered pipe |
| $1_{sewer}$ | | Upstream of main trunks | Distributed | 4 parameters* | Calibrated on rainfall events on the whole sewer scale | TSS concentration at the sewer outfall |
| $1\tau_{sewer}$ | | | Distributed | 5 parameters** | | TSS concentration at the sewer outfall |
| $1\varphi_{sewer}$ | | | Distributed | 4 parameters* | | TSS transport rate at the sewer outfall |
| $2_{dn}$ | | Along the whole main trunks | Distributed | 4 parameters* | | TSS concentration at the sewer outfall |
| $2_{up}$ | | On the very upstream sewer lines | Lumped | 4 parameters* | | TSS concentration at the sewer outfall |
| 3 | Double source | Organic layer on the upstream of main trunks + another deposit on the very upstream sewer lines | Distributed + Lumped respectively | 4 parameters* | | TSS concentration at the sewer outfall |

*4 parameters: $d'$, $b$, $\tau_{cu}$, $M$ with $\tau_{cs}$ taken to be the shear stress of the dry weather flow occurring just before the rainfall event

**5 parameters: $d'$, $b$, $\tau_{cu}$, $\tau_{cs}$, $M$with $\tau_{cs}$ modulated from one point to another according to the ration of the maximum dry weather flow shear at this point to the maximum dry weather flow shear on all the zone having the organic layer

The major outcomes of this benchmark are:

- The modelling results reinforce the conclusions of the statistical analysis carried out in the previous chapter on the SOERE URBIS database: the organic layer is not the preponderant source, and might be negligible where another source exists and might be preponderant. The results do not however permit to dispel the uncertainty on the importance of the organic layer contribution, whether it is minor or negligible. As for the other source, the localization in the upstream sewer lines is quite possible, but the conceptual approach employed to represent the source does not permit to privilege the hypothesis relative to a source distributed along the whole main trunks.
- The MCMC method was shown to provide an interesting and reliable framework to parameters' identification and uncertainty analysis. The models calibrated thereby were

then evaluated on a set of validation events using two *independent* indicators: the mass balance and the event dynamics represented by the correlation between observations and predictions. The results obtained for the best scenario show that for 6 events out of 9, the absolute error on mass balance is less than 30%; and that for 7 events the explained variance of the TSS transport rate is greater than 50% for which at least 45% of the concentration variability is explained by the model. We observed also that calibration in terms of concentration yield comparable results to calibration in terms of transport rate.

- The performance of the best scenario is significantly better than a site mean concentration model for the mass balance, whereas the dynamics of transport rate are replicated with an analogous quality for the two types of modelling. These results do not converge with other research works carried out on other combined sewer systems that showed that the total volume is a good indicator of the mass on the event scale, whereas the flow rate is not sufficient to predict the transport rate inside a rainfall event.



# General Conclusion and Perspectives

## Recalling the objectives

This work developed in the framework of OPUR program takes the opportunity of new knowledge made available in the framework SOERE URBIS as well as new numerical methods for solving SWEs to test the capacity of a distributed solid transport model to replicate the TSS pollutographs observed at the outfall of the Marais combined sewer during storm events for different sewer source hypotheses.

The principal objectives are:

- Evaluate the interest of a distributed hydrodynamic model specifically adapted to collectors of highly varying slope and sections and assess the precision level of data required to efficiently operate this model
- Exploit the database acquired in the two observatories OPUR and OTHU in order to obtain a coherent vision concerning the contribution of different possible sources of TSS to wet weather pollution discharges in combined sewers
- Develop a solid transport model suited to an extensively documented catchment (le Marais) and define and benchmark several scenarios concerning the location and characteristics of TSS source during rainfall events

## Hydrodynamic modelling

A well balanced finite volume numeric scheme using HLL Riemann solver was developed and validated on reference configurations in order to deal with highly variable longitudinal and transversal sewer profiles. Such profiles can be induced by coarse deposits, which are extensively present in the main sewers of the Marais and remain in a steady state conditions for long periods. The impact of grits on suspended solids production and transfer were studied by calculating distributed meaningful hydraulic parameters (shear stress and flow velocity) fed into a generic solid transport model (excess shear stress) to derive global parameters of pollutants' production (eroded mass) and transfer (advection time). It was found that the effect of coarse deposits on these parameters is worth considering especially in terms of production phenomenon. Ignoring the effect of coarse deposits on hydrodynamic module might lead to an underestimation up to 70% of the overall TSS event load. The effect of coarse deposits on sediment production is mainly attributed to the increase in the flow velocity especially at the upstream sections. In terms of transfer process, the steeper slope resulting from coarse deposits was shown to locally accelerate water flow and hence advection process of suspended solids. However the integrated effect on transfer time is rather limited (maximum 15%).





The spatial resolution of data required for coarse deposits' profile definition in the model was investigated. It appeared to depend on the numerical scheme being used. For the model developed in this thesis the data required were suited to practitioners' capacities, as a deposit level acquired at 50m space step yielded almost the same results as a higher resolution profile. A classical scheme (e.g. Preissmann finite differences) induces more error with this space step when compared with a detailed description of the bathymetry (e.g. a spatial resolution as low as 5 m).

## Data analysis

A statistical analysis was performed on the database of flow rates and TSS transport rates on the Marais and Clichy catchments in Paris and Ecully in Lyon. The objective was to assess the contribution of different sources of particles production in different contexts, especially regarding the slope and fouling state of collectors. Previous studies have shown that despite the differences between sites, sewer sediment contribution to wet weather SS discharges were very similar. So the organic layer found specifically on the Maris catchment could be a minor contributor and another source is probably involved. The different number and characteristics of rain events used for mass balance calculation on each site may have masked important differences between the contributions of different sources. To evaluate this possible bias a homogenization of data was performed before comparing again the sewer deposits' contribution

Results proved that the principal source in the Marais is not the organic layer observed in the upstream section of main sewer facilities, yet it contributes to solid production in a proportion to be specified. The principal source(s) is (are) unknown and may be either distributed randomly along the sewer system and/or located in the upstream secondary sewer that connects the urban surfaces to the main channels. This source is present on all investigated sites, whatever their geometric characteristics.

## Solid transport model and production scenarios

A quality module was coupled to the hydraulic model presented here above. It is based on Skipworth production equation (lumped on subcatchments and distributed in main trunks) and a transfer function (linear reservoir on subcatchments and simple advection in main trunks). A difficulty imposed by this module is the necessity to calibrate the production function parameters. For this aim, an automatic calibration algorithm based on Markov Chain Monte Carlo was coupled to it and demonstrated a reliable performance in estimating the optimal parameters and the uncertainties associated. As the main contributing source is not identified, five production scenarios were tested:





- Organic layer in identified sections with Skipworth parameters calibrated locally from flushing experiments
- Organic layer in identified sections with Skipworth parameters calibrated with data at the outfall of the catchment
- No organic layer but a single source distributed uniformly in the main sewer with Skipworth parameters calibrated with data at the outfall of the catchment,
- No organic layer but a single source distributed uniformly in the upstream lines, with Skipworth parameters calibrated with data at the outfall of the catchment
- Organic layer in identified sections with Skipworth parameters calibrated from flushing experiments coupled with another source distributed uniformly in the upstream lines, with Skipworth parameters calibrated with data at the outfall of the catchment

Variants were also tested regarding the number of calibrated parameter and the observed variable used for calibration (concentration or transport rate).

The benchmark confirmed that the organic layer is not the major source of sewer production but could not give more precision on the importance of its contribution. It basically showed that another source is major or even preponderant and that can be located at the upstream branches as well as along the principal collectors with a slight preference to the former case. Actually it appeared that the calibration of Skipworth parameters overshadow the physical effect of distributed hydraulic parameters and the locations of the potential sources.

Anyway the calibration algorithm applied (MCMC) succeeded to optimize a model capable of replicating the event mass within 30% error for 6 validation events out of 9 and explaining 50% variance for 7 events out of 9. The performance was found to be better than a site mean concentration model in terms of mass and comparable in terms of transport rate dynamics. This finding re-launches the debate on the predicting power of volumes regarding masses and flow rates regarding transport rate, i.e. is it worth trying to predict concentrations if mass or mass discharge are needed.

## Perspectives

The mixed lumped/distributed conception of the hydrodynamic model is not quite satisfying when it comes to source localization. This is specially an issue since the results showed some preference for the source located on the upstream sewer lines, where a lumped model was applied. So it would be interesting to extend the distributed hydraulic model to this upstream level. For that purpose the code should be optimized to attain reasonable calculation times. Moreover the description of multiple distributed inputs may raise some difficulties concerning the input data necessary for this level of description along with some

numerical problems in modelling sewer hydraulics (e.g. risk of dry bed due to very weak flow especially if the deposits' profile is considered).

The hydrodynamic model developed in this thesis was only used to simulate erosion processes, by assessing that potential sources are uniformly distributed along the whole considered sewer length and build up in a few hours. These assumptions may be questioned and the localization and available quantity of potential sources could be approached by modelling organic matter sedimentation processes during dry periods on the basis of the same hydrodynamic model. This would need a good representation of water and SS production in dry weather, and this topic will be developed later on.

The hydrodynamic tool was used to model the sewer flow over a fixed deposit bed. It can also be used in a mobile bed approach to study the temporal evolution of these deposits. This would need a suitable solid transport model including sedimentation and bed load transport. Again the difficulty resides in determining the input data on the production and characteristics of solid particles to be considered. After validating this approach, it could provide an efficient tool for sewer managers to predict the frequency necessary for channel scouring.

A last point that needs further investigation is the integration of the transient component of the shear stress in the hydraulic model, which is currently formulated in terms of the steady state shear.

To improve knowledge of source localization, it is necessary to acquire some field data, especially on upstream lines. This could be performed by visiting or CCTV inspecting these sewer lines, and by conducting localized cleansing operation and collecting the scoured deposits for identification and quantification. The identification of suitable tracers of potential sources would be very useful but this approach is presently not very developed. Biological tracers (DNA) may be promising.

Time series on the hydraulic parameters and TSS transport rate at the outfall of several upstream catchments in different cities would also be very useful to verify the existence and importance of such sources. Dry weather measurements at these outfalls would be needed for assessing the permanent wastewater inputs from dwellings and economic activities (if deposited masses are negligible compared with daily production). A more direct approach can be applied for dwellings by a stochastic modelling of the behaviour of human beings and using high resolution data of water consumption. Actually these permanent inputs may be quite variable and explain a significant part of the variance of wet weather SS discharges.

An important room for improvement still exists for the current SS production equations used in the solid transport model. This is attainable through field investigations and in-situ

controlled flushing experiments in different locations (upstream lines, silted sewer sections, non-silted sewer sections…) to identify the involved processes, the relevant transport modes, and the driving parameters of these processes.

A core problem in all urban drainage quality models is the absence of a clear vision of the objectives of these models and that are necessary to define the principal criteria to evaluate these models. Such criteria must be defined for different applications (simulation of the efficiency of existing and new facilities, real time control, and simulation of the impact of urban planning options…). Their identification is still a challenge and needs collaboration between research teams and operators. It may provide some hints for developing simpler models suited to specific tasks.





