Bogotá's urban drainage system: context, research activities and perspectives

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Abstract

In this paper an overview of the development and current state of the urban drainage system of Bogotá city is presented, with recent research results and identified perspectives on priorities towards sustainability. Bogotá is the capital city of Colombia, with 7 million inhabitants and approximately 330 km^2 of urban area. The urban drainage system consists of combined and separated systems, with a very large number of wrong connections. Domestic and industrial wastewater and combined sewer overflows are discharged without treatment into three urban rivers (Salitre, Fucha and Tunjuelo) and other open channels across the city. The dry weather wastewater flow is about 17 $m^3 s^{-1}$ while the capacity of the wastewater treatment system (the primary treatment plant at Salitre) is only 4 $m^3 s^{-1}$. The receiving main stream, the Bogotá River with a mean upstream flow of 10 $m^3 s^{-1}$, is therefore one of the most polluted rivers in the world, with an anaerobic stretch of about 60 km. Current research is focusing on analysing the impact of the urban area on available water resources, with emphasis on water quality. This includes instrumentation of pilot catchments, rainfall–runoff and water quality modelling of the sewer system, water quality modelling of the receiving watercourses, and first attempts at integrated urban catchment modelling.

Introduction

It is a fact that many countries experience continuous urbanisation[1] (Andrieu and Chocat, 2004). In Colombia, around 36 million inhabitants live in urban areas, nearly 80% of the total population (World Health Organization and United Nations Children's Fund, 2004). 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; EAAB, 2006). It is expected that by the year 2020 the population will be around 8.4 million inhabitants. Such urbanization implies the construction of urban drainage infrastructure generating a considerable impact on the catchment water balance and water quality (e.g. floods, overflows, pollution of receiving waters, etc) and consequently on ecological and chemical status of rivers (Bertrand-Krajewski *et al.*, 1993; Ostrowski and Schroter, 2004; Muschalla, 2008).

Goonetilleke *et al*. (2005) and Polaskova *et al*. (2006) summarized some of the effects of urbanization processes as follows: changes in runoff ratios, changes in impermeable areas, increased runoff peak and runoff volume, reduced time to peak, reduction in the retention capacity, and change in the water infiltration into the soil.

Predicting the impact of these urban areas at a river basin scale, and finding optimal mitigation measures, are challenges for modern urban planning and engineering (Niemczynowicz, 1999; Nafo and Geiger, 2004) for both developing and developed countries (see, for example, Lee (2000) and Yaya-Beas *et al*. (2007)). In Colombia, nearly 91% of the domestic and commercial wastewater is discharged directly, without previous treatment, into the receiving watercourses (Camacho *et al.*, 2006). For these reasons, integrated urban drainage modelling is needed to understand the effects of pressures exerted within a catchment, to establish reference conditions, to design monitoring programmes, to perform operational planning as an instrument for cost-effective implementation of measures, and to assess impacts to produce management plans (Solvi, 2006).

This paper briefly outlines the current situation with wastewater management, together with results obtained from monitoring and modelling activities and the experience gained from previous research projects in the Bogotá urban drainage system. The main aim is to set an appropriate background which could contribute to the further development and implementation of an adequate

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[1] It is estimated that half of the world's population are living in urban areas. In many countries, the land occupied by the urban population is often less than 5% of the total area (Zoppou, 2001)

modelling approach or the particular reference conditions.

The sewer system of Bogotá

The Bogotá sewer system consists of three main sub-catchments: Salitre, Fucha and Tunjuelo. Each one is drained, from east to west (Figure 1a). The drainage system is a combination of the two traditional types of sewer systems, combined and separated. The first sewer system developments, in the central part of Salitre sub-catchment and the eastern part of Fucha sub-catchment, consist of a combined system (approximately 74 km^2) (Figure 1b), while newer ones (since 1965) consist of separated systems. Due to the very high population density of Bogotá city and the large dry weather flow compared to rainfall runoff, the combined system seems to be a suitable system for the city. In 1998 approximately 1.3 million inhabitants were served by combined systems.

About 96% of the waste water system has been developed already (some 5400 km of pipes, tacking into account the primary and secondary networks) and about 93% of the storm drainage system has been constructed (some 2000 km of pipes) (EAAB, 2006). Other important characteristics of the sewer system are the infiltration flow estimated as 50% of the mean wastewater flow and the mean coefficient of imperviousness over the total urban area of approximately 50%. By means of computer simulations, it was estimated that the storm drainage system has a return period capacity of five years.

Per capita water consumption was approximately 150 litres per day between 1990 and 1995. By 2004 such consumption was down to 94 litres per day due to educational campaigns on rational water use and by 2010 it is expected to be 88 litres per day (EAAB, 2006). Currently, the water consumption rate in Bogotá is roughly 14 m^3 s^{-1}, where 20% is demanded by commercial activities. The return factor (ratio between wastewater flow and water consumption) is nearly 0.85.

In Bogotá, the combined system typically consists of one channelized stream and one or two parallel wastewater interceptors discharging into the separated sewer system. Problems related with the combined system in Bogotá can be summarized as follows: direct discharges of wastewater without treatment as a consequence of the absence or lack of adequate infrastructure, and combined sewer overflows (CSO) discharges, even during dry weather, into the streams. The separated system has a similar structure to the combined system: storm drainage open channels and wastewater interceptors. There are many wrong connections from the waste water system flowing into the storm drainage system.

Water quality measurements in the open channels for storm drainage in the Fucha sub-catchment indicated up to 22% of connections from the waste water system entered the channel. Also, there are wrong connections from the storm drainage system flowing into the waste water system. Based on flow surveys in some interceptors, the percentage of wrong connections from the storm drainage system into the waste water system varied from 23% up to 90% (Grucon – IEH - Soprin, 1999). As a consequence, the separated system exhibits poor water quality in the

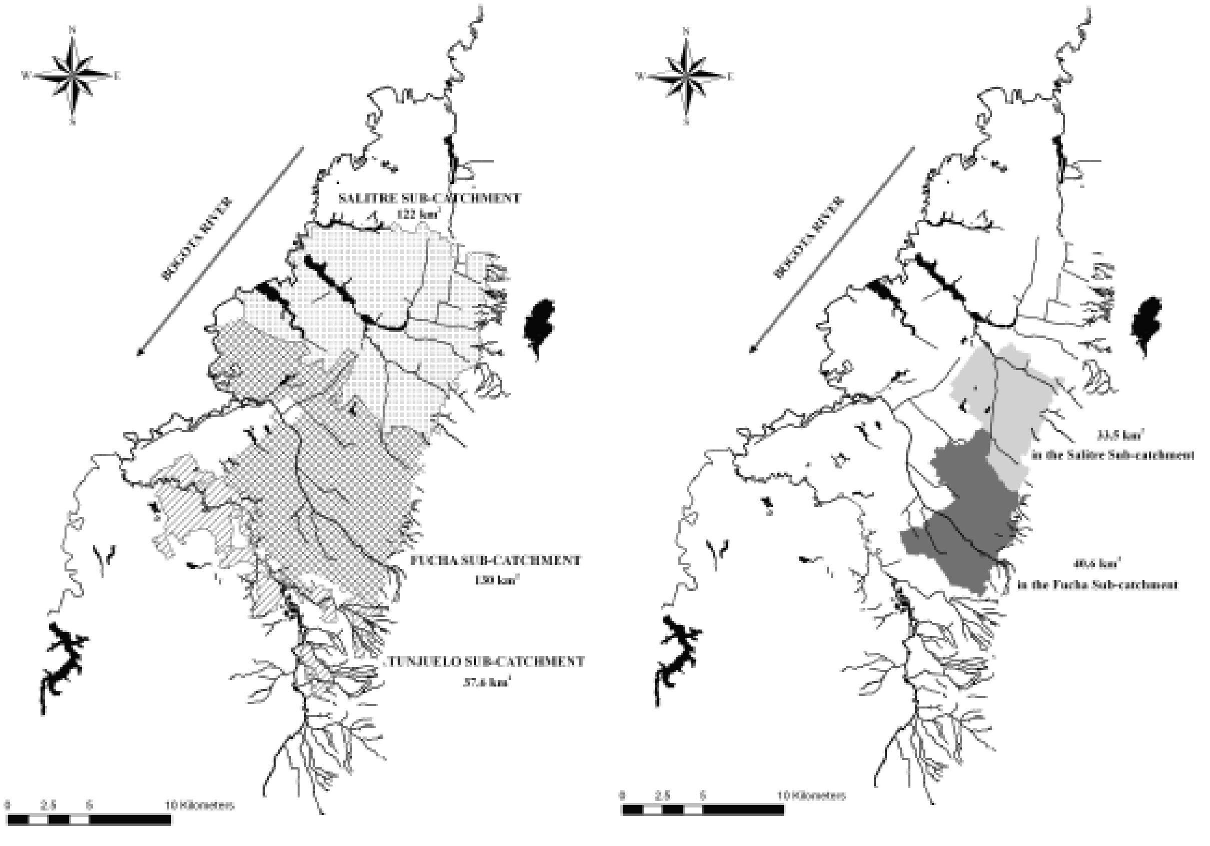

Figure 1 *(a) Main sewer system sub-catchments (b) Combined sewer system in Salitre and Fucha sub-catchments.*

storm drainage channels and there is a high risk of sewer flooding during intense rainfall events. Actually, the separate system acts better as a 'dual' combined system rather than as a separate one.

Díaz-Granados and Camacho (2003) presented the first attempt to quantify and analyse the wastewater quality (dissolved oxygen (DO), pH, conductivity, temperature, biological oxygen demand (BOD), biochemical oxygen demand (COD), nitrates, phosphates, dissolved solids (DS), suspended solids (SS) and total solids (TS)) during dry and wet weather flows in the Bogotá sewer system, by means of a 0.93 km^2 pilot study conducted in a combined urban catchment named El Virrey (in the Salitre sub-catchment) (Figure 2a). High resolution (one minute) rainfall time series were collected between June 2000 and June 2001 (using three rain gauges with resolution of 0.1 mm). The dry atmospheric deposits were characterised using measurements over a period between June and November 2000. Wastewater dry weather flows and runoff produced during wet weather were monitored using three automatic ISCO samplers coupled with one ultrasonic level sensor and one multiparametric sonde (between August 2000–August 2001). Simplified SISO (single input – single output) and MISO (multiple input – single output) (Young *et al.*, 1996) rainfall runoff models (Figure 2b) and water quality models (ADZ – QUASAR, Lees *et al.*, 1998) (Figure 2c)) were implemented and calibrated. Additionally, two field campaigns (between April–July 2006 and February–August 2007 respectively) in the Salitre, Fucha and Tunjuelo sub-catchments were recently carried out to identify daily water quantity and quality patterns of dry weather flow using ISCO automatic samplers with level sensors and multiparametric sondes (Díaz-Granados *et al.*, 2008). Monitoring was conducted at 12 different sampling stations in the first campaign (see Figure 3a) and at 17 locations in the second one (Figure 3b) during a period of 24 hours. At each sampling point the following hydrological and water quality variables were monitored: DO, pH, temperature, water level and rainfall. A high sampling resolution (Dt) of between 1 and

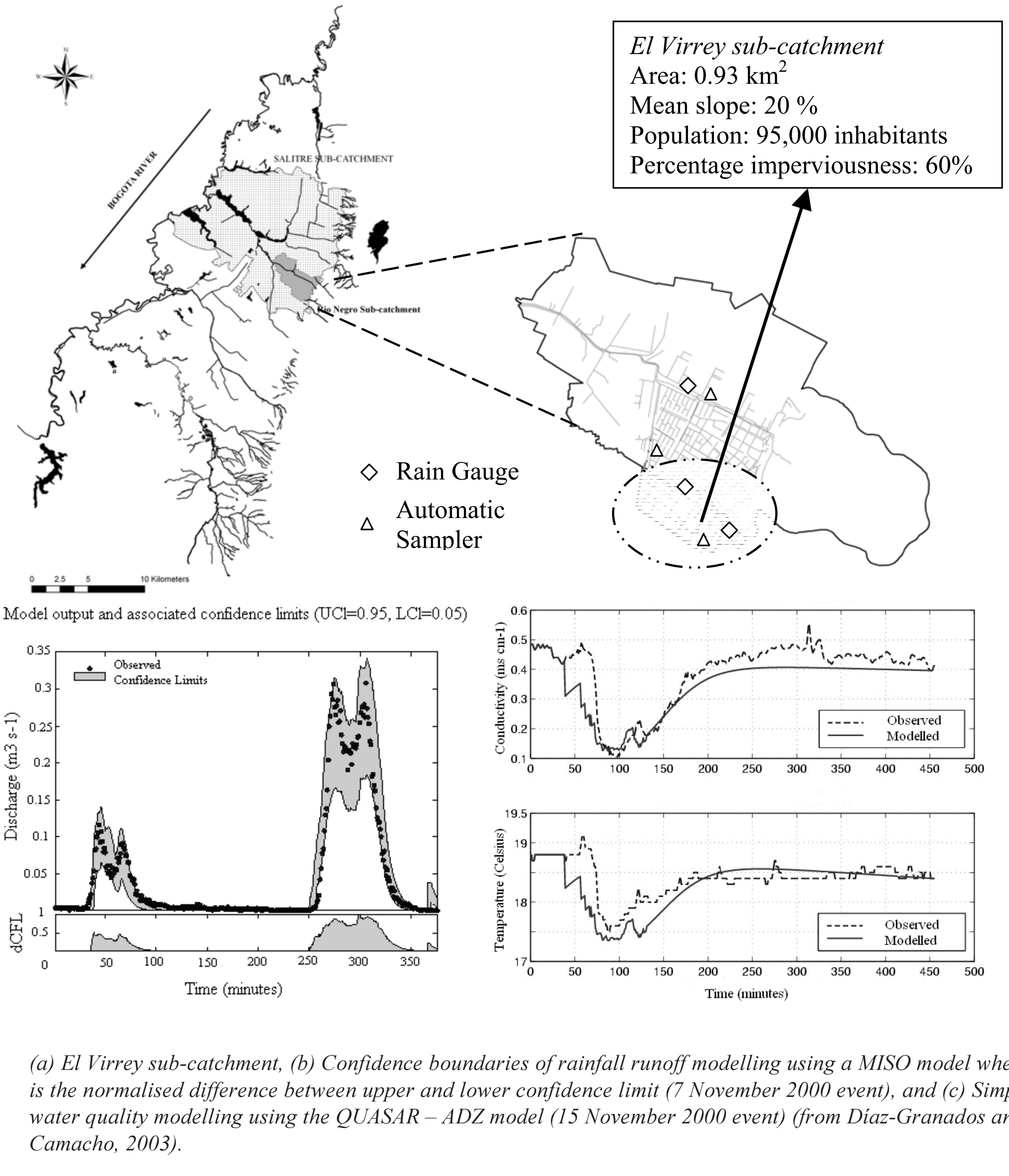

Figure 2 *(a) El Virrey sub-catchment, (b) Confidence boundaries of rainfall runoff modelling using a MISO model where dCFL is the normalised difference between upper and lower confidence limit (7 November 2000 event), and (c) Simplified water quality modelling using the QUASAR – ADZ model (15 November 2000 event) (from Díaz-Granados and Camacho, 2003).*

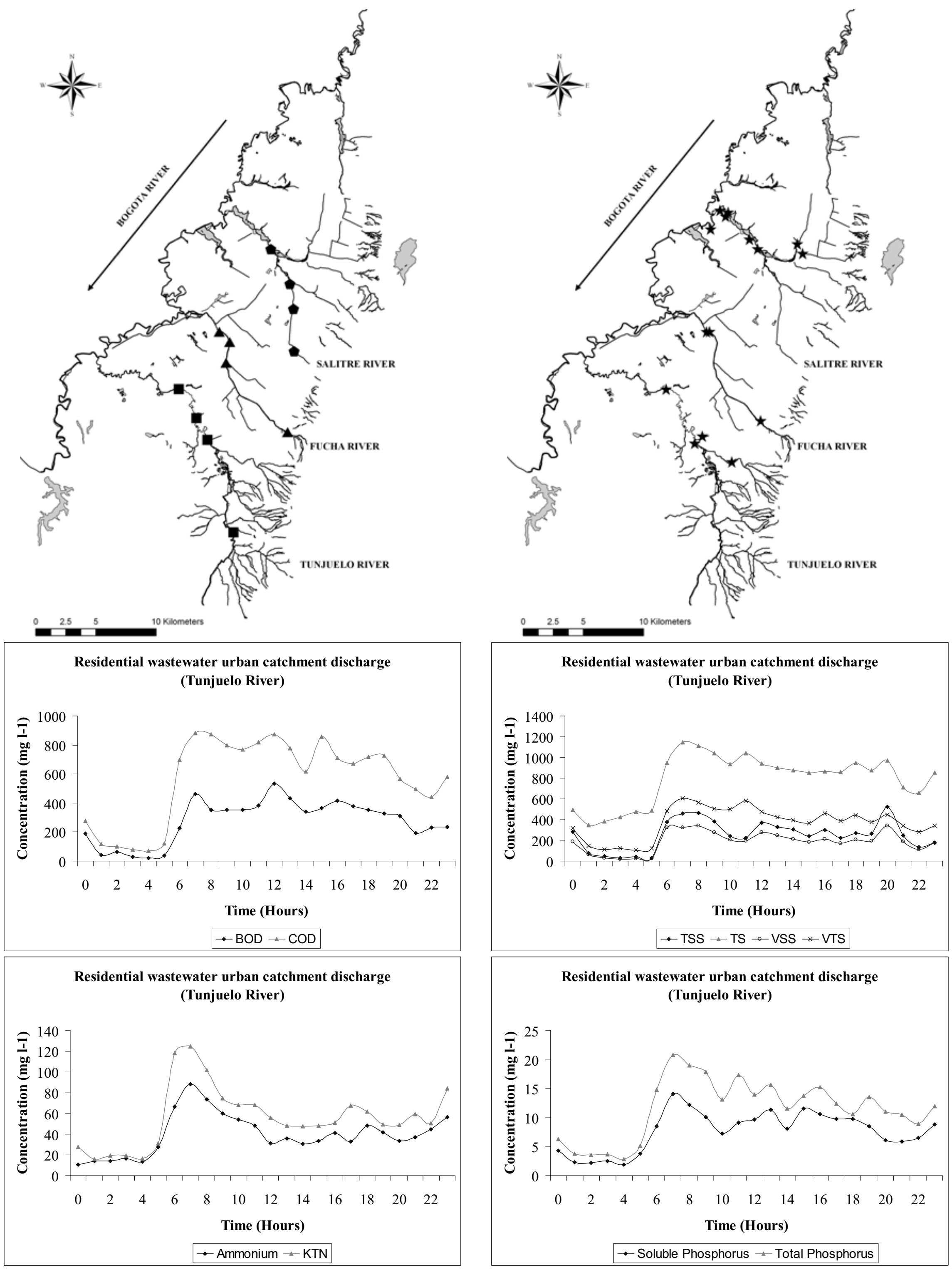

Figure 3 *(a) Sampling stations during the 1st field campaign, (b), Sampling stations during the 2nd field campaign and (c) to (f) Example of wastewater quality dry weather flow pattern (Wastewater discharge from "Barrio La Coruña" into The Tunjuelo River) (from Díaz-Granados et al., 2008).*

5 minutes was applied. In addition, hourly water samples were taken and analyzed in the laboratory for ammonium, total BOD and COD (soluble fraction was analyzed only in the second field campaign), total and soluble phosphorus, nitrates, nitrites, total suspended solids (TSS), volatile suspended solids (VSS), volatile total solids (VTS), TS, sulphates and sulphurs (Figure 3c–f). The sampling stations include: direct wastewater discharges, CSOs which actually act as permanent discharges into the rivers, some locations in open pluvial channels and in sub-catchment sewer systems.

The waste water treatment plant

In many European countries the wastewater infrastructure is nearly complete, in the sense that almost all the sewage is collected and treated to a certain extent. For example, sanitation provision period (emphasis on clean water supplies and safe sewage disposal) in the UK took place between 1850s and 1950s. After a pollution control stage, the UK is in the sustainable development phase (Harris, 2008). In contrast, Bogotá city only has one wastewater treatment plant (WWTP) in operation (in the Salitre sub-catchment). The Salitre WWTP was built between 1997 and 2000. Currently, it has 4 $m^3 s^{-1}$ of treatment capacity (roughly 25% of the total amount of wastewater generated in Bogotá) using physical/chemical treatment. Local environmental standards demand at least a treatment performance of 40% regarding the organic load and 60% in the case of the sediment load. BOD *per capita* load is estimated as 53 g per day (WRc plc and Unión Temporal Saneamiento Río Bogotá, 2002). In 2007, the environmental authority and the sewer system managers agreed to upgrade the Salitre WWTP (increasing the capacity to 8 $m^3 s^{-1}$ and adding a secondary treatment) and the construction of a new WWTP which will treat the wastewater produced in the Fucha and Tunjuelo sub-catchments. A good understanding of the flow and water quality characteristics of the Bogotá urban drainage system is required for the design of these new installations.

There is evidence of backwater effects and low velocities in the wastewater interceptors which feed the Salitre WWTP. This leads to sedimentation problems and subsequent resuspension of contaminants during runoff events, and hence over-loading of the WWTP. However the extent and effect of low velocities on water quality dynamics, and the potential for solving the problem, are not clear. In an ongoing project at Los Andes University, this question is being addressed (Rodríguez *et al.*, 2008a). The relationships between COD and BOD, and COD and TSS at the outflow of the main interceptors have revealed some differences regarding the 'age' (see Nielsen *et al.* 1992) of the wastewater. These results are due to long retention periods in the sewer system and backwater effects in some interceptors. These findings reinforce the necessity of appropriate integrated modelling tools to fully understand the dynamic interaction between the sewer system, the WWTP and the receiving water courses.

The potential benefits of a coupled operation of the sewer system and the WWTP, guided by what is best for river water quality, are well recognized (Langeveld, 2004). Research results point to the importance of the dynamic interactions between sewer and WWTP to assess performance of the urban water system. The same remains true at the CSO-river and WWTP-river interfaces. Each integrated solution has to be tailor-made for the case study and depends on the volume or treatment capacities, the receiving water, the rain events, etc. (Solvi, 2006). A sensible way forward in developing countries (such as Colombia), which are initiating treatment infrastructure, is to start integrated analysis at an early stage.

The receiving watercourses

Lijklema *et al*. (1993) and House *et al*. (1993) presented comprehensive reviews of impacts on receiving water quality due to urban drainage systems, considering the physical, chemical and biological characteristics, processes in the receiving system and chemical characteristics of urban runoff. As a consequence of these impacts, direct discharge of urban dry weather wastewater flows into receiving waters is no longer generally acceptable (Vollertsen and Hvitved-Jacobsen, 2000). However, this type of pollution source is very common in the Bogota River catchment watercourses due to the absence of appropriate infrastructure. The fact that the self-purification capacity of the Bogotá River is very limited in the middle catchment (Bogotá city) due to low flow (low dilution capacity), the small longitudinal slope (0.006%, limiting reaeration processes), high altitude (2556 m a.s.l., see Figure 4a) and medium temperature decreasing the saturated dissolved oxygen concentration, make the situation worse (Camacho *et al.*, 2002).

Modelling the river water quality in Bogotá River offers the opportunity to simulate the effects of improvements to the urban wastewater drainage and treatment system, hence are valuable planning tools for evaluating and optimising different strategies. Since 2001,

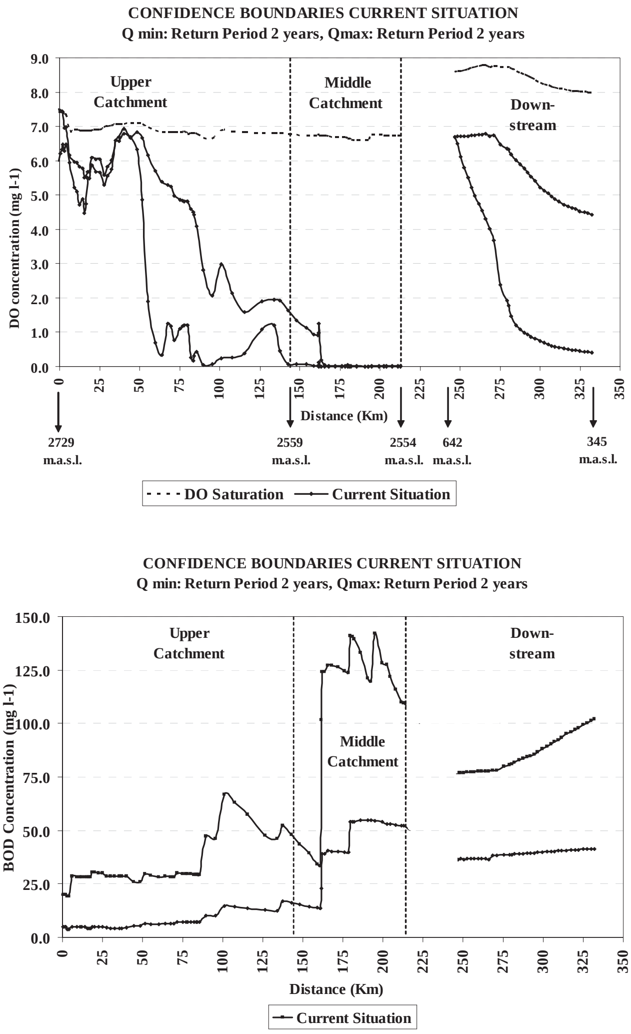

Figure 4 *Bogota River water quality modelling (from Camacho et al., 2002; Los Andes University, 2003) (a) DO and (b) BOD profiles.*

there have great efforts (through research cooperation between the water supply and sewer system managers and the Environmental Engineering Research Centre at Los Andes University) to implement water quality models in the receiving water courses: Bogotá River (Camacho *et al*., 2002; Camacho and Díaz-Granados, 2003) and Salitre, Fucha and Tunjuelo Rivers (Raciny *et al*., 2008). In both cases, the QUAL2K model (Chapra *et al*., 2007) was used.

Camacho and Díaz-Granados (2003) presented a river water quality modelling framework, building on the work of Rientjes and Boekelman (1998). This framework is a result of the Bogota River modelling activities and includes: (a) preliminary analysis of current and future water uses in the stream taking into account pollutant loads, (b) field visits and inspections to identify appropriate sampling stations and processes to be modelled, (c) model selection and implementation, (d) tracer experiments and hydraulic characterisations (useful for calibration of travel time, longitudinal dispersion and/or dispersive fraction, and transient storage parameters estimation), (d) field campaigns: design, planning and execution (it is proposed to sample the same water mass flowing from upstream to downstream sampling stations in order to identify reactive processes and to reduce parameter and data uncertainty), (e) observed data analysis, (f) model calibration based on appropriate objective methodologies, (g) uncertainty and sensitivity analysis and estimation of confidence limits (e.g. using the Generalized Likelihood Uncertainty Estimation methodology GLUE (Beven and Binley, 1992)), (h) model verification and (i) water quality simulations.

Figure 4 a and b present some results obtained in the Bogotá River modelling case using this framework. During a two-year research project, five field campaigns were carried out, covering different hydrological conditions. The results, including a stretch of 60 km under anaerobic conditions and BOD concentrations up to 140 mg l^{-1}, illustrate the main problem of the Bogotá River. Camacho *et al*. (2002) obtained modelling results that clearly demonstrate that a sanitation plan involving the construction of three secondary treatment waste water plants was not sufficient to recover the water quality of the Bogota River and to solve the public health problems caused by bacteriological contamination (mean Total Coliform concentration is around 1×10^8 MPN/100 ml). Bogotá city is not the only contributing source of pollutant load. In the upstream reach, the Bogotá River receives direct wastewater discharges from other urban settlements and diffuse loads from agricultural activities.

Due to the presence of a natural fall in the Bogotá River (Tequendama's fall), a small reach between the middle catchment and the down-stream reach was not monitored during the field campaigns (Figure 4a). DO after Tequendama's fall is near saturation, around 6 and 7 mg l^{-1}, as a consequence of the natural reaeration process (the altitude decreased by approximately 1900 m over a very short river stretch, see Figure 4a). Water from the Bogotá River is pumped into the Muña Reservoir at the

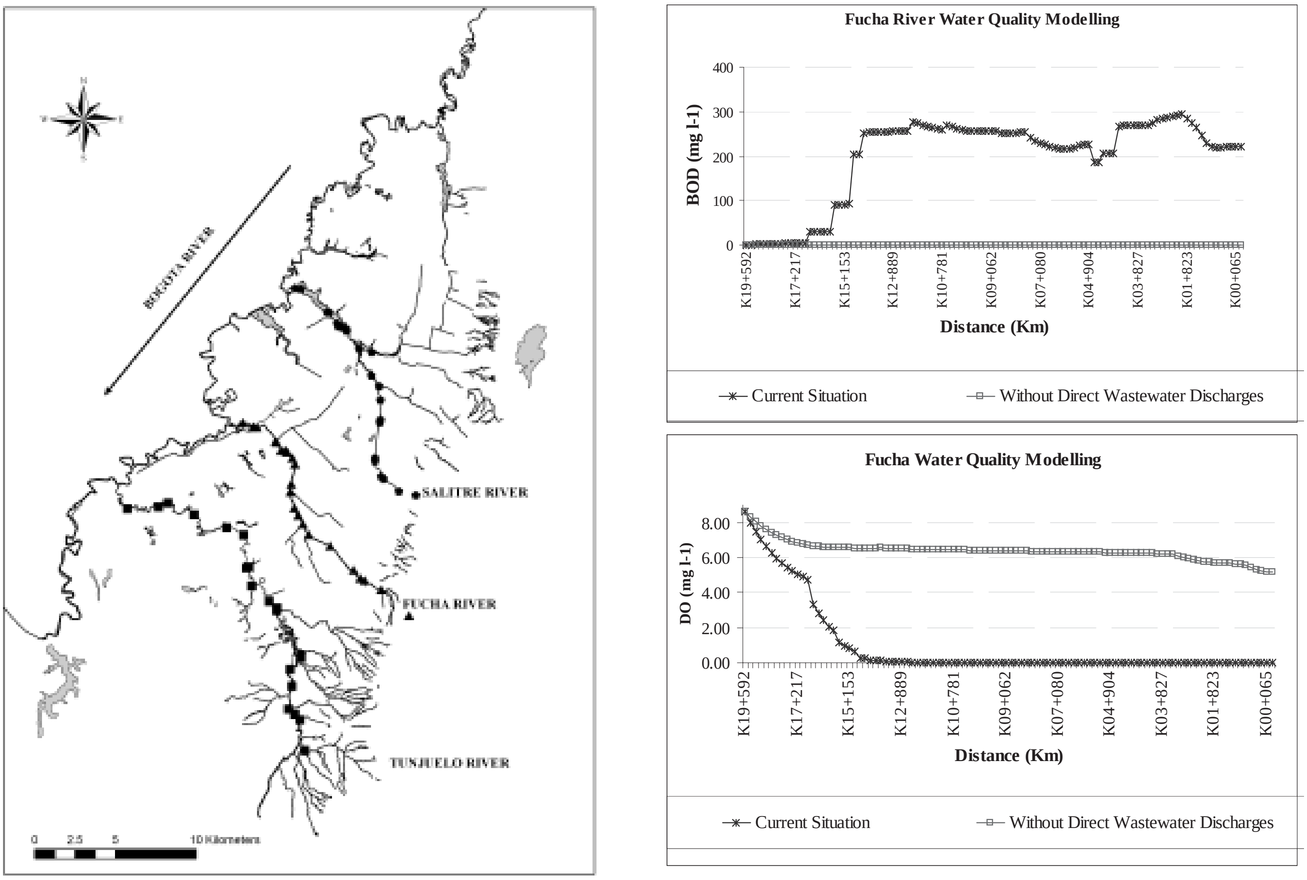

Figure 5 *(a) Sampling stations, (b) Fucha River BOD, and (c) Fucha River DO modelling (from Raciny et al. (2008))*

end of the middle catchment, at the site named Alicachín, and it is continuously used for hydropower generation by the Pagua's chain which takes advantage of the fall between the Bogotá Savannah and the low part of the river basin. The water from the old Casalaco's hydropower generation chain, which currently is operated a few times during the year, also feeds into the Bogotá River. Both processes of hydropower generation contribute to the increase of DO in the Bogotá River through the effect of the very high slope, the falls, and the action of the Pelton turbines (Los Andes University, 2005). DO in the down-stream reach of the Bogotá River decreases up to 0.5 mg l^{-1} as a consequence of nitrification and organic matter degradation (Camacho *et al*., 2002).

Based on two field campaigns covering dry weather flow, Raciny *et al.* (2008) implemented water quality models for the Salitre, Fucha and Tunjuelo rivers. Scenarios of no intervention (the current situation in Figure 5) and the construction of a new WWTP (provisionally named the Canoas WWTP, which will treat the waste water from the Fucha and Tunjuelo sub-catchments) plus the upgrade of the Salitre WWTP demonstrated the low assimilation capacity of the three streams due to the short travel times (which means anaerobic conditions, low oxidation rates of organic matter, and high concentrations of different pollutants) and the urgent necessity of construction of the new WWTP and interceptor sewers. Figure 5 presents the current situation in the Fucha River and the expected condition if direct wastewater discharges are intercepted and conducted to the Canoas WWTP.

Perspectives and conclusions

Historically in Bogotá, several efforts have focused on analyzing and improving the sewer system performance as a separated system without taking into account the treatment facilities and the receiving streams, and mostly regarding only the quantity component (avoiding the water quality issue). However, water resources practice in Bogotá is now shifting from the 'separate' into an 'integrated' approach (as was proposed by Camacho *et al*., 2002). A consensus between the sewer manager, consultants and research groups is emerging, towards planning and implementing strategies to improve the sanitation situation, taking into account technological, environmental and socio-economic considerations. As part of this, Bogota city needs the development and application of modelling tools at different levels of detail, considering overall urban water fluxes and various treatment schemes, including their economic aspects.

Research results have shown that there is a need to consider the three sub-systems (the sewer, the WWTP and the river) as one entity when considering pollution control objectives. In this way, the dynamic and complex interactions between the individual sub-systems and the impact of the whole system on the river water quality can be investigated (Lau *et al.*, 2002). With this approach as a background, EAAB (the sewer system manager) work is focusing on: (a) construction of wastewater interceptors, (b) design and implementation of the waste water treatment scheme (treatment capacity and technology), (c) implementation of a water quality monitoring network in the receiving watercourses (operated with cooperation between the water supply and sewerage managers and the local environmental authority), and (d) installation of a water quality monitoring network in the sewer system (to increase the understanding of the system and as a database to support further modelling efforts). In addition, in an ongoing project at Los Andes University (Rodríguez *et al*., 2008b) work is focusing on the implementation of an integrated model for Bogotá's urban drainage system, using the City Drain model (Achleitner *et al*., 2007) and under the framework proposed by Solvi (2006) (see Figure 6). This project is also aiming to develop homemade water quality sondes (pH, temperature, and conductivity) for sewer systems in order to provide feasible and reliable instrumentation for a preliminary water quality network in the sewer system (Caicedo *et al*., 2008).

This paper has provided an introduction to current and future research and development for an integrated approach to urban drainage system management in Bogotá. Facts such as the urbanisation processes (annual growth rate of 1.4%), severe water quality problems in the watercourses, lack of treatment facilities infrastructure, and a traditional separated waste water management approach, pose particular challenges. There is expected to be considerable investment in the Bogotá urban drainage system in the near to medium term. Now is the time to develop plans for an efficient integrated system which maximises the benefits from the resources available. The relatively undeveloped state of the current Bogotá system provides an excellent opportunity for integrated planning and development. Current work by the waste water system manager, the environmental authority, consultant firms,

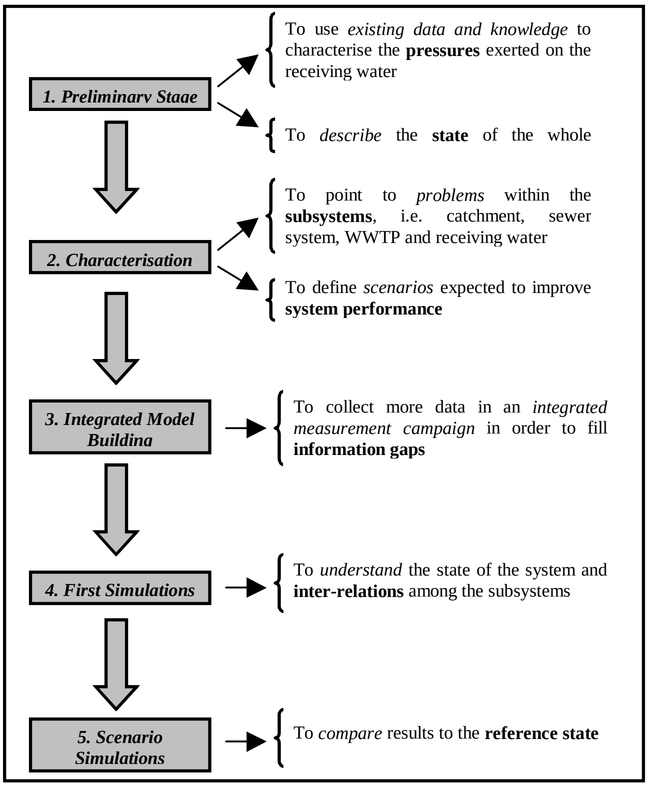

Figure 6 *Integrated modelling framework proposed by Solvi (2006)*

Los Andes University and Imperial College London, including monitoring and modelling programmes, is working towards this goal.

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