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Abstract

In developing countries, lack of sanitation coverage and continuously growing populations are increasing the pressures on receiving waters. In the context of Bogotá (Colombia), this paper presents recent and ongoing research towards improved management of urban drainage systems using an integrated framework. Research results have shown there is a need to assess the urban drainage system as one entity when considering pollution control objectives. This holistic approach offers the opportunity to investigate the interactions between sub-systems and the impact of the whole system on the river water quality. In Bogotá, now is the time to develop plans towards an efficient integrated system which maximises the benefits from the resources, supporting data and software tools available. It is needed the development and application of modelling tools at different levels of detail. As part of this, an integrated modelling toolbox named City Drain which operates under MATLAB/Simulink is being upgraded, customised and used as a research tool.

Keywords

Integrated management and modelling; developing countries; Bogotá city; pollutant and sediment loads; wrong connections.

INTRODUCTION

Urban wastewater systems consist principally of three sub-systems as follows: the sewer system, the waste water treatment plant (WWTP) system, and the receiving body system. Up to now most sewer systems and WWTPs are designed, operated, and improved as separate entities as a consequence of the difference in their main functions (Langeveld, 2004; Schroeder et al., 2005; Gill et al., 2006). However, research results point to the importance of the dynamic interactions between sewer and WWTP to assess performance of the urban water system (Langeveld, 2004). The same remains true at the combined sewer overflow (CSO)/river and WWTP/river interfaces. For example, previous research showed that for a hypothetical case study prolonged hydraulic overloading of the WWTP, in order to reduce overflow spills, can in turn affect the treatment processes efficiency exerting considerable impact on the receiving system water quality (Rauch and Harremoes, 1997). Additionally, each receiving water body presents its own properties and must therefore be evaluated under a holistic framework with respect to the discharges from the urban catchment (Solvi, 2006).

The idea of an integrated urban drainage modelling is not new. Beck (1976) discussed a "water quality system" which involves the water distribution network, the sewer system, the treatment plant and the river. It was not until the early 1990s that the concept of the holistic approach began to be adopted in academic studies (Mitchell et al., 2007). Currently, it is widely accepted that an integrated assessment of the emissions from sewer systems and WWTP is necessary when attempting to reduce the total impact of the urban drainage system on the receiving water body (Langeveld, 2004). In this context, models can be used to gain better understanding of certain phenomena and to predict the spatial and temporal evolution of a system when looking towards an integrated management of urban drainage systems. Simulation models play a crucial role in environmental management plans due to they can apply best available scientific knowledge to predict responses to changing controls. Detailed integrated studies of the sewer network – WWTP – receiving water system are comparatively rare due to high cost (Rauch et al., 2002b; Ashley et al., 2004b) and practical applications of the holistic approach are still limited. However, progress has been made in developing integrated modelling tools, allowing for application at full catchment-scale as presented for example in Freni et al. (2008) and Devesa et al. (In Press). Furthermore, in order to increase the application of such holistic approach, the Central European Simulation Research Group (HSGSim) prepared a guideline document proposing a seven-step procedure to integrated modelling (Muschalla et al., 2008).

Historically in Bogotá (Colombia), efforts have focused on analyzing and improving the individual performance of the urban water cycle components without taking into account the interactions between them. Bogotá city needs the development and implementation of measurement programs and modelling tools at different levels of detail, considering overall urban water fluxes and various treatment schemes, including their economic aspects. These efforts are considered to be useful for the development of best management practices. Within this framework, this paper presents recent research results in the context of Bogotá on developing software tools for estimating percentage of wrong connections in the separate sewer system (Mestra, 2008), assessing CSOs performance (Fonseca et al., 2008), and evaluating sediment accumulation rates in the sewer system (Uniandes, 2008b). Additionally, relevant data on domestic and industrial wastewater loads and in-sewer sediments characteristics and properties which are now available as inputs for the integrated management and modelling in Bogotá are presented (Uniandes, 2008a).

SUPPORTING DATA AND TOOLS FOR INTEGRATED MODELLING – THE BOGOTÁ CASE

Context

Bogotá, the capital city of Colombia, is located at an approximate altitude of 2600 m.a.s.l with approximately 330 km^2 of urban area. The Bogotá Savanna is the most densely populated area of the country, being an important industrial and agricultural region. The population of Bogotá city increased by approximately 4 million in the last 30 years, from 2.9 million inhabitants in 1973 to 6.8 million in 2005 (DANE, 2005). It is estimated that the saturation population will be around 12 million inhabitants, accounting for about 20% of the total population of Colombia. Bogotá city is a prime example of a mega-city under stress due to unplanned and unregulated urban developments, severe water quality problems in the water courses, lack of sanitation coverage and water treatment facilities, lack of institutional co-ordination, mismanagement of water resources, financial constraints, lack of wise expenditure on the required infrastructure, and a conventional fragmented wastewater management (Rodríguez et al., 2008b). A detailed description of the development and current state of the components of the urban water cycle of Bogotá city, their interactions and previous research under a holistic approach can be found in Rodríguez et al. (2008b; In preparation).

Domestic and industrial wastewater loads: a comparative assessment

Based on measurements from field campaigns in the sewer system sub-catchments, which were carried out in order to identify daily water quantity and quality patterns of dry weather flow (Díaz-Granados et al., 2008), domestic pollutant loads were estimated (see Table 1). When comparing found ranges and average values for the Bogotá city, with typical values reported in specialized literature (Butler and Davies, 2004), it can be concluded that there are accordance as presented in Table 1.

Table 1: Measured domestic pollutant loads for the Bogotá city (Uniandes, 2008a)

Parameter	**Per capita pollutant loads (g/inhabitant-day)**				**Total pollutant loads (Ton/day)**
	Minimum	*Maximum*	*Average*	*Reported in specialized literature**	*Average*
Ammonium (NH_4^+)	6.76	13.46	9.42	8	66.4
BOD_5	48.41	77.49	59.82	60	421.7
COD	108.87	194.59	151.59	110	1068.7
Soluble Phosphorus	1.06	1.97	1.53		10.8
Total Phosphorus	2.04	2.79	2.45	3	17.3
Nitrates (NO_3)	0.08	1.55	0.58		4.1
Nitrites (NO_2)	0.02	0.28	0.10		0.7
Total Kjeldahl Nitrogen (TKN)	10.74	18.64	15.40	12	108.5
Total suspended solids (TSS)	43.54	171.91	92.84	60	654.6
Volatile suspended solids (VSS)	39.96	85.95	55.36	48	390.3
Volatile total solids (VTS)	63.24	150.84	99.60		702.2
Total solids (TS)	143.76	493.94	268.50		1893
Sulphates (SO_4)	12.69	32.50	21.10	20	148.7
Sulphurs ($S^=$)	0.53	1.44	0.94		6.6

*Butler and Davies (2004)

The secretary of district for the environment (Secretaría Distrital de Ambiente - SDA) carried out a detailed monitoring program between 2003 and 2007 in order to assess industrial wastewater loads in Bogotá city. Nearly 600 industries were monitored including 148 related with food industry, 107 with leather industry, 109 with oil and gasoline stations, 11 with printing industry, 52 with metal-mechanics industry, 58 with chemical industry, 55 with textile industry and 43 with service and health industry. Table 2 presents measured pollutant loads from industrial activities of selected parameters in Bogotá and their contribution in comparison with domestic pollutant loads.

Table 2: Comparison between measured domestic and industrial pollutant loads in the Bogotá city (Uniandes, 2008a)

Parameters	Total pollutant load from domestic activities (Ton/day)	Total pollutant load from industrial activities (Ton/day)	Industrial contribution
BOD_5	421.7	43.1	9.27%
COD	1068.7	121.5	10.21%
TSS	654.6	19	2.81%
Sulphates (SO_4)	148.7	0.5	0.37%
Sulphurs ($S^{=}$)	6.6	0.15	2.17%

Wrong connections: a GIS-based tool for identifying their likelihood

There are many wrong connections from the wastewater system flowing into the storm drainage system in Bogotá city. The separate sewer system acts more as a "dual" combined system rather than as a separate one. Mestra (2008) presented a GIS-based computational tool in order to identify the likelihood of wrong connections presence in the Bogotá's separate sewer system, specifically misconnections from the wastewater system into the storm water system. Based on interviews and surveys to engineers and contractors in charge of households/properties' connection to the sewer system, it was found that main factors which have a relevant effect on the presence of wrong connections are urban densification processes, sewer system ageing level, construction gap between the storm water and wastewater systems, socioeconomic level and strata, land use, pipe depth and distance between property and the wastewater and storm water systems, pipe material, road type and property type. The mentioned computational tool uses 8 variables which take into account all these factors. Each of the variables has a numeric value ranging from 0 to 2, where 0 means the minimum likelihood of wrong connections and 2 the maximum likelihood. The sum of the 8 variables values allows qualifying the existence of wrong connections in three different ranges: 0 – 4 low, 4.1 – 8 medium, and 8.1 – 13 high likelihood of misconnections. This GIS-based tool was tested using a catchment named Jaboque located in the Salitre sub-catchment in Bogotá. It was possible to identify properties with a high likelihood of wrong connection presence. By means of dye experiments and CCTV inspections in 69 properties situated in an area of the Jaboque catchment (see Figure 1a), a total number of 19 misconnections were identified (Figure 1b). Mestra (2008) concluded that the developed tool appropriately predicted this condition. Additionally, the tool was applied to the entire Salitre sub-catchment with an area of about 122 Km^2 (see Figure 2). It was possible to identify areas with high potentiality for misconnections in which field inspections should be focused. Regarding the entire city, it is planned to apply this GIS-based tool for assigning percentages of wrong connections in areas without any data from field inspections and measurement campaigns.

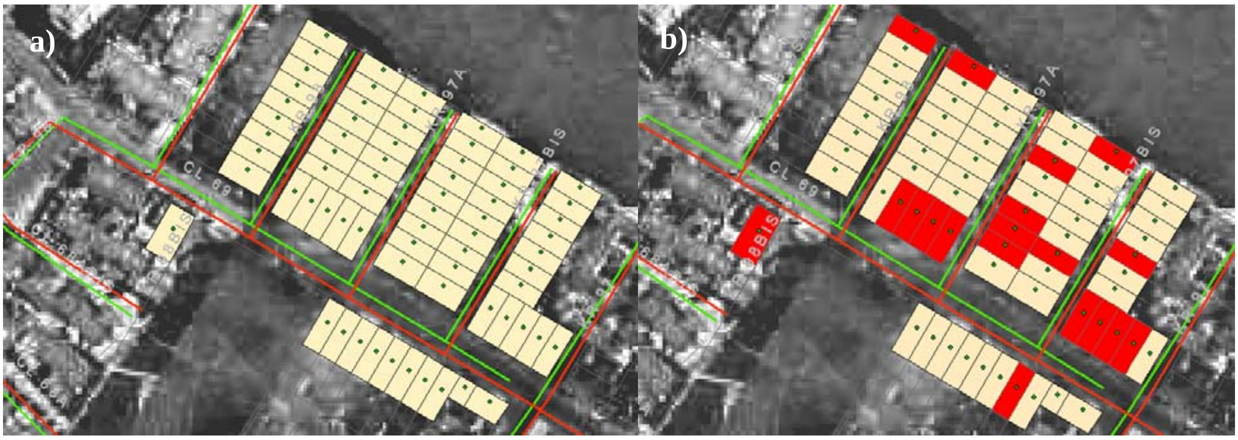

Figure 1: (a) 69 properties in which dye experiments and CCTV inspections were performed (b) 19 of 69 properties with presence of wrong connections (Mestra, 2008)

Figure 2: Application of the GIS-based tool to the Salitre sub-catchment. Green dots represent low likelihood of misconnection at a address point/property level, yellow medium, and red high likelihood (Mestra, 2008)

Sewer sediments: their properties and a GIS-based tool for estimating accumulation rates

Sewer sediment is defined by Butler et al. (1996) as: "*any type of settleable particulate material that is found in storm water or foul sewage and is able to form deposits in sewers and associated hydraulic structures*". Types, sizes and quantities of sewer sediment can vary widely according to the sewer type, geographical location, catchment type, catchment slope and local procedures. Particles transported by domestic sewage are mainly organic, while particles in stormwater presents mineral properties (Bertrand-Krajewski et al., 1993). There are five main sources of solids entering sewer systems (Ashley et al., 2004a): the atmosphere, the surface of the catchment, domestic sewage, processes inside the sewer system, and industrial and commercial effluents.

Sewer solids are of importance not only in terms of transport phenomena but also for wastewater quality processes in urban drainage networks due to the solids providing a transport matrix for different pollutants (Ristenpart, 1998). It has been observed that total suspended solids (TSS) are the main vector for many pollutants such as COD, hydrocarbon, heavy metals, micro-pollutants, etc. (Chebbo et al., 1995; Gong et al., 1996; Mark et al., 1996; Arthur et al., 1999; Otfinowska et al., 2007). As a consequence, the management of sewer solids is a key component in developing a holistic approach to the design and operation of wastewater systems (Ashley et al., 2004a).

The Environmental research centre (Centro de Investigaciones en Ingeniería Ambiental - CIIA) at the Universidad de los Andes in cooperation with the sewer system managers (Water utilities of Bogotá, EAAB) carried out an extensive sewer sediment characterisation program. Sampling stations included sewer pipes and manholes, gully pots and storm channels. They were selected based on experts' knowledge (by means of surveys), customers claims data base, and a GIS-based prioritizing matrix which includes aspects such as road type, land use, transport capacity, ageing of the system, network material, and population density (Uniandes, 2008b). A total number of 2293 simple samples were characterized, including 2121 manholes, 460 gully pots and 3 storm channels. Main sediment characteristics and properties in the Bogotá's urban drainage system are presented in Table 3.

Table 3: Sediment characteristics and properties in the Bogotá's urban drainage system (Uniandes, 2008b)

Parameter	**Sewer pipes and Manholes**			**Gully pots**	**Storm Channels**
	Residential	**Industrial**	**Commercial**		
pH	6.39 – 10.77	6.52 – 8.42	7.1 – 8.57	7.1 – 11.29	7
Granulometry (mm)	Fine sediment 0.00775-0.09922 (D50) – Coarse sediment 0.074-4.57 (D60)*				
Density (kg/m^3)	1262.9 – 2007.9 (average 1583.88; standard deviation 162.3)*				
Viscosity (cps)	250 – 276000 (average 24844.6; standard deviation 55198.1)*				
%TS	41.7 - 67.6	45.1 – 68.5	45.7 – 71.7	61.9 – 78.1	54 – 80.6
%VS	5.3 – 16.9	5.6 – 24.7	5.6 – 19.5	3.9 – 12.6	1.9 – 10.5
COD (g/kg)	34.5 – 176.5	60 – 1125	65 – 133	24 – 190	16 - 116
Benthic demand (g/m^2*day)			1.2 – 12.17*		
Total Kjeldahl Nitrogen – TKN (%)	0.18 – 0.88	0.185 – 2.6	0.17 – 0.42	0.006 – 0.86	0.31 – 0.32
Amoniacal nitrogen	0.003 – 0.21	0.004 – 0.06	0.007 – 0.14	0 – 0.21	0.006 – 0.01
Phosphorus	0.08 – 1.1	0.17 – 0.4	0.14 – 0.23	0.06 – 0.26	0.04 – 0.17
Fat oil and grease (%)			0.42 – 9.47*		
Faecal coliforms (MPN)	$1.2x10^3$ – $10.4x10^7$	$4.8x10^3$- $1.5x10^6$	$5x10^3$-$2.4x10^6$	<2.6-$5.4x10^4$	$3.3 x10^3$- $5.1x10^4$

*Values are representative for sewer pipes, manholes, gully pots and storm channels

Additionally, a GIS-based tool named SIGTASED was developed for quantifying the amount of sediments which are accumulated in the sewer system at a sub-catchment scale (Uniandes, 2008b). The main formulation used in the tool, based on regression analysis of field data surveyed from Cleveland (OH), is known as the Cleveland simplest model (Fan et al., 2003) which estimates the sediment accumulation rate based on the sewer system length, per capita flow including infiltration and sewer system average slope. The software tool uses information such as sewer network characteristics (pipe length, diameter and slope), address points and the bi-monthly consumption rate (m^3) for estimating the accumulation rates. Figure 3 presents the

GIS tool user interface in which a coloured map represents the expected accumulation rate in each of the sub-catchments.

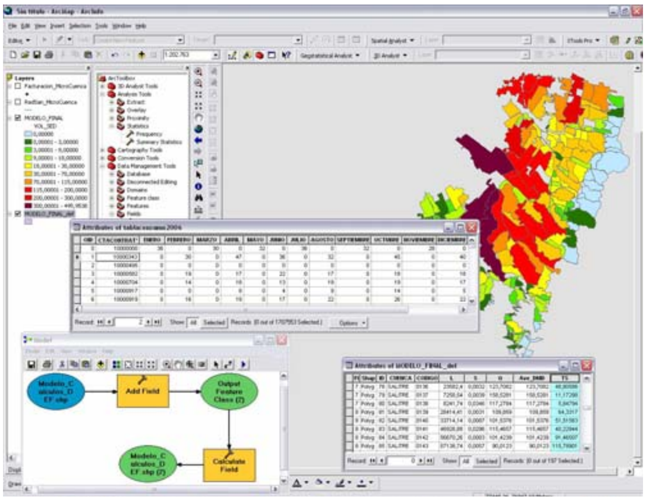

Figure 3: SIGTASED user interface (Uniandes, 2008b)

Setting water quality objectives for the receiving water courses: the Salitre, Fucha, Tunjuelo and Torca urban rivers case

Based on available data from the water quality monitoring network in the urban receiving water courses in Bogotá (SDA, 2008), the Canadian Council of Ministers of the Environment Water Quality Index (CCME WQI) (CCME, 2001) was estimated for each of the four main urban rivers which drain the city (Uniandes, 2008a). The CCME WQI is a tool for simplifying the reporting of water quality data and gives a broad overview of environmental performance. Water quality can be ranked by relating it to one of the following categories: excellent, good, fair, marginal and poor. In the Bogotá case, The CCME WQI clearly demonstrates that the water quality in the receiving water courses is frequently threatened or impaired and conditions often depart from natural or desirable levels (see Table 4).

Table 4: CCME WQI for Bogotá's urban rivers (Uniandes, 2008a)

	Reach 1	**Reach 2**	**Reach 3**	**Reach 4**
Salitre River	50 (marginal)	31 (poor)	31 (poor)	59 (marginal)
Fucha River	100 (excellent)	34 (poor)	45 (marginal)	27 (poor)
Tunjuelo River	80 (good)	27 (poor)	31 (poor)	23 (poor)
Torca River	64 (marginal)	71 (acceptable)	-	-

In order to improve water quality conditions in the Bogotá's urban rivers, the local environmental authority (SDA) and the environmental research centre (CIIA) at Universidad de los Andes set gradual water quality objectives (WQO) for each of the four reaches in which each one of the main receiving water courses in Bogotá (Salitre, Fucha, Tunjuelo and Torca rivers) were divided. Four different temporal stages were established as follows: 4, 10, 20 and 40 years. These objectives were defined using monitoring records from the water quality monitoring network in the urban receiving water courses in Bogotá (between July 2006 and May 2007) to assess current state and modelling results using the QUAL2K software for prospective scenarios (Raciny et al., 2008). Temporal stages are: *WQO to be achieved in 4 years* (Water quality objectives take in to account expected sanitation infrastructure developments), *To be achieved in 10 years* (It is based on the planned water quality objectives for the Bogotá River by 2020), and

To be achieved in 20 and 40 years (The main goal behind these objectives is to preserve aquatic environments. As a healthy ecosystem relies on appropriate quality of the sediments, sediment quality objectives were defined regarding heavy metals, polycyclic aromatic hydrocarbon (PAH) and organo-chlorine pesticides and polychloride biphenyl (PCB)).

THE APPLICATION OF AN INTEGRATED MODELLING TOOL IN THE CONTEXT OF BOGOTÁ CITY

Different modelling approaches can be applied, where the main difference is the amount of data required, the information that can be obtained from the model, the analysis performed and the simulation period. There are a variety of modelling approaches to describe water motion as well as the transport and conversion of matter. Schuetze and Alex (2004) concluded that the combination of sub-models with different complexity and models with a modular building structure facilitate the integrated modelling. Many different tools have been developed such as GEMINI (Guderian et al., 1997); SYNOPSIS (Schuetze, 1998; Schütze et al., 2002), WEST (Meirlaen, 2002), REBEKA (Rauch et al., 2002a; Fankhauser et al., 2004), SEWSYS (Ahlman, 2006), SIMBA (ifak), Mannina et al. model (Mannina et al., 2004a; Mannina et al., 2004b), CITY DRAIN (Achleitner, 2006; Achleitner et al., 2007) and SMUSI (Muschalla, 2008) among others.

Achleitner (2006) developed an open source toolbox based on the European Water Framework Directive (WFD) requirement. This model, named CITY DRAIN, has been developed using Matlab/Simulink©. The key aspect of using this modelling environment is that the user can choose and freely adapt from a block library representing the elements of the total system (Rauch, 2006). The software is designed for the integrated modelling of urban drainage systems aiming to provide a flexible and adjustable tool for different scenarios. One of the main advantages of this tool is the possibility to modify the code behind it or even to implement and add new blocks according to specific needs (Vojinovic and Seyoum, 2008). Overall the computation is based on a fixed discrete time step approach where each subsystem uses the same time increments, usually being predetermined by the temporal resolution of the rain data used. For allowing long term simulations the blocks implemented are based on simple conceptual models for hydraulics (frequently denoted as hydrological models (Durchschlag et al., 1991)). Mass transport of pollutants is implemented for conservative matter/tracer substances.

An application of the City Drain toolbox in the context of Bogotá can be found in Fonseca et al (2008), where this toolbox was coupled with fuzzy logic techniques in order to assess CSOs performance. The assessment is based on operational parameters, design standards, receiving bodies' water quality regulations and experts' knowledge. There are four variables (operative dilution factors, CSO setting, dry weather CSO spills and receiving bodies' water quality impact) which collectively give an assessment value ranked between 0 and 10 according with the fuzzy logic rules in each of the calculation time steps. The City Drain toolbox coupled with the fuzzy logic module was applied to the sub-catchment "El Virrey" (see Figure 4). Nine CSOs structures were dynamically assessed for two day simulation period with two hypothetical rain events. Results from CSO No. 1 indicate a value of 6.29 as the minimum and 9.25 as the maximum in the dynamic CSO assessment (average value of 7.76 with a standard deviation of 0.43). In contrast, downstream CSO No. 7 has a low assessment value of about 4 in dry weather period due to the occurrence of CSO spills even during this hydrological condition. As during rainfall events the operative dilution factor increases and if there are not a considerable impact on the water quality in the receiving body, the CSO assessment can considerable improve. It was concluded that a CSO assessment should be based on not only their typological characteristics but on operative parameters, upstream CSOs structures performance, water quality state and impact on the receiving watercourse.

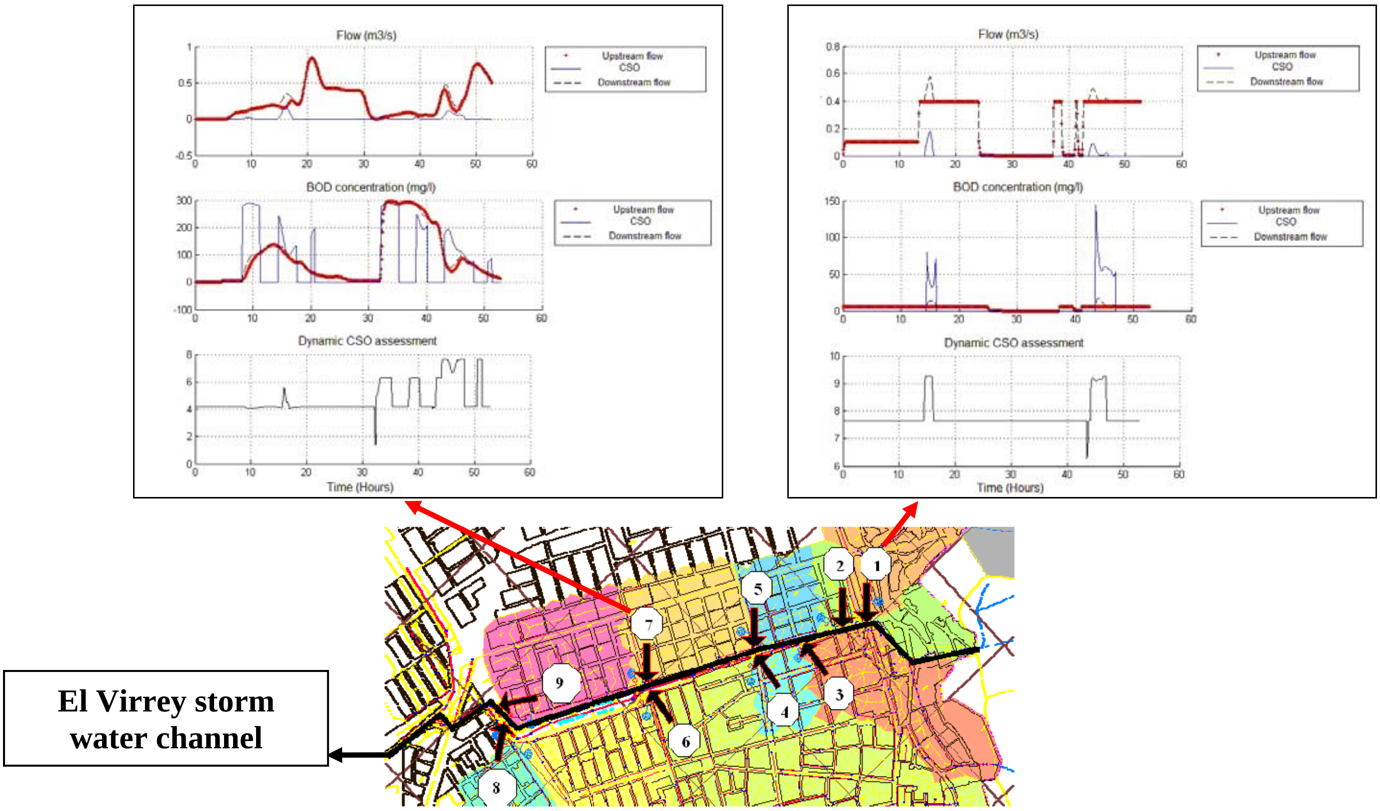

Figure 4: City Drain application to the El Virrey Sub-catchment – obtained dynamic results from CSO No. 1 and No. 7 (Fonseca et al., 2008)

ONGOING WORK TOWARDS AN INTEGRATED MANAGEMENT AND MODELLING IN BOGOTÁ: PERSPECTIVES AND CONCLUSIONS

This paper has provided an overview of recent research and development for an integrated approach to urban drainage system management in Bogotá which pretends to maximise the benefits from the resources, supporting data and software tools available. Complementarily, ongoing research in the context of Bogotá plans to contribute to the development of an integrated urban drainage system modelling framework. Modelling work is planned at two different scales: sub-catchment modelling and macromodelling scale. The subcatchment modelling scale aims to perform comparative models of sewer systems using two study cases, including one experimental subcatchment in Bogotá (Colombia) (Uniandes, 2001) and one subcatchment in Linz (Austria) (Hochedlinger et al., 2006). The main goal is to test and implement computational routines for improved representation of sediment transport processes and water quality transformations in the sewer system compartment. The gained results will serve as a basis for identifying the modelling scheme to use when looking at the macro-modelling scale. Comparing results and performance of different case studies, with different characteristics in their boundary conditions and data sets, offers the opportunity to perform more robust analysis and tests on the developed modelling approaches. Modelling of sediment transport becomes useful for the prediction of the water quality in the receiving waters and for the assessment of the efficiency of different measures to reduce pollution loads (Berlamont and Torfs, 1996). In addition, models allowing for the simulation of solid production and transport during storm events can be very useful for dynamic management and operation of WWTPs. An inadequate representation of nonpoint source pollution can lead to implementation of ineffective and inappropriate measurements (Vaze and Chiew, 2002).

Integrated modelling is planned at a macromodelling scale aiming to increase the understanding about the comparative performance of different types of sewer systems (combined and separate) by means of an analysis of Bogotá's urban drainage system, in which separate systems are used under a high presence of wrong connections. Obtained results could improve the knowledge about how to manage and/or operate, and how to prioritize investments on individual parts of the urban drainage system under such specific conditions but allowing transferability to other developing cities. Additionally, this modelling scale is planned to be used to perform a model-based effectiveness evaluation if implementing structural best management practices (BMPs) in the stormwater system of Bogotá. It is proposed that this task be based on the BMPs' comparative assessment methodology proposed by Scholes et al. (2008), and it aims to develop a model-based framework to support decision-making processes to implement BMPs in Bogotá and other cities in developing countries. It is planned that macromodelling analysis be based on the ongoing implementation of the Bogotá city urban drainage system using the City Drain model initially presented by Rodríguez et al. (2008a). From this implementation, it is clear the complexity of the system and how the interactions between the different elements (i.e. rural catchments, combined and separated urban catchments, combined sewer overflows, channels, interceptors, pumping stations, etc.) determine the water quality of the receiving water courses.

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