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THE RELATIVE IMPORTANCE OF METEOROLOGICAL EVENTS, TIDAL ACTIVITY AND BATHYMETRY TO CIRCULATION AND MIXING IN KINGSTON HARBOUR, JAMAICA

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ABSTRACT

The objective of the study was to determine the influence of meteorological events (rainfall and wind) as well as tides and bathymetry on the circulation patterns of an enclosed embayment, Kingston Harbour, Jamaica. Current velocity, water temperature and water salinity were assessed at 20 stations within the harbor between December 1993 and February 1995. Meteorological events such as rainfall, wind velocity and tidal periodicity and amplitude were determined in association with routine sampling conducted at the 20 harbor stations. Results indicated that the harbor behaves in a complex manner and is best presented in sectors (zones). The outer harbor has estuarine characteristics and appears to be driven primarily by density/salinity gradients. After heavy rainfall (> 65 mm), there is an upper layer (0–5 m deep) of low-salinity water (31–35) flowing quickly (14 cm s^{-1}) out of the harbor, while below 5 m, more saline water (35–36) flows more slowly (~ 3 cm s^{-1}) into the harbor. A characteristic of the outer harbor is a deep, but narrow shipping channel where fast currents (max = 15 cm s^{-1}) facilitate constant water renewal, thus high water quality. Inner harbor circulation is most affected by tides, but the area also comes under the influence of low salinity water flowing from Hunts Bay as well as high winds from the southeast. Greatest water movement in the inner harbor (18 cm s^{-1}) was achieved when high winds combined with ebb tidal period. The upper basin is primarily affected by winds, which induce horizontal and vertical gyres in the area with little net horizontal movement. Surprisingly, the fastest currents (24 cm s^{-1}) were recorded in the eastern section of the upper basin; however, this was under conditions of high wind (> 4 m s^{-1}), high rainfall (> 65 mm) and a flooding tidal cycle, which produced the greatest movement throughout the harbor.

Kingston Harbour is a semi-enclosed body of water with an area of over 50 km^2. The harbor is situated on the south coast of Jamaica between 17° 57′ and 59′ N and 70° 46′ to 52′ W (Goodbody, 1970; Wade, 1972). It is bounded on the North by the city of Kingston with a population of > 600,000 and on the south by the Palisadoes; a narrow sand spit linking a number of limestone knolls (Steers, 1940; Goreau and Burke, 1966; Goodbody, 1970). The harbor is approximately 16.5 km long (east–west) and 2.7–6.5 km wide (north–south) and connects to the sea through an opening of approximately 3.2 km in width (Fig. 1).

Kingston Harbour may be divided into four regions (Fig. 1). These are the outer harbor, inner harbor, upper basin and Hunts Bay (Goodbody, 1970; Wade, 1976). The outer harbor is the area south of the ship channel, west of Middle Ground Shoal and extending to the north of the harbor between Lazaretto and Port Royal. It includes Hulk Hole (in the region of Mammee Shoal) and Port Royal Harbour, which are separated from one another by Pelican Shoal. The bathymetry of the outer harbor is variable, but is between 12.2–18.3 m. The Port Royal mangrove swamp, Middle Ground Shoal and the ship channel separate the outer harbor from the inner harbor. The ship channel has a maximum depth of 18 m near the outer harbor and minimum depth of 12 m near Mammee Shoal with the narrowest section of the channel being 243.84 m wide (Government of Jamaica, 1968;

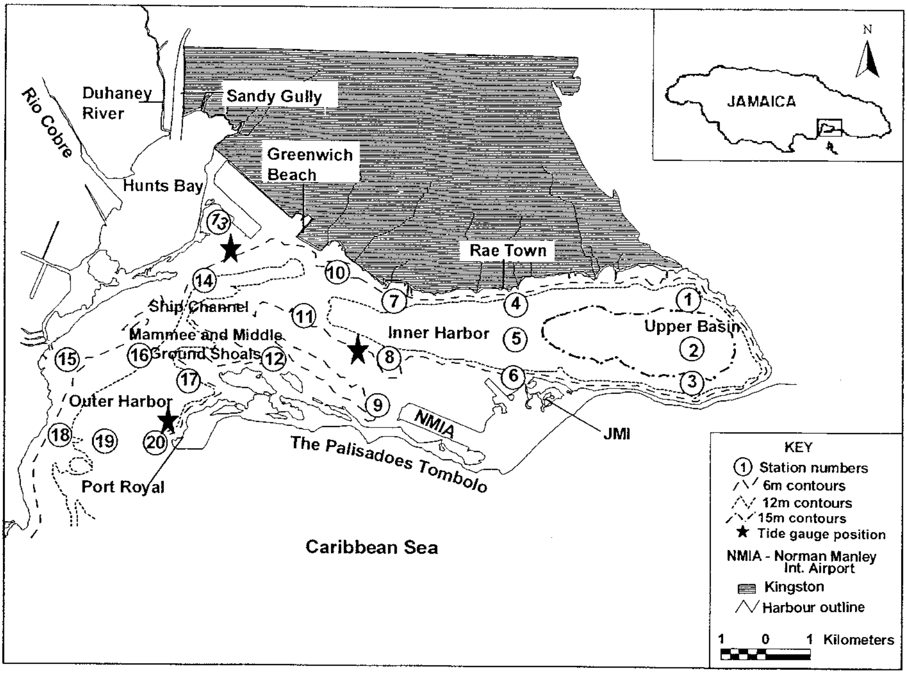

Figure 1. Map of Kingston Harbour showing major features, stations sampled and the position of tide gauges.

Goodbody, 1970). However, with a minimum depth of 10 m the ship channel does not allow direct communication between the deep waters on both sides of the channel (Goodbody, 1970).

The inner harbor comprises an area of approximately 25.90 km^2 with the landlocked basin at the eastern end known as the upper basin (Goodbody, 1970), deeper than both the inner and outer harbor (Fig. 1). Around most of the margin of the upper basin, the shoreline is steep and there are few areas of shallow water, the maximum depth recorded at 18 m. The southern section of the inner harbor is characterized by sand shoals and mangrove swamps that range in depth from 0.3–5.5 m, known as Mammee Shoal (Wade, 1976).

Hunts Bay is a shallow basin of an area of 10.10 km^2 with an average depth of 2.4 m. The actual depth ranges from 0.31–4.57 m (Goodbody, 1970; Wade, 1976; Ranston and Webber, 2003). The bottom sediments consist of soft mud and the waters are subjected to considerable salinity fluctuations due to fresh water run off from the Rio Cobre, Ferry and Duhaney rivers and the Sandy Gully (Fig. 1). Hunts Bay is now only connected to the harbor by a 213.36 m opening since the construction of the Causeway Bridge in 1969 (Fig. 1).

The increasing pollution of Kingston Harbour has become of major concern to many. The Government of Jamaica (1968) report provided insufficient evidence to determine circulation patterns and retention time of water within the harbor. Efforts to further determine the factors affecting the major circulation processes of Kingston Harbour amounted to estimates by Goodbody (1970) and some calculations based on salinity and temperature values by Sherwin and Deeming (1980).

With the continued developments along the shores of Kingston Harbour and increased pollution, knowledge of the circulation patterns and retention times within the harbor became more important. The Government of Jamaica (1968) report, which claimed that the harbor currents are mainly tidally driven, was refuted by Sherwin and Deeming (1980) who used mathematical formulae to show that the tidal amplitude was too low to be the driving force in the harbor. Sherwin and Deeming (1980) noted that the tidal prism flushing could make only a marginal contribution to harbor circulation, but there were no current velocity data available to confirm, or refute the claims. Also, the Government of Jamaica (1968) report made little reference of wind driven circulation or density driven circulation caused mainly by salinity gradient set up by fresh water input.

Goodbody (1970) and Wade (1976) suggested that wind could be the main driving force for currents in the harbor. They suggested that wind driven currents may override the tidal effect at the surface. This assumption was purely theoretical as there were no actual measurements. Sherwin and Deeming (1980) suggested that wind-induced circulation was the most important factor contributing to the longitudinal mixing of the harbor while density currents acted against the wind. In later years, it became generally agreed that density currents dominated the outer harbor (Shurland, 1988), however, these conclusions remain open to further speculation because sampling was conducted during the dry season.

Sherwin and Deeming (1980) provided the first estimate of the flushing rate within the harbor and calculated flushing rates and exchange flux for the inner and outer harbor. The flushing time was estimated as 28.9 d in the absence of low freshwater and 27 d after large freshwater inflow. Although Sherwin and Deeming also calculated the flushing time of the inner harbor (25 d) and outer harbor (3.3 d), they suggested that a more detailed examination was needed to determine the fate of pollutants in the harbor. Moreover, there was evidence of biological and aesthetic deterioration in the harbor as shown by the abiotic conditions in the bottom sediments and the increasing occurrence of red tides and phytoplankton blooms (Grahame, 1977). Changes in zooplankton abundance and composition (Grahame, 1974), and disappearance of benthic fauna were documented by Wade (1976) who predicted that if the influx of organic matter (both soluble and insoluble) and nutrients were not greatly reduced the ecology of the harbor would be irreversibly changed. The present study uses direct measurement to provide information on the circulation patterns within Kingston Harbour under different environmental conditions.

Materials and Methods

Twenty stations were selected within the harbor based on the criteria that they adequately represented the harbor and could be realistically sampled within the four hour tidal phase (Garcia, 1993, 1994; Fig 1). Station location was determined by triangulation using land marks and navigational buoys.

Bimonthly sampling was carried out between May 1994 and July 1995; between 0600–1000 hrs, or 0700–1100 hrs depending on the day length. The sampling times varied depending on the tide, wind and rainfall events. Current vectors were recorded using a Tojo Dentan CM2 model current meter (accuracy ± 1.0 cm s^{-1}). Readings were taken at 0.2 m from the surface and subsequently at 1 m intervals through the water column. The current data were grouped and chosen for presentation according to the dry and wet season, tidal cycles (ebb and flood) and windy and calm period they represented. Monthly rainfall and daily wind data were obtained from the meteorological station at the Norman Manley International Airport (NMIA) situated on the Palisadoes southern boundary of the harbor (Fig. 1). Wind speed and direction were also recorded at the time of sampling using an anemometer. Summarized wind data for the sample period were used to determine windy and calm periods (Williams, 1997; Bigg and Webber, 2003). Horizontal current vectors were plotted across the harbor at surface, 1 and 9 m depths. Temperature and salinity data were collected contemporaneously with the current data using a YSI model salinity/temperature meter (accuracy ± 0.5 salinity and ± 0.5° C temperature).

Tide data were obtained from three Valeport BTH 720 self-recording tide gauges placed at three stations (KH-1, KH-3, KH-4) in the harbor, during the summer of 1993 (Fig. 1). Data from these were used to determine tidal amplitude over long periods within the harbor (Williams, 1997; Bigg and Webber, 2003). Another tide gauge (model SR10) was placed at the Port Royal Marine Laboratory from November 1994 to July 1995. The data obtained from the SR10 tide gauge were used to determine the tidal cycle over which sampling was conducted. Bathymetry of the upper basin, inner and outer harbor used in the consideration of depth related currents and temperature profiles were obtained from a 1995 detailed bathymetric survey of Kingston Harbour (Williams, 1997).

Results and Discussion

The circulation patterns that regulate the mixing processes in Kingston Harbour and the interchanges with the open sea are governed by the following factors: fresh water input to the harbor, which is evidenced by its salinity, the prevailing wind and tides, and the change in bathymetry in the different areas/zones of the harbor.

Effect of Rainfall on Kingston Harbour.—Jamaica experiences alternating wet and dry seasons annually. During the sampling period there were three wet seasons and two dry seasons. The major wet seasons occurred between May and June 1994 and between October and November 1994 (Fig. 2). These corresponded to those noted by Goodbody (1970), Lindo (1988) and Webber (1990). There was a significant difference between the wet and dry seasons with the wet season having 5.5 times more rainfall than the dry season (> 65 mm per mo indicating the wet season).

Fresh water enters the harbor at Hunts Bay from two main rivers, the Rio Cobre and the Duhaney, and by a drainage scheme, the Sandy Gully as well as via several intermittent streams. The most important source of fresh water is the Rio Cobre, which has a mean discharge of approximately 6.2 m^3 s^{-1}, but during flash flood peak flow may rise to 283

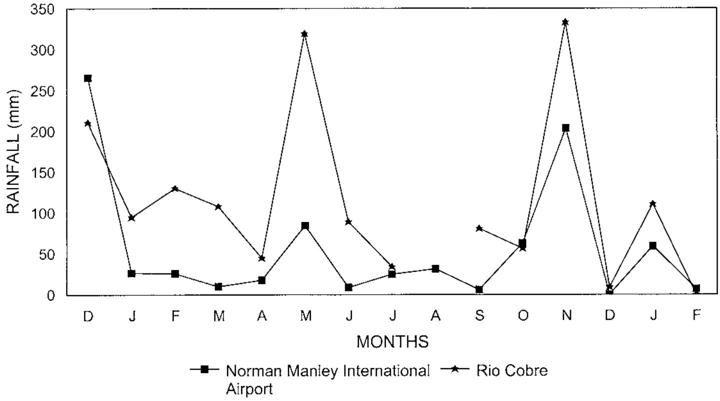

Figure 2. Plot of annual rainfall distribution in mm for the sampling period December 1993 – February 1995 at the Norman Manley International Airport and at the Rio Cobre (Dam Head) meteorological stations.

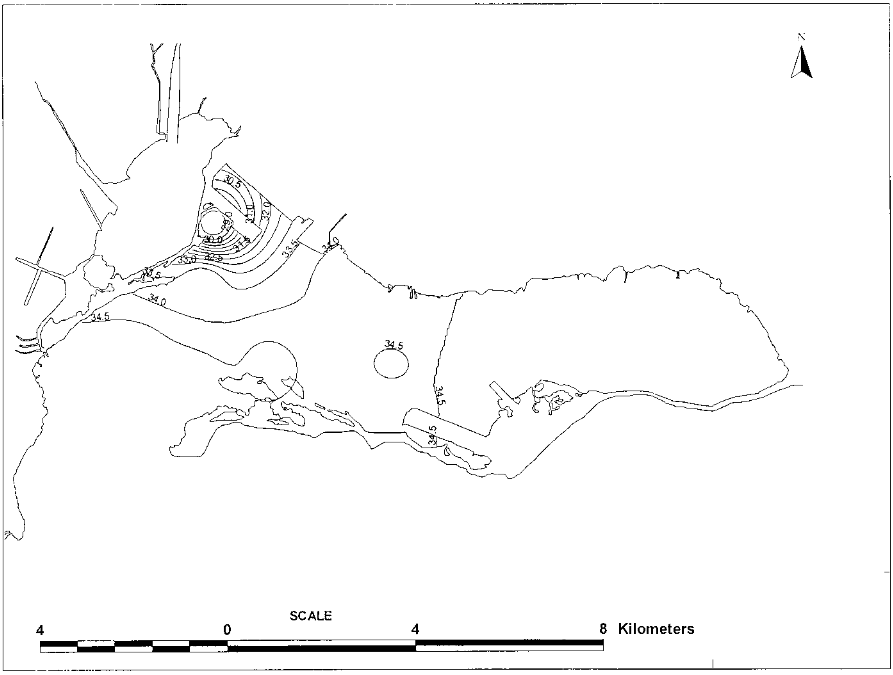

Figure 3. Horizontal distribution of salinity in the surface waters (0.2 m) of Kingston Harbour during the conditions of dry season, no wind and ebb tide (DCE).

$m^3 s^{-1}$ (Government of Jamaica, 1968; Wade, 1976). On the other hand, the Duhaney river maintains a fairly uniform discharge throughout the year and has an average flow of about 2.83 $m^3 s^{-1}$, or less than half that of the Rio Cobre. The discharge rate of the Sandy Gully over a one-year period was approximately 61,317 million liters, or 1.9 $m^3 s^{-1}$ (Government of Jamaica, 1968; Wade, 1976).

When there is significant land runoff, water also enters the harbor along its northern shore via several gullies. The flow rate of these gullies on the north shore was 1.7 $m^3 s^{-1}$, or 54,504 million liters per year. It is estimated that 662 km^2 of land drains directly into Hunts Bay, but only 52 km^2 drains directly into the inner harbor (Government of Jamaica, 1968; Wade, 1976).

For the sampling period, it was evident that during the dry season the mean discharge to the harbor, via Hunts Bay, was sufficient to maintain a superficial layer (0.25 m), in the outer harbor (Fig. 3). This superficial salinity layer created a strong density driven current (22 cm s^{-1}) flowing southeast out of Hunts Bay, then south into the outer harbor, where it slowed to 6 cm s^{-1} (Fig. 4). This Hunts Bay outflow current was among the fastest currents recorded in the harbor over the entire sampling period. At the same time there was a strong (9–15 cm s^{-1}) subsurface (9 m) reverse current flowing into the harbor through the ship channel (Fig. 5).

The expected influence of increased surface currents associated with the introduction of large volumes of low salinity water was not obvious during the sample period. Upper basin surface currents were faster under dry conditions (Fig. 4) when gullies to the north of the harbor were dormant and slower during wet conditions when both river and north

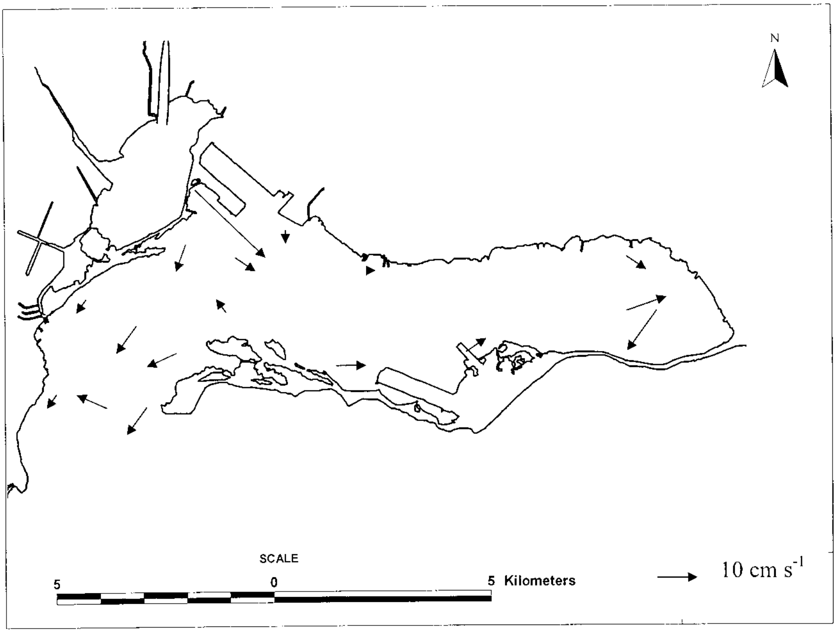

Figure 4. Currents in the surface waters (0.2 m) of Kingston Harbour during the conditions of dry season, no wind and ebb tide (DCE).

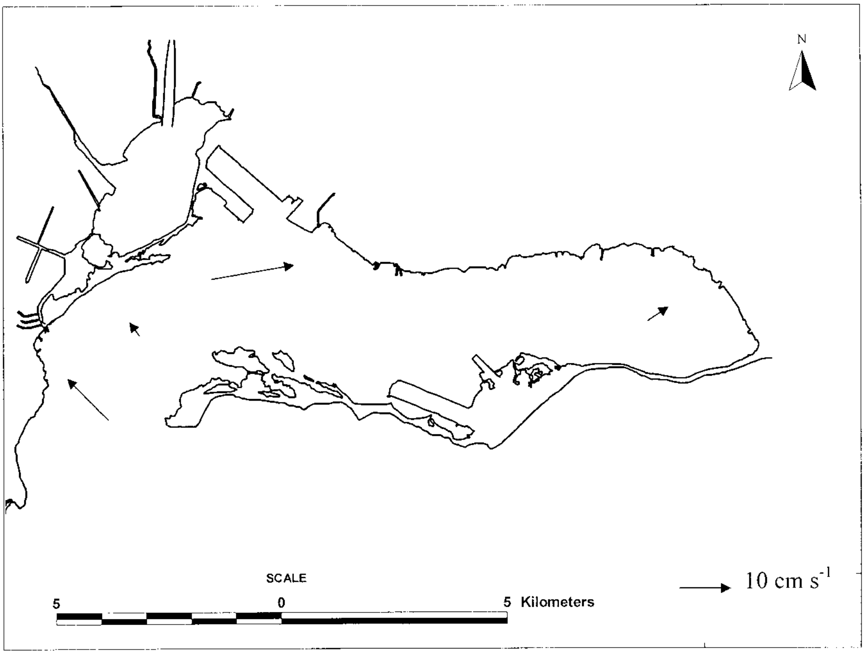

Figure 5. Currents in the deep waters (9.0 m) of Kingston Harbour during the conditions of dry season, no wind and ebb tide (DCE).

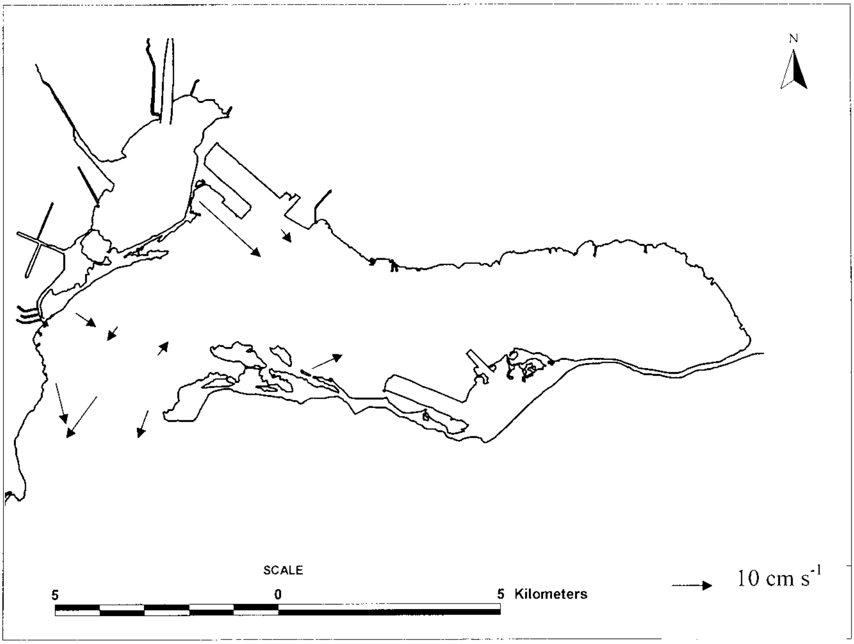

Figure 6. Currents in the surface waters (0.2 m) of Kingston Harbour during the conditions of wet season, no wind and ebb tide (WCE).

shore gullies contributed significant fresh water (Fig. 6). Therefore, the upper basin surface currents are not salinity dominated. In addition, the weak subsurface (9 m) currents recorded under dry conditions dissipated under wet conditions (Fig. 7).

When rainfall > 65 mm (high rainfall or wet season) and strong surface currents (maximum 22 cm s^{-1}) exit Hunts Bay, their effect is felt as deep as 5 m in the outer harbor. In fact, density currents dominated the circulation pattern in the surface layer of the outer harbor, during both the wet and dry seasons, but only extended their effect to the deeper layers of the outer harbor during the wet season. This is similar to the findings of the Government of Jamaica (1968), Sherwin and Deeming (1980) and Shurland (1988), who suggested that the density currents are most important in the outer harbor. Sherwin and Deeming (1980) quantified density driven currents for the outer harbor and calculated speeds at the surface of 3.6–6.5 cm s^{-1}. A maximum velocity of 120 cm s^{-1} was reported associated with a 10 yr flood event by Goodbody (1989), with a mean non-flood flow of 23 cm s^{-1}. During this study, a maximum speed of 22 cm s^{-1} for the density currents in the outer harbor was recorded. Although density/salinity currents still dominated surface currents, their increased depth of influence significantly reduced the deep (9 m) return (northeast) current, slowing these to 2–5 cm s^{-1} (Fig. 7).

During the wet season, the high discharge from Hunts Bay towards the inner harbor, caused the density controlled layer to be extended to 1 m depth within the inner harbor. This was further influenced by the northern gullies that contributed significantly to lowered salinity in the upper basin (Fig. 8). Wet conditions clearly disturbed the circulatory process in the upper basin and inner harbor by retarding current speeds, confirming that high currents and greatest mixing in this part of the harbor are not density/salinity depen-

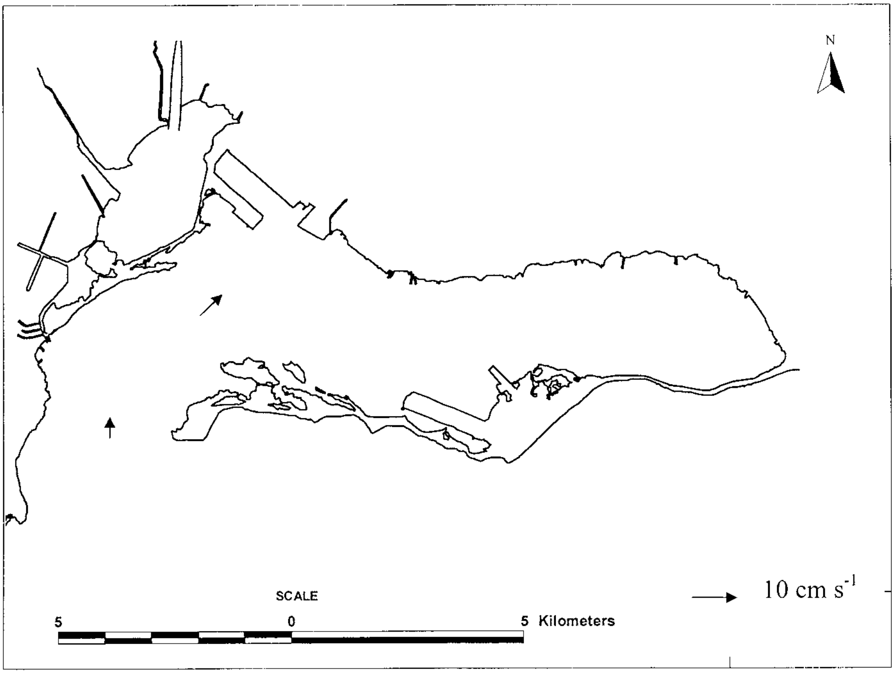

Figure 7. Currents in the deep waters (9.0 m) of Kingston Harbour during the conditions of wet season, no wind and ebb tide (WCE).

dent. Deep waters within the entire harbor showed negligible salinity variations, thus strong deep currents such as those entering the outer and inner harbor via the shipping channel must be either wind or tidally driven.

EFFECT OF WIND ON KINGSTON HARBOUR.—Winds were strongest from July–September. However, the strongest gusts were in July, with a wind gust (e.g., 1995: 27.5 m s^{-1}) of more than twice the regular speed (1995: 12.5 m s^{-1}). Winds were mainly from the ESE for most of the sampled year (Table 1). When there was a change in direction, winds came from the SE. During the dry season the wind was stronger (Max. 14.5 m s^{-1}) than during the wet season (Max. 9.0 m s^{-1}). During the day, the wind peaked (13 m s^{-1}) between 1000–1600 hrs and low wind speeds (2.1–5.0 m s^{-1}) occurred between 0000–0900 hrs (Williams, 1997). This agrees with previous studies by Government of Jamaica, (1968) Wade, (1972); Hendry, (1979); Sherwin and Deeming, (1980) and Shurland (1988), who stated that winds varied diurnally, were mostly sea breezes from ESE and SE, and were invariably > 5 m s^{-1}. While the diurnal pattern was maintained during this study, the winds in the calm periods were mainly from the ENE (< 3.5 m s^{-1}) and during the windy periods the winds were mainly from the SE and ESE (15 m s^{-1}). The findings by Shurland (1988) that wind speeds were usually < 5 m s^{-1} in the early morning hours and increased by a factor of 2–3 in the early to late afternoon, agreed with the present study.

It has been estimated that the frictional drag of the wind blowing in a constant direction for a prolonged period of time induces currents or wind drift, which in the open sea averages 1.5–2 % of the wind velocity. This was evidenced in this study where SE winds of 4 m s^{-1} produced current speeds of approximately 9 cm s^{-1}, 2.2 % of the wind speed.

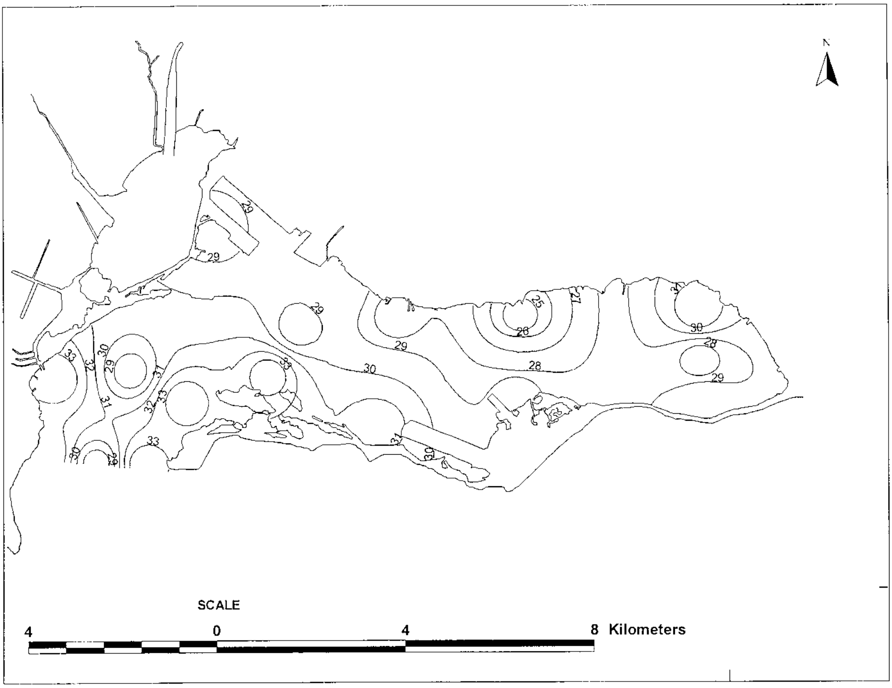

Figure 8. Horizontal distribution of salinity in the surface waters (0.2 m) of Kingston Harbour during the conditions of wet season, strong wind and ebb tide (WWE).

Table 1. Average wind speed (m s^{-1}) and direction (in degrees and Cartesian coordinates), and wind gusts for Kingston Harbour for the sampling period (April 1994–July 1995, inclusive).

Month	Average wind speed (m s^{-1})	Average wind direction	Average wind direction	Wind gust speeds (m s^{-1})
April	10.5	292	ESE	20.0
May	11.0	289	ESE	22.5
June	14.0	284	ESE	23.5
July	14.5	280	ESE	25.0
August	12.5	275	ESE	22.5
September	12.5	275	ESE	22.0
October	9.0	275	ESE	22.0
November	9.5	305	ESE	20.0
December	9.0	337	SE	21.0
January	9.5	337	SE	24.5
February	9.5	335	SE	20.0
March	9.5	280	ESE	22.5
April	12.0	265	ENE	22.0
May	12.0	275	ESE	23.0
June	13.0	277	ESE	24.5
July	12.5	285	ESE	27.0

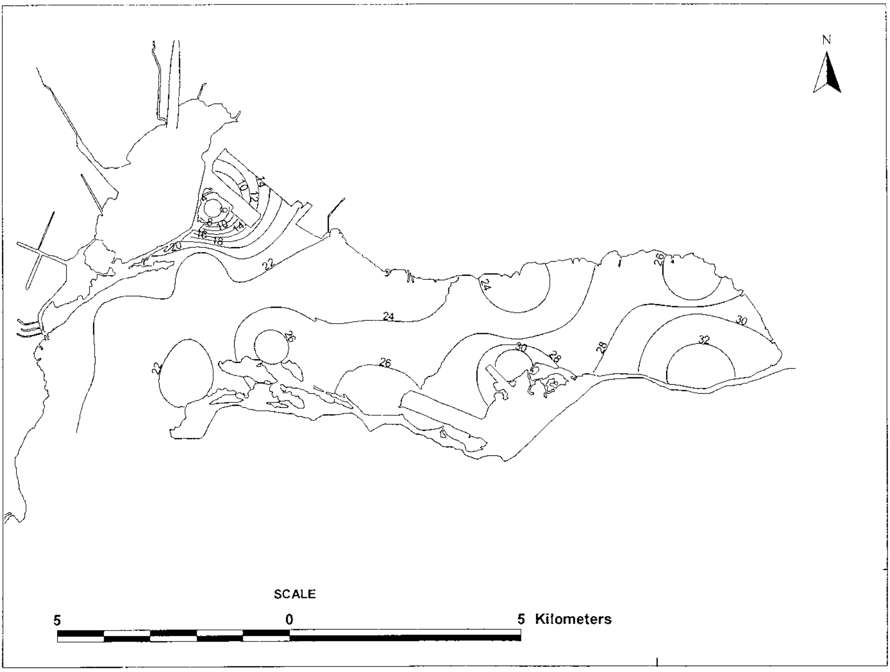

Figure 9. Horizontal distribution of salinity in the surface waters (0.2 m) of Kingston Harbour during the conditions of wet season, strong wind and flood tide (WWF).

Wind blowing from the NE for most of the night would produce currents flowing mainly towards the SW during the night. In the day, as the wind blows from the SE and SSE, the currents in the southern region would be the first to be influenced and the currents in these regions would flow towards the NW and NNW.

The effect of the winds on the distribution of low salinity waters of Kingston Harbour was most notable during high wind periods. Under windy and wet conditions, wind from the ESE, or SE entrained water onto the north shore such that low salinity waters had less of an effect on the inner harbor and upper basin (Fig. 9). The high winds also promoted greater mixing in the upper basin by promoting a vertical gyre, due to opposing surface and deepwater movement (cf. Fig. 10,14), which resulted in upwelling in the southeastern section of the upper basin. As low salinity surface water (22–24) is entrained to the northwest shore, the upwelling of more saline water (30–32) in the southeastern section of the upper basin becomes evident (Fig. 9). This vertical gyre seems to have been initiated by the opportune alignment of ESE winds along the east–west long axis of the inner harbour and upper basin, which terminates at the shallows that separated outer and inner harbor areas.

These opposing currents along with higher temperatures in deeper waters (1.5–2.0º C differences) resulted in thermal inversion through the water column. During the rainy season, the colder low salinity water flowed on top of the usually warmer harbor water resulting in further differences in temperature between surface and bottom layers. Sherwin and Deeming (1980) showed that surface temperatures have a larger diurnal variation than those at the bottom. This leads to a temperature inversion between 2300–0700 hrs.

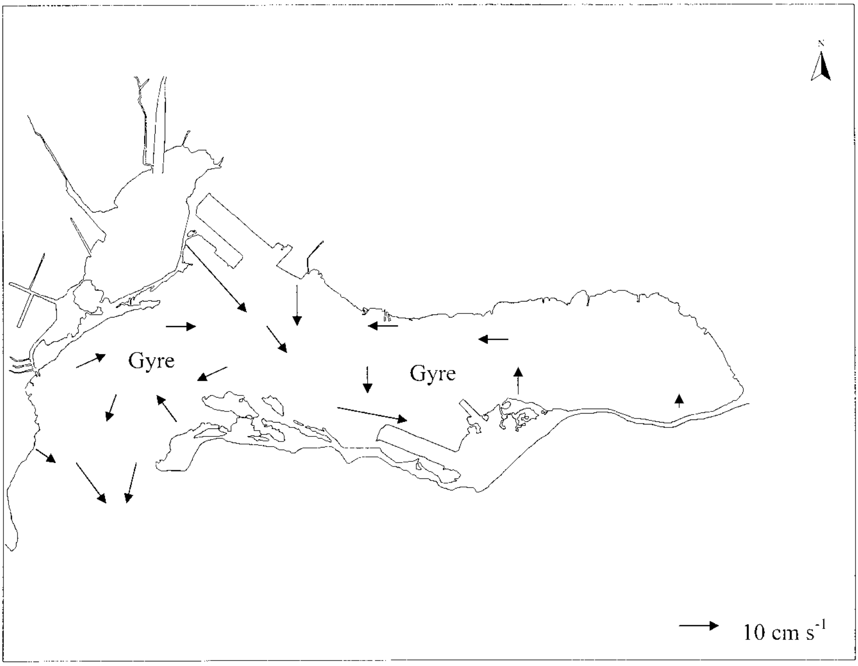

Figure 10. Currents in the surface waters (0.2 m) of Kingston Harbour during the conditions of dry season, strong wind and ebb tide (DWE).

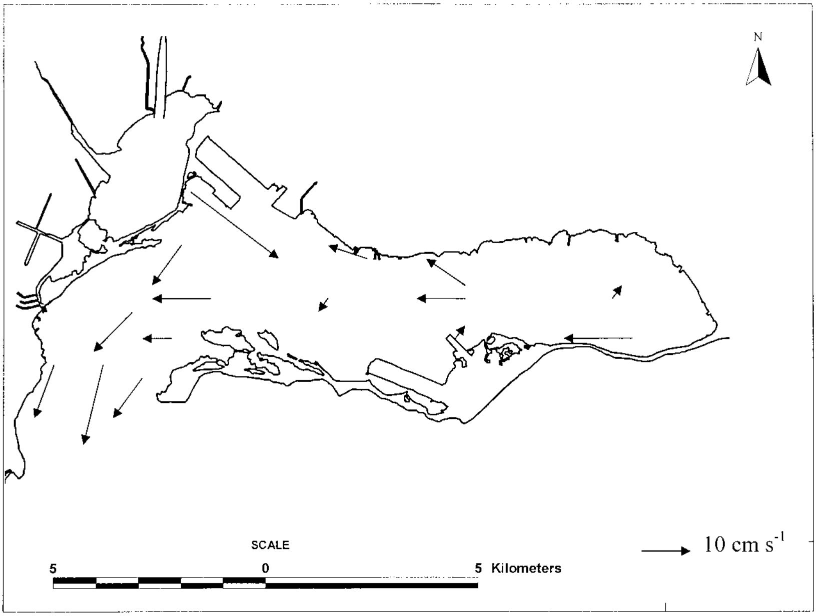

Figure 11. Currents in the surface waters (0.2 m) of Kingston Harbour during the conditions of wet season, strong wind and ebb tide (WWE).

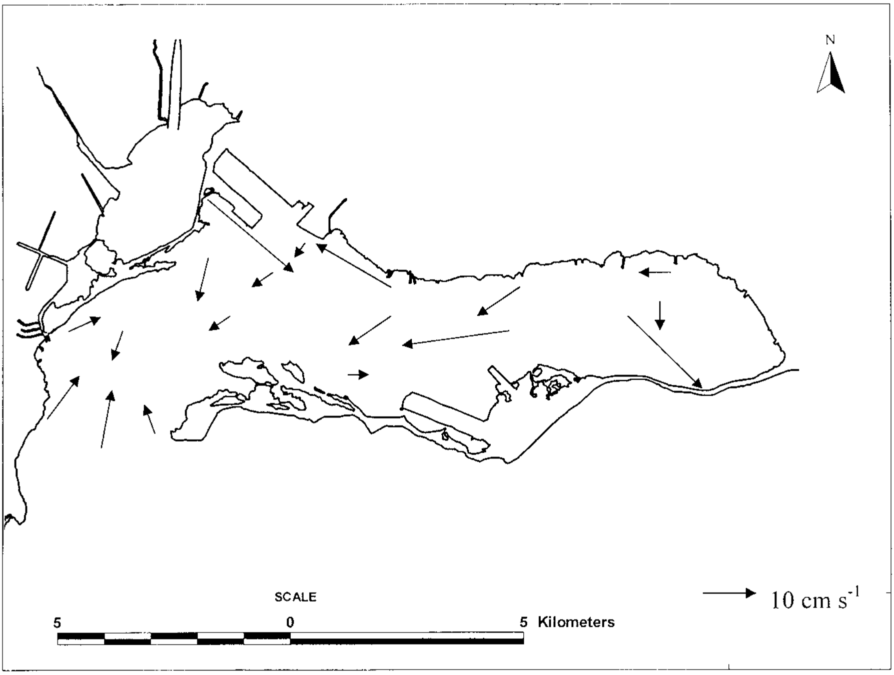

Figure 12. Currents in the surface waters (0.2 m) of Kingston Harbour during the conditions of wet season, strong wind and flood tide (WWF).

The inversion of the temperature causes the water column to become unstable, resulting in vertical mixing even in the absence of wind (Sherwin and Deeming, 1980).

The characteristic outflow from Hunts Bay often separates into two streams, one flowing ESE towards the inner harbor and the other SW towards the outer harbor. The ESE inner harbor flow, when combined with strong SW winds, initiated a horizontal gyre in the inner harbor (Fig. 10). Thus, in the upper basin currents flowed in all directions and effected mixing, but there was no net outflow from the basin. A second, but less defined horizontal gyre, was also observed in the outer harbor. Wind generated gyres in the harbor occurred more than once during the sampling period. Although, most common in the upper basin, gyres were also observed in the outer harbor under conditions of dry season, high wind and ebb tide, and wet season, high wind, and flood tide (Figs. 10,12).

Increased wind in the absence of high rainfall had little effect in the outer harbor where currents remained the same under high and low wind conditions (Fig. 10). Inner harbor currents were increased under windy conditions, while upper basin currents were decreased to less than 1 cm s^{-1} (Fig. 11). Windy conditions during the rainy season resulted in significantly faster currents throughout all three zones of the harbor (Fig. 12). Strong outer harbor surface currents (14 cm s^{-1}) flowed southwest (leaving the harbor) while inner harbor surface currents (10 cm s^{-1}) flowed west out of the harbor. The deep (9 m), strong (9–15 cm s^{-1}) return current in the ship channel that was reduced during rainy calm conditions, remained reduced (4 cm s^{-1}) under windy conditions. The effect of high wind, therefore, has less influence than tides on deep-water circulation in the harbor and has different effects in surface and 1 m layers, especially in the upper basin and inner harbor.

The combination of high wind with rainy conditions yields the greatest circulation throughout the entire harbor (Fig. 12). The fastest current (24 cm s^{-1}) was recorded under wet season, high wind, and flood tide conditions.

Effect of Tides on Kingston Harbour.—Over the sample period the tides become diurnal as the north declination of the moon increased. After 15 d the period of the tide changed, resulting in one flood tide and one ebb tide in a 24 hr period. This agreed with the previous study by Government of Jamaica (1968), which stated that the tides in Kingston Harbour are semi-diurnal when the moon is over the equator, and become diurnal during north and south declination of the moon.

From the previous study by the Government of Jamaica (1968), it was stated that important tidal parameters, obtained from tidal predictions and the Admiralty Chart, indicated that the highest tide was 0.457 m and the lowest tide was 0.122 m. Sherwin and Deeming (1980) reported that the tidal constituents were very small at Port Royal. The biggest harmonic was the K1 (lunisolar), which had an amplitude of 0.08 m. This was followed by the M2 (principal lunar), which had an amplitude of 0.05 m.

Because of the small tidal amplitudes, it was believed that the tides were not very significant to the circulation in the harbor. The maximum tidal amplitude of 0.25 m and the mean amplitude of 0.12 m recorded in this study, however, were sufficient to generate movements of relative importance in the harbor. Since windy conditions have been shown to result in greater circulation in the inner harbor and winds were strongest during dry conditions, comparisons of the currents under ebb and flood tides associated with dry, but windy conditions are meaningful. During ebb tide, surface circulation in the outer and inner harbor was active with currents flowing generally to the south and east, respectively at 4–14 cm s^{-1} with two large gyres in the outer and inner harbor (Fig. 10). Flood tide contributed to keeping low salinity surface water from leaving the harbor; thus, surface currents in the outer harbor were reduced (Fig. 13) and deep (9 m) return currents observed during ebb tide dissipated during flood tide.

Circulation in the inner harbor, while being most affected by tides, is also strongly influenced by both wind and fresh water outflow. Tidal currents in Kingston Harbour are effectively the result of horizontal ebb and flow movement in and out of the system with rising and falling tides. It was clear that tidal currents are important in the transport of saline water at depth. However, fresh water discharge has the effect of reducing flood flow while increasing ebb flow (Government of Jamaica, 1968). When wind induced circulation was combined with the tides there was significant water movement in the inner harbor, especially during the dry season. High wind combined with ebb tides produced greater water movement at 9 m (Fig. 14) than high wind combined with flood tides (Fig. 15), although both resulted in water entering the harbor. However, with constant high wind, ebb and flood tides created similar current speeds in surface waters, but as expected, flowing in opposite directions (cf. Figs. 10,13).

During the sampling period, it was evident that tidal currents brought saline water into the harbor in the subsurface layers, and near the Port Royal coast, water sometimes entered at the surface on the flood tide. Previous studies by the Government of Jamaica (1968), Goodbody (1970) and Wade (1976) stated that both surface and bottom tidal currents are similar and basically flow into all parts of the harbor on the flood tide and outward on the ebb tide with limited eddy effect caused by land configuration. The Government of Jamaica (1968), therefore, concluded that the principal currents in Kingston Harbour were tidal in nature. The report (Government of Jamaica, 1968) also showed the

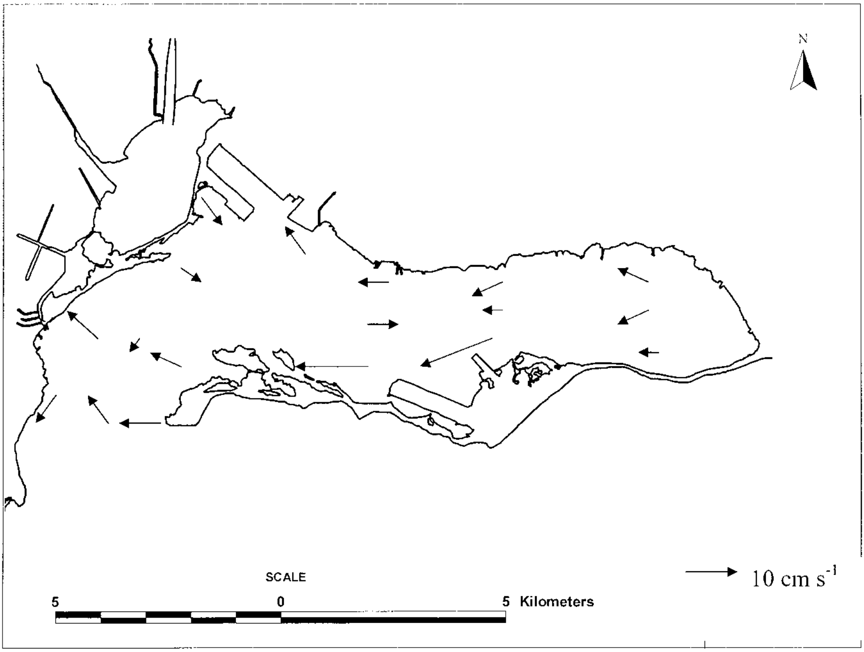

Figure 13. Currents in the surface waters (0.2 m) of Kingston Harbour during the conditions of dry season, strong wind and flood tide (DWF).

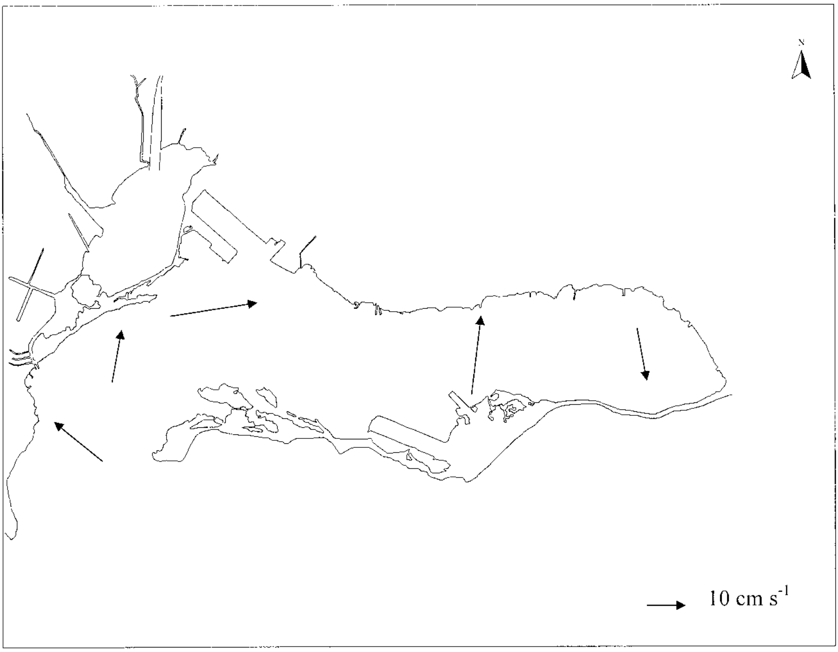

Figure 14. Currents in the deep waters (9.0 m) of Kingston Harbour during the conditions of dry season, strong wind and ebb tide (DWE).

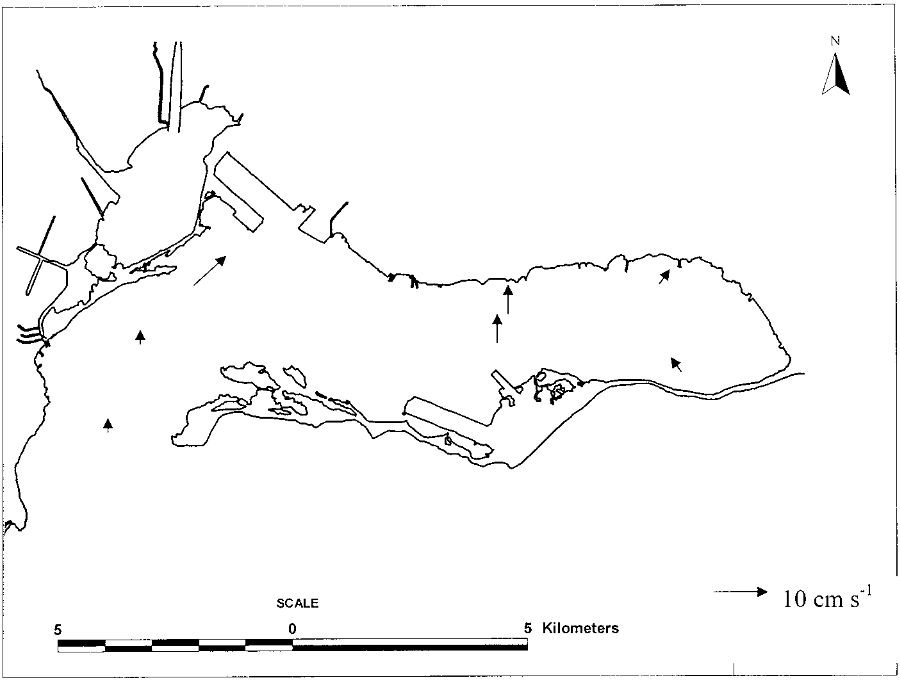

Figure 15. Currents in the deep waters (9.0 m) of Kingston Harbour during the conditions of dry season, strong wind and flood tide (DWF).

currents moving generally from the entrance of the harbor to the inner harbor during flood tides with the reverse on the ebb tide.

These findings were not supported by the present study as surface currents during this sampling period were usually faster than the bottom currents. The Government of Jamaica (1968), however, reported that there are occasional minor variations between bottom and surface currents with bottom currents having half the velocity of the surface currents. In general, the longest period of tidal flow was on the ebb tide, but the most rapid change in tidal flow was on the flood tide (Government of Jamaica, 1968). In this study it was also evident that on occasion, surface currents flowed seaward, from the outer harbor on both the ebb and flood tide. In the inner harbor and upper basin, surface currents flowed both into and out of the harbor on both the ebb and flood tide, and the speeds were dictated by the density currents and the wind generated currents.

Tide charts covering the period October 1966–April 1967 indicated that the water level at the old United Fruit wharf (inner harbor near station 7) averaged about 0.043 m higher than at Port Royal. At the Texaco wharf, at the east end of the harbor near station 1, the water level averaged 0.024 m, while at the Sandy Gully jetty the water level averaged about 0.091 m higher than the water level at Port Royal. While wind stress, density differences and freshwater inflow may be responsible for differences in water height, it is probable that the tide never completely ebbs before the incoming floodwaters cause the water level to rise again. This results in a lag in each tidal phase at opposite ends of Kingston Harbour. The fastest currents in the inner harbor and upper basin occurred during the flood tide associated with high wind and high rainfall (Fig. 12). This flood tide followed an incomplete ebb tide producing strong currents in the deep upper basin and maximum upper basin and inner harbor circulation. The observation is consistent with differences in calculated retention times in the outer and inner harbor and the upper basin, and the ebb and flood tide periods (Williams, 1997).

Therefore, there are three major types (based on source) of currents in Kingston Harbour: density or salinity driven currents, wind driven currents, and tidal currents. All sources act in concert with each current type to determine the circulation pattern in the different zones of the harbor. The outer harbor behaves as a true estuary with density currents dominating surface circulation patterns while deep currents are tidally driven. The inner harbor is more tidally driven due to shallow areas within that sector and the single deep shipping channel, which accentuates the tidal currents. High rainfall and winds significantly influence the inner harbor surface layers, with wind and density generated currents often opposing each other. The upper basin appears to be least active and is dominated by wind driven currents that are strong, but short-lived. These currents produce gyres of circulation enhancing mixing within the upper basin, but there is little net current motion between inner harbor and upper basin.

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