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Characteristics of currents in a section of the Guayas River

Características de las corrientes en un tramo del Río Guayas

Artículo

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Leonor Vera San Martín
Oceanographer
Oceanographic and Antarctic Institute of the Ecuadorian Navy Guayaquil-Ecuador, leonor.vera@inocar.mil.ec
Orcid: 0000-0001-6265-6847

Freddy Hernández-Vaca
Dr. in Oceanography
Oceanographic and Antarctic Institute of the Ecuadorian Navy Guayaquil-Ecuador, freddy.hernandez@inocar.mil.ec
Orcid: 0000-0002-1923-9826

Magda Mindiola Robayo
Oceanographer
Oceanographic and Antarctic Institute of the Ecuadorian Navy
magda.mindiola@inocar.mil.ec
Orcid: 0000-0001-6109-8644,

Jorge Nath Nieto
Oceanographer
Oceanographic and Antarctic Institute of the Ecuadorian Navy
Guayaquil-Ecuador, jorge.nath@inocar.mil.ec
Orcid: 0000-0002-8818-2536

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Abstract

This work exhibits the analysis of the currents measurements made during maximum tidal height period of june 2006, in a river Guayas section, between south of Santay island to Matorrillos channel. With the Eulerian method the velocity in the water column was determined in four points located throughout the study area, using a profiling currentmeter that recorded the velocity from 3 m to the bottom. In order to measure the circulation pattern in the superficial layer, a Lagrangian method was used, with floatings from 0 m to 3 m. The results showed that the ebb tide lasts approximately seven hours in the study area,i.e. It is 65 % to 70 % longer than the flood tidal, which has four hours of duration. Likewise, It was registered that the velocity direction is dealt by the tide state, during the flood It is predominant towards north and in the ebb towards south. Since the change of tide state to the change in velocity direction there is a gap of one hour approximately. The change in the current direction, from flow to ebb, begins in the upper layers; while from ebb to flow, in the lower layer. The maximum magnitude of currents were found below 3 m depth during the ebb state of 27 and 28 of june specially. The highest value was 1.83 m/s in 7 m depth.

Keywords: Tidal cycle, tidal currents, Guayas river.

Resumen

En este trabajo expone el análisis de las mediciones de corrientes realizadas durante el de máxima altura de la marea de junio de 2006, en un tramo del río

Guayas, entre el sur de la isla Santay hasta el Canal Matorrillos. Con el método Euleriano, se determinó la velocidad en la columna de agua en cuatro estaciones situadas a lo largo del área de estudio, utilizando un correntómetro perfilador, que registró la velocidad desde los 3 m de profundidad hasta el fondo. Con el método Lagrangiano se midió el patrón de corrientes en la capa desde 0 m a 3 m, usando derivadores. Los resultados mostraron que la marea menguante tiene una duración aproximadamente siete horas en la zona de estudio es decir, es entre un 65% y un 70% más larga que la marea viva, que tiene cuatro horas de duración. Asimismo se observó que la dirección de la corriente está regida por el estado de la marea, en el flujo es predominante hacia el norte y en el reflujo, hacia el sur. Desde el cambio del estado de la marea y la respuesta observada en el cambio en la dirección de la corriente, el lapso es de aproximadamente una hora. El cambio de la dirección de las corrientes, del flujo al reflujo empieza en las capas superiores; mientras que del reflujo al flujo, en las capas inferiores. Las corrientes de mayor magnitud se encontraron después de los 3 m de profundidad durante el reflujo, especialmente el 27 y 28 de junio. El máximo valor registrado fue de 1.83 m/s en 7 m.

Palabras clave: Ciclo de marea, corrientes de marea, río Guayas.

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Introduction

The Guayas River (GR) is formed by the Daule and Babahoyo tributaries, which contribute 40% and 60%, respectively, to its flow (Soledispa, 2002). It has a slight slope, less than 1 x 10^{-5}(Stenfert *et al*., 2017) and a tidal range between 2.6 m and 3.5 m (Murray *et al*., 1975). The RG is the main source of freshwater for the Gulf of Guayaquil or RG Estuary (ERG), as it is also called. The ERG begins at Puná Island and extends as far as the tidal and salinity influx is present, approximately 100 km into the mainland, to the Daule and Babahoyo rivers (Montaño & Sanfeliu, 2008).

The RG estuary is classified as "*poorly developed and partially mixed, type B*" (Montaño & Sanfeliu, 2008). Circulation in the RG is estuarine, with current vectors parallel to the RG axis, which change direction due to the action of its main forcing agent, which is the tide. The magnitude of the current is strong, with a value of up to 2 m/s (Stevenson, 1981).

The tides in Ecuador are semi-diurnal, in a period of 24.8 hours two tidal cycles are completed, comprising the states of flow (rising), ebb (ebbing), in other words with two high tides and two low tides. Each ebb and flow has unequal duration, not more than 5% difference, the ebb is of longer duration with 7.5 hours, (Murray *et al*., 1975). The tidal amplitude in the RG also depends on the oscillation of sea level and the contributions of the Daule and Babahoyo tributaries (INOCAR, 2000).

Despite the importance of this aquatic resource, no information on currents in the RG after 2000 is found in the bibliography. Technical reports from INOCAR indicate that current measurements were taken in 1997 and 2000 using Eulerian and Lagrangian methods in areas close to the current study. Currents of up to 2.5 m/s were reported in the west channel of Santay island and to the south of the same island, in october 2000, a maximum velocity of 1.28 m/s was reported.

The objective in this study was to estimate the currents in the water column in a stretch of the RG, their variation during the tidal cycle and the time delay between the change of tidal direction and that of the current, all of which constitutes a contribution to the knowledge of the physics of the estuary, considering the scarcity of published information on this body of water.

This paper presents the results of current measurements from june 27 to 30, 2006 during the spring tide, and estimates the duration time and height of ebb and flow tide in typical dry season (August) and rainy season (February) periods.

Materials and Methods

Study area

The study area corresponds to a section of the RG, part of the Guayas inner estuary on the coast of Ecuador, shown in red in Figure 1. Current profiles were measured in the study area at four stations named E1, E2, E3 and E4 (Figure 1).

The distance between E1 and E4 is 13 km. In E2, E3 and E4 the river axis has a north-south direction; while in E1 the direction is northeast-southeast. The width of the river is not constant; in E1, E2, E3 and E4 it is 2.95 km, 2.00 km, 2.88 km and 3.00 km, respectively. The depths, referring to the average of the low tides of syzygy, in E1, E3 and E4 are 6m and in E2 (the narrowest) 9m, which will vary depending on the tidal cycle. The measurements were taken between june 27 and 30 during the lunar phase of spring tide.

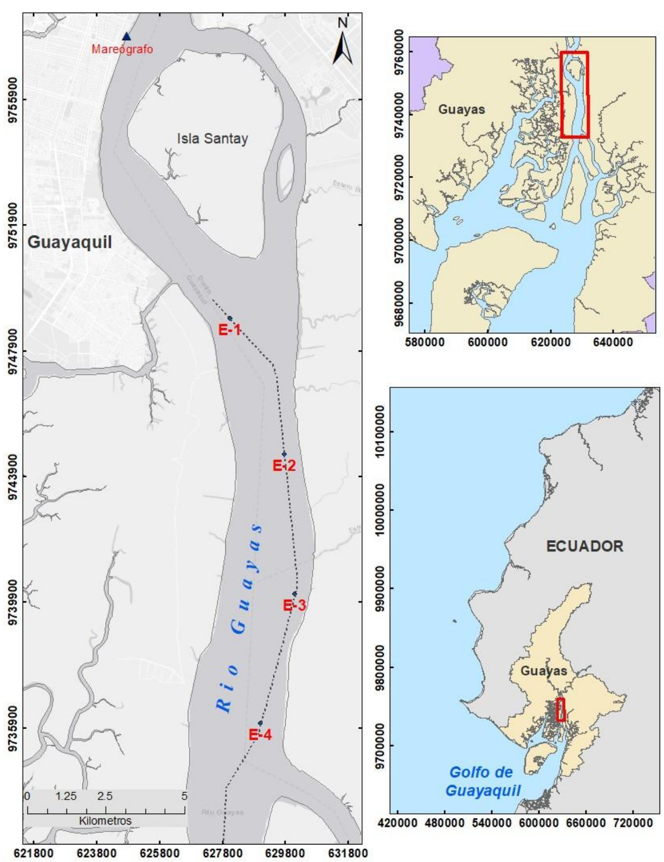


Figure 1. Study area and location of current and tide gauge stations.

Tides

To characterize the behavior of the tidal cycle in quadrature and spring tide, information from an INOCAR tide gauge was used, installed to the north of the current measurement area, next to the seawall in the center of the city of Guayaquil. The tide gauge consists of a counter pulley sensor, solar power and records information every minute, two months of information were used, february and august 2019.

The average tidal range and average time of duration of high and low tide were established. In addition, the daily tide curves of spring tide and quadrature were contrasted; and those of february and august, as representative of the two climatic seasons that occur on the coast of Ecuador; january to april, the rainy season, and may-december, the dry season (Cañadas, 1983).

Current measurements

a) Eulerian

The Eurelian method consists of measuring the current passing through a fixed point. Measurements were taken between june 27 and 30, 2006, at four named stations in the study area, for eight hours at each (Figure 1). A self-contained Acoustic Dopple Current Profiler (ADCP) from RD INSTRUMENTS was used. Instantaneous recordings of magnitude and direction of current profiles were made with the equipment submerged at 50 cm from the surface and the sensors directed towards the bottom of the river. In the configuration of the equipment, the recording of a profile every five minutes was established. Due to the characteristics of the equipment, measurements between 0 m and 3 m are not obtained. The first level with records was at 4 m, from there the vertical resolution was 1 m to the end of the water column. Due to the morphology of the measurement site, at stations E2, E3 and E4, the meridional component of the velocity (V) is parallel to the RG axis and the zonal component (U) is perpendicular. By convention, the U and V components are positive in the eastward and northward direction, respectively.

The variation in current direction due to the change in tidal state was analyzed at the four stations using the meridional velocity profiles, in addition, the zonal velocity profile (U) was also considered at the total change in current direction is represented as a 180° variation throughout the water column. In addition, the time lag between the tidal stoa and the change in velocity direction was calculated.

The depth was normalized, the values were referred to two levels, 0 and -1 (dimensionless); the value 0 represented the surface and -1 the maximum depth of each station at the instant of measurement (PRI). The ratio between the depth of each level and PRI represents the normalized depth (PRN), which has no units. The first meters, including the water layer without records (0 m to 3 m), correspond to the upper layer (CS), with PRN between 0 and-0.3; the intermediate layer (CI), with PRN between -0.4 and -0.6 and the deep layer (CP), with PRN between -0.7 and -1.

The section plots were made with Surfer 8 software, using the Krigging interpolation method.

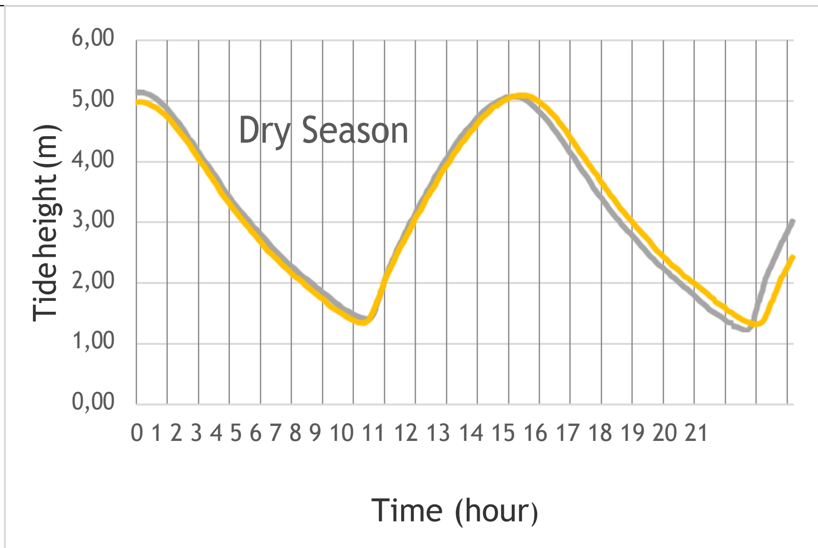
b) Lagrangian

The method consists of following in time and space the trajectory of the fluid. Drifters were used, whose structure consists of three parts: The lower part, which is submerged and is dragged by the current, is formed by two metallic sheets crossed each other, at a 90 degree angle; in the middle part, in order to obtain buoyancy, three buoys of approximately 15 cm in diameter and 8 cm thick, are placed on a central rod; while in the upper part, to facilitate identification when they move, flags of different colors are placed. The lower part is regulated at distances of 0 m and 3 m from the buoys, thus obtaining drifters to measure at the surface and at 3 m depth. These floats were placed in defined geographical positions so that they could move freely along the river, while their trajectory was tracked with a boat and their geographical coordinates were recorded in Universal Transverse Mercator (UTM) using a portable GPS, at 20-minute intervals, and finally the magnitude and direction of the currents were estimated. Measurements were taken on june 27 and 30, 2006, attempting to measure during the ebb and flow states of the tide.

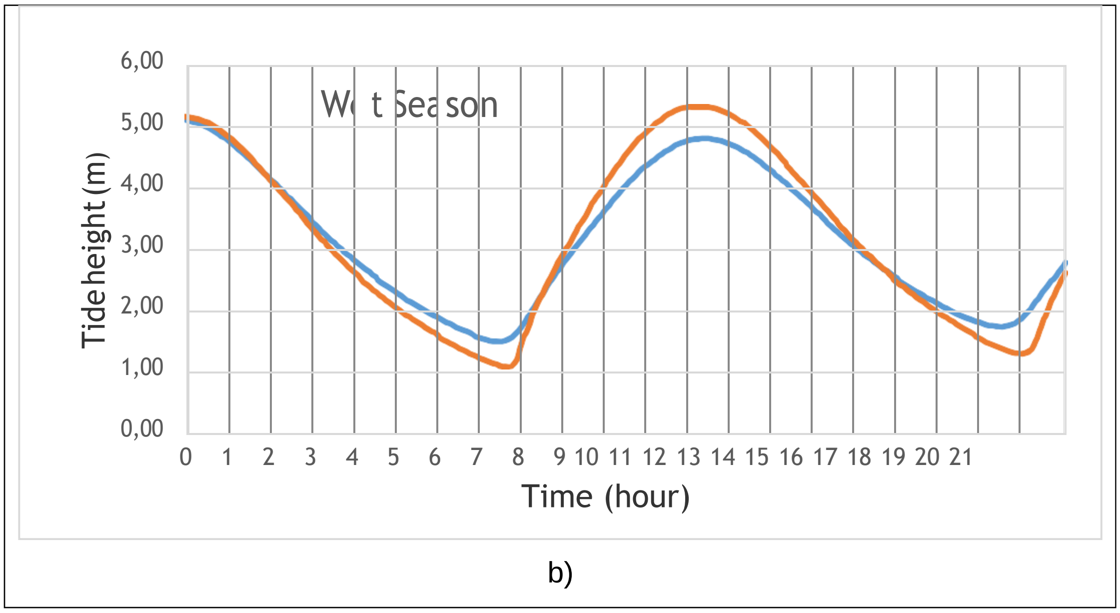
Results

Characteristics of the tide in the Guayas River.

In 2019, in february, the average tidal range amplitude in spring tide was 4.32 m and in quadrature 3.61 m; while in august it was 3.93 m and 3.77 m in the same order: This indicates that on average in the dry season the amplitude is lower than in the rainy season.



a)



b)

Figure 2. Tidal curve in the Guayas River. a) Dry season (August 2019 and b) Wet season (February 2019).

The analyzed measurements were taken during the dry season, in june in Sicily, so the mean depth of each station could increase up to 3.93 m at high tide.

As for the duration of the tidal states, it was verified that they varied according to the lunar phase and not the month. The flow, in quadrature has a duration of 4H50 minutes and in spring tide 5H5 minutes; while in ebb, in the same order, the duration was 7H20 minutes and 7H10 minutes, (Figure 2). The difference in time of each tidal state, quadrature or spring tide, is between 65% and 70% less in the ebb, a percentage that is not comparable with the 5% reported by (Murray *et al*., 1975), because they refer to a different sector in the inner estuary of the Gulf of Guayaquil

CURRENT PROFILES

Station 1

On june 27, 2006, observations were made at E1 with ebb tide, during most of the measurement time, bottom panel of (Figure 5). Observations started at 09H00, at ebb, 26 minutes after the high tide stoa (8H34) and ended at 17H00, at flow, almost two hours after the low tide stoa (15H25), in total measured for 6H with 48 minutes.

Four profiles of the meridional component of the current (V) are shown in (Figure 3). At 09H00 during the ebb (black profile in Figure 3), the V over most of the depth still retains a positive direction, with a maximum of 0.1 m/s at the CP. Five and fifteen minutes later the values are negative and positive, which is interpreted as double-layer circulation. From the bottom, -1(PRI) to -0.7 (PRI), the direction corresponds to flow and from that depth towards the surface, it is negative or ebb, with a range of currents between -0.15 m/s and 0.14 m/s. The 9:20 profile was completely negative (ebb direction) with a maximum absolute value of -0.25 m/s at -0.55 (PRI). The change in direction throughout the water column occurred after 46 minutes of the flow stoa.

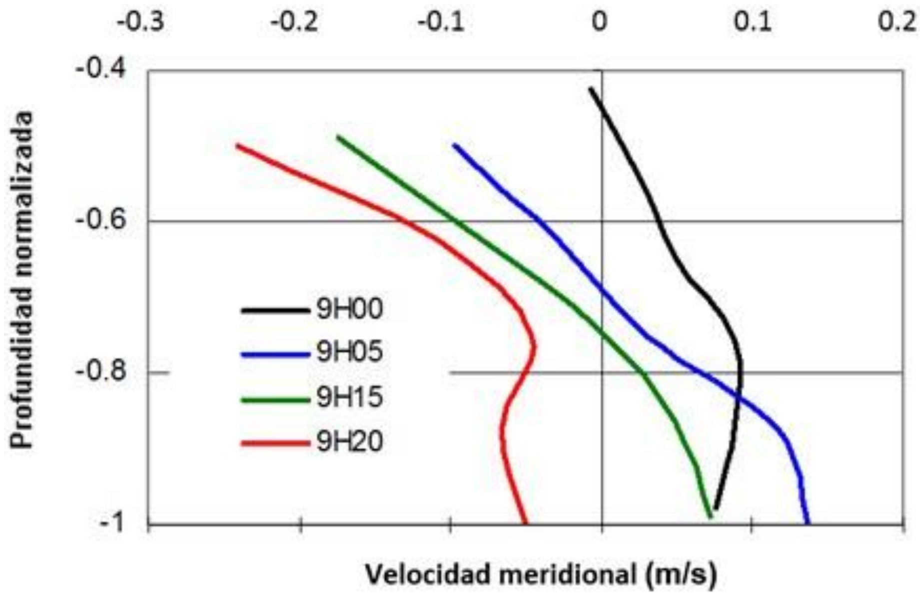


Figure 3. V-component velocity profiles during the change from the flow to the ebb direction at E1**.**

Figure 4 shows the change of direction of the zonal current (U), due to the effect of the tidal change (from ebb to flow). Although in the U component, the two-layer circulation was not as evident as in the V component, at 16H25 the change of direction towards the flow (west) from the deep layer began and at 16H35 (10 minutes later) the direction was westward in the entire water column. At low tide (15H25), the time that the change in velocity direction lasted was 1 h and 10 min.

The current in the ebb direction, throughout the water column, lasted for 7 hours, from 09H20 to 16H20.

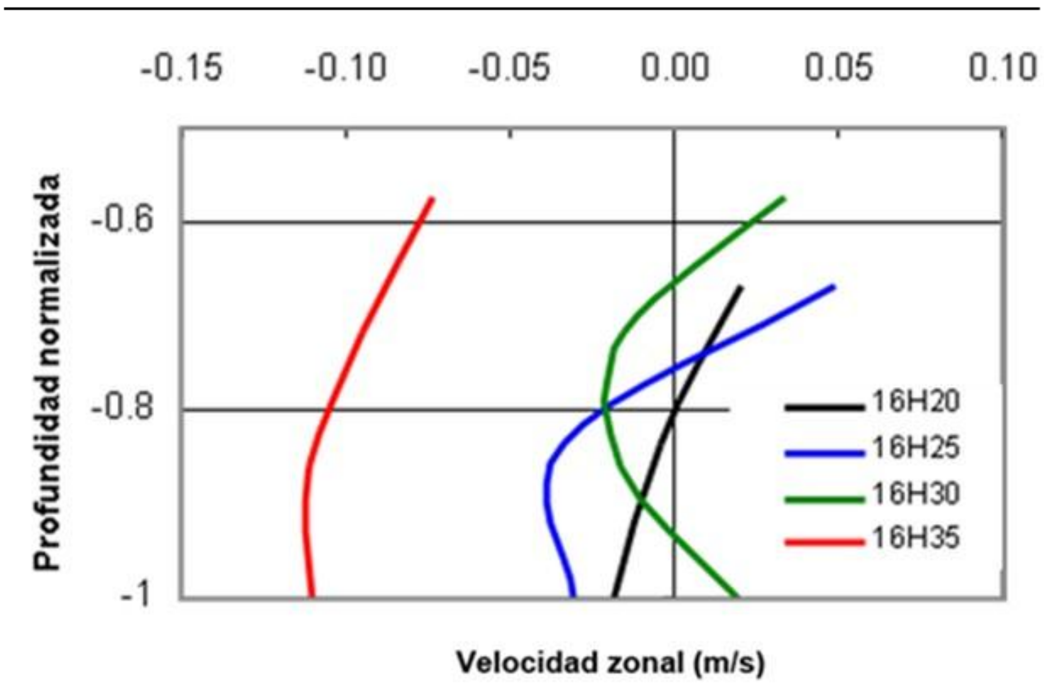


Figure 4. Profiles of the U component of the velocity during the change of direction from ebb to flow at E1.

The V and U components, (Figures 5a and 5b), had similar temporal patterns in the water column during the sampling time. The highest velocity occurred around 12H00 (~ 3 hours after high tide), when the V component, had a maximum of -0.8 m/s; while U had the highest record of 0.9 m/s. In U there was another maximum between 14H00 and 15H00, which was not recorded. Between 16H00 and 17H00 the inversion of the components was observed due to the change of tidal state, going from negative to positive values and from positive to negative in V and U respectively. At 16H15, after 50 minutes of low tide, the velocity was minimal (null).

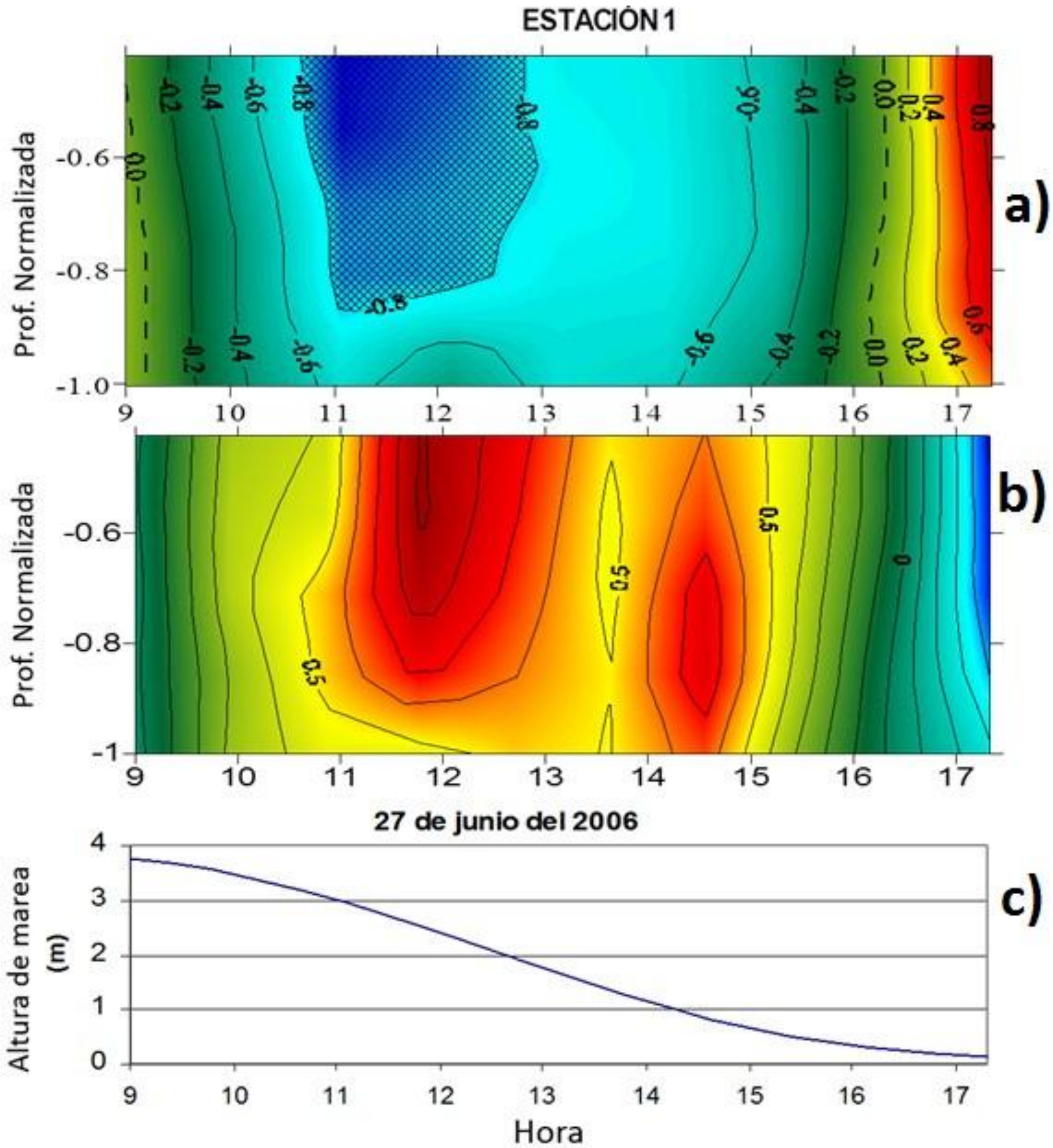


Figure 5. V (a) and U (b) components of velocity at E1, with respective tidal plot (c).Tidal data source: Online tide table, INOCAR, revised 2015.

The maximum total velocity at E1, was 1.38 m/s, with southeast direction (138°) and occurred at 11H40 at 6 m depth (CI), in ebb, which is reported in Table 1.

Station 2

In E2 the measurements were during 6H with 54 minutes on 28 june 2006, started at flowing tide and continued during ebb (Figure 7) bottom panel. The records started at 6H55, at flow, more than two hours before high tide and extended until 16H25, a few minutes after low tide (16H04).

The V component at the beginning of the day was positive or northward (flow) until 09H45 (35 minutes after high tide), when in the upper part of the profile (CI), a southward (negative) direction was observed, this change of direction occurred in the entire water column 25 minutes later, at 10H10, (Figure 6). Until the end of the measurements, the currents maintained the southward direction. One hour elapsed between the high tide and the change of direction in the entire profile.

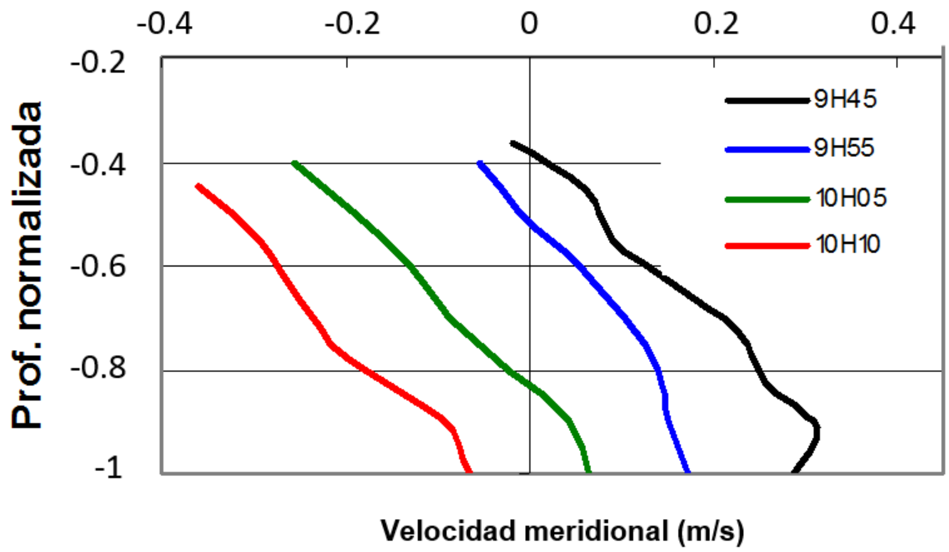


Figure 6. Profiles of the V component of the velocity during the change of flow direction to ebb at E2.

In (Figure 7), it was observed that the V component is 3.5 times larger than the U component, and that the U component hada predominant westward direction in the flow and eastward in the ebb. During the first two hours of flow, around 07H45, a maximum velocity (1 m/s) was observed only in the V component. After 10H10, in the ebb the maximum velocities occurred around 13H00 (four hours after high tide), with approximate values of -1.4 m/s and -0.4 m/s for V and U respectively. The direction of the V component remained southward until the end of the measurements (16H25), after 6 hours and 15 minutes.

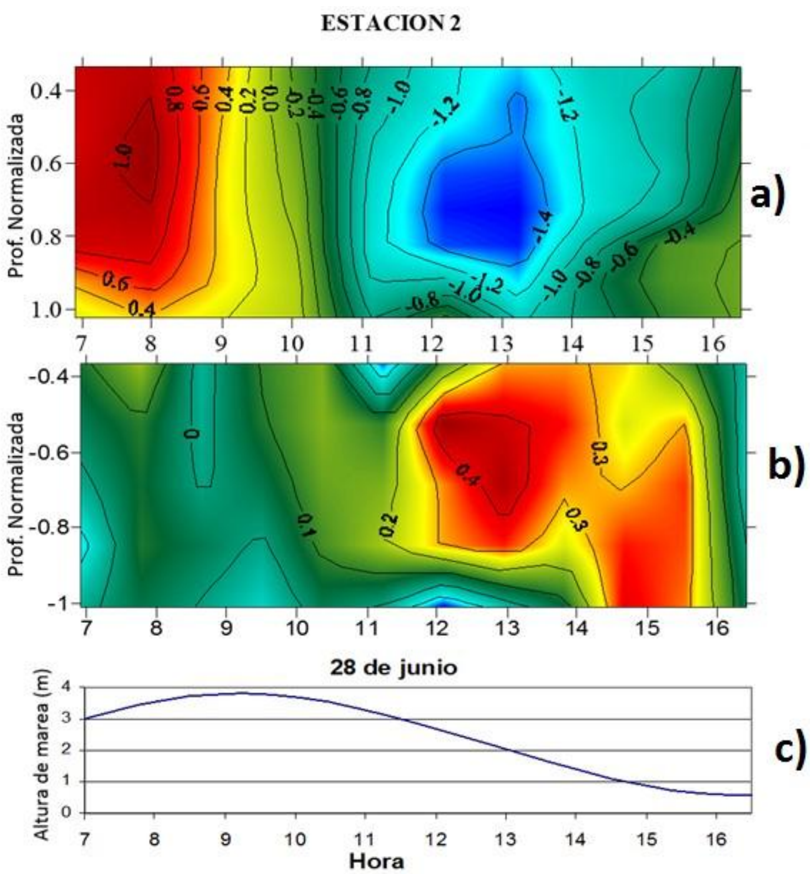


Figure 7. V (a) and U (b) components of the velocity at E2 (June 28th-20006), with their respective tide graph (c).

In the flow, the maximum total velocity value was 1.42 m/s with direction 356°. In the ebb, the maximum was 1.85 m/s (170°), at 13H42, at a depth of 7 m, (Table 1).

Station 3

In E3 the river axis has a north-south orientation, the measurement was made on June 29, 2006, from 09H05 in flow, 40 minutes before high tide stoa, to 16H00, 40 minutes before low tide stoa. Most of the measurement was performed during ebb, (Figure 9) bottom panel.

The change of direction of the V component of the flow velocity to ebb, started from the CP to the IC, 35 minutes after the stoa (10H20), 15 minutes later, at 10H35, the whole profile changed to negative or ebb direction, (Figure 8). From the high tide stoa (09H45) to the change of the flow current to ebb (10H35) in the whole profile, 50 minutes passed.

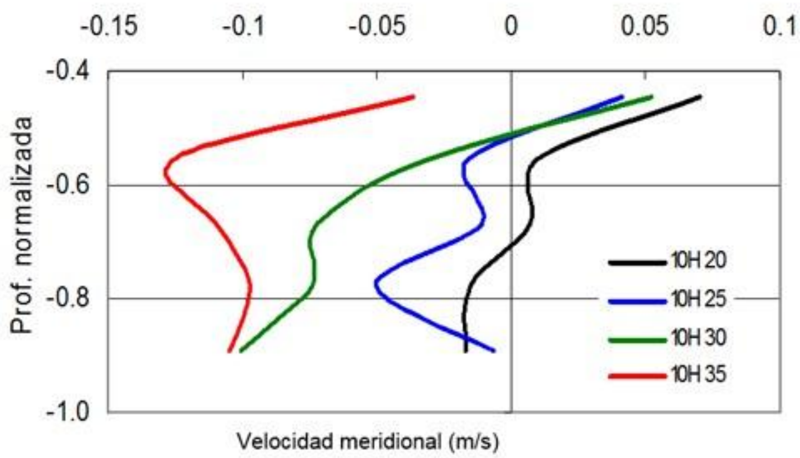


Figure 8. Change of current direction V from flow to ebb at E3.

The time section of the U and V components is shown in (Figure 9), the V component showed its maximum velocity in the ebb tide measurements, around 14H00. The U velocity, had no pattern in the tidal influence on the direction, and oscillated between positive and negative during the ebb. From 10H35 until the last measurement at 16H00, the ebb direction was maintained.

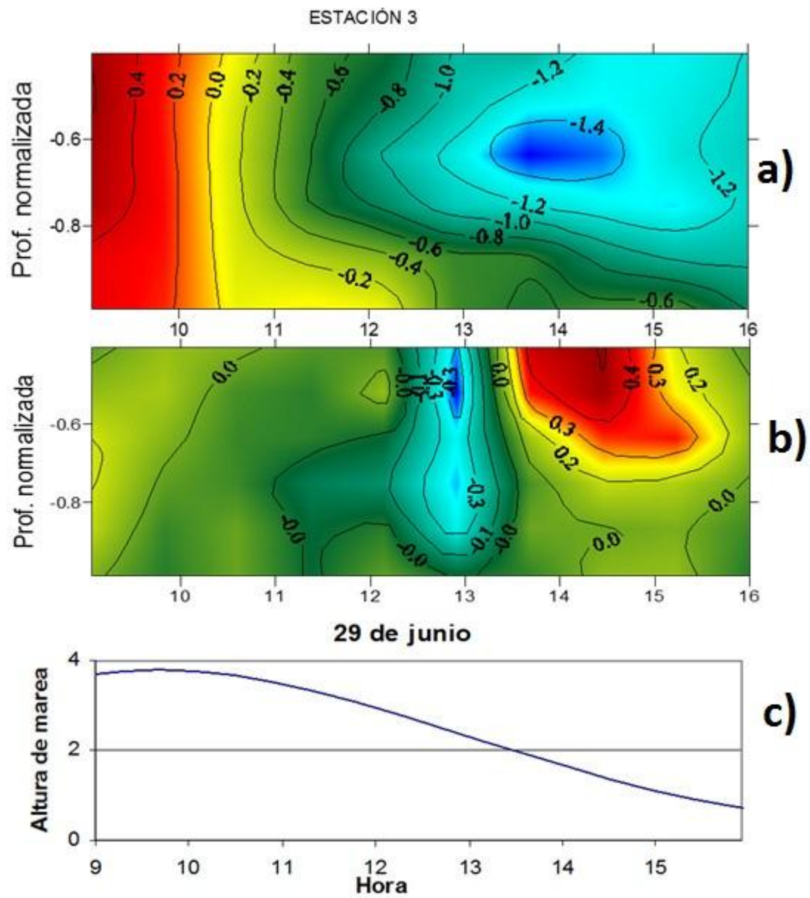


Figure 9. V (a) and U (b) components of the velocity at E3 (June 29th-20006). c) Tidal state during the measurement (c).

The maximum velocity value was during the ebb, at 13H50, with magnitude of 1.77 m/s with 180° direction at a depth of 5 m. (Table 1).

Station 4

At E4, measurements were made on june 30, 2006, from 07H10, three hours before high tide, to 16H35, at ebb. In the first hours the direction of the V velocity was northward.

The tidal change of direction (Figure 10), started 40 minutes after the stoa, at 11H00, from the intermediate layer to the surface and took 10 minutes (11H10) to completely change direction to negative or ebb, (Figure 10). 50 minutes elapsed from the high tide stoa (10H20) to the change of direction of the V current from flow to ebb.

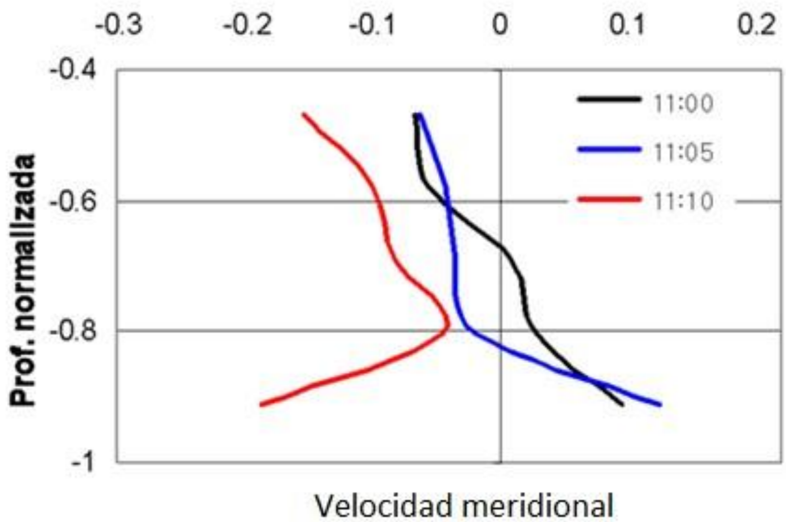


Figure 10. Change in current direction V at E4, from flow to reflux.

In the temporal distribution of (Figure 11), the change of direction of the flow current started at 11H00, 40 minutes after the high tide stoa, evident in the V component of the current, upper panel (Figure 11), the values changed from 0.6 m/s to -0.5 m/s in the water column.

The U component showed uniformity in the water column until 09H00 with positive values up to 0.3 m/s, then at ebb the component changes sign, not exceeding -0.1 m/s in absolute value.

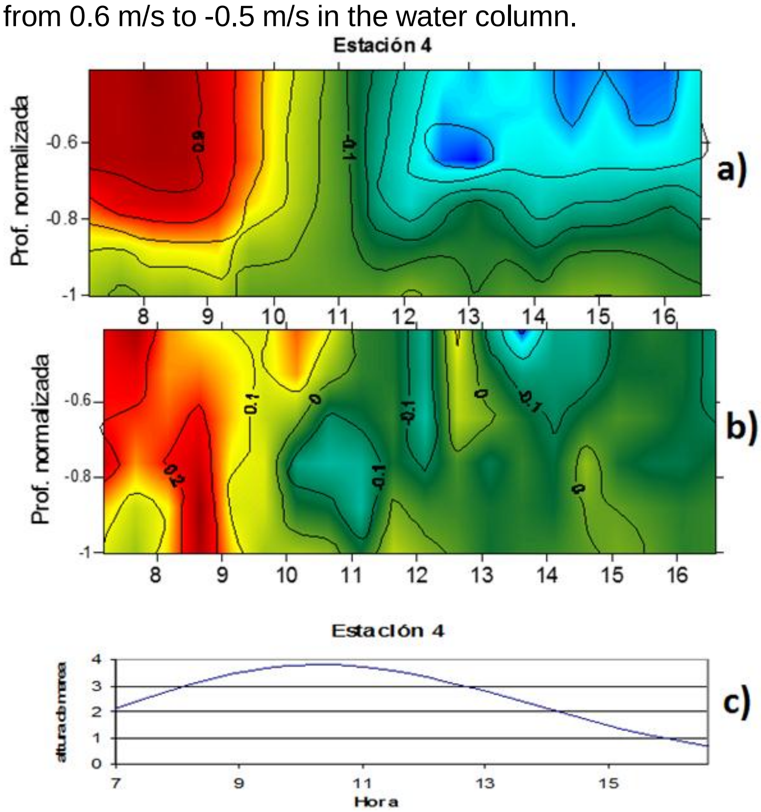


Figure 11. V (a) and U (b) components of the current at E4 with their respective tidal plot (c).

The maximum velocities for ebb and flow were found at mid-tide, (Table 1). In the flow the maximum velocity of 1.15 m/s magnitude and 1.8° of direction, occurred at 08H25, at 4 m depth and in the ebb at 13H10 (5 m) with magnitude of 1.19 m/s and 166° of direction.

Table 1. *Maximum speeds at each station.*

Station	Depth (m)	State of the tide	Magnitud (m/s)	Address (°N)	u (m/s)	v (m/s)
1	6	Reflux	1.38	138.2	1.01	-0.96
2	10	Flow	1.42	356	-0.11	1.42
	7	Reflux	1.85	170	0.267	-1.84
3	5	Reflux	1.77	180	0	-1.77
4	5	Reflux	1.19	166	0.284	-1.16
	4	Flow	1.15	1.8	0.156	1.14

At all four stations, most of the measurements were during ebb. In three of the stations, E1, E2 and E4, the change of direction began in the first measurement layers and then spread to the entire profile in a time between 10 and 25 minutes, being E2, being the deepest (9 m), the one that took the longest time to change the entire profile, (Table 2).

The response time between the stoa and the change of direction from flow to ebb was between 46 minutes and one hour. At the only station where, due to the characteristics of the measurement, it was possible to observe the change from ebb to flow, the response time of the current was one hour and fifteen minutes, (Table 2).

Table 2. *Time response of the direction of currents in the water column during tidal change.*

Station	Duration of total change of current direction in the water column (minutes)		Response time from stock to current change in the water column (minutes)		Direction of change
	V	U	V	U	
1	20		46		Flow to Reflux
		15		75	Reflux to Flow

2	25	60	-	Flow to Reflux
3	15	50		Flow to Reflux
4	10	50		Flow to Reflux

Currents between 0 and 3 m

Measurements were taken on june 27 and 30 at ebb and flow. The surface floats (0 m) are shown as a solid line and the 3 m deep floats are shown as a dotted line in (Figures 12 and 13).

In the ebb state, the maximum velocities were found with magnitudes up to 1.83 m/s at 3 m depth. The range of average values was between 0.41 and 1.07 m/s. At ebb tide, currents were of lower intensity with a maximum of 1.36 m/s at the surface and averages between 0.12 and 0.59 m/s (Table 3).

On june 27, the measurement began near the end of the flow tide and the drifters were released southwest of Santay island. At the surface level, it was observed that the floats near the shores of Guayaquil and Santay island (orange and yellow) headed northeast (direction of flow) for a short period (Figure 12A), while the one in the center of the channel (purple) immediately headed south. The 3 m floats behaved similarly to those planted superficially on the sides (Figure 12B).

The drifters followed along the entire study area from north to south; at the surface level, the drifters that reached the highest velocity were those that approached the eastern margin of the RG, (Figure 12A). At 3 m depth, the velocity was greatest where the drifters' trajectory coincided with the channel axis. The tidal change and the beginning of the high tide phase were observed, with the drifters heading north, parallel to the river margin.

Table 3. *Maximum and average velocities of the surface (s) and subsurface (p) floats.*

DATE	FLOAT	V.AVERAGE (m/s)	V.MAXIMA (m/s)	STATE OF TIDE
27/Jun/2006	0 m	1.05	1.71	REFLUX
	3 m	1.07	1.83 83	
	0 m	0.59	1.36	FLOW
	3 m	0.48	1.06	
30/Jun/2006	0 m	0.45	0.55	REFLUX
	3 m	0.41	0.88	

0 m	0.15	0.16	FLOW
3 m	0.12	0.34	

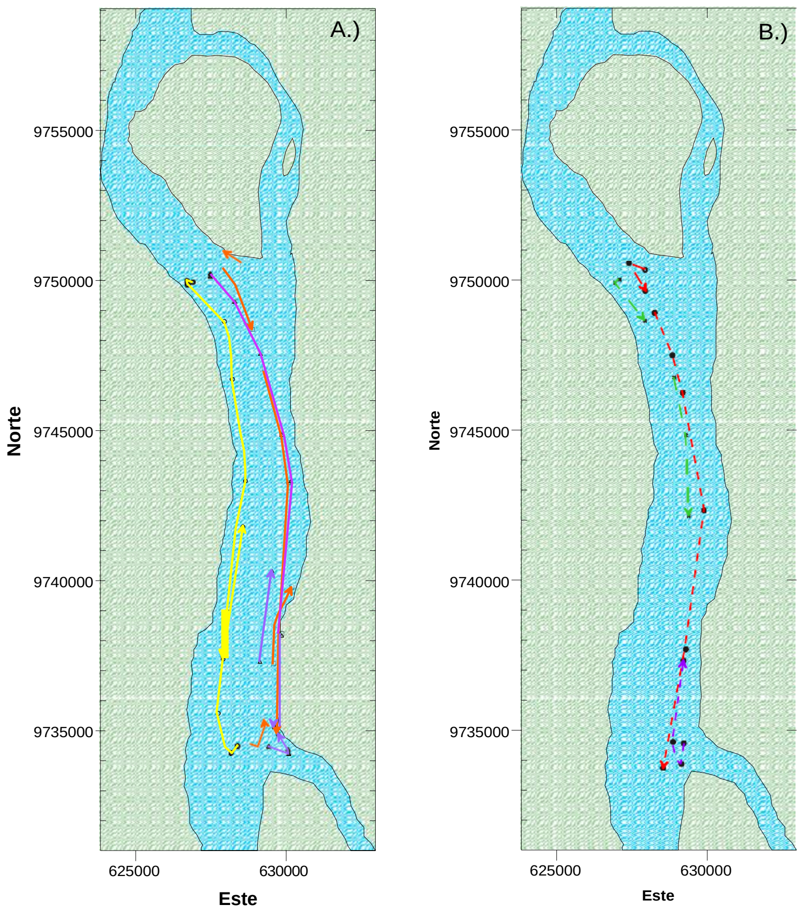


Figure 12 A-B. Float trajectory on June 27, 2006. a) 0 m depth and b) 3 m depth.

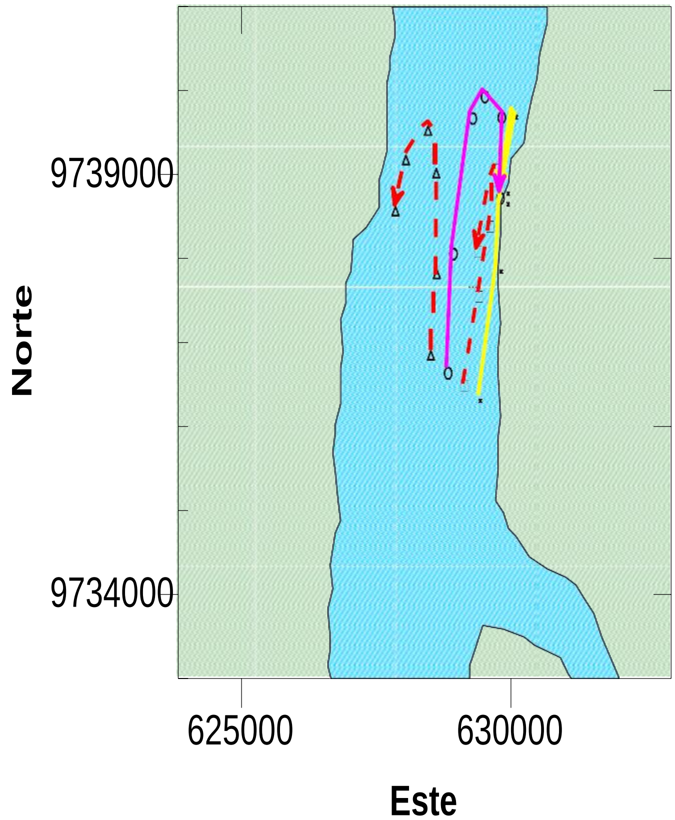


Figure 13. Float trajectory on June 30, 2006. The solid lines correspond to measurements at 0 m and the dashed lines to measurements in the 3 m layer. The measurement started with the tide in flow.

On june 30, the measurement period was shorter, which coincides with the change of tide from high tide to low tide, so minimum values of flow velocity are recorded, as shown in Table 3, however, despite the limited measurement time at low tide, the velocities recorded in ebb are higher than those of flow (Figure 13).

The change in direction of the current lines is parallel to the river margin, in the ebb state the current is directed towards the south; while in the flow state the currents are directed towards the north. In both states of the tide, the floats tend to cluster on the eastern margin of the Guayas river, close to the axis of the channel.

Conclusions

The orientation of the river Guayas in the study area is south-north, so the greatest changes in the current are in the meridional component. Its mouth is to the south of the study area, during the flow or inflow of seawater; the V component is to the north (positive) and during the ebb it is to the south (negative). Regarding the east-west component (U), it depends on the morphology of each station, only in E1 the east (positive) direction of the current is well identified characteristic of the ebb and flow, while in the other stations, it is variable.

The currents correspond to an estuarine system in which the direction and magnitude of the currents is basically governed by the state of the tide, so the minimum values occur between 10 and 15 minutes after the corresponding tidal wave (high or low tide).

The change of direction in the current profiles, on average, occurs 45 to 60 minutes after the stocking and the maximum values approximately 3 to 4 hours after the stocking.

At three stations, the change in tidal current direction from ebb to flow began in the upper layers, between 25 and 40 minutes after low tide; contrary to the change in direction from ebb to flow, which began in the lower layer, 56 minutes after high tide.

Ebb tidal velocities were higher than flow velocities, in other words, the river current meets the restoring force in the seaward tidal change. Generally speaking, inertia makes the change from ebb to flow direction more difficult than the opposite.

The highest velocities and the longest response time of the profile to the change of direction occurred at station 2, due to the greater depth with respect to the other stations.

The magnitudes of the velocities reached by the surface and subsurface floats during the observation days were higher during the ebb state as well as at the profiling stations.

The maximum velocities obtained in this study are in line with the order of magnitude of the velocities obtained in other studies carried out in the Guayas River, with a maximum of 1.83 m/s at 3 meters and 1.85 m/s at 7 meters.

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