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Urban Stormwater Management Projects in Belo Horizonte

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Abstract
The present paper describes experiments on sustainable urban drainage systems carried out in Belo Horizonte as part of the research and demonstration actions developed by the SWITCH project in the city. The focus of the paper is on experiments with detention and infiltration trenches. Preliminary monitoring results are here presented and discussed. Previous to the experiment description and result analysis, a general description of the storm water management system in Belo Horizonte is presented and discussed in order to better explain the reasons justifying the experiments conceived as part of the SWITCH project in this demonstration city.

Keywords: stormwater management, infiltration trench, detention trench, water quality, SUDS

1 Introduction

Belo Horizonte has recently experienced important progresses on governance of water and urban water management policy (Nascimento et al, 2008). An example is the recent constituted COMUSA, the Environmental Sanitation Municipal Council, composed by representatives of the municipality as well as of different social sectors, in charge of formulating the municipal policy and to decide on investments in the water domain, among other responsibilities. Another example is certainly the water planning process, divided in two main branches, the sanitation and the stormwater management plans, started in the 1990's and that since then has contributed to a paradigm change on river management in the urban area, to the constitution of a significant database on urban waters and related domains (e.g.: urban development, health aspects, …), to improvements on modelling and monitoring stormwater processes, to capacity building and to other institutional and managerial aspects of this domain.

Nevertheless, major challenges on water management still persist, related as an example to the contamination of receiving water by wastewater dumped to watercourses due to the lack of interceptor pipelines, wet weather diffuse pollution and flooding, mainly caused by a high level of urban occupation of the municipal area. These challenges will require important investments in the coming

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future combined with major changes on the urban water management strategy. For instance, within an intensely urbanised area, the use of sustainable urban drainage systems, particularly source control systems for runoff and wet weather pollution control, requires important developments on ways of retrofitting them to already existing conventional urban drainage systems. Uncontrolled pollution sources, as scattered and illicit solid waste deposits and inadequate interconnections between storm and sanitary sewers cause operational difficulties to stormwater devices based on runoff storage and infiltration processes. If not adequately set up these devices may also lead to increasing environmental and health risks. On the other hand, a more generalised and well adapted use of these alternatives for stormwater management will require further institutional developments in Belo Horizonte, particularly on legal adjustments, capacity building accompanied by well established design and building methods, maintenance planning and implementation and possibly new funding models.

The stormwater experiments carried out in Belo Horizonte under the SWITCH context were conceived to address most of the above described challenges, combining research as well as demonstration purposes. They are briefly described in the present paper, with focus on source control devices. Other experiments addressing water pollution abatement by constructed wetlands are described in a companion paper (Seidl et al, 2008).

2 Stormwater management in Belo Horizonte

2.1 The origins

The urban development of Belo Horizonte exerted considerable influence on the stormwater management in Belo Horizonte up to the 1980's. Planned to be the capital of the state of Minas Gerais, the construction of BH began at the end of the nineteenth century. The project was inspired by the positivist principles that were strong during that time. A general geometric design oriented the urban plan, resulting in rigidly regular streets and broad avenues meeting at right angles to form square blocks. This urban model intentionally ignored natural, local characteristics such as the region's topography and hydrography. The geometric regularity of the road system expressed the intention of facilitating the traffic flowing and making easy the construction and functioning of the water supply network as well as the wastewater and storm water drainage separated systems. During the early years of the capital, most of the streams located in the planned area were lined following the road system. Later, many of these streams were covered by concrete structures in order to meet the traffic demand.

The original plan classified the municipal area according to three land use zones: the urban, the suburban and the rural ones. No social housing provision was established, not even for those who work in the construction of the new city. As a consequence, from the beginning of the new capital setting up, uncontrolled informal settlements materialised in areas outside the planned one. Urban informality characterised these new developments where the lack of the most basic urban infrastructure and services was the rule. Also, slums informally occupied several areas within the urban zone.

During the 1960's and the 1970's most Brazilian big cities experienced population growth at rates of 6 to 8% per year. In Belo Horizonte, as in other Brazilian cities, welfare inequalities clearly reflected in the urban space occupation during this process, with a significant increase of informal new developments lacking infra-structure and services and showing high risks related to landslide, flooding and poor sanitation. This scenario is still current in many Brazilian cities, although different municipal governments have developed significant efforts leading to the regularisation of these urban areas, a policy usually encompassing housing, education, water supply, sanitation and other programs.

During the 1970's, the military government then on power adopted a centralised and sector-based plan for urban water management, called PLANASA, essentially covering drinking water and sanitation. This policy contributed to the improvement on quality of the drinking water and sanitation services, although federal investments on the provision of drinking water have been clearly more significant than on sanitation. In most of the cases, municipalities kept the responsibility for directly managing sanitation, storm water and solid waste services, a situation that still prevails at present.

In Belo Horizonte, traditional stormwater management prevailed up to the end of the 1980's, although experiences with more innovative approaches, as detention ponds, have existed since the 1950's. The apparent simplicity of stormwater management, as perceived during most of the last century, led to the use of very simple methods for stormwater system design, usually resulting in underestimations of flood risk and flood effects. Also, the municipality did not invest in hydrologic monitoring, increasing uncertainties on hydrologic simulations, hydraulic design and environmental impact assessments.

The intense urban growth during the 1970s combined with inequalities in the distribution of income led to huge impacts on water quality in receiving bodies and an increase of flood risk. This is mainly due to the impacts of new urban developments causing an increase of imperviousness and also to the occupation of flood prone areas. Water pollution by wastewater discharges and diffuse pollution inputs, including solid waste and the products of severe erosion processes have caused the degradation of water quality in streams and the reduction of conveyance capacities of sewers and channels due to sediment deposits. Detention basins have also been heavily impacted (Nascimento *et al*., 1999).

2.2 Current times

From the 1990's on important changes on urban water management have emerged in Belo Horizonte, concerning institutional development and technological issues. These changes are materialised by the Municipal policy for urban water management, which states as main objectives:

- ensuring to the municipality the formulation of urban water policies at the municipal level;
- promoting the universality of access to environmental sanitation services, comprising drinking water, sanitation, storm water management, solid waste management and the control of vectors;
- promoting a significant reduction on the pollution of water bodies;
- ensuring that urban waters will be managed on the base of public participatory processes.

A detailed description of new institutions and management instruments for the water sector in Belo Horizonte can be found in Ellis et al (2007) and Nascimento et al (2008).

The DRENURBS is one of the main programmes issued from the new urban water management approaches adopted in Belo Horizonte. This programme focus on creek recovering in the BH area by means of a participatory process which also involves actions on housing, sanitation, stormwater management, health control, and the creation of green areas and leisure facilities in the urban environment. Associated to this programme is the municipal stormwater management planning process, involving actions as the stormwater modelling programme and the monitoring programme.

The monitoring programme aims at establishing and operating a rainfall, discharge and water quality measurement network to allow the identification of BH stormwater problems at the present time and to contribute to the future evaluation of the efficiency of control measures implemented according to the stormwater plan. The stormwater modelling programme aims to simulate all the existing stormwater system in order to diagnose the main causes of system operational problems, to evaluate the risk of flooding and to simulate different control measures scenarios. One of the main issues of this programme is the ongoing establishment of flood risk maps for all the municipal area.

Belo Horizonte counts in present time on a comprehensive well established institutional process leading to integrated urban water planning and management and, at least partially, on financial resources to fund actions coming from the Municipal Sanitation Fund (FMS). Also, through the Environmental Sanitation Municipal Council (COMUSA) as well as other participatory organisations (e.g.: participatory budgeting, DRENURBS local commissions) a comprehensive process of social inclusion, citizen involvement on the urban administration and citizen appropriation of the local urban environment, as in the case of the linear parks created by the DRENURBS project, is well established.

3 Contributions of the SWITCH project to improving stormwater management in Belo Horizonte

In spite of recent progresses, it is evident that problems of frequent flooding, with flash flood characteristics, and high pollution of receiving waters at the urban area as well as downstream, in the river Velhas, still persist. At the institutional sphere, needs on improvements leading to enhancement on decision-making, budget planning, policy evaluation and technology update are recognised.

In this context, the SWITCH project is providing to the city of Belo Horizonte outstanding contributions on integrated urban water management, in general, and stormwater management in particular. There are several examples of these contributions: (i) inclusion of sustainability issues in the Belo Horizonte agenda on urban water management and related domains; (ii) adoption of non-structural measures for flood management; (iii) inclusion of wet weather diffuse pollution on the agenda of stormwater management; (iv) development of sustainable urban drainage systems (SUDS) and promotion of their use, among others.

Most of the SWITCH experiments and demonstrations carried out in Belo Horizonte are oriented to the provision of sound scientific basis for the application of SUDS under different conditions, recognizing not only local physical and urban characteristics, but also taking into account the views and needs of local communities. This general purpose requires a well-established knowledge on urban hydrology processes, including rainfall-runoff processes; flood risk and wet weather diffuse pollution assessment, as well as social and institutional aspects, as for instance, land use and environmental legislation, participatory processes, public perception of the urban environment, etc.

The experiments on SUDS involve detention and infiltration trenches, artificial wetlands, and rainfall harvesting. Some of main specific objectives of these experiments are as follows:

- establishing criteria for identifying where and which type of SUDS may be appropriate for use;
- establishing procedures for the design, the implementation and the operation of SUDS;
- defining SUDS operational and maintenance requirements;
- assessing building and maintenance costs and life cycle costs;developing professional skills and capacity building on stormwater management with focus on the use o SUDS.

This paper focuses mainly on the experiments about detention and infiltration trenches. Some of the results obtained with creek monitoring during the 2007-2008 period are also briefly commented. The wetland experiment is described in detail in Seidl et al (2008 *a* and *b*). The rainfall harvesting experiment is still in process of setting-up at a municipal high school, the Anne Frank School.

4 Experiments with infiltration and detention trenches

Four experiments on infiltration devices and one experiment on detention trenches are operating now in Belo Horizonte, carried out in the context of the SWITCH project. Three of them are monitored: the infiltration trenches on the UFMG campus and on the N. S. da Piedade catchment, and the detention trench at the campus UFMG. The other two experiments address mainly issues related to retrofitting this kind of device in already built areas.

4.1 Infiltration and detention trenches at the Campus UFMG

The experiment set up at the campus area of UFMG receives runoff flow from a main road linking the central area of Belo Horizonte to its North districts, the Presidente Carlos Luz Av. The contributing area is 3,600 m^2, essentially draining a stretch of the 4-way avenue oriented northward. The runoff generated in this area is drained through gutters till an inlet where it is collected and conveyed to the experimental area. The runoff volume and discharge effectively collected by the inlet depends on its inflow efficiency, which is a function of the flow magnitude. Estimates of the maximum peak flow that the system is able to collect are around 40 l/s. Figure 1 illustrates the contributing area and the Parshall flumes used for flow measurement. Figure 2 shows the infiltration and the detention devices.

a) b)

Figure 1: a) Partial view of the contributing area; b) Inflow measurement devices

A 10-year design rainfall, based on the IDF regional equation for the Belo Horizonte Metropolitan Area - BHMA (Pinheiro & Naghetini, 1998), was adopted for the design rainfall. The design rainfall duration was defined by simulation of different durations, adopting the one leading to the highest device peak outflow. Inflow hydrographs were calculated using a synthetic hydrograph based on the rational method. Hydrograph routing through the devices was performed by the modified Puls method. In order to estimate the infiltration trench outflow, several measurements of the saturated hydraulic conductivity were performed in the area, using a Guelph permeameter. The conductivity value adopted was $K = 5.21\ 10^{-5}$ m/s, the average of the measurement issues, a typical value for silt soils.

The experiment monitoring protocol comprises the following hydrologic variables:

- Rainfall, measured by a tipping bucket rainfall sensor installed near the experimental set;
- Inflows to each device measured by Parshall flumes equipped with water pressure sensors;
- Water levels at each trench measured by water pressure sensors, allowing the estimation of stored volumes and outflows during events;
- Soil moisture monitored around the infiltration trench by means of calibrated gypsum blocks;
- Water quality monitoring by means of inflow and outflow composed samples. Monitored water quality parameters are conductivity, pH, temperature, turbidity, total suspended soils, metals (Cu, Ni, Zn, Cd, Mg) and PAH.

The monitoring of this experiment also includes the collection and the physical and chemical analyses of sediments and solid wastes settled at the road drainage inlet (Figure 3), which will be associated to rainfall characteristics as intensity, volume and antecedent dry periods to the observed rainfall events.

a) b)

Figure 2: a) Infiltration trench; b) Detention trench

Figure 3: Drainage inlet at the Presidente Carlos Luz Av: deposits of sediments and other debris

During the construction of the infiltration trench, soil samples were collected at 4 different depths: 0.5, 1.0, 1.5 and 2.0 m from its bottom level. These samples were submitted to physical and chemical analyses in order to detect in the soil the presence of metals (Cu, Ni, Zn, Cd, Mg), PAH, $Norg_{tot}$ P_{tot} and COD_{tot} previous to the operation of the infiltration trench. These parameters characterise the initial state of the soil at the trench site and will be compared to the same soil parameters obtained from soil samples coming from the same site, after three years of the trench operation. This procedure will allow the risk assessment of soil contamination due to the infiltration trench operation.

4.2 Infiltration and detention trenches at the Campus UFMG: preliminary results

At the end of May 2008 the trenches were already installed at the UFMG campus. Nevertheless, apart from the inlet collection of sediment deposits, no other measurements were performed up to October 2008 due to the 6-month dry season typical of the local climate.

Deposits of sediment and other materials were collected at the road inlet in four different occasions. Physical analyses of these deposits allowed them to be classified in four different categories: sediments (granular material); garbage, mainly composed by plastic, metallic cans and glasses, as well as organic matter, mainly constituted by dread leaves and brushwood (see Table 1). The number of samples analysed is still too small to investigate relationships between the deposit weight and composition with dry period durations and rainfall characteristics. Nevertheless, it seems evident that rainfall increases the percentage of sediments on the deposit composition and total weight.

Table 1: Characterists of inlet deposits

Days since the last sample	Rainfall depth in the period	Rainfall duration	Estimated rainfall return period	Sediment weight		Organic matter weight		Garbage weight		Total sample weight
-	(mm)	(days)	(years)	(kg)	(%)	(kg)	(%)	(kg)	(%)	(kg)
21	0.0	0	-	6.50	53.4	5.00	41.1	0.68	5.6	12.18
9	23.8	1	< 1	56.30	89.9	5.00	8.0	1.30	2.1	62.60
14	66.8	3	< 1	67.45	89.0	8.11	10.7	0.24	0.3	75.80
6	12.8	1	< 1	23.82	82.9	4.88	16.6	0.14	0.5	28.84

Soil samples obtained under the bottom of the infiltration trench, as previously described, were analysed (Table 2). These results are below the limits of parameter concentration according to the Brazilian standards (Cetesb, 1999). Hydrocarbons, Cu and Cd were not detected. In conclusion, the soil under the infiltration trench presents no contaminated initial conditions.

Table 2: Results of soil analyses: samples collected under the infiltration trench bottom

Parameters	Concentration (mg/kg)				
	Depth (m)				Limits
	0.5	1.0	1.5	2.0	(Cetesb, 1999)
Pb	6	5.54	7.7	5.25	17
Cr	9.07	10.61	10.35	10.72	40
Ni	1.44	2.04	1.36	2.15	13
Zn	9.64	12.96	10.41	12.35	60
Mg	15.4	17.99	17.79	17.05	not available
P	147.56	178.7	210.28	88.33	not available

Regarding hydrologic monitoring, four events could be measured from the beginning of the rainy season. Two of them are here briefly discussed, the 1st November and the 7th November events. On 1st November, the rainfall started at 1:16 am and stopped at 2:26 am, accumulating a rainfall depth of 55 mm, with a return period estimated at 20 years. On 7th November the rainfall event presented a longer duration, at about 4 hours, and a depth of 18.6 mm, with an estimated return period lower than 1 year. Figure 4 illustrates the 1st November event at the infiltration trench, and Figure 5 the 7th November event at the detention trench

The infiltration trench outflow was calculated by two methods: (i) the discrete-time continuity equation (Equation 1), and (ii) the modified Puls method.

$$S_j = S_0 + \sum_{i=1}^{j} \left(I_i - Q_i \right) \tag{1}$$

The inflow (I) to and the storage at the infiltration trench (S) in any time during the event are estimated through the water level measurements at the Parshall flume and at the trench, respectively. Outflows (Q) are then obtained for each time interval during the event, using Equation 1. In Figure 1, the so obtained outflow hydrograph shows a numerical instability at its rising limb, possibly due to the time interval adopted in the measurements, 5 minutes. This issue led to the adoption of a 1-minute time step for forthcoming measurements.

The modified Puls was the method employed for the infiltration trench design. For this reason it was also employed here to simulate the 1st November event, adopting the same hydraulic conductivity from the trench design phase (K = 5.21 10^{-5} m/s). In this case, only the observed inflow hydrograph is used for simulation. Comparing both outflow hydrographs, one can state that there is a relatively good agreement between them, in spite of the numerical instability of the continuity method, particularly considering that the Puls method is a linear conceptual model possibly too simple to represent the infiltration and percolation processes involved in the infiltration trench functioning.

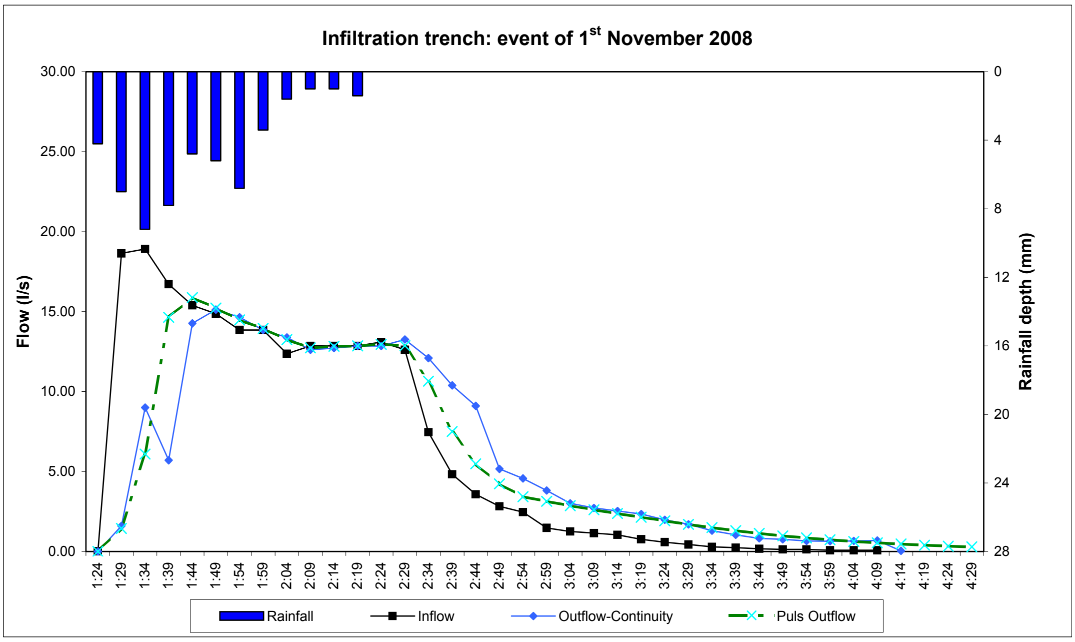

Figure 4: Infiltration trench: rainfall hyetograph, inflow and infiltration hydrographs

The 1st November event has led the infiltration trench to fail, what was expected due to its return period, much higher than the one adopted for the trench design. According to water levels measured at the infiltration trench, the overflow started at 1:40 am, just 15 minutes after the beginning of the rain, and stopped one hour later. Using the Puls simulation it was possible to estimate the overflow volume in 38.8 m^3, with the infiltrated volume reaching 26.6 m^3. Even considering its failure, the infiltration trench proved to be more efficient in reducing the peak flow than the detention one, as for a peak inflow of 19.4 m^3/s the peak outflow for the former was 12.5 m^3/s, against 16.1 m^3/s for the later.

An example of a much more frequent event occurred on 7th November, showing feeble rainfall intensity and longer durations. The Infiltration trench absorbed all the inflow volume of 34.1 m^3. The functioning of the detention trench for hydrograph abatement was as expected (Figure 5); the peak flow of the event was reduced in 22 %. Since this device was designed to control a 10-year event, it tends to be less efficient in controlling very frequent events. A longer detention time for frequent events would improve its efficient in pollution abatement, an issued to be addressed at this experiment.

SS were evaluated on composed samples for the 31st October and the 7th November events (Table 3), for the inflow and outflow hydrographs. Both events are frequent, with return periods lower than 1 year. They show major differences in terms of their duration and antecedent dry period. This later factor can possibly explain the higher SS concentration for the 31st October event in respect to the 7th November one. The detention trench portrayed efficiencies in pollution abatement from 60% (7th

November) up to 80% (31st October). The SS figures for the infiltration trench are clearly inconsistent. It is possible that the procedure for sampling infiltrated water is being contaminated by soil mobilised by the sampling drain. The sampling procedure will have to be changed for the forthcoming events.

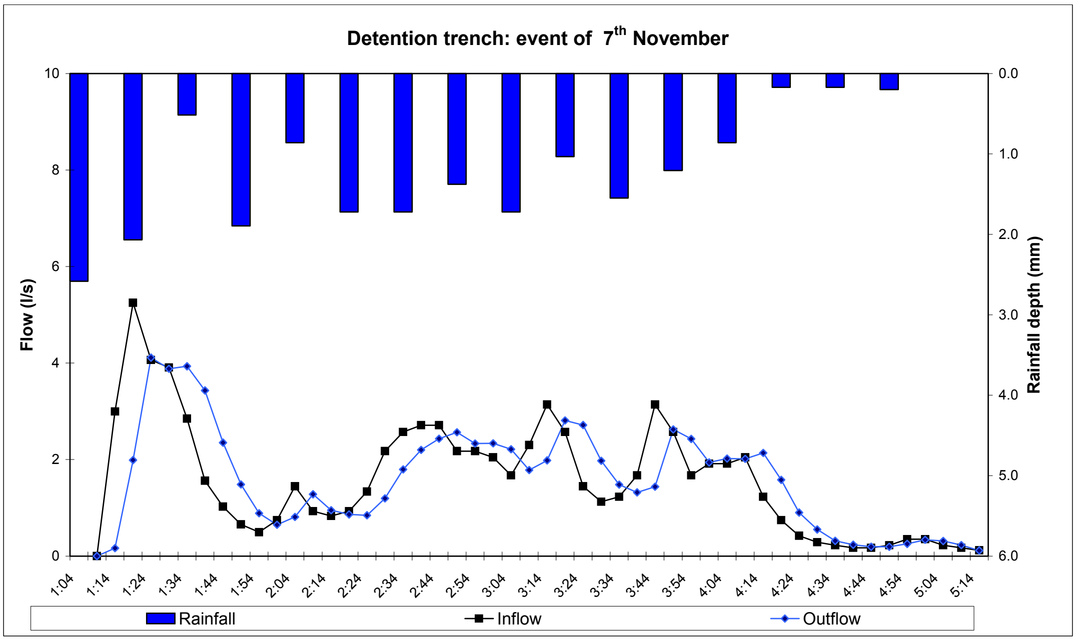

Figure 5: Detention trench: rainfall hyetograph, inflow and outflow hydrographs

Table 3: Inflow and outflow water quality assessment

Event data	**Rainfall characteristics**				**Water quality parameters**		
	Dry period before rain	**Rainfall duration**	**Rainfall depht**	**Estimated return time**	**Sample site**	**SS**	**pH**
	(days)	**(minutes)**	**(mm)**	**(years)**		**(mg/l)**	**-**
31 Oct.	12	30	13.0	< 1	**Inflow**	1596	7.9
					Outflow I*	874	8.7
					Outflow D**	308	8.0
7 Nov.	1.5	420	19.4	< 1	**Inflow**	616	7.3
					Outflow I	1082	8.0
					Outflow D	256	8.1

* I: infiltration trench; **D: detention trench

5 The Quaresma catchment experiment: characterising water pollution

In Belo Horizonte, one of the main limitations in water pollution control is the lack of sewer interceptors to transport the collected sewage to the two existing large wastewater treatment plants. From the approximately 600 km of sewers that are needed, about 300 km have already been implemented. The existing sewers collect about 93% of the generated sewage, but only half is treated. The main problem is not treatment plant capacity, but the transportation of the wastewater to the plants. To preserve the water resources a major effort is needed to increase the intercepting capacity, and the Water and Sanitation Company (COPASA) is directing substantial efforts in accomplishing this. However, in many cases, a temporary or even a permanent cheaper alternative might be to treat the polluted small watercourses by some simple natural ways. One of these alternatives, widely adopted for stormwater pollution control, is the utilization of constructed wetlands.

Within the SWITCH project, two small catchment areas were investigated, starting with the characterization of their water quality and pollutant loads, aiming at obtaining input data for the conception and design of constructed wetlands for treatment of river water. The main concept is the full treatment of the dry-weather flow and the partial treatment of the wet-weather flow. This paper presents the research project on the Quaresma stream, a tributary of Vilarinho stream. The research area is located within the designated area for a detention pond for stormwater control. At peak flows the detention ponds might be used, flooding the entire area designated for treatment. After the flood event, the treatment system needs to come back to operation again. This of course represents a real challenge, thus requiring a detailed knowledge of the behaviour of the Quaresma stream, both in terms of water quality and quantity. The Quaresma stream has a length of 1500 m, with a watershed area of 120 ha and a population around 15,000 inhabitants.

The monitoring process began in May 2007, with samples being collected in dry weather (not less than two days without rain) and in rain events. In dry weather the programme was for 12 collections with samples taken every 30 minutes for a period of 24 hours, totalling 12 composite samples. For the rain events the programming comprised 10 collections taken every 10 minutes at the beginning, during and after the rain in events lasting between 2 and 4 hours. Main water quality constituents were monitored.

During dry weather, the concentrations of the main constituents clearly show that the water quality behaviour is entirely dominated by the hourly variations of raw wastewater discharged in the stream. The pollutogram closely resembles in shape the typical hydrograms of water consumption and wastewater generation throughout the 24 hours of the day: low values at night, peak values in the morning).

Significant decreases in concentrations of the parameters conductivity, COD, BOD, TKN, NH_4^+, P-total and heavy metals could be observed in the rain events, allegedly due to the phenomenon of dilution promoted by the substantial increase in the volume of water carried by the stream, which ranged from a flow of 0.07 m^3/s in dry weather to a maximum of up to 4.75 m^3/s during the rain events. On the other hand, there was an increase in the concentrations of nitrate and SS, and in the results of turbidity in rain events. The increase in the concentrations of nitrates may be related to the integration of water from rainfall. In the cases of increase in turbidity and SS, they must be mainly related to the erosive processes in the stream troughs and in the soil of the basin, carrying sediments to the stream during the rain events.

The results of statistical tests showed, for all parameters, except for heavy metals (Zn and Cu) and coliform (*E.coli* and total), the condition of occurrence of variability ($p < 0.05$) between the results of dry and rainy weather, i.e., the parameters behave differently under the weather conditions (wet and dry) analyzed.

The annual pollutant loads generated in the catchment area were calculated for the dry and wet periods, and are presented in Table 4. The values during rain events suggest a highly significant contribution when compared to dry weather, because these loads on rain events are generated in a period comprising only 7% of dry weather period. The estimates generated by the annual rainy events for indicators of organic matter present a percentage of approximately 50% of what is generated in periods without rainfall. And in the case of SS, they represent an estimate approximately 4 times higher than the dry weather.

Table 4 - Annual pollutant loads generated in the catchment area (kg/ha.year).

Condition	COD	BOD_5	SS	TKN	P-total	Cu	Zn
Dry Weather	5748	2762	3.842	374	44	0,3	0,97
Rain event	2838	1275	13.903	86	19	0,129	0,53
Total	8585	4037	17744	460	63	0,43	1,5

6 Conclusions

The experiments carried out by the SWITCH project in Belo Horizonte address relevant questions on stormwater management, usually not taken into account in the city by the current urban drainage approach. They were conceived to meet associated objectives of research and demonstration and. They also focus on some of the main questions raised by different stakeholders who are members of the Belo Horizonte Learning Alliance.

The first measurement results are being produced through the infiltration and detention experiments, with the beginning of the rainy season. A one-year cycle of hydrologic measurements has already been obtained at the Quaresma catchment. These results will constitute a central reference for further developments in terms of statistical analyses, modelling the different phases of the rainfall runoff processes and the functioning of SUDS devices, uncertainty analyses on measurements and modelling, among other forthcoming activities to be carried out by the SWITCH project in Belo Horizonte.

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