Stormwater quantity and quality for sustainable management of runoff in an industrial district

Preliminary analysis and modelling of first foul flush effect

Matteo Trigatti, Roberto Perin, Matteo Nicolini, Daniele Goi
Dep. Chemistry, Physics and Environment
University of Udine
Udine - Italy

Abstract— When water flows on impervious surfaces, a huge amount of various pollutants is dragged away throughout the drainage system; stormwater management is essential because it is an applied discipline whose practical applications deal with quality and quantity characteristics of water coming from rain. The main deal is to understand how to manage and treat stormwater according to the land use and the hydrologic-hydraulic performance of the basin. The present study reports the numerical model of the first foul flush phenomenon in an industrial district by using EPA SWMM 5.0. The paper was written considering numerical methods and inspections on the field, focusing attention on grits and sediments transported thru the outlet: they are a serious problem for the primary unit of the treatment plant and for the receiving systems in case of overflowing. This numerical approach was applied on a case study in the CIPAF Industrial District of Friulian Region (North-Eastern Italy) where mainly stainless steel and woody industries are located. The first flush phenomenon is very significant because of the presence of large and uncovered working areas: polluted scraps coming from ordinary activities settle down on the ground so they are available for washoff processes. This work looks forward to obtain basic elements to evaluate toxicity charge coming from the stormwater, in order to set a quality-quantity integrated environmental protection model.

Keywords—stormwater; first flush; sustainable stormwater management

I. INTRODUCTION

In recent years climate changes increase the sensitivity of technical communities on environmental issues connected to sustainable stormwater management, because it is an applied discipline whose practical applications are evident in many diverse activities (Wanielista, 1978). Nowadays urban settlements must respect hydraulic and hydrologic invariances because no more urban flooding are acceptable. Receiving waters and surrounding soils have to be protect from urban pollution and stormwater charges as well. Designing a drainage system usually means focusing on flow rates and hydraulic risk but nowadays it is not possible to ignore pollutants coming from rainproof surfaces and urban activities. As the impervious grade on the urban-industrial areas increases, the quantity of pollutants dissolved or mixed in the sewage waters grows up depending on the land use. Table 1 reports a fundamental work of the EPA (1993), defining the most important categories of pollutants related to municipal areas: the origin of each kind of pollutant is reported in Table 1 as well. It is well known that in urban areas the most common polluted materials are hydrocarbons coming from exhaust of internal combustion engines (vehicles) and organic particles related to the tree seeds or pollen (Wicke, 2012).

Table 1 - *Main pollutants in urban areas flushed from surfaces by stormwater (EPA, 1993)*

Categories	*Parameters*	*Source*	*Effects*
Sediments	TSS, turbidity, dissolved solids	Construction sites, urban/agricultural runoff, landfills, septic fields	Turbidity, habitat alteration, contaminant transport, bank erosion
Nutrients	Nitrate, nitrite, ammonia, organic nitrogen, phosphate, total phosphorus	Urban/agricultural runoff, landfills, septic fields, atmospheric deposition, erosion	Algal blooms, ammonia toxicity, nitrate toxicity
Pathogens	Total coliforms, faecal coliforms, faecal streptococcus, viruses, E. Coli	Urban/agricultural runoff, septic systems, illicit sanitary connections, boat discharges	Ear/intestinal infections, shellfish bad closure
Organic enrichment	BOD, COD, TOC, dissolved oxygen	Urban/agricultural runoff, landfills, septic systems	Dissolved oxygen depletion, odours, fish kills
Toxic pollutants	Toxic trace metals, toxic organics	Urban/agricultural runoff, septic systems, pesticides/herbicides, underground storage tanks, landfills, industrial discharges	Bioaccumulation in food chain organisms and potential toxicity to humans and other organisms
Salt	Sodium chloride	Urban runoff, snowmelt	Vehicular corrosion, contamination of drinking water

In order to control the drainage system, it is necessary to investigate on the hydraulic network, geomorphological characteristics of the basin and rainfall events; pollutants concentrations and flow rate have to be evaluated together. Recently, some studies have also highlighted the influence of rainfall on pollutant wash-off (Wei Zhang, 2015) and the need to consider the large number of short-intensity and high frequency events in designing drainage systems (Guo, 2002). Anyway, a comprehensive and analytical approach has to be preferred in order to defend surface waters from ordinary non-point pollution (Fletcher, 2013). The adoption of non-point treatment and detention standards is going to be more effective than conventional centralized methods: Best Management Practices (BMPs, 2013) or Low Impact Development approaches are the way to reduce runoff and to preclude urban pollution spreading (Kinnaman, 2012; Colford, 2007).

Unfortunately, regulations about stormwater first flush are not well defined or agreed and recognized worldwide (Balascio and Lucas, 2009). In Italy several improvements about understanding stormwater runoff problems were made, but there is still a lot to do: some significant examples of modern and strict regulations can be found in Lombardia, Veneto and Emilia Romagna regions. Only a few cases of good practice and research were reported about stormwater sustainability: one of these is i.e. the Cascina Scala basin (Ciaponi and Papiri, 1994). Modelling pollutants together with the flow rate can give important information to understand how to solve the regulation problem too.

In this work, the authors investigated on an industrial area in order to understand how the substances arrive to the wastewater treatment plant (WWTP) and how the first flush phenomenon should be controlled.

II. STUDY AREA

The industrial area subject of this paper is the CIPAF (Consortium for the industrial and economic development in the middle-high Friulian Region). The history of this Industrial Consortium begins in the 60s with a couple of industries: now it counts more than 40 factories distributed on 215 hectares. CIPAF is located in middle Friulian plane (Fig. 1) with the Tagliamento river on the West side and the Ledra river on the East side. The area is almost impervious and the sewerage follows the main directions of the internal street network.

Fig. 1 - The CIPAF area in the Friulian Region (Italy)

The industrial district exhibits many rainproof surfaces, as shown in Table 2, where asphalt, roads and roofs are the impervious fraction; mounds, grass and wood are surfaces related to the most pervious fraction, so in those areas the coefficient of discharge is quite modest. During the runoff, drainage pipes and channels convey stormwater to the outlet thru the WWTP.

A numerical model of the drainage network was implemented at the University of Udine by using the software EPA-SWMM 5.0 (Storm Water Model Management by EPA; Rossman, 2010). This software permits to use hydrologic and hydraulic modules to model basins; sub-basins were defined very rigorously to reach the highest level of detail (roofs, parking areas, grass…): 90 sub-basin, 313 nodes and 319 links. In this work, the SWMM was used because it is very simple to compile: defining sub-basin is really schematic and it is also a free software. Fig. 2 shows CIPAF's drainage network (combined sewer) as set up in the model. There is only one overflow in the S-E side of the industrial district flowing runoff to the Ledra Channel. The WWTP has been modified since 2004 to treat also stormwater charges.

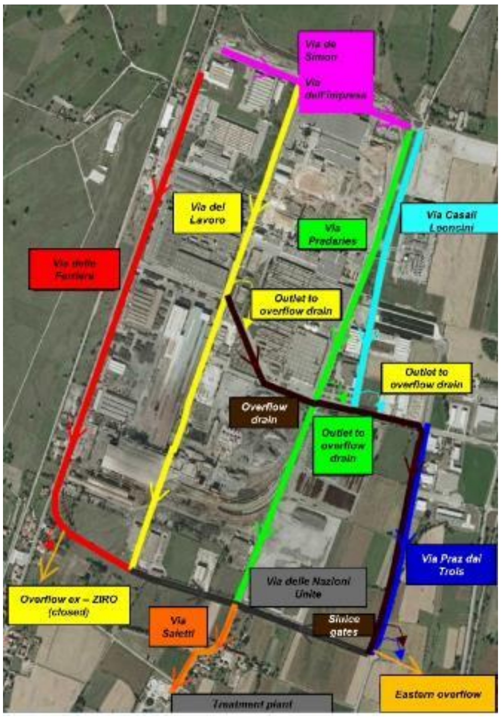

Fig. 2 - *Drainage network of the CIPAF in EPA SWMM 5.0 (2011)*

Table 2 - Parameters used for the characterization of the different surfaces of the CIPAF area

Surface	Impervious Fraction		% Slope	Description	N Imperv
Asphalt	min	0.80	0.50	Service areas	0.016
	max	1.00	0.50		0.016
Roof	min	0.80	1.99	Roofs of hangars and depots	0.011
	max	1.00	2.01		0.011
Mound	min	0.30	0.50	Piles of production scraps	0.050
	max	0.50	0.50		0.050
Grass	min	0.00	0.50	Lawn and fields	0.035
	max	0.01	0.50		0.035
Wood	min	0.30	0.50	Piles of wood and shavings	0.035

In Table 2 we reported the parameters used in the model: variability of parameters was studied by several inspections on the field, and they reflect common values used in similar applications in modelling urban storm runoff, depending on land use (Ouyang, 2012). The hydraulic model showed a short time of concentration, (45 minutes) which is an important information in order to understand first flush variability (Joo-Hyon Kang, 2008). Surfaces slopes are modest; in fact, there are parts in the district where some floods result also after low-intensity rainfall events. The drainage network is a combined sewer, grew up year after year, so the pipes are not homogeneous: we have found most circular sections but also rectangular channels.

III. Material and Methods

A. Hydraulic Model Calibration

A rain gauge located in Gemona del Friuli (2 km far from the CIPAF) was taken as reference in order to calculate probability pluviometric curves; another rain gauge located nearly the WWTP was used to validate the model in SWMM. We used area-velocity Nivus PCM-4 flow meters distributed on the CIPAF area (**Fig. 3**).

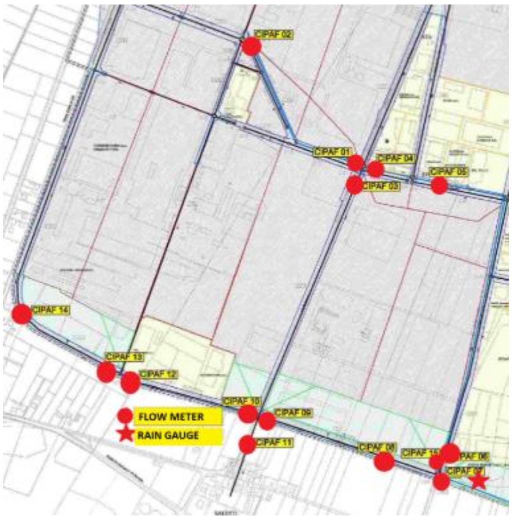

Fig. 3 - *Measure points in the CIPAF area (2011)*

Flow meters remained on site for 6 months; in this paper we report the calibration results for the main event occurred on 05/14-15/2011 (***Fig. 4***). We reported an example of validation for the flow-regression curve due to groundwater infiltration as well (***Fig. 5***). The recession period is very long (***Fig. 5***) and it is the cause of a large number of issues at the WWTP (energetic costs and high dilution level). In addition, CIPAF is located in a karst-system discharge area.

This part of work permitted to assess the behaviour of the hydraulic system depending on hydrological characteristics.

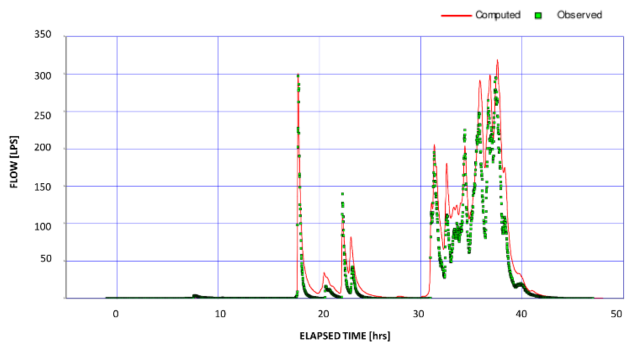

Fig. 4 - *Calibration curve at the outlet of the basin – Cipaf 11 pointer in Fig. 3 (04/14-15/2011)*

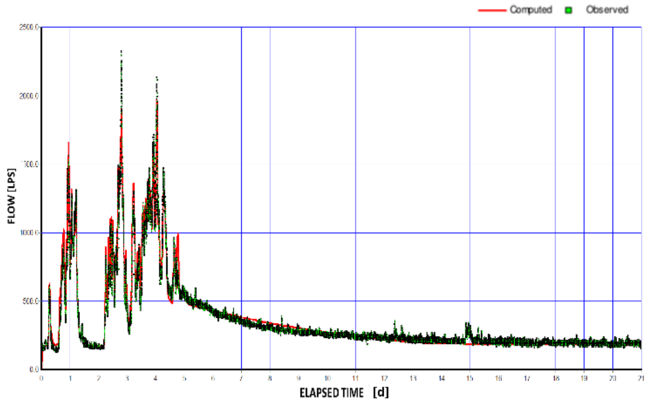

Fig. 5 - *Calibration curve on flood recession at the outlet of the basin (03/15-16/2011)*

B. *Land Use and Washoff Functions*

Results obtained by simulation provide important information to integrate the non-point source pollution analysis in the industrial district. The issue was to understand how the substances flow throughout the pipes and how to model them on SWMM, according to land use which is basically one of the key-factors (Shuming Wang, 2013), so a land use survey was required.

In the industrial district the most important pollution is attributable to the solid material dragged off by stormwater. In ***Fig. 6*** the solid material is shown: the photo was taken in the equalization tank of the WWTP. At the bottom of the tank, a lot of dark and heavy solid material settled down, wrecking pumps and causing several blocks in the other sections of the WWTP. We found out mainly wood and foundry scraps for about 40 cm from the bottom every time after 2-3 of rainfall events.

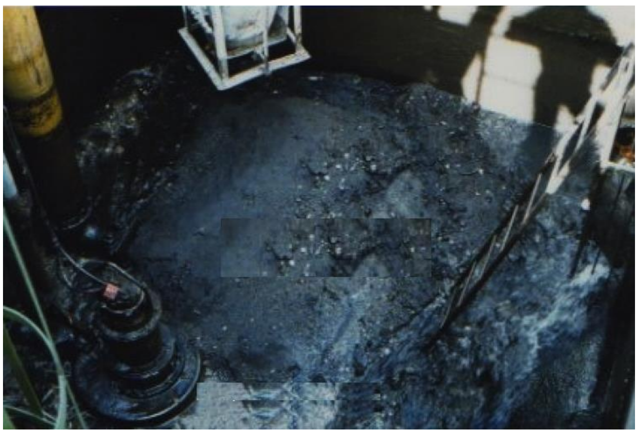

Fig. 6 - *Solid material dragged into the equalization tank*

This solid matter form a liquid organic-inorganic mixture flowing thru the WWTP. In order to assess the percentage of organic-inorganic solid material, laboratory analysis were done on three samples of stormwater sediments: the DIVAPRA procedure (Divapra, 1998) was followed to calculate volatile solids (VS). The mean value of VS was around 2.8 %: there is a very high quantity of inorganic material in the runoff of the CIPAF, as we expected to be. In ***Table 3*** we reported the results, which show the percentage of inorganic and organic material.

Table 3 - *Example of collected samples characterization*

	Sample1 [g]	Sample2 [g]	Sample3 [g]
Tare (T)	60.02	60.09	58.47
Net sample wet (c)	36.19	53.69	52.01
Dry weight + Tare (a)	89.36	101.83	98.99
Ashes + Tare (b)	88.64	100.55	97.79
SV(g/kgSS)	24.46	30.57	29.55
SV(%)	2.45	3.06	2.96
Ashes (%SS)	97.55	96.94	97.04
Total Solids (a-T)/c [g/kg]	810.75	777.34	779.00
Total Solids (a-T)/c [%]	81.08	77.73	77.90
Humidity (%)	18.92	22.27	22.10
SV/ST	3.02	3.93	3.79

According to several inspections on the field, we set up the model in SWMM by defining solid pollutants and buildup/washoff functions (***Table 4*** and ***Table 5***). Many authors modelled runoff quality with SWMM (Vassilios, 1998; Maria di Modugno, 2015, Cambez, 2008), so common parameters were used as first approach also in this paper. Each solid scrap has been associated to an exponential buildup function; each land use has been related to a washoff function, which was exponential as well.

Table 4 - *Buildup and washoff functions used in the EPA SWMM model of the CIPAF*

Washoff Function [kg/h]	$W = C_1 \cdot q^{C_2} \cdot B$
Buildup Function [kg/ha]	$B = C_3 \cdot (1 - e^{-C_4 t})$

In ***Table 5***, all the pollutants we defined in SWMM have been reported: a *TSS* prefix was assigned referring to solid material . We look forward to analyse other pollutants, which are usually studied in runoff quality approaches (Deletic, 1997; Soonthornnonda, 2008), in order to assess also ecotoxicity of stormwater volumes; anyway, in the CIPAF area the main issue was up to the solid scraps. The water quality routing in SWMM behaves as a Continuously Stirred Tank Reactor (CSTR): the concentration of substances is calculate by integration of the conservation mass equation. In the SWMM model of the CIPAF solid material was assumed as dissolved; it is a rough hypothesis but it could be accepted because solid material correlates generally with most particulate-bound metals (Han YH, 2006), which result in a huge amount (foundry, mechanical industries, …). The major part of the solids are very tiny so studying them as dissolved is not far from their physical behaviour, as a primary approach.

Table 5 - *List of the solid pollutants defined in the SWMM model of the CIPAF*

		Buildup		*Washoff*		
Land Use	***Solid type***	C_1	C_2	C_3	C_4	***Description***
Roads	TSS_GENERIC_ROAD	15	0.8	3	1.2	Dust and tiny gravel
Rolling Mill	TSS_INORG_LAMELLA	50	2	0.6	1.2	Thiny metal layers, metallic needle and round scraps
	TSS_INORG_AGHI	15	2	3	1.5	
	TSS_INORG_FINE	10	2	3	2	
Foundry	TSS_INORG_AGHI	20	0.8	2	1.1	Heap of metal, foundry junk
	TSS_INORG_FINE	10	0.8	2	1.1	
Furniture factory	TSS_ORG_FIBRE	50	15	3	1.2	Wood scraps and slivers
	TSS_ORG_FINE	10	1.5	2.5	1.1	
Road's granule	TSS_INORG_FINE	10	1.2	2	1.1	Heavy grain from the road
Mechanical industries	TSS_INORG_FINE	10	1.3	2	1.5	Metal scraps from minor industries
Park	TSS_GENERIC_SQUARE	5	0.8	3	1.1	Tiny grain from the truck park
Roofs	TSS_GENERIC_ROAD	2	0.8	3	1.1	Dust
Timber storage	TSS_ORG_FINE	50	3	0.5	0.9	Wood scraps and slivers

Each name of solid material indicates if it is organic or not, and each one it is related to a specific land use. The pollutant list reports the situation at the CIPAF on 2012: several surveys on the field and some indications coming from the workers of the industrial district helped to calibrate roughly pollutant parameters. Each factory, roof, park or street was labelled in order to define solid pollution transport and consequently, buildup and washoff functions from impervious surfaces. A mass balance for each type of solid was implemented in the model. Buildup and washoff coefficients characterize particles behaviour during the dry weather period and the rainfall event: with this informations, a representative pollutograph at the outlet can be reconstructed.

IV. Results and Discussion

The SWMM hydrologic-hydraulic model was calibrated and then it was integrated with buildup and washoff functions: according to this arrangement, a basic quality&quantity response model of the basin was implemented. In **Fig. 7**, the pollutant washoff in the CIPAF under 10 mm of rain falling in 30 min was reported.

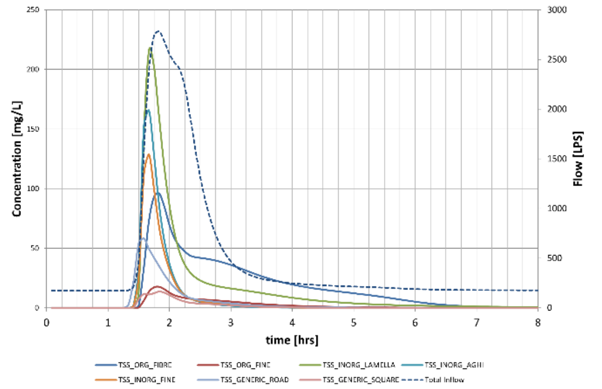

Fig. 7 - *First Flush effect in the closure section (10 mm falling in 30 min after 4 dry days)*

At the outlet, the first flush phenomenon was clearly observed: pollutograph peak anticipates the flow peak of the hydrograph. Almost all pollutants reach the treatment plant at the same time, according to observations and stormwater sediment samples; the first flush is impulsive for all pollutants, except of the *TSS_ORG_FIBRE* which pollutograph is wide in time. This curve is due to the type of wood material deriving from the furniture factory, which is farthest away from the final section at the outlet. A calibrated model can be a starting point to study and evaluate options to treat and to manage the non-point pollution on the CIPAF area. The authors are looking forward to calibrate more rigorously the quality model by automatic sampling as well as the quantity model, for more specific parameters.

In addition, a mass-volume graph was plotted: almost 70% of first flush mass reaches the treatment plant in the first 30% of the stormwater volume (**Fig. 8**). Mass-volume curves were quite used in recent years to determine first flush relevance (Chang, 1990; Piro, 2010) and they are used to compare pollutant discharges from different rainfall events (Bertrand, 1998).

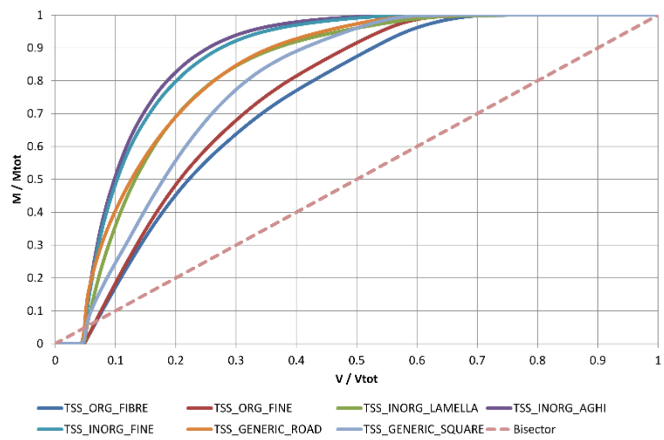

Fig. 8 - *M / V curves in the closure section (10 mm falling in 30 min)*

In order to analyse the quality-response behaviour of the basin, we carried out also the combined sewer overflow pollutograph, which showed another important phenomenon: the *last flush*. Depending on the position of the hydraulic CSO (Combined Sewer Overflow), the pollution peak could delay in respect to the flow peak. In **Fig. 9** the hydrograph and the pollutograph of the combined sewer were reported. This is a very important issue in designing a CSO: the function of this hydraulic device is to discharge a large amount of diluted water in order to solve a drainage system insufficiency. Of course, we have to be sure about *when* the hydraulic device can begin its activity. Modelling a sewer network is a fundamental way to understand how to coordinate overflow functioning; furthermore, we can understand if / where / when a discharge is needed. Improving design models means to find the best elevation of the gateway in order to deflect water only when dilution effects are positive and sustainable for the receiving systems. Simulations in the CIPAF area show an important delayed peak of the wood scraps coming from the furniture factory. We can explain this behaviour in two ways: first of all the furniture factory is the farthest factory in the district in respect of the outlet. In addition, water coming from the furniture factory is diverted by internal overflows, as indicated in **Fig. 2**, and this hydraulic scheme cause the delay of wood scraps.

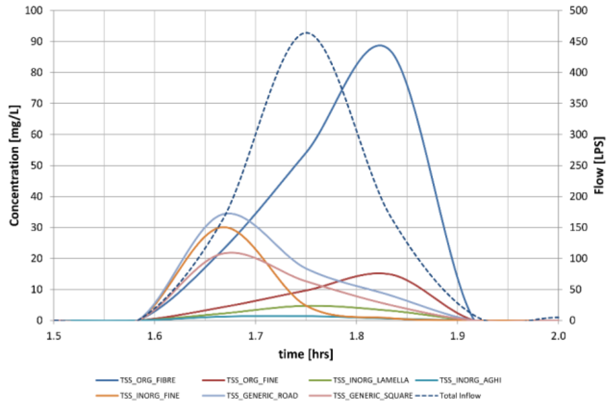

Fig. 9 - *Last flush phenomenon in the combined sewer at S-E corner of the district (10 mm falling in 30 min)*

V. CONCLUSIONS

Stormwater simulation is certainly useful to evaluate how crucial is the non-point source pollution and consequently the first flush phenomenon; the sustainability of urban and industrial activities is equally bound to the characterization of pollution coming from stormwater runoff.

In this paper, the case study of the CIPAF district confirms this assertion: the simulation of runoffs and washoffs leads to better understand the non-point source pollution and gives precious information on how managing these phenomena. Basic outcomes substantially confirm the inspections on the field and underline the importance of stormwater management in quantity and quality. Studying stormwater is the key to assess toxicity of combined sewer discharges into the rivers or into detention ponds; by simulation analysis a first flush can be calculated, and also last flush can be evaluated. Simulations can significantly support stormwater management: this deals with the characterization of potential ecotoxicity of stormwater in order to understand the actual role of residual pollution. The impact of stormwater runoff pollutants can affect ecological systems, so the designers have to pay attention to first flush mass and to short-intensity events which occur with even more higher frequency. The case study leads to further insights with the aim to calibrate strictly the quality model and to find solutions to manage stormwater in a more sustainable way. WWTP blocks are no more acceptable because of high maintenance cost, so reducing the source of solid materials by covering storages or by gully grating, could be positive also for CSO discharges.

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