Towards a Paradigm Shift in Urban Drainage Management and Modelling in Developing Countries

Hacia un cambio en el paradigma del manejo y modelación de sistemas de drenaje urbano en países en desarrollo

Recibido 2 de octubre de 2009, modificado 21 de enero de 2010, aprobado 22 de enero de 2010.

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PALABRAS CLAVES

Bogotá, herramienta CITY DRAIN, manejo y modelación integrada, sistemas de drenaje urbano.

RESUMEN

En países en vía de desarrollo, la falta de infraestructura de saneamiento básico y el número creciente de habitantes en sus centros urbanos han venido aumentando las demandas sobre los recursos hídricos disponibles. En el contexto de Bogotá (Colombia), este artículo emplea un marco de modelación integrada y presenta una revisión de estudios que han buscado una mejora en el manejo de los sistemas de drenaje urbano. Es sabido que hay una necesidad de evaluar estos sistemas como una única entidad cuando se busca propender por el control de la contaminación, su manejo y operación óptima. Esta visión holística ofrece la oportunidad de estudiar las interacciones entre los sub-sistemas y el impacto de la totalidad del sistema en la calidad del agua de los cuerpos receptores.

KEY WORDS

Bogotá, CITY DRAIN toolbox, integrated management and modelling, urban drainage systems.

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 an overview of earlier, recent and ongoing research towards improved management of urban drainage systems using an integrated modelling framework. Research results have shown that there is a need to assess the urban drainage system as one entity, when considering pollution control objectives, and optimum management and operation. This holistic approach offers an opportunity to investigate the interactions among sub-systems and the impact of the whole system on the river water quality.

INTRODUCTION

Urbanization in developing countries is increasing the risk of considerable impacts 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 receiving water systems [1, 2]. Some of the effects of these processes can be summarized as follows: changes in runoff ratios, changes in impermeable areas, increased runoff peak and overland runoff volume, reduced time to peak, reduced water retention capacity, decreased evapotranspiration, and change in the water infiltration into the soil [3, 4, 5, 6]. Even though this summary of effects is mainly related to water quantity, impacts on water quality within all environmental compartments, such as surface waters, wetlands, soil, groundwater and biota, cannot be avoided [7]. Predicting these impacts at a river basin scale and finding optimal mitigation measures, considering conflicting demands by various users on water services, are challenging goals for modern urban planning and engineering in both developing and developed countries [7, 8, 9, 10].

Under a holistic framework, the water supply, wastewater, stormwater and groundwater systems are viewed as components of an integrated physical system which collectively provides water supply, wastewater sanitation, flood protection, surface and ground water management, and ecosystem maintenance and protection [11]. However, such facts as unplanned and unregulated urban developments, severe water quality problems in 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 approach pose particular challenges in developing countries [4, 9, 12]. Unfortunately in such conditions, the less affluent segments of the society tend to be the most vulnerable due to the weak regulatory capacity of authorities and the ineffective solutions often applied [4, 13].

WHY TO SHIFT THE PARADIGM?

Urban wastewater systems consist principally of the sewer system (including combined sewer overflow (CSO) structures, pumping stations, stormwater channels, etc.), the wastewater treatment plant (WWTP), and the receiving system (normally rivers). Up to now most sewer systems and WWTPs were designed, operated, and improved as separate entities as a consequence of the difference in their main functions. However, research results point to the importance of the dynamic interactions between sewers and WWTP and the need to assess performance of the whole urban water system [14]. The same remains true at the CSO/river and WWTP/river interfaces, in which each receiving water body exerts its own properties and must therefore be evaluated under a holistic framework with respect to the discharges from the urban catchment [15]. Each integrated solution increasing the urban water system performance has to be based on local conditions in individual case studies, such as the volume or treatment capacities, the receiving waters, and the rainfall events.

As a part of this analysis, 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, because they can be used to apply the best available scientific knowledge to predict responses to changing controls, as stated by [16] regarding basin management plans. The idea of an integrated urban drainage modelling is not new. Beck [17] discussed a “water quality system” which involves the water distribution network, the sewer system, the treatment plant and the river. Currently, it is widely accepted (in scientific discussions) that an integrated assessment of the discharges from the sewer system and WWTP is necessary when attempting to reduce the total impact of the urban drainage system on the receiving water body. A paradigm shift in the definition of performance indicators for urban wastewater systems has occurred in recent years in developed countries [18, 19, 20, 21, 22]. The main aim is to quantify the efficiency of different measures in reducing the amount of pollutants discharged into receiving water bodies and minimise the consequent negative impacts on water quality.

Detailed integrated studies of the sewer network – WWTP – receiving water system are relatively rare due to high cost and high complexity of the entire urban drainage system that prevents a simple connection of the existing detailed deterministic models of the individual subsystems [23] and practical applications of the holistic approach are still limited. However, progress has been made in developing integrated modelling tools, allowing for application at a full catchment-scale [24, 25]. Furthermore, in order to increase the application of such a holistic approach, the Central European Simulation Research Group (HSGSim) prepared a guideline document proposing a seven-step procedure for integrated modelling [22]. Such guideline covers the aspects of system analysis, identification of relevant system, processes and evaluation criteria, model setup and analysis, calibration and validation, scenario analysis and documentation. From this guideline it is clear that it is not only important to identify possible causes of negative impacts and/or to determine the potential of the system to be optimised, but it is also possible to identify the relevant state variables and significant processes [26, 27, 28, 29]. In the case of Bogotá it is also relevant to include the interactions between rural and urban sub-catchments, the storage and attenuation effect of reservoirs and natural wetlands (there are 13 natural wetlands in Bogotá which totalled approximately 555 Ha), and the presence of cross-connections in the separate sewer system. In order to include all these relevant aspects, interactions and components, 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. The type of simulation required principally depends on the objectives of the modelling [30, 31, 32]. The degree of detail in the different elements must depend on the available data and the available knowledge of the processes which have to be modelled.

There are a variety of modelling approaches to describe water motion as well as the transport and conversion of matter. Most of the integrated modelling tools use conceptual models instead of complex approaches due to computational demand issues, as stated by [33]. The application of complex models, models with physically based descriptions in which parameters have a clear physical meaning representing a specific characteristic of the simulated system, appears to be limited by the lack of adequate data [34, 35, 36]. Using complex models the calculation time start to be a limitation and the calibration becomes difficult [37]. As a consequence some authors have suggested to avoid unnecessary complexity in modelling approaches [38, 39]. For example, Carstensen et al. [40] presented a comparison between three different methodologies (with different level of complexity) which provide predictions of the hydraulic load to the WWTP. They concluded that simple models perform better than the complex models. Schuetze and Alex [41] concluded that the combination of sub-models with different complexities through a modular building structure can facilitate integrated modelling. Freni et al. [42] stated that when data availability is scarce, the use of complex physically oriented models can be unnecessary. In addition, they suggested that an integrated tool can use more complex approaches for downstream (river system) and less detailed approaches upstream (sewer system) without loosing model predictability and robustness.

There are two different conceptual approaches to integrated modelling: sequential and parallel. Compared with sequential modelling, parallel modelling offers major advantages when a feedback is necessary (e.g., for real time control – RTC – applications). This is possible because all the components of the urban drainage system are simulated simultaneously [43]. For example with a parallel simulation, the current and predicted states of the river water can be used to determine the control actions in the sewer system, whereas in sequential simulation this is not possible, since the water quality is only calculated after the simulation of the other system is completed [44]. Another classification distinguishes between offline and online modelling [32]: offline modelling is used for the design and the development of control strategies and online modelling is applied for online evaluation and prediction for choosing operation and control options.

BOGOTÁ'S URBAN DRAINAGE INTEGRATED MODEL

Historically in Bogotá, efforts have focused on analyzing and improving the performance of individual components of the urban water cycle, without taking into account the interactions among them. Nevertheless, effective planning and operation demand a shift from the "*fragmented*" approach into an "*integrated*" one as proposed by [45, 46, 47, 48, 49, 50]. With this approach as a background, work at different universities, management institutions, environmental agencies, and consultancy firms, including monitoring and modelling programmes, is conducted towards the development of an integrated management framework for Bogotá's urban drainage system.

Achleitner et al. [51] developed an open source toolbox based on the European Water Framework Directive (WFD) requirements. This model - named CITY DRAIN - has been realized within Matlab/Simulink and is being used, customized and implemented for Bogotá city. A pilot application in the context of Bogotá can be found in [52], where the CITY DRAIN toolbox was coupled with fuzzy logic techniques in order to assess CSO performance. The fuzzy logic module was applied to the sub-catchment "El Virrey", where nine CSO structures were dynamically assessed regarding spills flow and BOD concentrations. 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 spills and receiving bodies' water quality impact) which collectively are ranked between 0 and 10 according to the fuzzy logic rules in each of the calculation time steps. It was concluded that such an evaluation should be based not only on typological characteristics of the sub-catchment but also on operative parameters, upstream CSO structures performance, dynamic water quality state and impact on the receiving watercourse.

Figure 1 gives a summary of the main research projects at the Universidad de los Andes and Universidad Nacional de Colombia which are contributing with supporting data, complementary tools or associated regulatory framework to the Bogotá's City Drain model set-up. Most of these efforts are briefly described below.

Components represented in the integrated model

A schematic description of Bogotá's urban drainage, including its components and interactions, was performed using a GIS platform. It was used to define spatial units (or sub-catchments) for sewer management and operational purposes (called UGA from its Spanish name – Unidad de Gestión de Alcantarillado). The full model includes 469 UGAs (89 rural, 106 combined sewer and 274 separate sewer sub-catchments). Table 1 presents main properties of Bogotá's UGAs such as area, slope, hydraulic length, mean DWF and water use distribution. For example, from this table it is possible to identify that 90% of the total number of the UGAs cause less than 9% of the industrial water use. Complementary to the UGAs, the integrated model includes other components such as: 6 reservoirs, 11 natural wetlands, 13 pumping stations, 82 CSO structures, 4 urban rivers and 1 WWTP.

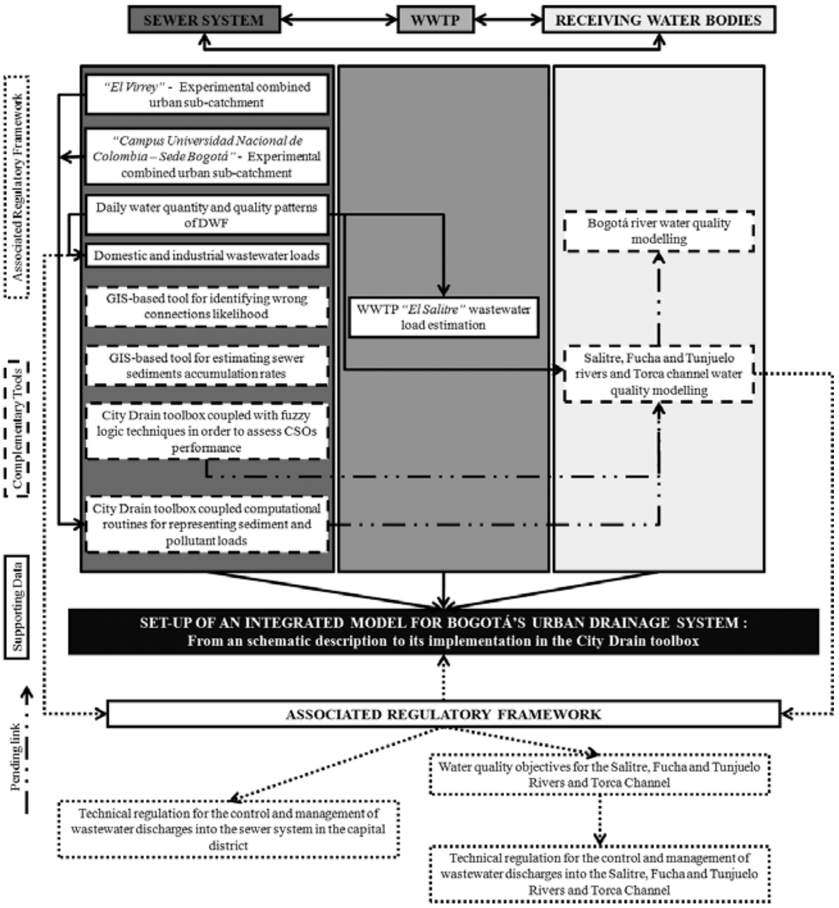

Figure 1. Supporting data, complementary tools and associated regulatory framework for integrated modelling of Bogotá's urban drainage system.

Percentile	Area (Ha)	Slope (m/m)	Hydraulic length (m)	Mean DWF (m3/s)	Use (%)		
					Residential	Industrial	Comercial
10	25	0,010	835	0,006	41,66	0,00	1,01
20	42	0,011	1051	0,011	57,80	0,08	1,77
30	53	0,012	1211	0,015	68,99	0,24	2,78
40	64	0,014	1341	0,020	76,53	0,57	3,79
50	75	0,015	1449	0,024	81,00	1,01	5,60
60	86	0,017	1613	0,027	85,29	1,75	7,49
70	102	0,027	1728	0,031	88,61	2,66	11,11
80	121	0,067	1930	0,037	91,42	4,36	16,43
90	147	0,119	2193	0,046	94,05	8,85	27,86
100	243	0,249	3486	0,092	98,95	69,81	60,57

Table 1. Main properties of Bogotá's UGAs

INCREASING UNDERSTANDING OF WASTEWATER FLOW AND WATER QUALITY DYNAMICS

The first attempt to quantify and analyse the wastewater quality during dry and wet weather flows in the Bogotá sewer system was conducted by means of a pilot study in a combined urban drainage area named El Virrey, located in the Salitre sub-catchment [53, 54, 55]. More recently, two field campaigns (between April - July 2006, and February - August 2007, respectively) in the main sub-catchments were carried out in order to identify daily water quantity and quality patterns of dry weather flow (DWF). Monitoring was conducted at twelve different sampling stations in the first campaign and at seventeen locations in the second one during a period of 24 hours. The flows sampled included: direct wastewater discharges into the urban rivers, CSOs which actually act as permanent discharges, and some locations in open storm water channels and in sub-catchment sewer systems were also sampled. At each sampling point the following hydrological and water quality variables were monitored: dissolved oxygen (DO), pH, temperature, water level and rainfall. A high sampling resolution (Δt) of between 1 and 5 minutes was applied. In addition, hourly water samples were taken and analyzed in the laboratory for ammonium, total biochemical oxygen demand (BOD) and chemical oxygen demand (COD) (soluble fraction was analyzed only in the 2nd field campaign), total and soluble phosphorus, nitrates, nitrites, total suspended solids (TSS), volatile suspended solids (VSS), volatile total solids (VTS), TS, sulphates and sulphurs. A detailed description of monitored sites and parameters, and the monitoring framework can be found in [56, 57, 58].

Based on the distribution of properties shown in Table 1, a new field campaign was designed and carried out between December 2008 and June 2009. A total of 80 sites were monitored and characterized over a period of 24 hours each. These sites include: 7 urban UGAs with combined sewer systems, 19 UGAs served by separate sewer system (7 of which are an aggregation of several unitary UGAs; these measurement sites are rather important as they will provide calibration and validation time series), 4 pumping stations, 7 stormwater channels in the combined sewer areas, 8 stormwater channels in the separate sewers areas, 9 CSOs and 10 rural UGAs. Water samples were taken and analyzed in the laboratory for the same parameters as the 2006 and 2007 field campaigns plus others such as fat oil and grease, coliform, E. coli, alkalinity, aluminium, cadmium, calcium, chloride, copper, chrome, iron, magnesium, mercury, nickel, silver, lead, potassium, sodium, and zinc. The ongoing work is processing newly acquired daily time series data on water quantity and quality, using several analytical techniques, such as: (a) Fourier series fitting and (b) multivariate regressions. Initial results from the multivariate regressions were already presented by [56], who clearly demonstrated the usefulness of such techniques for estimating water quality parameters based on the data obtained from multiparametric sondes. The main aim of these analyses is to define a set of stochastically-defined DWF patterns for each non-measured/monitored UGA and each state variable (wastewater flow, BOD, COD, TSS, etc.) based on their own well-known properties (land use, per use consumption distribution, area, slope, catchment lag or travel time, etc.).

TOOLS TO SUPPORT THE BOGOTÁ'S URBAN DRAINAGE INTEGRATED MODEL

CROSS-CONNECTIONS: A GIS-BASED TOOL FOR IDENTIFYING THEIR LIKELIHOOD

There are many cross-connections between the wastewater and stormwater systems in the Bogotá city. The separate sewer system acts more as a “dual” combined system rather than as a separate one. Mestra [59] presented a GIS-based computational tool serving to identify the likelihood of cross-connections in the Bogotá's separate sewer system, and specifically the cross-connections from the wastewater system into the stormwater system. Main factors which have a relevant effect on the presence of cross-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. 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 presence. 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, it was identified a total number of 19 misconnections. [59] concluded that the developed tool appropriately predicted this condition. The tool was also applied to the entire Salitre sub-catchment with an area of about 122 km2. It was possible to identify areas with high potentials for cross-connections on which field inspections should be focused. Results were used as input data in the CITY DRAIN toolbox coupled with data from on-site measurements. It is planned to extend the model to the entire city (including the Fucha and Tunjuelo sub-catchments) for assessing percentages of cross-connections in areas without any data from field inspections and measurement campaigns.

SEWER SEDIMENTS: THEIR PROPERTIES, A GIS-BASED TOOL FOR ESTIMATING ACCUMULATION RATES AND HOW TO MODEL IT

Sewer sediments are of major importance for wastewater quality processes in urban drainage systems because of the solids provide a transport matrix for different pollutants [60]. It has been observed that TSS is the main vector for many pollutants such as COD, hydrocarbon, heavy metals, micro-pollutants, etc [61, 62, 63]. 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 [64]. In Bogotá, an extensive sewer sediment characterisation program was carried out (including characterisation for pH, granulometry, density, viscosity, %TS – total solids, %VS – volatile solids, COD, benthic demand, TKN – total Kjeldahl nitrogen, amoniacal nitrogen, phosphorus, fat oil and grease, faecal coliform). Sampling stations included sewer pipes and manholes, gully pots and storm channels. They were selected based on experts' knowledge (by means of surveys), a customers' claims data base, and a GIS-based prioritizing matrix which includes such data as road type, land use, transport capacity, ageing of the system, network material, and population density. A total number of 2293 simple samples were characterized, including 2121 manholes, 460 gully pots (or catch basins) and 3 storm channels [65]. Additionally, a GIS-based tool named SIGTASED was developed for quantifying the amounts of sediments which are accumulated in the sewer system at the UGA scale. Main formulation used in the tool, based on regression analysis of field data surveyed from Cleveland (OH), is know as Cleveland simplest model [66] 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 water use rate (m^3) for estimating the accumulation rates.

Robust modelling of pollutants in urban drainage systems is crucial since an incorrect estimation can easily lead to an inadequate design and poor management of the system [67]. Pollution from urban drainage systems originates mainly from the erosion processes triggered by the runoff of particulate pollutants accumulated during dry weather periods on the catchment's surface and in the sewer network. During the last 30 years a number of sewer modelling tools, including sediment modules, have been developed such as: Mosqito [68], Flupol [69], Mousetrap [70], Hypocras [72], Stormnet [73], Simpol [74], Sewsim [34, 75, 76], Horus [77, 78], STSim [79], Remuli [80], and Cosmoss [81] among others. Despite the efforts that have been made to understand pollutant accumulation, erosion and transport dynamics, stormwater quality modelling still poses difficulties, and the generality and transferability of stormwater pollution models are still limited [82, 83]. In an ongoing research, the goal is to implement and test computational routines for representing sediment and pollutant loads which may be applicable to Bogotá's urban drainage and other urban drainage systems. The focus is on simple conceptual models for allowing long term simulations. Three different approaches regarding the accumulation processes and five for the wash-off phenomena were implemented in the CITY DRAIN toolbox. They were tested for their ability to calibrate to the suspended sediment transport conditions. Initial results indicate, when there is more than one peak during the rainfall event duration, wash-off processes probably can be better represented using a model based on the flow instead of the rainfall intensity. Additionally, it was observed that using more detailed models for representing pollutant accumulation do not necessarily lead to better results [84].

DETAILED WATER QUALITY MODELS FOR THE RECEIVING WATERS SYSTEM

The Bogotá River drains the Bogotá Savanna along a course of about 330 km until it joins the Magdalena River. The monthly mean discharge of the Bogotá River varies from 1 m^3/s at the upper catchment to 40 m3/s at the confluence with the Magdalena River, thus, it is a relatively small river. It receives the wastewater discharge from about 8.5 million inhabitants. The river crosses eleven small municipalities before reaching the City of Bogotá. Most of these municipalities have a wastewater treatment system, commonly a facultative lagoon. However, the constructed treatment systems do not perform as designed. While the Bogotá River flows from the Savanna to the Magdalena Valley, it crosses several other municipalities. Due to the heavily polluted condition of the Bogotá River, the supply of water to the municipalities located along its length is a problem of major concern. It is clear that there is a gap between the desired uses of the water along the river and the quality required to support such uses. The fact that the self-purification capacity of the Bogotá River is very limited in the middle catchment (the area influenced by Bogotá city) due to low flow, small longitudinal slope, high altitude and medium temperature, worsens the situation.

In general, direct discharge of urban dry weather wastewater flows into receiving waters is no longer acceptable. However, this type of pollution source is very common in the urban watercourses in Bogotá due to the absence of an appropriate water treatment infrastructure. Models of the water quality in the receiving system offer the opportunity to simulate the effects of improvements to the urban wastewater drainage and treatment systems; hence they are valuable planning tools for evaluating and optimising different strategies. Since 2001, great efforts have been carried out to implement water quality models for the Bogotá River [45, 85] and the Salitre, Fucha and Tunjuelo Rivers [86]. In all the cases, the QUAL2K model was used. More recent efforts were concentrated on the improvement of the hydraulic modelling of urban rivers, having as a consequence an overall improvement in model prediction capabilities.

Recently, three detailed hydraulic, solute transport and water quality measuring campaigns along the whole main branch of the Bogotá River (330 km) have been carried out by the Universidad Nacional in order to obtain the data required for calibrating a dynamic water quality model [87]. An extended version of the QUASAR water quality model [88, 89, 90, 91], operating in the SIMULINK/MATLAB environment, has been implemented and compared with the newly extended HEC-RAS vs.4.0 hydraulic and water quality model along the whole studied stretch [92].

The SIMULINK extended QUASAR model nicely reproduces the output of the latter model. Due to its flexibility and the advantages of an open source code, once calibrated using objective methodologies, this model could be easily extended and integrated with the CITY DRAIN toolbox to perform integrated modelling scenarios of Bogotá city impacts on the receiving waters.

ASSOCIATED REGULATORY FRAMEWORK

Environmental standards have a fundamental role in the protection of the water quality in water courses. In order to improve the water quality by restricting discharges into receiving watercourses, most efforts have historically focused on the sources of pollution. In recent years, changes in the planning for urban drainage have been occurring in developed countries [93, 94]. New ways of assessing the performance of urban drainage systems are based on "*stream standards*" and no longer based on a "*discharge standard*". These changes offer an integrated vision of the urban drainage systems that serves as a basis in some environmental regulations such as the Water Framework Directive (WFD) in the European Union, and the Urban Pollution Management (UPM) in the United Kingdom. There are other similar standards for the WFD in some developed countries, such as the Environmental Protection Agency's Water Quality Criteria and Standards Plan in the United States, the National Water Quality Management Strategy in Australia and the Environmental Quality Standard for Surface Water in China. Research efforts at Universidad de los Andes in cooperation with the District Secretary of the Environment (SDA) have contributed to the generation of technical regulations under the stream standards concept as described below.

DOMESTIC AND INDUSTRIAL WASTEWATER LOADS

Based on the described measurements from field campaigns in the sewer system sub-catchments, domestic pollutant loads were estimated for Bogotá city. Besides this, the SDA carried out a detailed monitoring program between 2003 and 2007 in order to assess industrial wastewater loads. Nearly 600 industries were monitored including 148 related to the food industry, 107 in the leather industry, 109 related to oil and gasoline stations, 11 in the printing industry, 52 in the metal manufacturing industry, 58 in the chemical industry, 55 in the textile industry and 43 in the service and health industry. Using these data sets, it was concluded that the industrial contribution for BOD5, COD, TSS, Sulphates and Sulphurs total loads into the drainage system were 9.27%, 10.21%, 2.81%, 0.37% and 2.17%, respectively. These analyses were used as a basis for generating a technical regulation for the control and management of wastewater discharges into the sewer system in the capital district [95].

SETTING WATER QUALITY OBJECTIVES FOR THE RECEIVING WATERCOURSES

Based on the data available from the water quality monitoring network in the urban receiving watercourses in Bogotá, the Canadian Council of Ministers of the Environment Water Quality Index (CCME WQI) was estimated for each of the main urban rivers, which drain the city. The CCME WQI is a tool for simplifying the reporting of water quality data and gives a broad overview of the environmental performance [96]. In the Bogotá case, The CCME WQI clearly demonstrates that the water quality in the receiving watercourses is frequently threatened or impaired and conditions often depart from natural or desirable levels. In order to improve water quality conditions in Bogotá's urban rivers, 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 were divided [97]. Four different temporal stages were established as follows: 4, 10, 20 and 40 years. These objectives were defined using (a) monitoring records from the water quality monitoring network in the urban receiving water courses to assess the current state and (b) modelling results using the QUAL2K software for prospective scenarios [86]. Complementary to the WQO, a technical regulation was derived for the control and management of wastewater discharges into the Salitre, Fucha and Tunjuelo Rivers and Torca Channel [98].

CONCLUSIONS

This paper has presented the development of an integrated modelling approach for the Bogotá's urban drainage system (model set-up). This includes an overview of the older, recent and ongoing research towards improved management of urban drainage systems using an integrated framework. Relevant data, modelling tools and associated environmental regulations which are being used as inputs, complements or regulatory frameworks for the integrated model, were briefly presented.

A need of an integrated model for the Bogotá´s urban drainage system was described. Integrated modelling is needed to understand and predict the behaviour and performance of the integrated system in order to assess the effects of environmental pressures exerted within the catchment, to establish reference conditions, design monitoring programs, perform operational planning, and as an instrument for cost-effective implementation of measures and the assessment of impacts, in order to produce management plans and a decision-making framework.

A considerable investment is expected in the Bogotá urban drainage system in the near to medium term. Now is the time to develop plans towards an efficient integrated system which maximises the benefits from the resources available. Besides to the research efforts that have been presented in this paper and complementary work at other universities, management institutions, environmental agencies, and consultancy firms, Bogotá city still needs the development and implementation of continuous measurement programs for management purposes and for reliable feeding 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.

Detailed integrated studies of the sewer network –WWTP– receiving water system are comparatively rare and practical applications of the holistic approach are still limited. Based on this, we can conclude that the scheme used for setting-up a model in this case study can be useful and applicable in other urban centres of similar size (population, area, etc.) and facing lack of supporting data for a full implementation. A sensible way forward in developing countries, which are initiating to build the treatment infrastructure, is to start integrated analysis and more efficient planning control measurements at an early stage. It is not feasible to build costly WWTPs which are not properly integrated with the sewer system and which are not solving the river pollution problems.

Further efforts have to be focused on calibration/validation procedures, uncertainty analysis, and definition of modelling scenarios (during dry and wet weather). The final aim of this model is to be used as an on-line tool for contributing towards optimum management and operation. It is expected in the near future that a water quality monitoring network in the sewer system will be implemented and will feed data to the integrated model. Additionally, modelling work is also planned to increase the understanding of the comparative performance of different types of sewer systems (combined and separate). Obtained results could improve the knowledge how to manage and/or operate, and how to prioritize investments in individual parts of the urban drainage system with cross-connections. Performing a model-based evaluation of structural best management practices (BMPs) in the stormwater system of Bogotá, where they are implemented, is also identified as a relevant topic.

ACKNOWLEDGMENTS

We thank the two anonymous reviewers for their valuable feedback and constructive comments that helped improve the paper.

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Archivo, Grupo de Estudios en Sostenibilidad Urbana y Regional (SUR). Departamento de Ingeniería Civil y Ambiental. Universidad de los Andes.