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**DYNAMIC CONDITION APPROACH TO STUDY THE SELF-
PURIFICATION CAPACITY OF COLOMBIAN WATER BODIES
CASE: CAUCA RIVER AND SALVAJINA DAM**

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The impact on water resources caused by municipal wastewater discharge has become a critical and ever-growing environmental and public health problem. In order to be able to efficiently address this problem, it is important to adopt an integrated approach that includes a decrease in and control of contamination at its source. These principles have been successfully applied in the industrial sector and now these concepts are also being applied to integrated water resources management. In this context the conceptual model of the Three Steps Strategic Approach (3-SSA) was developed, consisting of: 1) minimization and prevention, 2) treatment for reuse and 3) stimulated natural self-purification. This paper is focused on the third step. The study area is the Upper Cauca river basin, which extends from the Salvajina dam to the Anacaro station (416.5 km). MIKE 11 model is used to analyze the behavior of the hydraulics (flow, velocity, depth) and quality parameters (temperature, DO, BOD) of the river. Different scenarios were modeled taking into account that the reservoir is also used for power generation and flood control. Additionally, two dynamic events associated with an eventual wastewater treatment plant (WWTP-C) failure and the water quality impact into the Cauca river due to a rainfall event (first flush effect) in the urban drainage system of Cali city have been explored. The results show also the potential of considering Step 3 of 3-SSA in the planning of investments aimed at restoring the water quality of the Cauca river for different uses.

INTRODUCTION

In order to be able to efficiently address the problem caused by municipal wastewater discharge, it is important to adopt an integrated approach that includes a decrease and control of contamination at its source. In this context, the conceptual model of the Three Steps Strategic Approach (3-SSA) was developed, consisting of: 1) minimization and prevention, 2) treatment for reuse and 3) stimulated natural self-purification (Gijzen [2]). When a river is polluted, the water quality deteriorates, limiting water use and ecosystem functions, as only a few species are able to survive in the presence of chemicals, nutrients, salinity and other anthropogenic pollutants (González *et al.* [3]). However, the self-purification capacity of a river allows it to restore (partially or fully) its quality through the recreation and natural processes of degradation (von Sperling [18]; Salazar [11]; Hynes [4]). The mechanisms of self-purification can be in the form of dilution of polluted water with an influx of surface and groundwater or through certain

complex hydrologic, biologic and chemical processes (Vagnetti *et al.* [17]; Ostroumov [8]; Ifabiyi [6]).

The research and application of river control technology began with the United States and some European countries in the 1950s. River eco-restoration became an important international issue after the 1980s. Other parts of the world entered the stage of comprehensive river control and eco-restoration in the late 1990s (Wang *et al.* [19]). The beginning of the 21st century, some elements of the function theory of aquatic ecosystems was developed. However, the role of aquatic biota in the control of water quality still needs to be covered by a scientific analysis, and an enormous amount of relevant data needs to be organized (Ostroumov [9]). The self-purification capacity of a water body can be artificially stimulated. A generated wetland surface area will contribute in terms of self-purification of the water body. Other options include the construction of small dams to cause rapids and turbulence in streams for improving aeration of the river water. Another possibility is the introduction or stimulation of controlled algal development to stimulate oxygenation (UNESCO-IHE *et al.* [13]). In addition, building large multipurpose dams has as one of its objectives the improvement of the self-purification capacity of the water body. Here the objectives of flood control, improved water quality and power generation are shared. However, the dams may also adversely affect water quality and the self-purification capacity of the water body (Wei *et al.* [20]).

The DO concentration is a primary measure of a stream's health; it responds to the biochemical oxygen demand (BOD) load (Khan and Singh [7]). This is why oxygen demand (OD) has been traditionally used to assess the pollution degree and self-purification of a water body. Its measurement is simple; however the complex mechanisms involved in OD must be studied by mathematical modeling (von Sperling [18]). The first models were developed by Streeter and Phelps in 1925. They developed a balance between the dissolved oxygen supply rate from reaeration and the dissolved oxygen consumption rate from stabilization of an organic waste in which the biochemical oxygen demand (BOD) deoxygenation rate was expressed as an empirical first order reaction, producing the classic dissolved oxygen sag (DO) model. Temporal variability defines two categories of model: the steady state, when the variables describing the system are considered constant over time and dynamic models, using variable values. Selection of a model will depend on the study objectives, specific characteristics of the study site and the availability of information (IDEAM [5]).

This article considers the use of dynamic modeling in order to investigate the impact of the Salvajina reservoir in the water quality and self-purification capacity in La Balsa - Anacaro reach (416.5 km). The Salvajina reservoir began operation in 1985 and an earlier prospective study had showed potential positive impacts on water quality and self-purification capacity of the Cauca river for steady flow condition analysis (Galvis [1]). However, in recent decades the water quality of the Cauca river has deteriorated significantly. This deterioration can be explained by the pollution load increase (domestic and industrial) generated in the basin, the limited effectiveness of wastewater treatment plants and limited benefit of the Salvajina reservoir to improve the water quality of the Cauca river. Using the MIKE 11 model made it possible to show the impacts on quality of the operation of the reservoir at downstream stations (quantity and quality). The results show the potential of considering Step 3 of 3-SSA in the planning of investments aimed at restoring the water quality of the Cauca river for different uses.

METHODS

Study area

The Cauca river is the second most important fluvial artery of Colombia and the main hydric source of the Colombian southwest. It has a longitude of 1,350 km with a basin of 63,300 km². The study area is the Upper Cauca river basin (Figure 1). This stretch of the river has an average width of 105 m. The depth can vary between 3.5 and 8.0 m. The longitudinal profile of the river shows a concave shape with a hydraulic slope, which oscillates between 7×10^{-4} m/m and 1.5×10^{-4} m/m (Ramírez et al. [10]). The sugar cane crops and the Colombian sugar industry are located in the flat area along the Upper Cauca river basin. In the mountain area there are coffee crops and industry associated with this type of crop. In this basin there are also other farming developments, and mining and manufacturing industries.



Figure 1. Upper Cauca river basin

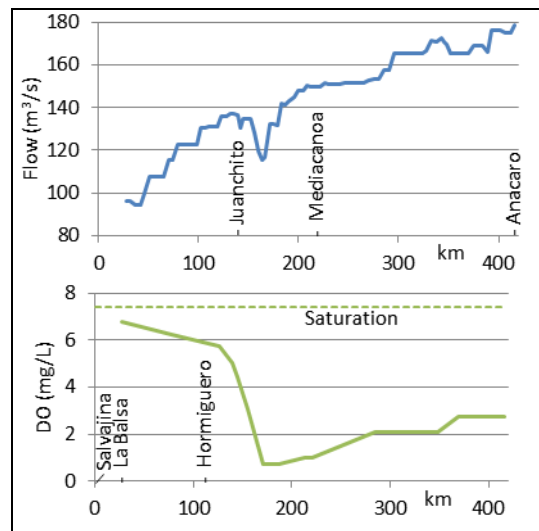


Figure 2. Cauca river. Flow and DO of the Salvajina - Anacaro stretch

The Cauca river has been used for fishing, recreation, energy generation, riverbed matter extraction, human consumption, irrigation and industry. The Salvajina reservoir began operations in 1985 and is part of the regulation project of the Cauca river, implemented for flooding control, improving water quality, self-purification capacity and electricity generation. The reservoir has a capacity of 270 MW. The reservoir operates between levels of 1,110 and 1,150 m.a.s.l. and it has a minimum discharge for generation of 60 m³/s and an average daily flow rate of 140 m³/s in the Juanchito station (Sandoval *et al.* [12]). The Cauca river is also used as a receiving source for solid waste and dumping of industrial and domestic wastewater, which has caused a deterioration in water quality (Figure 2). In the study area there are currently 3.8 million of inhabitants and the Cauca river receives 133.3 ton/d of BOD₅ approximately.

Data collection

The Cauca river has 15 monitoring stations in the "La Balsa - Anacaro" reach. There is more than 50 years of quantity (flows, levels, cross sections) and quality (temperature, DO, BOD) information. This information has been classified into two major periods: before and after the Salvajina dam construction. The Cauca river also has information on quality and quantity for

the main tributaries, wastewater discharges and water intake for domestic and industrial use. As for the Salvajina reservoir operation, there is information on water quality, levels, effluent flows and power generated. In the last decade, quantity and quality dynamic data has been measured which has been considered in this study (Univalle and CVC [14]; Univalle and CVC [15]; Univalle and EMCALI [16]).

Hydrodynamic and water quality model implementation

The hydrodynamic and water quality model of the Cauca river implemented in the MIKE 11 was calibrated and verified for dynamic flow conditions (Univalle and CVC [14]). In this research, some minor adjustments to this calibration-verification process were carried out. The MIKE 11 model reproduces in an acceptable form the values of flow, depth, velocity, DO, BOD_u, and temperature in the monitoring stations of the Cauca river. The model consists of 387 cross sections, 2 external boundaries: La Balsa (km 27.4) and Anacaro (km 416.5), 95 internal boundaries which include 34 rivers and streams, municipal wastewater discharges (3.8 million of inhabitants), 24 industrial wastewater discharges and 36 water extraction sites.

Scenarios: formulation and modeling.

A baseline (dry season conditions in 2013), both of the input data to the model and the expected response (water quality along the Cauca river) was defined. This enabled a model 'validation' as an additional calibration process. Additionally, the reservoir operation between 1985 and 2013 was analyzed. Typical associated behaviors along with the reservoir operation policies were studied. High, medium and low water levels of the reservoir were defined and each of these levels were associated with typical series of power generation and outflow of the reservoir along with discharge time series in the upstream boundary (La Balsa) and in the reference station (Juanchito). A statistical analysis demonstrated typical combinations of water levels in the reservoir with discharges in the Cauca river for typical winter, summer and transition conditions. With this analysis the number of studied scenarios was optimized, allowing a better use of the quality information under dynamic conditions at monitoring stations near the dam. All the scenarios analyzed correspond to the baseline. The scenarios are formulated in order to study the possible behavior of the river with and without the effect of the Salvajina reservoir.

RESULTS

Model calibration

According to previous calibration and verification of the model, the Strickler roughness values were set between 20 and 60 m^{1/3}s⁻¹ and the BOD degradation constants varied between 0.15 and 0.4 d⁻¹. The quality component of the MIKE 11 model at Level 1 and the Churchill equation for the reaeration calculation were applied. The period of simulation was set in 17 days.

Baseline scenario 2013

The summer condition of 2013 was defined as baseline scenario with a mean discharge of 143 m³/s at Juanchito station and associated with a high water level defined as 1145 m.a.s.l. in Salvajina reservoir. The mean flow in Juanchito station corresponds to 88 m³/s (approx. 95% in the flow duration curve) and it is expected to increase to about 55 m³/s. Table 1 presents the BOD₅ loads discharged to the Cauca river for the baseline scenario 2013. The Cauca river receives 134.11 t/d of BOD₅ distributed as follows: 7.85 t/d (5.8 %) in the La Balsa-Hormiguero reach; 105.27 t/d (78.5 %) in Hormiguero - Mediacanoa reach and 20.99 t/d (15.7 %) in Mediacanoa - Anacaro reach. The major contribution of contaminants is present in the

intermediate reach of the Cauca river where it receives direct discharges from the Cañaveralejo's Waste Water Treatment Plant (WWTP-C) of Cali city, the south drainage system of the city of Cali (South Channel) and the sewer system of Cali with its industries. It is estimated that the WWTP - C removes on average 37.1 t/d.

Table 1. BOD₅ discharged to Cauca river.
Base line 2013. Dry season

Reach	Tributaries	BOD ₅ (t/d)
La Balsa - Hormiguero	Palo river	4.48
	Jamundí river	1.00
	Other	2.37
Hormiguero - Mediacanoa	South Channel (Cali city)	1.61
	WWTP-C (Cali city)	51.80
	Industrial zone	13.27
	Yumbo river	2.22
	Guachal river	8.15
	Cerrito river	7.25
Mediacanoa	Tuluá river	7.74
	Morales river	1.20
Anacaro	Other	12.05
Total		134.11

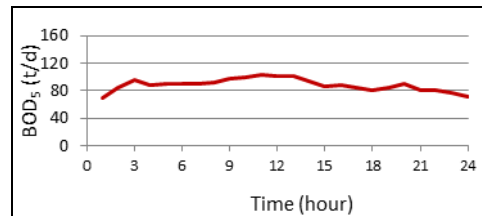


Figure 3. BOD₅ influent to WWTP -C. Baseline, dry season 2013. Flow Juanchito station= 143 m³/s

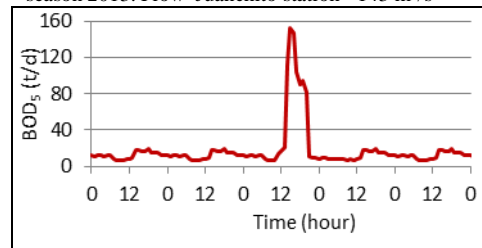


Figure 4. BOD₅ discharged into the Cauca river. Rainfall event in the South Channel drainage area, August 23, 2003.

Dynamic conditions analysis of the river

Figure 3 shows the load variation in the WWTP-C and Figure 4 presents the BOD load produced by a rainfall event (first flush effect) generated in the south drainage system of Cali. This event corresponds to August 22, 2003. This kind of event is frequently observed and it generates the suspension of the water supply for 2 million inhabitants in the city of Cali. For the dynamic flow condition in the upstream boundary of the river (La Balsa station) is considered that it only depends of the Salvajina reservoir (Figure 5).

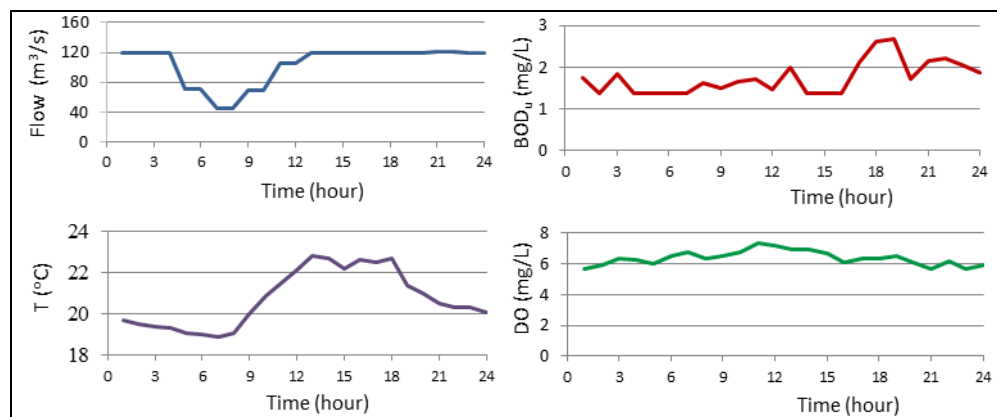


Figure 5. Cauca river. Dynamic characteristics of La Balsa station. High water level in Salvajina reservoir and average flow of Juanchito station= 143 m³/s.

As it was stated before a summer condition with a mean discharge of 143 m³/s (Juanchito Station) and a high water level of 1145 m.a.s.l. (Salvajina reservoir) have been considered in the

baseline scenario. It is noted that for this condition the flow in La Balsa varies between 40 and 120 m³/s. For the dynamic condition of the quality parameters, specific data sets measured were used. Figure 5 shows temperature, BOD and DO hourly registered variations associated with a summer condition and high water level in the Salvajina reservoir

Scenario analysis

Two scenarios (S1 and S2) were built for a steady river condition and four scenarios (S3 to S6) for a dynamic river condition analysis.

Impact of Salvajina reservoir considering a steady condition. S1 and S2 scenarios

The S1 and S2 scenarios were considered as the pos-Salvajina (143 m³/s) (S1) condition and pre Salvajina condition (88 m³/s) (S2). The results are shown in Figure 6. The minimum DO is presented in Paso de La Torre station. The condition with the reservoir operation generates a minimum DO of 0.3 mg/L at this station.

Impact of Salvajina reservoir considering a dynamic river condition S3.

For a mean flow of 143 m³/s of Juanchito station and considering flow variation, temperature, BOD and DO in the upper boundary condition (Figure 7) a value of zero in the concentration of DO in the Paso La Torre station (171.03 km) was obtained.

WWTP-C is out of operation. Discharge directly to the Cauca river Scenario S4.

This condition implies that the pollutant load discharged to the Cauca river increases in 37.12 t/d. In this case zero values of DO are reached in the Puerto Isaac station (Figure 8). There is also a sharp decrease in DO in Paso del Comercio station where it varies between 0.6 and 2.7 mg/L

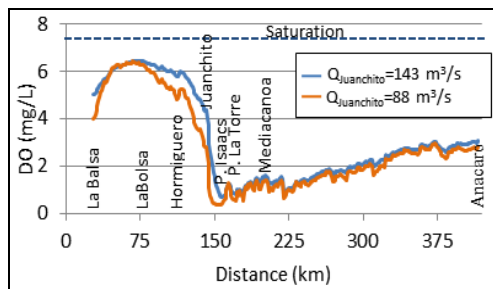


Figure 6. Water quality modeling of Cauca river. DO Profile for steady condition. Mean flow of Juanchito station: with Salvajina reservoir= 143 m³/s and without Salvajina reservoir= 88 m³/s.

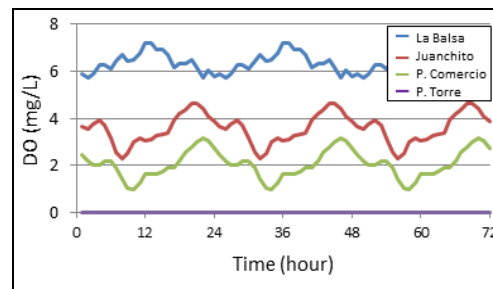


Figure 7. Water quality dynamic modeling of Cauca river. High level in Salvajina reservoir and average flow of Juanchito station= 143 m³/s.

Rainfall impact event in the south drainage system of Cali city. Scenarios S5 and S6.

Two scenarios have been analyzed. The first one S5 when the pollution peak (Figure 4) coincides with the lowest flow of Cauca river at the point of discharge. Scenario S6 is defined when the pollution peak coincides with the highest flow of the Cauca river at the point of discharge. For both scenarios sharp declines in the minimum DO in Juanchito and Paso del Comercio stations are presented. Anaerobic conditions are achieved in Puerto Isaacs station (155.04 km). Furthermore, the modeling results (Figure 9) show low DO values of 0.3 mg/L (S5), 0.9 mg/L (S6) and a difference of 10 hours between the occurrence of these two extreme values.

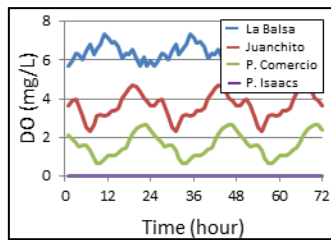


Figure 8. Water quality dynamic modeling of Cauca river. Impact when the WWTP-C is out of operation. High level in Salvajina reservoir and average flow of Juanchito station= 143 m³/s.

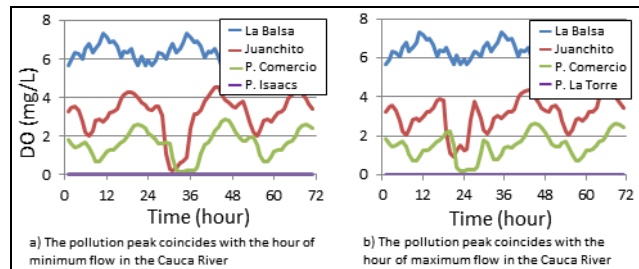


Figure 9. Water quality dynamic modeling of Cauca river. Impact of rainfall event in the South drainage system of Cali city. High level in Salvajina reservoir and average flow of Juanchito station= 143 m³/s.

CONCLUSIONS

The pulsed regime effect of the Salvajina reservoir on the hydraulic behavior of the Cauca river and its impact on the water quality and self-purification capacity must be studied under dynamic conditions. For average flow of 143 m³/s of Juanchito Station and a steady state condition, the Cauca river would remain under aerobic conditions whereas in a dynamic flow condition a DO value equal to zero is shown at Paso de La Torre Station

The WWTP-C removes approx 37.2 t/d of BOD₅. Furthermore, this pollutant load is not sufficient to prevent anaerobic conditions at the critical point (Paso de La Torre Station) with a mean flow below 143 m³/s in a dynamic condition generated by the operation of the Salvajina reservoir.

The pollution associated with rainfall events (first flush effect) in the south drainage system of the city of Cali (South Channel) generates sharp reductions in DO concentrations in the water intake point. Values below 1.0 mg/L are presented at this point, which is associated with frequent closures in the water purification plant. The pollution impact due to rainfall events is less critical when the peak of pollution is generated during the day, when the Cauca river flows are higher. This condition also shows the effect in the water quality of the Cauca river as a source of water supply for the city of Cali due to the reservoir operation.

Further dynamic conditions analysis for water quality studies in the colombian rivers needs to be implemented within the legislation and regulatory requirements especially for those with a dynamic activity such as the Cauca river.

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