CEER M-64 HYDROLOGIC MODEL OF GUAYANILLA BAY, PUERTO RICO
Michael A. Chartock
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TABLE OF CONTENTS

EXECUTIVE SUMMARY

Objectives and Purpose: A hydrologic model is developed to account for the average water flow patterns in Guayanilla Bay as a guide to understand the function of the bay, to identify controls over bay processes, to describe important data uncertainties, and to inform decisions on the effective uses of the bay. Wind, tide forces, industrial pumping, and freshwater input are the major external forces affecting the bay, although each of the bay's five major compartments are unique in the extent to which these forces dominate. Precipitation, evaporation, and ship activity affect the water budget to a much lesser degree. Bottom topography or bathymetry of the bay is the most critical feature controlling the flux of water and the unique characteristics of the bay compartments. Biological processes control the rate of exchange between several compartments. Mangroves are important in the thermal cove and Southeast Bay compartments. Seagrasses are important in the Western Bay, Southeastern Bay.

Central Bay, as they affect sill depth and wind drift. Wind drift and equilibrating (surface) return flows are both the largest flows and those associated with the greatest uncertainty. Based on this study, a research effort to characterize wind drift flow rates across shallow bay sills, together with an evaluation of equilibrating return flows in deeper channels, would be the most beneficial studies for predicting the physical behavior of Guayanilla Bay. Management options affecting the bay can influence the bay's productivity, use as a port, and the characteristics of water used for power plant cooling. Wind, geomorphology, and intake and discharge location have the greatest control over power plant cooling water intake temperature. Sills between bay compartments and the freshwater from surface and groundwater of the Yauco and Guayanilla River watersheds have the greatest control over biological productivity (from a hydrologic standpoint). Currents and biological

communities could be managed to control sedimentation rates and stabilize bottom topography. Thus, management decisions in the development of the bay can be informed by a hydrologic model to sustain and enhance productive uses in an efficient manner.

a. Resumen Objetivos y propósito: Se desarrolló un modelo hidrológico que considera el patrón de flujo promedio de las aguas de la bahía de Guayanilla. El mismo sirve de guía para comprender el funcionamiento de la bahía, identifica lo que controla sus procesos, describe incertidumbres relacionadas con datos importantes e informa qué decisiones deben tomarse para su uso efectivo. El viento, las fuerzas de las mareas, el bombeo de agua para usos industriales y el agua dulce aportada por los ríos constituyen las fuerzas externas mayores que afectan la bahía, aunque cada uno de sus cinco divisiones principales (compartimientos) son únicas en el modo de estas fuerzas ejercer su influencia. La precipitación pluvial, la evaporación y el tránsito marino afectan el sistema hidrológico.

En un grado menor, la topografía submarina y la batimetría de la bahía son los factores más críticos en el control del flujo de agua en la bahía, siendo además características de naturaleza única en los compartimientos que componen la misma. La estructura biológica afecta la hidrología de la bahía mediante el control de las tasas de intercambio entre sus distintas secciones y compartimientos. La marea es importante en los compartimientos demarcados por la caleta terminal y el sureste de la bahía. Las presiones de fanerógamas son importantes en las secciones delimitadas por el oeste, sureste y la parte central de la bahía donde estas afectan la profundidad del umbral de la bahía y el material acarreado por los ventisqueros. Los flujos de agua resultantes de la tasa de acumulación por los ventisqueros y retorno al equilibrio son los dos tipos de grandes corrientes que a su vez están más sujetos a inconsistencias y variaciones. De acuerdo a este estudio, sería beneficioso llevar a cabo una investigación para caracterizar las corrientes provenientes de acumulación de agua por los ventisqueros a través del umbral de bahías claras junto a una evaluación de flujos resultantes de contracorrientes de equilibrio en canales profundos. De esta manera se podría predecir el comportamiento físico de la Bahía de Guayanilla. Las opciones o alternativas de manejo que afectarían la bahía podrían muy bien influenciar su productividad, su uso como puerto y las características del agua a usarse para enfriamiento en las centrales generadoras. Su geomorfología y la velocidad del viento ejercen un mayor control sobre la temperatura del agua a usarse para enfriamiento. Los umbrales entre los distintos compartimientos de la bahía y el agua dulce de superficie y niveles freáticos de las cuencas pluviales de los ríos Yauco y Guayanilla tienen un mayor control sobre la productividad biológica (desde el punto de vista hidrológico). El desarrollo de puertos podría ser afectado por corrientes marinas. ---Página siguiente--- Y

Biological communities that control sedimentation rates and stabilize underwater topography. Land use decisions and the development of the bay could be influenced by information generated by a hydrologic model so that its productive uses can be sustained and even increased in a cost-efficient manner.

HYDROLOGIC MODEL OF GUAYANILLA BAY

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1.0 INTRODUCTION

The hydrologic flux among geographic areas is an important process mediating the transfer of energy and materials in the coastal zone. In the coastal bays of southern Puerto Rico, this flux is affected primarily by wind drift, tides, runoff (Xunel and Iadjathwodorou, 1970; Goleman, 1979), industrial cooling water pumping, and groundwater flow. Storm surges and ship traffic affect the water budget less frequently or on a smaller scale.

This paper describes a hydrologic model of Guayanilla Bay, Puerto Rico (Fig. 2). The model accounts for the mass balance of water among five major hydrologic subdivisions (or compartments) of the bay, describing daily flux as an average of events that occur on an hourly, daily, monthly, and seasonal basis. It is useful for understanding the relative importance of different flows, their respective controls, and their effect on habitat types and industrial uses within the bay.

The model is based on the information summarized below and appended, and should provide a reference for acquiring improved data for more accurate prediction and management applications. This model is one part of a series of models that describe environmental and economic processes in Guayanilla Bay and its surroundings that are formulated at the Marine Ecology Division, Center for Energy and Environment Research, Mayaguez, Puerto Rico.

Guayanilla Bay is located on the south coast of Puerto Rico (Fig. 1) and consists of the five sub-areas (compartments) shown in Fig. 2 and

The text is characterized in Table 1. Compartment boundaries are defined by submerged bars, jetties, headlands, seagrass beds, cays and dredge spoil banks. Sills shallower than 0.7 m are indicated in Fig. 2 and are critical for isolating several bay compartments. Openings, including channels and pipes or other industrial structures, facilitate communication between the compartments. This communication or "interface" between compartments, occurs along the exposure between subareas, and is in part dependent on depth characteristics (see Table 1 and Section 2).

2.0 SOURCES OF WATER MOVEMENT

Five primary factors affect water movement in the bay: tides, wind direction, runoff, groundwater, and pumping of industrial cooling water. Additionally, shipping and storm surges can occasionally affect coastal water flow. Quantification of these parameters in the following sections provides the basis for developing the generalized annual hydrologic budget, model presented in this paper.

2.1 Tides

The tidal range at Guayanilla Bay varies between 15 to 45 cm (e.g., 1972) with a daily average range of 30 cm. Based on this range, the flux for the bay is 2.65 x 10^3 m3 daily. Tidal flux is a small proportion of Central Bay volume (7%). However, tidal flux is a large proportion of...

The water volume of the Western Bay is significant (20+), and is also relevant in the other shallow water compartments. The Western Bay may be the most "powerful" in terms of productivity and respiration (Chartock, in preparation), meaning that the exchange of materials through tidal forces is critical for the bay system.

2.2 WIND DRIFT

Surface water movement in Guayanilla Bay is significantly influenced by the wind (Goldman, 1979). Surface wind drift has been reported to be 2.6 to 5.8 percent of wind velocity, based on a review of 16 coastal and oceanic studies (Lange and Wuhnorfuss, 1979). In shallow bays with limited fetch, Goldman estimates that the drift in the upper (2-3 meters) mixed layer is approximately 1% in South Coastal Caribbean Bays, as supported by studies done from 1977 through 1979 (Goldman, 1979).

This is in near agreement with estimates of 2-3% for fetches of 4 to 10 km, summarized by Von AEX (1960). Estimates of surface water movement induced by wind at Guayanilla Bay, as seen in Table 2, are based on an average 24-hour wind velocity of 2-9 m/sec (see Appendix A). The average vector of the wind is easterly, shifting from the southeast (120°) to the northeast (60°) on a diurnal basis.

Water movement at the Caribbean interface is affected by circadian and seasonal variation in wind direction. This effect is due to the southern exposure of the Central Bay - Caribbean interface and results in switching the wind drift in and out of the bay. This switching has not yet been verified with drift bottle sequences (Goldman, 1973). Thus, wind vector fluctuations must be accounted for to estimate flows.

As summarized in Appendix 4, two directions of wind predominate: northeast (60°) at night, and most of the day during winter months (January through March) and southeast (120°) during the day for most of the year. The northeast component dominates approximately 50% of the time, and the southeast component dominates 60% of the time. These two average wind vectors are included in the wind drift data summarized in Table 2. As indicated in Table 2, the

The volume of flow from wind drift is most significant for the exposed Central Bay, where surface water drifts into the bay during the day and exits at night. The wind-driven flow entering the bay is 2.92 x 10^8 m^3 and the flow driven out of the bay is 1.95 x 10^6 m^3 daily. These quantities compare with the 2.65 x 10^8 m^3 per day moved by tidal forces (see Section 3-0). However, the wind-driven circulation of the bay is a critical variable for the exchange of water in Guayanilla Bay, as this factor fluctuates seasonally and daily, and may control upwelling (see Section 2.6). National Oceanic and Atmospheric Administration data from Ponce is confirmed with selected monthly measurements at Guayanilla Bay (Chartock, in preparation).

TABLE 2 Hydrologic Flux Summary (10^8 m^3 per day)

Compartment Wind Industrial Wind and Compartment Vortex Tidal Summary

Punching Groundwater

Western Bay 3.30 0.0 1.82 - 0.072

Central Bay 37.6 2.65 3.89 - 0.150

Intake 1.38 0.0 0.03 - 0.008

Thermal Cove 0.52 0.0 0.672 - 0.002

Southeast 1.56 1.24 4.08 0.0

Exbayent Total 44.33 0.0 0.0 - 2.02

Data tabulated are aggregate flow. Separate flows among compartments are presented in Table 5. The total flux of the bay system passes through the Central Bay (volume of Central Bay changes 1.30 * 10^6 m^3 during a tidal cycle). Wind drift estimate of deeper channels is based upon movement of upper 5m of water at 1% of wind velocity (2.9 m/sec). For shoals or sills where this depth was less than 3m, average sill depth was used. See Appendix B for detailed wind drift data.

2.3 INDUSTRIAL PUMPING. Hydrologic budgets of the intake, thermal cove, and southeast embayment are significantly affected by the Costa del Sur Oil-fired Power Plant, which operates using once-through seawater cooling. When all six units (boilers) are online, the cooling water flow is 37.6 m^3/sec. This plant operates with a power factor of approximately 60%, so the estimated pumping is 2.16 x 10^6 m^3 per day. This pumping alone exchanges the volume of the thermal cove.

Five times daily. 2.4 RUNOFF AND GROUND WATER: Western Bay receives runoff from the Yauco River Watershed, and the Central Bay receives runoff from the Guayanilla and Hacafa Rivers. The Yauco River is impounded at the Luchetti Reservoir, and some flow is diverted out of the watershed. The river valleys in all the watersheds in Fig. 2 are developed for irrigated agriculture, primarily sugar canes. Runoff is highest in June through November, and low from December through May. The average annual streamflow for the Guayanilla River, measured approximately two km upstream from the bay discharge, is 29.6 x 108 m3 per year; for the Yauco River, it is 13.5 x 108 m3 per year; and for the Hacafa River, it's 9.8 x 106 m3 per year (Crooks, et al., 1968). Summary data for watershed flows are included in Appendix B. Potential water entering bay compartments from groundwater and runoff is 26.3 x 108 m3 per year to the Western Bay and 54.3 x 106 m3 per year to the Central Bay. Actual freshwater entering is likely to be somewhat less due to domestic freshwater use and evaporation in agriculture. The geological structure of Guayanilla Bay is heterogeneous with a karst topography in Miocene Limestone that outcrops at the surface (Morelock, et al., 1979). A variety of marine and alluvial sediments occur at the surface. Both the Limestone and unconsolidated sediments serve as aquifers, and the alluvium has been extensively developed for irrigation supply. Groundwater influx into the bay has been estimated from average groundwater flow along the south coast of Puerto Rico. A daily average discharge of 2.1 m3 per linear foot of shoreline has been estimated (Puerto Rico Water Resources Authority, 1972). This estimated value is within a factor of 0.5 of the groundwater flow from the watersheds above Guayanilla Bay estimated by the U.S. Geological Survey (Crooks, 1968). The freshwater flow is small as an annual average, approximately 8.08% of the tidal flux, but seasonal variation and individual storm events can make this a very important factor, with

Some measurements of peak runoff of 1.4 x 106 m per day for the Guayanilla and Yauco Rivers "Rises Gata" are based on evapotranspiration losses of water entering the lower basin, based on similar losses in U.S.G-3 upper basin measurements.

Almost one-half the tidal flux during which rainfall persists, the freshwater flux is also important for maintaining the brackish water conditions of the Western Bay. This is a critical physical factor in structuring the biotic community and its energy flow patterns.

2.5 OTHER SOURCES

Four other sources of hydrologic flux occur: precipitation, evaporation, storm surges (storm tides), channel dredging, and ship traffic. These sources of flux, however, are either small or infrequent. Direct precipitation from the annual average rainfall of 30 cm in the relatively arid coastal environment (Cintrén, Hugo, Pool and Morris, 1978) results in an addition of 7,409 m^3 of water annually, divided among bay compartments according to surface area. Most of this addition occurs from May through October. This flux is about three orders of magnitude smaller than categories shown in Table 2. Annual pan evaporation is 19.9 inches at Ponce, with very similar values at Guanica and Sabana Grande (Seat, National Oceanic and Atmospheric Administration, personal communication). This results in a flux of 18 x 10^3 m^3 annually or approximately 49,000 m^3 daily from the entire bay (see Table 1).

Storm surges accompany the tropical depressions, storms, and hurricanes that frequent the Caribbean. The hurricane force winds and storm surge contact Puerto Rico an average of once every six years (Puerto Rico Water Resources Authority, 1972). These storms have different intensities, but a maximum expected storm surge along the south coast would result in about a 3m storm tide (Puerto Rico Water Resources Authority, 1972). This tidal stand would pass during a two to four hour period and result in a displacement of 26 x 10^3 m^3, about one-half the volume of the

Bay. The large container ships and tankers entering Guayanilla Bay displace approximately 100,000 metric tons, or 48,000 m3. On average, one tanker enters and leaves the bay daily (Puerto Rico Port Authority Staff, personal communication, 1980). This exchange occurs at the interface between the Central Bay and the coastal water. Thus, water movement due to tanker traffic is similar in magnitude to evaporation water flow, although very localized. Greater rainfall occurs during tropical storms. Uncontrolled runoff from the three drainage basins can be equivalent to 1.9 x 107 m3 (10 cm of rainfall over a 24-hour period in the drainage basin). This is about 0.4 times the volume of the bay. Much of this runoff would be released within a one-day period (Gragg Morris, personal communication).

Water Flux from Precipitation and Evaporation (m3 per day)

Location	Precipitation	Evaporation
Western Bay	2.00	16.9
Central Bay	10.60	23.9
Intake	0.94	n/a
Thermal Cove	0.58	n/a

Southeast Embayment 2.00 4.49
Total 20.7 49.00

Propeller pumping by 2,000 horsepower tugboats displaces water across the bay-coastal water interface. The tugboats have a thrust that moves 29,900 m3 per minute. Approximately four tugboats per day transit the mouth of the bay, each crossing in an average of five seconds over the Central Bay-coastal interface. This results in an estimated localized movement of 10,000 m3 of water in each direction.

2.6 EQUILIBRATING FLOWS

Equilibrating flows are established in the bay that maintain the volume of compartments. Equilibrating flows are the result of gravitational force that results in flow to establish a uniform (level) geopotential surface. For example, industrial pumping reduces the volume of the Intake Bay so that water flows into the Intake Bay from the Central Bay to re-establish equilibrium. In this case, surface water of the Intake Bay is moved by wind into the Central Bay, and an equilibrating flow is the cool bottom water from the.

Central Bay. This movement of bottom water has been substantiated by Grogue and temperature studies (Golénan, 1979). The size of equilibrating flows are mass balance estimates of counter currents. They are based on the assumption that the average daily volumes of the Guayanilla Bay compartments are constant, (see Section 3). Increased easterly winds force surface water into the Western Bay. A bottom equilibrating current from the Western Bay is established as a counterflow that exits a narrow channel near Punta Verraco, resulting in an outflow of turbid Western Bay water into the Central Bay. This flow is substantiated by observations of the extension of turbid Western Bay water that moves east into the Central Bay and then south along Punta Verraco.

3.0 MODEL AND PROPERTIES

The model of the bay storages and flows is shown in schematic form in Fig. 4, indicating the inputs and discharges of water and the flows among compartments. The external energy sources are listed in Table 4 with a summary description of the magnitude and type of force described in the previous section. The flows are listed in Table 5, including the origin or source compartment when the source of flow is within the Guayanilla Bay system. The transfer coefficient, or proportion of the source compartment that flows each day, is also provided. The largest flow is an upwelling equilibrating counter current flowing into the Intake Bay, largely the result of westward wind drift and industrial pumping. Generally, wind-driven currents and equilibrating flows are the largest flows between compartments. The exchange of water in and out of the system as a whole, however, is dominated by both tidal flow and wind. Wind drives about 108 more water into the bay (J4) than tide, but tides flush much more water from the bay (31) than does wind (93). The magnitude of the equilibrating flow out of the bay is directly related to wind velocity.

Propeller pumping by 2,000 horsepower tugboats displaces water across the bay into coastal waters.

Interface. The tugboats have a thrust that moves 29,900 m³ per minute. Approximately four tugboats per day transit the mouth of the bay, each crossing in an average of five seconds over the Central Bay - coastal interface. This results in an estimated localized movement of 10,000 m^3 of water in each direction, 2.6 EQUILIBRATING FLOWS. Equilibrating flows are established in the bay that maintain the volume of compartments. Equilibrating flows are the result of gravitational force that results in flow to establish a uniform (level) geopotential surface. For example, industrial pumping reduces the volume of the Intake Bay so that water flows into the Intake Bay from the Central Bay to re-establish equilibrium. In this case, surface water of the Intake Bay is moved by wind into the Central Bay, and an equilibrating flow is the cool bottom water from the Central Bay. This movement of bottom water has been substantiated by drogue and temperature studies (Goldman, 1979). The size of equilibrating flows are mass balance estimates of counter currents. They are based on the assumption that the average daily volumes of the Guayanilla Bay compartments are constant (see Section 3). Increased easterly winds force surface water into the western Bay. A bottom equilibrating current from the Western Bay is established as a counterflow that exits a narrow channel near Punta Verraco, resulting in an outflow of turbid Western Bay water into the Central Bay. This flow is substantiated by observations of the extension of turbid Western Bay water that moves east into the Central Bay and then south along Punta Verraco. 3.0 MODEL AND PROPERTIES. The model of the bay storages and flows is shown in schematic form in Fig. 4, indicating the inputs and discharges of water and the flows among compartments. The external energy sources are listed in Table 4 with a summary description of the magnitude and type of force described in the previous section. The flows are listed in Table 5, including the origin or source compartment when the source.

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"The system of flow 4s is within the Guayanilla Bay. The transfer coefficient, which is the proportion of the source compartment that flows each day, is also provided. The largest flow is an upwelling equilibrating counter current flowing into the Intake Bay. This is largely the result of westward wind drift and industrial pumping. Generally, wind-driven currents and equilibrating flows are the largest flows between compartments. The exchange of water in and out of the system as a whole, however, is dominated by both tidal flow and wind. Wind drives about 10% more water into the bay (34) than tide, but tides flush much more water from the bay (J1) than does wind (53). The magnitude of the equilibrating flow out of the bay is directly related to wind velocity.

TABLE 4 External Energy Sources

Energy source Name Notes

1 Tide 30 cm sea elevation change, wind average 2.9 m/sec

2 Streamflow and Groundwater 87 x 106 m^2 per year from watershed

3 Precipitation 90 cm/year

4 Evaporation 200 cm/year

5 Shipping 60,000 m^3/day

6 Industrial pumping 2.16 x 108 m^3/day

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The interrelationship among causal forces and storages that determine system behavior is provided in the system equations in Table 6 and shown in the energy circuit diagram in Fig. 5 (Odum, 1971). Appendix C contains the hydrologic model written in BASIC with annual average values used for external energy sources. The simulation results are also provided. Appendix D lists a model that includes 24 hour wind direction shift and 25 hour tidal day. The equations and computer model can be used to predict responses to changes in either the external energy sources or the physical and biological characteristics that determine the transfer rates within the Guayanilla Bay system. Examples of biological properties that control system behavior are the mangrove forests and seagrass beds that control the rate of water movement across channels. Mangroves determine channel width and the seagrass beds stabilize bottoms and reduce wind driven currents (Scoffin, 1970). Many of the physical and biological structures controlling hydraulic flux have been manipulated by dredging, construction of jetties, and industrial pumping. For example, changing the intensity of industrial pumping dramatically alters the degree of upwelling in both the Intake and Southeast Bays. The effect of decreased pumping on the Southeast bay would be to substitute coastal water for the surface waters originating in the Intake and thermal cove areas. The amount of water upwelling in the Southeast expanse would nearly double if the industrial pumping ceased. The implication of selected management options for effective use of the bay is briefly described in Section 5 and in the Executive Summary.

Summary: 4.0 Model Verification

Much of the data used to develop estimates of system parameters are based on measurements of relatively stable characteristics such as shoreline dimensions and bathymetry. However, many system parameters are not directly measurable, are stochastic (with a high degree of variability), or must be inferred (e.g. the equilibrating flows). One purpose of the model is to identify parameters that critically affect system behavior but that are poorly understood. Summarized below are selected descriptions of the reliability of model data and some observations that substantiate fundamental interrelationships.

4.1 Storage Volume

Compartment sizes are based on measurements from National Oceanic and Atmospheric Administration Navigational charts. These have been cited from the "National Oceanic and Atmospheric Administration, June 3, 1978, 11th Edition. Charts No. 25681 Bahia de Guayanilla and

Bahia de Tallaboa."

Table 6: System Equations

1.) Western Bay (WE) Volume BTS KTR RT, + RTO, - T,0, + mGt,2, =H
2.) Central Bay (CB) Volume 2 Raby = ByTWRy = KyTyOy + Katy + MyPy ~ KeIgO> + RTO, ~ KyI\O, 1 Ey = Fabsa * Mel * KT, - 570 TO, ~ BOD TBaRaPs Bur @y * BYERS ~ by@ — 150) + Kt, - K,1,0,
3.) Intake Embayment (I) Volume BS Mets MyTeO) + Ty MI) KE, - KI, + HO, ~ KIO 4.0,
4.) Thermal Cove (TC) Volume RebSRe IST Maly TKS = ATW, - TO, = Tyg
5.) Southeast Embayment (SE) Volume BS MGR NES REM RTOS HRT, KT) = KTR, RRs * 1h) 440, a. O= rate of change of 9

This data has been selectively verified by depth soundings of the bay during Fall, 1979. Field trip checks on the geographic landscape have been provided by reviewing aerial photographs and by cruising along the shoreline to verify land - mangrove boundaries. These measurements are probably accurate within one percent. Average depths of bay compartments are based on map measurements of fine transects in each compartment, with an estimated error range of 2. Overall compartment size error is within 5%.

4.2 Currents Verification of

Water movements are based on drogue, current meter, and dye studies of current velocity. These studies substantiate wind velocity and surface current measurements in open water areas. However, detailed confirmation of wind-current relationships has not been made. Related studies of wind drift indicate a variation of 10 to 300 of actual values (Lange and Muhnerfurs, 1979). The existence of equilibrium currents has been substantiated with drogue studies (Goldman, 1976). In addition, the general relationship between wind velocity and the magnitude of equilibrium (return) flows is substantiated by observations; for example, of the extension of turbid Western Bay water into the Central Bay. Wind and current velocity relationships are also substantiated by multi-depth drogue observations (Goldman, 1972).

4.2 FRESHWATER INPUT

Surface water inputs have annual variation of ± 40% of the mean annual flow. Although large yearly variation in runoff occurs, the long-term average yearly runoff values used in this report are probably representative within 10-20%. Groundwater flow data are subject to considerable uncertainty. However, total freshwater influx can be verified independently by calculating dilution of Caribbean water in the bay. Dilution of Western Bay waters occurs to the range of 28 to 33 parts per thousand salinity. Total freshwater flow data used in this report are consistent with this range of salinity given the rates of tidal and wind-driven water flux (see Table 7). Salinity stratification and mixing data have not been evaluated, however, and error range is uncertain.

5.0 MANAGEMENT IMPLICATIONS AND CONCLUSIONS

Guayanitia Bay is a complex, multicomponent estuary with distinctive sub-areas. From a physical standpoint, the hydrology is affected by numerous separate forces that collectively characterize the bay. From a biological standpoint, the bay compartments also function distinctly, but are highly interdependent (Chartock, in preparation). The hydrologic behavior of the bay can be managed to affect its

"Biological Properties and Human Uses as an "Industrial Marine Ecosystem” (Tilly, 1979)

Chapter 7: Relationship of Salinity to Flushing in Western Bay

Salinity is accumulated in Western Bay. Here is a fraction of the volume of flushing (feed fresh):

1.0 Freshwater Time: 28 186 622,000 5.635
2.3 Salinity: 1598 526,000 7.3067
2.0 Freshwater Time: 29 430,000 5.97
2.10 Salinity: 334,000 46
3.2 Freshwater Time: 237,000 33
3.108 Salinity: 143,000 2.0

Central Bay has a salinity of 34.5 parts per thousand, and the volume of the Western Bay is 3.3 x 100. The freshwater input is 72,000 m³ per day.

Chapter 5.1: Management of Western Bay

The relative isolation of the Western Bay from the Central Bay can be modified by dredging the shallow sill that separates these compartments, as an example of a management action. The sill depth and width parameters influence the strata of water that enters or leaves Bay compartments and the source of water for equilibrating return flows. The channel, for example, that penetrates the sill near Punta Verrace provides for the equilibrating flow of deeper, poorly oxygenated water out of the Western Bay to the Central Bay, and may be one factor maintaining the oxygen concentration in the autotrophic Western bay (Cherlock's preparation) that sustains a small commercial fishery (Cole, 1976). Thus, effects of alternative dredging plans on the transfer coefficients for wind-driven currents and for equilibrium return flows should be evaluated with models such as the one described here.

Dredging is a continuing process used by industry in Guayanilla Bay to maintain adequate port conditions. Suspended materials in shallow waters moved by the wind drift are a major source of sediment that is transported in the bay. The sediment budget of the bay can be managed to reduce or divert sediment sources to minimize dredging expenditures.

Managing biological populations that stabilize the bottom may also be a mechanism to avoid or minimize costly dredging programs. The model described here only provides an initial framework for sediment management. A detailed analysis is required for comprehensive management."

A sediment budget is needed to implement an effective stabilization program.

5.2. WATERSHED MANAGEMENT

Groundwater and surface water flows are important for maintaining the biological and physical characteristics of the Western Bay such as community composition, productivity, turbidity, and total particulate matter. The freshwater flow is dependent on surface and subsurface development of the watershed (U.S.G.S., 1968). For example, increased groundwater pumping, coupled with severe drought, can result in seawater intrusion from the bay into the alluvial sediments in the Guayanilla Valley.

Development of storage and groundwater recharge capacity in the three rivers that enter Guayanilla Bay needs to be evaluated as a mechanism for both maintaining continued groundwater use and sustaining brackish water conditions in the Western Bay. Periodic floods affect the shoreline and bathymetric characteristics, especially in the Western Bay.

Management of the long-term average flows of freshwater can easily be included in an evaluation based on the model presented here, but the dramatic changes produced by periodic floods require additional model parameters.

5.2 INDUSTRIAL INTAKES AND DISCHARGES

Industrial pumping enhances upwelling at the boundary between the intake and central bays, and reduces upwelling at the mouth of the Southeast Bay.

Although water characteristics are modified in the bay system by this industrial operation (Ayres, 1977), the hydrologic flow between the transport area and the coast along the central bay water is not affected. This water exchange is critical in affecting the physical and biological characteristics of the bay.

Alternation of industrial intake and discharge locations must be compared to maintain the hydrologic exchanges within the bay and between the bay and the ocean. A potential option to relocate the Corredor del Sur Power Plant discharge outside of Guayanilla Bay to the adjacent Tallabos Bay would eliminate the continuous resource flow (as in Table 3) from the central bay.

Greatly increase the amount of coastal water entering the bay with the potential for substantial change in the bay's physical and biological characteristics. In this regard, the total bay system's hydrologic input/output budget is more like a natural system in its current configuration than with some alternative approaches. The point here is not that alternatives are better or worse, but that the outcomes must be earnestly compared for the entire bay when evaluating different options. One major use of the bay as a resource is to maintain or improve the high-efficiency of the Costa del Sur Power Plants and each valuable resource that serves as the heat sink that dissipates heat from the fossil fuel power plant. Heated water from the Costa del Sur Southeast Bay typically returns to the bay, similarly affected by the combination of surface wind and currents. If only surface currents were functioning (i.e., if there were no upwellings), then the more water entering the power plant would be pulling in water that has left the Southeast Bay. Thus, even small wind velocities can produce a significant increase in power plant efficiency. This could result in a reduction in cost of $5,000 to $10,000 daily, depending on fuel costs. Because water exchanges are affected by wind and bathymetry, managers of the bay should be careful in adjusting bathymetry or currents under the wind regime, especially on the eastern margin of the bay where wind effects are most closely coupled with man's activities and where wind fetch is short and potentially affected by shoreline configuration. 5.5 RESEARCH IMPLICATIONS A wide range of research has been conducted in Guayanilla Bay to characterize the physical and biological structure of the bay and the influence of industrialization (Gonzalez, 1979). The model submerged here can be used to review this research against the needs of understanding the function of the bay, and to inform.

Directions: January 2.0 ENE, February 2.2 NE, March 2.4 ESE, April 2.2 SE, May 2.9 SE, June 3.2 SE, July 3.3 SE, August 2.9 SE, September 2.6 E, October 2.4 NE, November 2.3 NE, December 2.3 NE. Based on the period 1946-1953. Sources: Puerto Rico Water Resources Authority 1976. "South Coast Power Plant Complex" Table 4.2-1. 26

Unfortunately, the next section of text seems to be garbled or encrypted and cannot be corrected without more context or information.

Footnotes to TABLE A2:

1. Channel between Cayo Mata and Commonwealth Refining Corporation (CORCO) Jetty.
2. Channel between Punta Gotay and Cayo Mata.
3. Channel between CORCO Jetty and Punta Papilio.
4. Communication from the east side of the Intake embayment is through forced pumping to thermal cove.
5. Deep portion of the channel from Punta Gotay to reef midway to Punta Verraco.
6. Shallow portion of the channel between reef (see above) and Punta Verraco.
7. Sectional area for wind drift is the width times sill depth or 3m, whichever is shallower.
8. Wind drift calculation is based on the velocity of wind-driven water through the channel.
9. Movement of water is estimated at 1/8 of average wind speed (2.9 m/sec), and direction (easterly).
10. Wind drift occurs in the upper three meters unless a sill is present, in which case the average sill height is used.
11. Wind direction has an annual average component of 120° for 60% of the year, and 60° for 40% of the year based on diurnal and seasonal variations in Appendix B (and summarized by the National Weather Service, 1978).
12. To account for the component of wind drive through embayment exposure, the cosine of velocity component and time duration corrections have been made for wind vector corrected daily flow.
13. For most exposures, this results in a... (text cuts off)

Correction factor 0-866. For the southern exposure of the Central Bay, the correction factor is 0.2 for flows to the south and 0.3 for flows to the north (e.g., cosine of angle of wind incidence normal to the exposure of the bay multiplied by the duration of the wind).

APPENDIX 8
Surface and Groundwater Data

TABLE 8-1. Annual rainfall on the three principal river basins, 1961 and long-term average.

River Basin	Drainage Area	Weighted Rainfall	1961	Long-term
Rio Aves Upper basin, (excluding Lago Lucchetti diversion)	39.1	132	163	
Lower basin	-	-	-	
Entire basin, (excluding Lago Lucchetti)	101	127		
Rio Guayanst1a Upper basin, above stream station	-	196		
Lower basin	8	9		
Entire basin	145	160		
Rio Macané Upper basin	19.5	198	15	
Lower basin	33.7	36	6	
Entire basin	332	150	150	
Three basins, (excluding Lucchetti) Upper basins	50.2	168	180	
Lower basins, Guayanilla	99	145		

Source: Modified from Crooks et al. 1968

TABLE B+? Annual amount of water received by the Guayanilla-Yauco River basins, 1961-63 and long-term average.

Source of water	Rainfall on upper basins
Rio Yauco (does not include drainage area above Luccetti)	82
Rio Guayanilla	89
Rio Macandé	31
Total rainfall on upper basins	178
Streamflow entering lower basins Rio Yauco (above first diversions)	20
Rio Guayanilla (gaging station)	27
Rio Macandé	-
Total streamflow entering lower basins	58
Rainfall on lower basins Rio Yauco	2
Rio Guayanilla	23
Rio Macandé	42
Water reaching lower basins	12

Source: Modified from Crooks et al. 1968

Listing of Computer Program (in BASIC) with Energy Sources Constant

```
100 Move
10 Time
```

12 439° GRAYT, JA MYPROLOCI MODEL OF GUAYANILLA BAY
SPR.= 130 OFA a5!
140 PRINT = Bye
150 PRINT = MICHAEL
CHARTOCK™ 160° PRINT
170 PRINT “CENTER FOR ENERGY & ENVIRONMENT RESEARCH™
180° PRINT "UNIVERSITY OF PUERTO RICO & U.S. D.O.E."
190 PRINT "January 90?"
200 REM
210 REM
230 REM PLEASE

Please read the REM statements for the specification of program variables.

240 REM: To operate, load program and enter 'RUN'.

To print, specify printer LO + PRE and enter RUN.

Bay compartment sizes are in section 400.

Statement 490 specifies the time increment, currently set for 24 hours. Integration is accomplished on hourly intervals (900 and 1200).

When printing, 'NOU' indicates total values.

280 REM: Energy sources do not vary in this version (set to 10.4 in 910 - 960).

270 REM: The model takes time to equilibrate (see results).

Initial compartments size mean low water without re-energizing the energy sources.

420 O2 = 37.6

430 O5 = 735

440 94 = 0.59

480 a5 = 9.82

490 Ler = 24

960 LE oes 7 = 37.6

304 REM: Time from crow's perch to water, F4 before dire circumstances.

704 REM: Tide from the Caribbean to CB.

508: Get the base.

707 REM: Turn from CR to cart, F6 before catastrophe.

711 REM: Wind from cart to CR.

720 CF: Battle before 721 REM counter current from WB to CB.

FBS LET xe ON ToS STA

324 REM: Wind from CB to UB.

736 LET nFTSTEEY Far SONB

27 REM: Tide from WB to CE.

F30 LET aT TSR PSF, 7

731 REM: Time from CB to WB.

735 LET KE = (0.972) / 7

737 REM: Fresh batch v0 Up.

740 KA = (0.0189, 7 3.3097)

Evaporation from UR KB = (0.007) 7

Rainfall into OR Ke = (0.15) 7

Freshwater to 'ce' KB = (0.24 7 3708) 7

Evaporation KE = Constant 7

Rainfall to CH KE = (0.008)

Groundwater to intake KG = (0.02 / 4.35) 7

Lubrication #88 is the main all for intake Wie (self n.35) 7

Gain from intake Kye C334 7 37, 1

The percentage from central to intake CMe 7 nas T

Pumping from intake to Te Wy = (29021 7.

I'm sorry, but the provided text is too garbled and lacks clear context for me to fix it appropriately. It seems to contain a mix of code, mathematical equations, and normal text which makes it challenging to understand what the corrected version should be. If you could provide further details or clarify the intended meaning, I would be more than happy to assist.

U.S. D.O.E. January 1960 TABLE OF COMPARTMENT VOLUMES (MILLIONS OF CUBIC METERS) AT WESTERN BAY, CENTRAL BAY, INTAKE BAY, THERMAL COVE, SOUTHEAST BAY

1. 37.8
2. 1.35
3. 1.35
4. 156
5. 37.6066268
6. 1435017463
7. 135017463
8. 1,54400456
9. 4135088281
10. 1135052981
11. 1182499988
12. 37.4293608
13. 43508475
14. 1
15. 3216399254
16. 1439137577
17. 135137877
18. 1156577946
19. 1135188736
20. 113818a731
21. 230373
22. 33.9205128
23. 303517723
24. 1.3537723
25. 37.6819827
26. 86677282
27. 37 -4540947
28. 1.352302
29. 1.3523081
30. 1.544903
31. 30547110
32. 5726874786
33. 1135280504
34. 32865588
35. 136720295
36. 3.30622787
37. 1135267026
38. 115633838
39. 3.396362
40. 3754762968
41. 1.35272704
42. 1.54740018

43. 3-30647939
44. 37.6774508
45. 1.35278974
46. 37.4784759
47. 1.300711
48. 4135280711
49. 37.4901455
50. 1.35284045
51. 1.54757099
52. 376014248
53. 1135291545
54. 155676352
55. 37.4924048
56. 113295346
57. 4.56767862
58. 37.4931
59. 1435297905
60. 1636771106
61. 37.4037307
62. 1135300018
63. 135300018
64. 37.4943714
65. 37.40506781
66. 1.35302078
67. 135302678
68. 37.4047678
69. 113530529
70. 113530329
71. 37.4940735
72. 1135304217

Note: The table is fixed to the best of my understanding, however, some numbers appear to be incorrect or incomplete (like "113818a731"). Please verify the data.

Ilesaoaziy I say 70754

Day WESTERN HAY 330723779 3130724597 19725813 3.307307 Beraea. 3130730133 B50730139 B.30730181 5.507302 5130730218 3130730253 3130730246 Biborsensy 5.30750267 3150730276 3.307 30283 B73e29 3.30730296 3150730808 5-30730306 3130730309 5-30720322 BH. 3.3073 315075 8 3.30730; 8 0 313078 3.307303 3SNE 3.30730327 3150730337 3130730327 3 3

CENTRAL BAY ey. ees9e 371838047 374981179 3728881799 2.052242 3.seuse4t Bi e5ES85h Fy -gesstg Te888338 32,0a5s3e3, Be eeSaare -egssses So.essees? 37.6895703 3718888758 37.6295007 37 1Ses3e5 37.6655888 So lesssvel 3716955997 376856016 37. 68s6034 376856048 57.4956061 3716856072 376836083 By sase081 37,4a%4098 sr baseios 370856112 Sieber te 32685612 SF. 68s013: ¥.s95612 Sr BSEL? 3768561 Sp .eesen 376056141 S7eBeeET ay

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INTAKE Bay yogssosse7 iabwai 1,355 T3s396726 T3550678 5396777 S506r96 psgoagze 35300852 Lzssoeaes itiseesse 1.350686. ivssseea77 135308086 1.35308093. 1.35306899 1135306908 1135306909 il3530e913 1. 38306917 113530693) 135304923 11306935) 4.35306920 4138308938 1.35506931 aTBSS62332 Ay3s30g933 Prec er sesesoagsg BL38500939 1. dsuoe938 it3ss0e938 135306938 EERO 3135306930 i:3ss0e938 1135306938 2s

THERMAL COVE yogugoessr iL38d0aGe5, 1.35z0s135 1138305348 306726 SSBB GS 3133306777 438588388 1 35z0ae16 138390889 Lagesoases 133eeas8 3530006 iTgssese77 135306866 siaeane 1.33506899 3135506904 iasseape9 i3sse6013 435306917 33880083 435307 shse8o0823° 1-3553069 4 :3ESG228 306938 3306938 5306938

SOUTHEAST Bay 1.36779203 $1867 79602 1356779876 angeraois 1.s67a0391 i:5¢ra0aes 1.56700786 3766780947 1.567a1088 bere est 155678352 SUPT 4.567149: 3678188 it 1.547e1878 TIB67E1908 3356781925 aiberareas iese7erges iiserarg7s 1.5¢781908 ivserarge9 1156782009 1454782018 1-56782025 1156762032 11sa7e2038 1156782043 1154782047 1.5678081 1456782054 11587e3057 i.5478206 118782062 1, 54782063, s7a2085 54782067 3588588 16782069 Se7e2071 6 1 +86782073 1186782073 4.56792073 1156702073 1136782073

Limiting of

The text appears to be a combination of various sentences, phrases, and formulas that are mixed up, likely due to some error in data extraction or transcription. Without further context or a clearer understanding of the intended information, it's impossible to correct the text accurately. Please provide more context or a more legible version of the text.

I'm sorry, but I can't correct the text as it seems to contain a mix of programming code, numerical data, and random characters, making it difficult to decipher the intended meaning or format. Could you please provide more context or clarify what you'd like me to fix?

I'm sorry, but the text you've provided appears to be a mix of random characters, numbers, and fragments of words. It doesn't form clear sentences in any language. Could you provide more context or a more clear version of the text? I'd be happy to help if I can understand what needs to be corrected.

I'm sorry, but the text provided contains a mix of alphanumeric characters and symbols that don't form coherent sentences or phrases in English or any other language I'm aware of. Could you provide more context or a more specific request? I would be glad to help if I can understand the request better.

I'm sorry, but the text provided seems to be heavily distorted or encrypted, and without context or the nature of the original content, it's not possible to correct or fix it.