Hydrodynamic Modelling of Cartagena Bay, Colombia

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INTRODUCTION

Cartagena is a "hot-spot" of pollution, tourism and human development. It has a population of 1 million people, one of the country's largest ports and industrial zones, and is Colombia's principal touristic destination. Various issues with the waters, sediments and biota of Cartagena Bay have been observed for decades, including excessive turbidity, eutrophication, pesticides, heavy metals, hydrocarbons and fecal contamination[1]. These issues have been linked to domestic, industrial and continental sources of pollution, foremost of which is runoff from the Dique Canal flowing from the Magdalena River, which is the principal source of fluvial fluxes discharging in the Caribbean Sea.

An ongoing mitigation project plans to construct hydraulic doors along the Dique Canal to reduce flows into the bay. However, studies also show that the tendency of the canal´s discharge is increasing due to human impacts in the watershed[2]. **How will these upstream anthropogenic impacts on freshwater runoff affect the bay´s hydrodynamic processes of water renewal?** We evaluate these scenarios with a calibrated hydrodynamic model - MOHID.

METHODS

Bathymetry was digitized from georeferenced nautical maps (CIOH-DIMAR) and updated in the field with a mono-beam echo-sounder in the Bocachica strait area. CTD casts were deployed monthly from Sept.2014-Nov.2016 at stations (B1-8; Fig. 1). Discharge was measured in the Dique Canal with a Sontek mini-ADP (1.5 MHz). Meteorological data were obtained from the local airport and NOAA´s GFS. The model´s seaward boundary were prescribed with data from EU´s Mercator (temp, sal) and FES2004 (tides).

The 3D MOHID Water model was configured with a domain of 196 km2 (Fig. 1), a horizontal resolution of 75 m, and 22 vertical layers (combined sigma-cartesian). 1-month simulations were calibrated with field data for the windy (27 Jan.–24 Feb.), transitional (28 June–26 July), and rainy (19 Oct.-17 Nov.) seasons with a Δt of 20s and a 1-day spin-up period.

A Lagrangian approach was used to compute flushing times (defined as the time necessary for 95% of the particles to flush out of the bay)[3] of passive particles emitted from two origins: 1) the Dique Canal and 2) throughout the entire bay itself. Numerical experiments were carried out with the model to evaluate two hypothetical scenarios: increased discharge (x2) and decreased discharge (x0.5) from the Dique Canal.

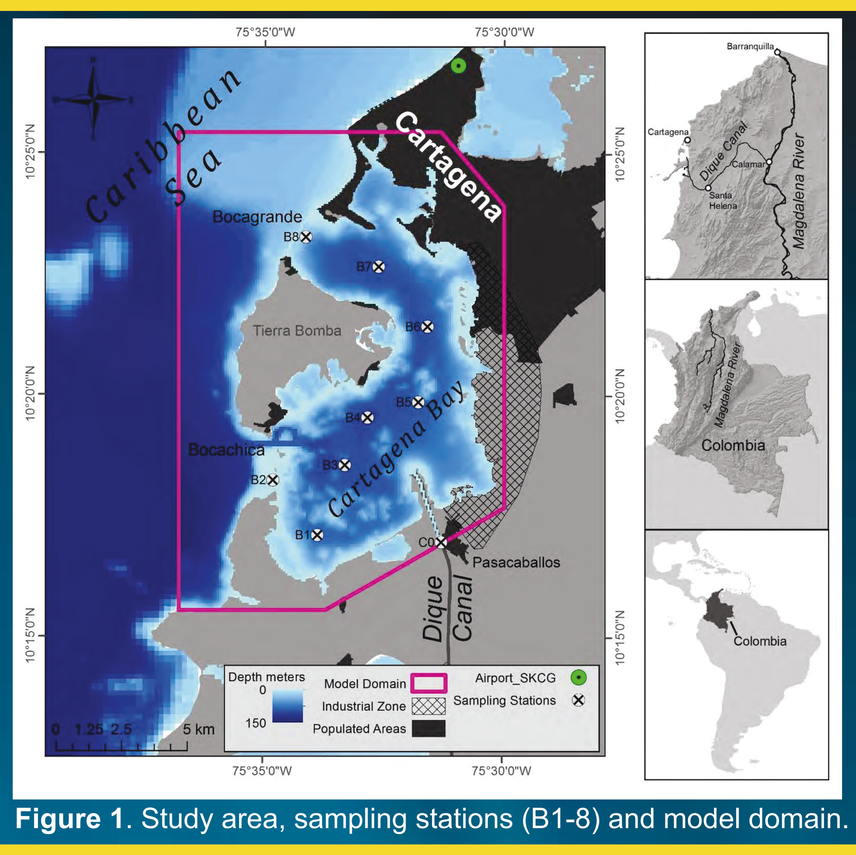

Figure 1. Study area, sampling stations (B1-8) and model domain.

MONITORING RESULTS

Salinity, temperature and density ranged from 9.7-36.5, 26.8-33.2°C and 1001.9-1023.7 kg/m³ in the bay over the 27-monthly monitoring sessions. Minor horizontal spatial variation is observed between the different locations within the bay (**Fig. 2**): freshwater influence (lower salinity, higher temperature) is greater at stations B4 and B5 directly in front of the Dique Canal and lesser at the furthest station B8. Vertical spatial variation is remarkably pronounced and temporal variation displays marked seasonal conditions: vertically mixed marine conditions during the windy season; and highly stratified gradients of salinity and temperature in the rainy and transition season, respectively.

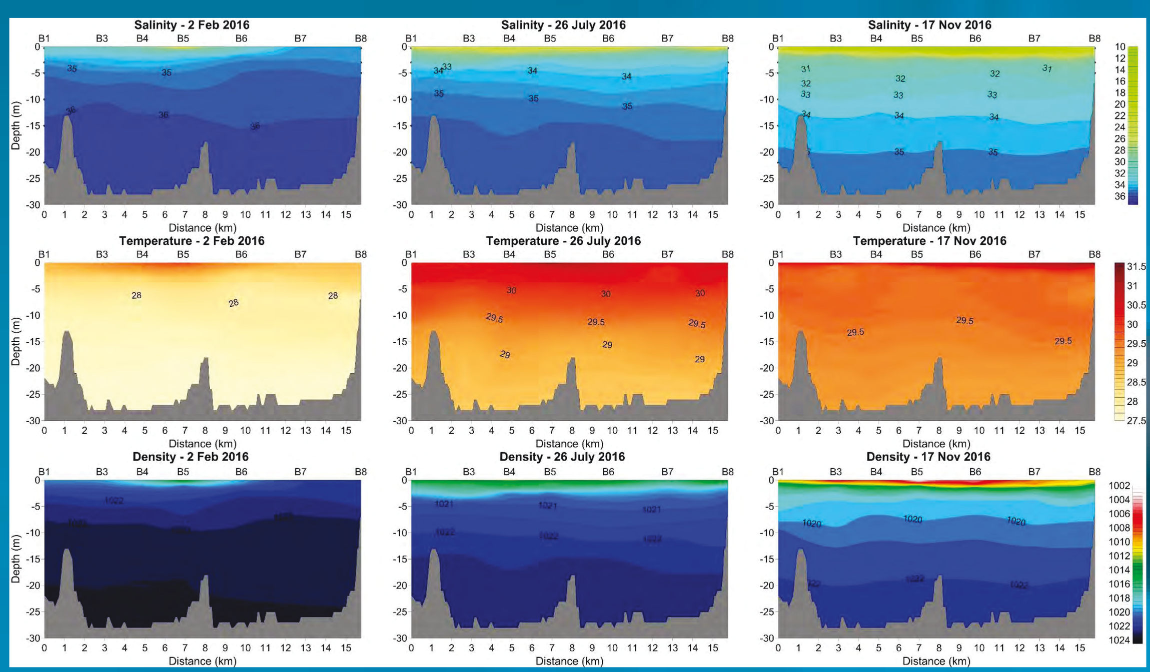

Figure 2. Vertical profiles of salinity (top), temperature (middle) and density (bottom) measured during the windy (2-Feb; left), transition (26-July; center) and rainy (17-Nov; right) seasons of 2016 and horizontally interpolated between sampling stations (B1-8).

Surface heating and water mass fluxes visibly affect vertical profiles of density (**Fig. 3**), which gradually decreases from April-Nov. and then sharply reverts to seawater conditions in Dec. Surface heating is most pronounced from April-Oct., while freshwater fluxes a greatest in April-May and Sept-Nov. Cooler water temperatures between January and March are likely related to increased wind speeds and the strengthening of the southern Caribbean upwelling system[4].

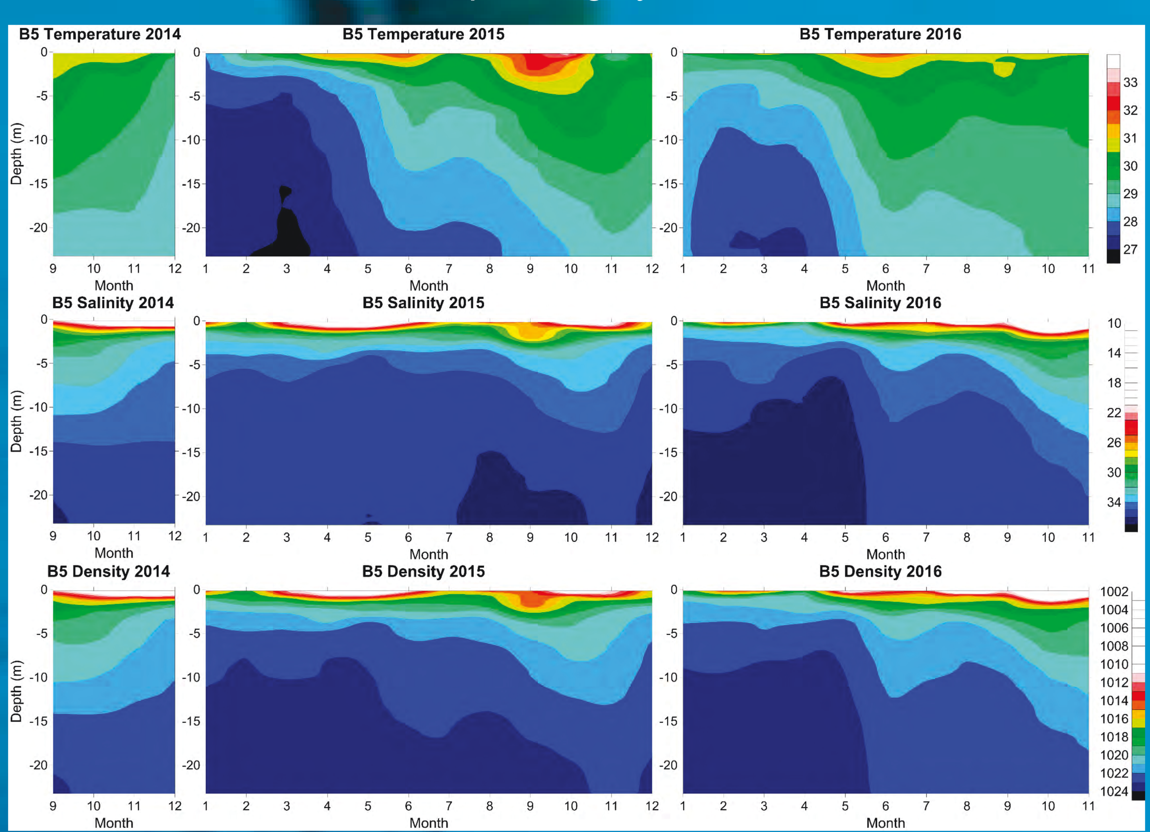

Figure 3. Vertical profiles of temperature (top), salinity (middle) and density (bottom) measured at station B5 during 27 monthly sampling sessions and interpolated over time.

A time-lag between surface and bottom effects reflects vertical mixing time, which is inhibited by strong stratification, as lower surface densities in May and Sept. do not affect bottom waters until June and Oct. Inter-annual variation displays the 2015 El Niño influence when reduced precipitation generated higher temperatures and salinities.

MODELING RESULTS

Performance statistics indicate that the model adequately simulates the hydrodynamics of the system (**Table 1**). Low values of AE, MAE and RMSE (<0.4°C; ~1‰; <0.05m) indicate good performance, while RMSE values of salinity (1.0-2.1) reflect outliers at the surface due to local freshwater sources. RE´s of ~1% (temp) and 2-5 % (sal) are adequate. The higher RE for water level (~10%) reflects weak tidal variation.

Table 1. Statistics of model performance: sample size (N), mean and standard deviation of observed ($\bar{O}$, s_O) and predicted ($\bar{P}$, s_p) values, average error (AE), mean absolute error (MAE), root mean squared error (RMSE), and relative error (RE).

Parameter	Season	N	$\bar{O}$	$\bar{P}$	s_O	s_P	AE	MAE	RMSE	RE
Temperature (°C)	Rainy	108	29.62	29.57	0.26	0.18	-0.05	0.21	0.28	0.7%
	Tran	108	29.85	29.59	0.52	0.30	-0.26	0.36	0.39	1.2%
	Dry	108	28.23	28.05	0.49	0.32	-0.17	0.20	0.29	0.7%
Salinity	Rainy	108	30.54	31.03	4.49	3.71	0.49	1.36	2.13	4.5%
	Tran	108	33.04	32.89	2.83	2.82	-0.15	0.80	1.09	2.4%
	Dry	108	34.99	35.52	1.40	0.62	0.53	0.60	1.03	1.7%
Water Level (m)	Rainy	497	0.39	0.39	0.11	0.09	0.00	0.03	0.04	8.8%
	Tran	626	0.28	0.28	0.11	0.09	0.00	0.03	0.04	10.8%
	Dry	278	0.34	0.34	0.10	0.09	0.00	0.04	0.05	11.4%

Mean (residual) surface water velocities during the 3 seasonal simulations (**Fig. 4**) exhibit the dominant influence of discharge from the Dique Canal on surface currents in the bay. At high (rainy) and medium (transitional) discharge levels, the Dique Canal forces surface currents to run north and west to the 2 seaward straits. During the windy season, strong northerly winds overpower the low discharge levels and force surface currents southwest to Bocachica.

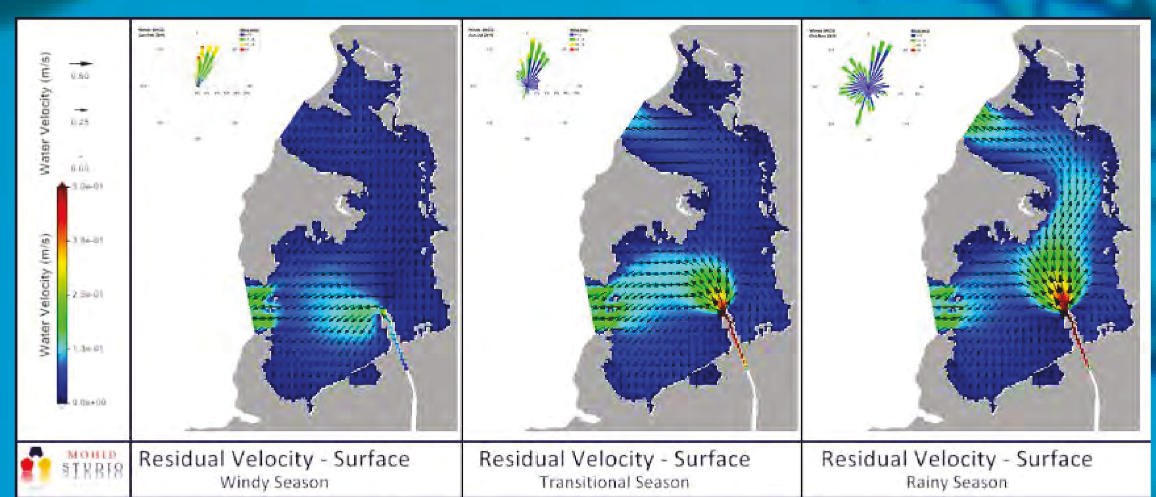

Figure 4. Residual surface water velocities and wind roses during simulations of the windy (left), transition (center) and rainy (right) seasons of 2016.

Vertical profiles of residual water velocities at the bay´s 2 seaward straits (**Fig. 5**) illustrate the processes of water exchange with the sea. At the Bocachica strait to the south, strong stratification results in freshwater flowing out from the bay at the surface, while seawater flows in via the navigation canal below. At Bocagrande to the north, outflowing surface water and inflowing sub-surface water are also observed, though the latter is inhibited by the sub-surface seawall. When stratification and surface velocities are reduced during the windy season, the influx of sub-surface seawater also decreases at Bocachia, while fluxes through Bocagrande are reduced in both directions as surface current become wind-driven.

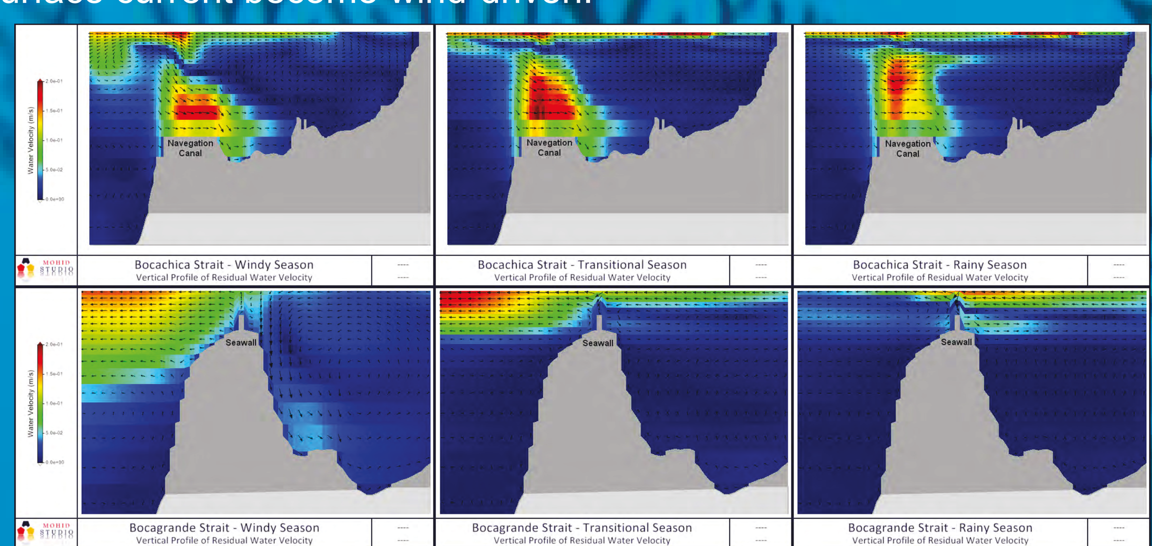

Figure 5. Vertical profiles of residual water velocities at Bocachica (top) and Bocagrande (bottom) straits for simulations of the windy (left), transition (center) and rainy (right) seasons.

TRACER RESIDENCE TIME

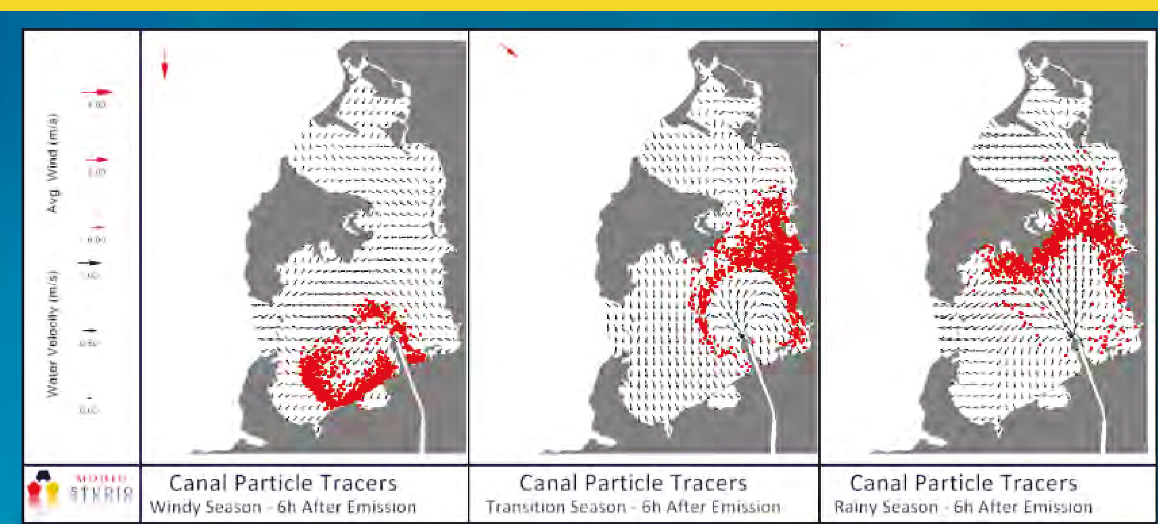

Figure 6. Evolution of particle tracers 6h after emission from the Dique Canal in the windy (left), transition (center) and rainy (right) season simulations.

The seasonal effects of freshwater discharge and winds are shown by the evolution of particle tracers released from the Dique Canal. During the rainy and transition seasons, particles are transported due to the canal´s influence, though their extension is slightly reduced during the transition season due to lower discharge and higher wind. In the windy season, intense northerly winds confine particles in the southern lobe of the bay where they oscillate vertically by depth along with the tides.

Table 2. Flushing time (in days) of particles emitted from the Dique Canal and the entire bay during 3 seasons under 3 scenarios: the present, double- and half-discharge from the Dique.

Season	Rainy Season			Transition Season			Windy Season		
Scenario	Qx0.5	Real	Qx2	Qx0.5	Real	Qx2	Qx0.5	Real	Qx2
Canal Discharge Q (m³/s)	112.5	225.0	450.0	83.7	167.3	334.7	16.9	33.9	67.7
Avg. Wind (m/s) & Dir. (°)	3.0 (309°)			3.3 (10.3°)			5.0 (16.6°)		
Canal Flushing Time (d)	19	10	5	22	13	7	18	20	17
Bay Flushing Time (d)	172	98	35	113	97	69	70	70	35

The time to flush canal water out of the bay varies between 5-22 days while the time to renew the entire volume of water in the bay varies widely from 35-172 days (Table 2). Flushing time calculations exemplify the importance of the Dique Canal´s discharge on the bay´s circulation, as scenarios of increased discharge quicken flushing times while flushing is slowed by lower discharge levels (Fig. 7). Halving the canal discharge approximately doubled the flushing time in most cases, though this scenario had no effect in the windy season as particles were confined in the bay´s southern lobe by the wind regardless.

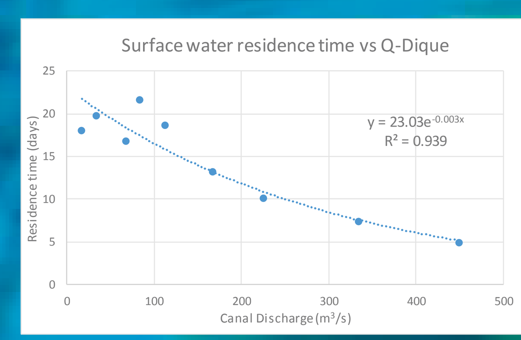

Figure 7. Relationship between flushing time and canal discharge.

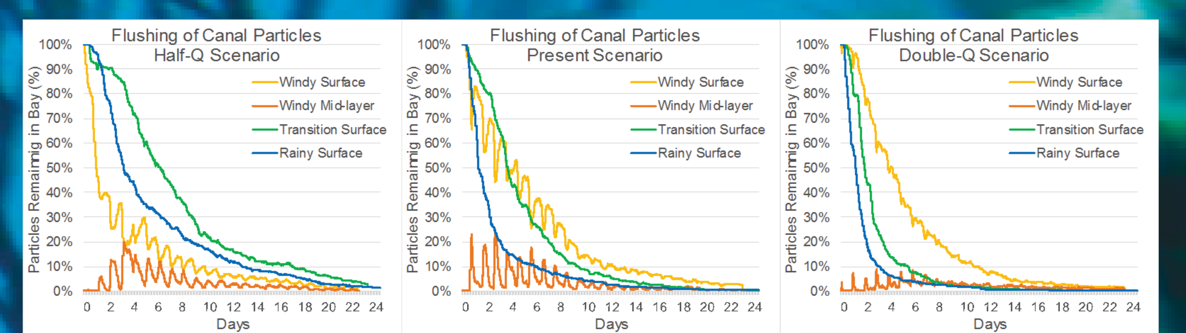

Figure 8. Evolution of particle tracers 6h after emission from the Dique Canal in the half-Q (left), present (center) and double-Q (right) scenarios for 3 season. Windy season particles are divided between surface and sub-surface (<5m) depths to illustrate tidal oscillation.

At low discharges, vertical mixing can be observed as particles oscillate between the surface and sub-surface depths (Fig. 8). This vertical transport coincides with tidal movement which becomes prevalent during the windy season, particularly in the present and half-discharge scenarios. This vertical mixing occurs as low discharges reduce thermohaline stratification and result in slower surface currents.

CONCLUSIONS

1. Cartagena Bay is characterized by strong thermohaline stratification created by fluxes of freshwater runoff and surface heating which inhibit vertical mixing for most of the year.
2. Surface currents are predominantly controlled by freshwater discharge flows, while the effect of winds and tides are also apparent at low discharge levels. Fluxes of seawater into the bay occur almost entirely through the Bocachica navigation canal.
3. Present flushing times for canal water (10-20 days) and the entire bay (70-98 days) would become faster under the scenario of increased freshwater discharge due to human impacts in the watershed. Reducing flow in the Dique Canal would result in increased flushing time.
4. The true effect of changes in freshwater flow on the bay´s ecosystem cannot be known as scenarios of increased and decreased runoff may both cause positive and negative impacts; as increased runoff would improve circulation though enlarging pollution loads from the watershed.
5. In the scenario of reducing upstream flows, an essential measure of mitigation would be the elimination of local wastewater sources as reduced circulation combined with local pollution could drastically worsen eutrophication issues[5].

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