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Model Integration To Improve An Early Warning System For The Pollution Control Of The Cauca River, Colombia

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MODEL INTEGRATION TO IMPROVE AN EARLY WARNING SYSTEM FOR POLLUTION CONTROL OF THE CAUCA RIVER, COLOMBIA

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One of the main problems in the water supply system in the city of Cali is related to the water quality of the Cauca River. An important source of pollution upstream of the intake of the Puerto Mallarino Treatment Plant (PMTP) is the south channel, part of the South Drainage System (SDS), which discharges into the Cauca River. The existing Early Warning System (EWS) prototype named EWS-Centinela aims to use real-time data from the Milán Station located in the Navarro area and data generated from the intake of the PMTP. EWS-Centinela estimates the risk level of a critical pollution event that may exceed levels of purification in the PMTP. In order to contribute to finding solutions, this research aims to show the potential that the integration of prediction models could have in improving the water quality estimation of the Cauca River. To this end, an urban drainage model of the SDS for Cali was developed using PCSWMM software. The existing water quality model of the Cauca River developed in MIKE 11 program was used along with the existing prototype EWS-Centinela. The input rainfall data to the urban drainage model was obtained from the Tropical Rainfall Measuring Mission (TRMM). The proposed integration shows not only the SDS effects in terms of quality and quantity of discharge into the Cauca River, but is also a tool for decision-making facing the high risk of pollution of the supply source for this city.

INTRODUCTION

The Cauca River is the main source of water supply for the city of Cali, Colombia. Heavy rainfall occurrences increase flows and turbidity levels in the river, leading to temporary closures in the Puerto Mallarino Treatment Plant - PMTP (Universidad del Valle [9]). In previous research a prototype Early Warning System (EWS) named 'Centinela: water quality of the Cauca River for the City of Cali' (Vélez et al. [12]) was developed. EWS-Centinela is a hydroinformatics tool which aims to use the real-time database from the Milán Station located in the Navarro sector and the intake of PMTP. The tool estimates the risk level of a critical pollution event that can exceed the purification levels in the water treatment plant. On the other hand, the South Drainage System (SDS), formed by the Cañaveralejo, Lili and Meléndez rivers, discharges into the Cauca River through the south channel. It is a major source of high organic pollution, increased flows and increased levels of turbidity in the PMTP. In order to predict the state of the water quality in the Cauca River hours before the occurrence of a pollution event by means of EWS-Centinela, it is necessary to have the SDS information available which represents the processes that describe its hydroclimatological behaviour in short time units (e.g. minutes, hours). This paper discusses the water quality prediction improvement of the Cauca River by integration of models. A dynamic simulation model of the SDS using the PCSWMM program (CHI [3]) has been developed. The SDS model generates knowledge of the urban catchment based on satellite data coming from the Tropical Rainfall Measuring Mission TRMM (Huffman et al. [5]). Flow data obtained from the SDS model in the outlet catchment have been used as input in the existing water quality model of the Cauca River, Mike 11 (Martínez et al. [6] in order to optimize the EWS-Centinela by improving the prediction of critical events present in the PMTP.

METHODOLOGY

Study area description

The study area corresponds to the Cañaveralejo, Lili and Meléndez rivers which form the SDS catchment located in the southwest of the Valle del Cauca region (Figure 1). The natural courses of the three rivers have been modified by the construction of the south channel interceptor in which its waters are collected and discharged to the Cauca River in the area of Navarro. One part of the catchment is located in a rural area and the other in the urban area of the city.

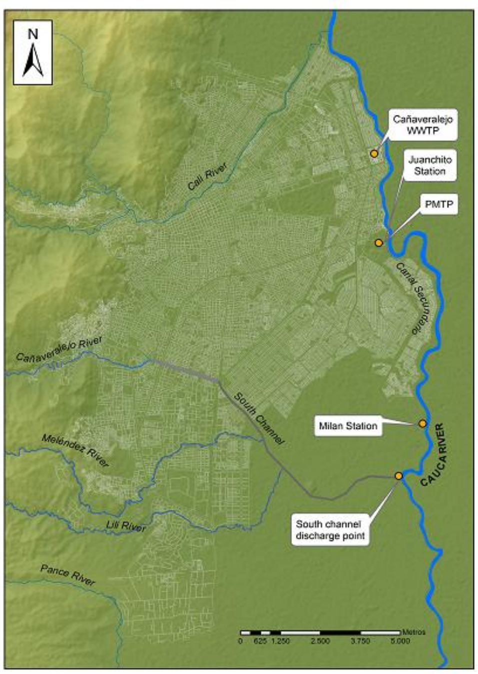

Figure 1 Study area

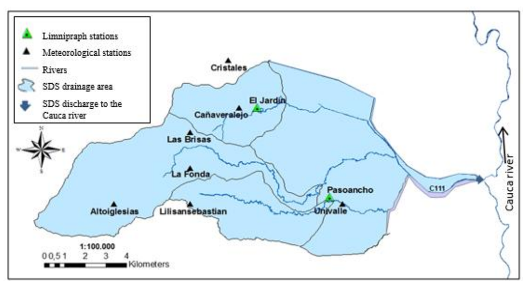

Figure 2 SDS measurement stations

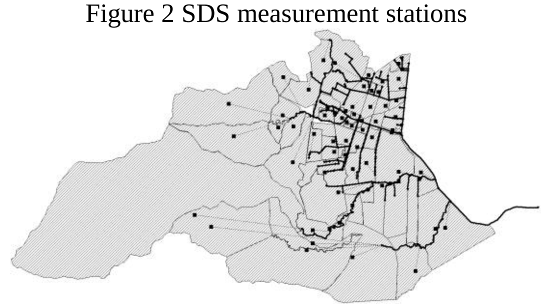

Figure 3 Urban drainage network

A preliminary calibration was performed using daily mean discharges measured at the Jardín Station located in the upper part of the Cañaveralejo River sub catchment and from the Pasoancho Station located in the Lili River sub catchment (Figure 2).

TRMM data and downscaling

A downscaling of rainfall data from the Tropical Rainfall Measuring Mission (TRMM) was carried out using a geostatistical interpolation model validated with measurement stations. The rainfall data obtained from satellite imagery is TRMM 3B42 type with a spatial resolution of 32 km and a temporal resolution of 3 hours according to the coordinates and catchment area. The downscaling was performed by using the geostatistical interpolation model Cokriging and applying a cross-validation process for three different models: Cokriging, Kriging and the Inverse Distance Weighting-IDW (Olivera [8]). Distributed rainfall is obtained using the geostatistical interpolation methods with a spatial resolution of 460 m and a temporal resolution of 3 hours. Taking into account that satellite information differs from ground stations, this information was fitting using bias correction parameters for the three interpolation methods. The coefficient of determination (R2), correlation coefficient (r), root mean square error (RMSE) and mean absolute error (MAE) were determined, leading to a definition of the interpolation method Cokriging as the best suited for the correlation between pairs of data through bias correction (Arias-Hidalgo et al. [1]). The equations for these statistical parameters are:

Bias Correction:

$$\mathrm{BIAS} = \sum_{t=1}^{N} \frac{(\phi t - \phi tobs)}{N} \tag{1}$$

Root Mean Square Error:

$$\mathrm{RMSE} = \sqrt{\sum_{t=1}^{N} \frac{(\phi t - \phi tobs)2}{N}} \tag{2}$$

Mean Absolute Error:

$$\mathrm{MAE} = \sum_{t=1}^{N} \left| \frac{\phi t - \phi tobs}{N} \right| \tag{3}$$

Where Ø*t* = predicted value for cell i; Øtobs = observed value for cell i, N = number of analyzed values.

Urban drainage model

The urban drainage network modelled with the PCSWMM program (CHI, [3]) consists of 66 sub-basins, 216 conduits (pipes and channels) and the 3 rivers Cañaveralejo, Lilí and Meléndez (Figure 3). Distributed rainfall data in an hourly timescale (3 hours) obtained through the TRMM downscaling procedure was used as input data to the urban drainage model. The data is associated with the PMTP temporary closures due to critical contamination events. A preliminary calibration was performed using available daily discharge measurements. From this SDS model it was possible to obtain the discharge in an hourly timescale at the point of the south channel discharges into the Cauca River, see Figure 1.

Water quality model

The existing Mike 11 water quality model of the Cauca River from the stations La Balsa to Anacaro was used to estimate dissolved oxygen (DO) in the river up to the PMTP in Juanchito Station (Martínez et al. [7]). The model consists of 93 internal boundaries corresponding to 33 rivers and tributaries, 10 domestic and 12 industrial wastewater discharges and 38 water intakes. The south channel discharge computed from the SDS urban drainage model was used as new input into the water quality model. The event modelled corresponds to 29 March 2009 when the PMTP was closed due to high organic load. Similarly, a measured event generated in the DO (mg/L) of the Cauca River at Juanchito Station during a rainfall event in the SDS was introduced into the water quality model (Universidad del Valle and CVC [11]). A maximum value of 150 Ton/day of Biological Oxygen Demand (BOD_5) was measured for this event (Figure 4).

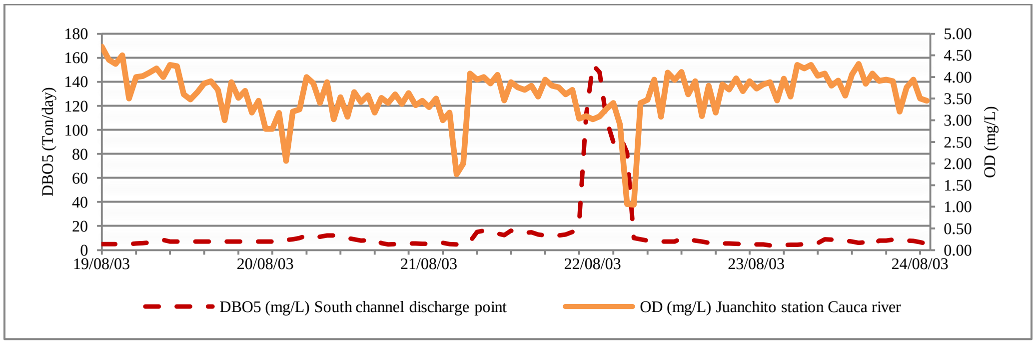

Figure 4 Organic matter discharge effect of the SDS into the Cauca River at Juanchito Station

EWS Centinela

The dissolved oxygen predicted at PMTP using the water quality model of the Cauca River for the 29 March 2009 event was used as input to the existing database of the EWS Centinela. Warning messages were generated to obtain the required management level. Detailed information of the EWS Centinela warning messages and its operation can be found in Vélez et al. [12]; Universidad del Valle and EMCALI [10].

RESULTS AND DISCUSSION

Table 1 presents the performance comparison used to determine the best method of geostatistical interpolation for rainfall downscaling. According to the cross-validation results for the three geostatistical interpolation methods, Cokriging was the method that presented a better correlation compared to the IDW and Kriging methods.

Table 1 Performance comparison between different geostatistical interpolation methods.

STATION	COKRIGING				IDW				KRIGING			
	R^2	r	MAE	RMSE	R^2	r	MAE	RMSE	R^2	r	MAE	RMSE
Cañaveralejo	0.65	0.80	1.00	2.64	0.004	0.06	12.61	33.37	0.02	0.15	7.08	18.73
Brisas	0.88	0.94	3.07	8.12	0.66	0.81	2.58	6.83	0.88	0.94	1.86	4.93
Cristales	0.75	0.87	6.96	18.41	0.51	0.71	11.71	30.97	0.76	0.87	7.00	18.52
Fonda	0.60	0.77	1.17	3.09	0.27	0.52	11.81	31.26	0.04	0.20	4.13	10.94
Alto iglesias	0.76	0.87	3.06	8.10	0.01	0.10	8.18	21.63	0.01	0.11	1.95	5.15
Lili	0.88	0.94	17.50	46.30	0.46	0.68	22.14	58.58	0.22	0.47	21.80	57.67
Univalle	0.89	0.95	5.64	14.93	0.09	0.30	4.75	12.57	0.09	0.30	5.46	14.46

Table 2 presents the bias correction between TRMM and ground data. In general, a good correlation can be observed (R^2 = 0.77, on average). In order to illustrate the validity of this simple procedure, Figure 5 shows the comparison of rainfall data from the gauges and TRMM corrected data. The period analyzed corresponds to February-April 2009.

Table 2 Bias correction, TRMM vs. ground data for February –April 2009 period

Validating station	Ground rainfall data (mm)	Uncorrected TRMM			Bias corrector	R^2	Corrected TRMM		
		Rainfall period (mm)	Rel. bias (%)	RMSE (mm)			Rainfall period (mm)	Rel. bias (%)	RMSE (mm)
Cañav	17	21.68	27.5	1.77	0.84	0.65	18.19	7.00	0.45
Bris	29	24.99	13.8	1.52	0.95	0.88	23.78	18.00	1.27
Cris	22	24.12	9.6	0.80	0.96	0.75	23.10	5.00	0.42
Fond	21	19.03	9.4	0.74	1.16	0.60	22.08	5.14	0.41
Altoi	22	27.47	24.9	2.07	0.98	0.76	26.84	22.00	1.83
Lilisan	68	51.26	24.6	6.33	1.07	0.88	55.08	19.00	4.88
Univalle	37	43.40	17.3	2.42	0.97	0.89	42.18	14.00	1.96

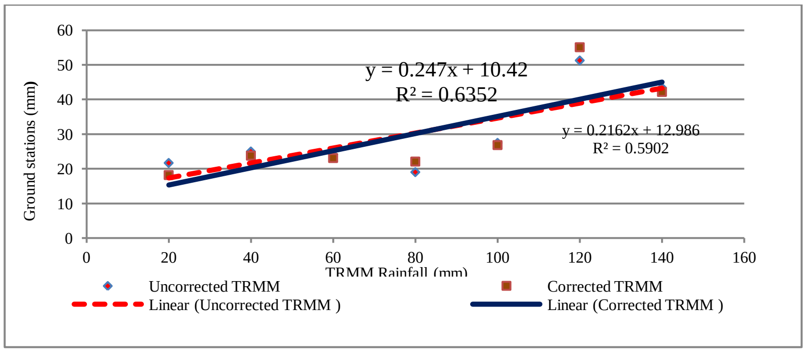

Figure 5 TRMM corrected rainfall

With the geostatistical interpolation method Cokriging, rainfall images with 16 pixel resolution were obtained every 3 hours for the period February-April 2009. Figure 6 shows the TRMM precipitation for the 29 March 2009 event at 09:00 hours on the SDS catchment with the rainfall values for each of the centroid pixels according to Asadullah et al. [2]. A sensitivity analysis and preliminary calibration of the urban drainage model were carried out taking into account previous modelling results (Vélez [13]; Martínez-Cano et al. [7]). Due to the lack of hourly discharge measurements, the daily mean discharge obtained was compared to those measured at the Jardín and Pasoancho stations (Figure 2). Figure 7 shows the model results for 0-1 conduit located at the Cañaveralejo River. An approximately 4.67 m^3/s peak hydrograph with a mean discharge of 0.84 m^3/s was obtained. Similarly, for the C103 channel located at the Lilí River, a peak hydrograph of 8.69 m^3/s with a mean discharge of 1.72 m^3/s was also computed. The daily mean discharge measured at the Jardín and Pasoancho stations were 0.82 m^3/s and 1.70 m^3/s respectively.

The resulting hydrograph up to the south channel discharge point (C111) for 29 March 2009 is presented in Figure 8. The results show a peak discharge of 9.62 m^3/s at 13:00 hours. The simulated discharges during a critical event occurrence such as 29 March produce effects on the treatment system for the city of Cali due to the discharge volume of the SDS into the Cauca River. Figure 9 presents the results of DO and BOD_5 modelling in mg/L in the PMTP, taking into account the simulated discharge data at the south channel point and the measured event in terms of BOD_5 presented in Figure 4.

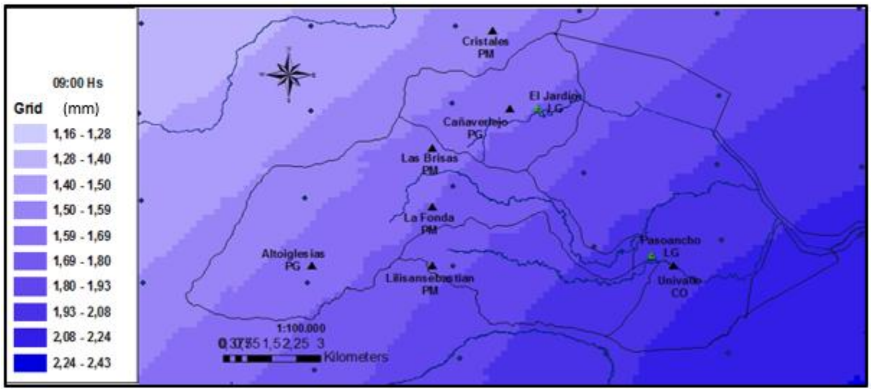

Figure 6. Distributed TRMM rainfall in the SDS. 29 March 2009 09:00 hrs

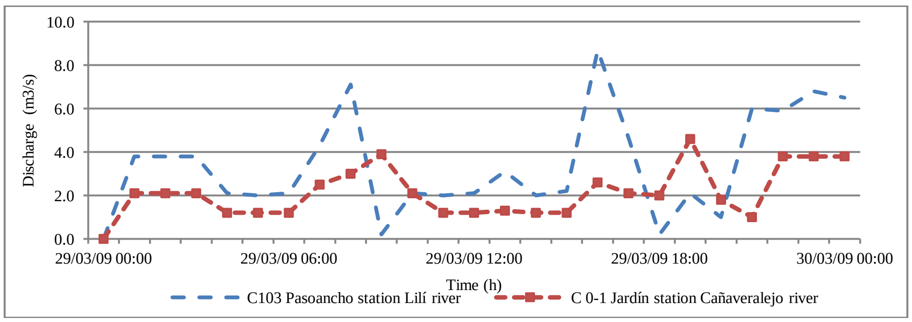

Figure 7 Simulated hourly discharges on 29 March, 2009. The PMTP had to be closed

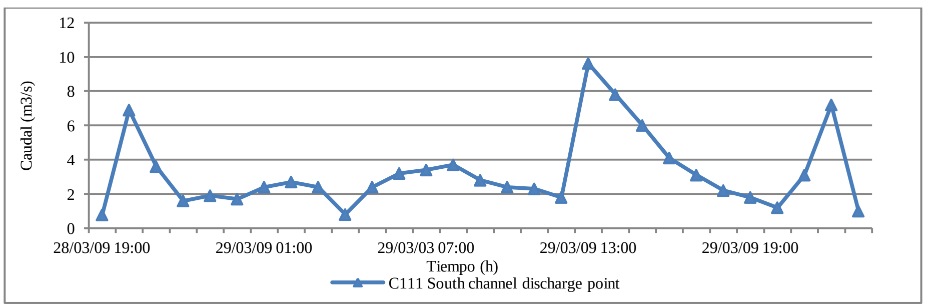

Figure 8 Simulated hourly discharges at the south channel discharge point on 29 March 2009

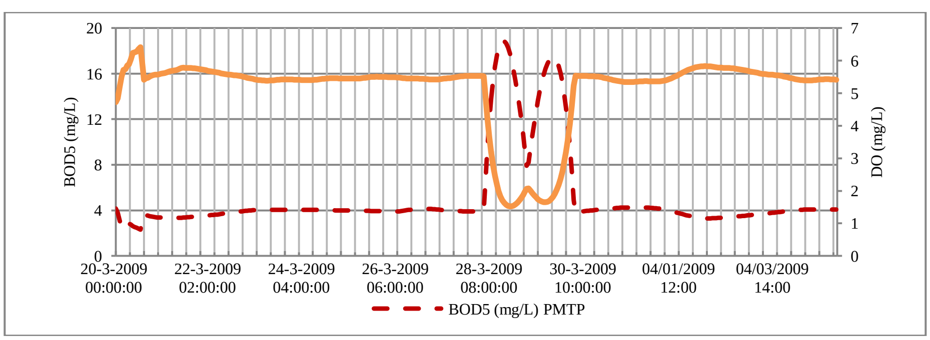

Figure 9 DO results in the PMTP intake due to a heavy rainfall event and organic load increase in the SDS.

Figure 9 shows that a significant DO concentration decrease occurred in the PMTP intake for 29 March 2009, the date on which the treatment plant was closed due to a high organic load in the Cauca River and reported by EMCALI [4], the public company in charge of the PMTP operation. A DO concentration with values greater than 5 mg/L from about 08:00 hours on 28 March can be observed. After that the concentration decreases sharply up to critical values below 2 mg/L, generating EWS-Centinela warnings until 03:00 hours on 30 March at which time the DO concentration stabilizes again. It is advisable to calibrate the water quality model for turbidity prediction, the parameter also used to generate warnings on the EWS-Centinela. Data obtained from the dynamic model of the Cauca River was used as input to the EWS database. Table 3 presents an example of the warning level output of the EWS-Centinela generated due to the DO concentration decrease in the PMTP. It is associated with the flow and organic load discharge from the SDS to the Cauca River. The description (display message) of warning level 2 for DO generated corresponds to '*Dissolved Oxygen Concentration unfavourable decreasing at a not continuous rate, monitoring for possible continued decline is needed, possible closing event.'*

Table 3 Early warnings from EWS-Centinela in PMTP with data obtained from SDS on 29 March 2009.

Date	DO (mg/L)	Warning level
29/03/2009 03:00	1.39	2
29/03/2009 04:00	1.39	2
29/03/2009 05:00	1.16	2
29/03/2009 06:00	0.82	2
29/03/2009 07:00	0.82	2
29/03/2009 08:00	1.56	2
29/03/2009 09:00	1.56	2
29/03/2009 10:00	2.25	2

CONCLUSIONS

The TRMM satellite product has shown the capacity to complement the information content in ground stations for short-term scale rainfall data needed to model a short respond catchment. In this research the use of the Cokriging method was an important step in order to get distributed rainfall data for the SDS. Therefore, the contribution of this approach is based on the fact that if bias is known, satellite data can contain information similar to the rainfall data provided by ground stations. In the process of SDS urban modelling, it was possible to reproduce adequately hourly discharges in the Cañaveralejo Lilí and Meléndez rivers and in the South channel discharge point. These discharges could be compared with the daily mean discharges measured in the Jardín and Pasoancho stations for the PMTP closing event on 29 March 2009.

The water quality model of the Cauca River adequately reproduced the DO and BOD_5 that could reach the PMTP as a result of the effect of organic matter discharge in the SDS. Thus, for a heavy rainfall event such as 29 March 2009 with a peak discharge of 9.62 m^3/s and high organic load in the south channel discharge point (BOD_5 = 150 Ton / day), it was possible to identify the DO effect generated in the Cauca River up to the PMTP (DO_{min} = 1.52 mg/L). The EWS Centinela prototype has also shown the capabilities of an Early Warning System for predicting pollution events in PMTP. The level 2 warnings that were generated on the specified closing date 29 March 2009 due to the high pollution load validate the existence of the SDS effect in the Cauca River. The model's integration results using the TRMM rainfall data along with the SDS urban model, water quality Cauca river model and the EWS-Centinela prototype show the potential that these tools have not only for the discharge and pollution in the south channel and in the Cauca River up to the PMTP but also in decision making due to the increased pollution risk of the supply source for the city of Cali.

Acknowledgments

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