CHAPTER 140

TIDAL HYDRAULICS IN THE CAÑO MACAREO

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ABSTRACT

Investigations have been undertaken to predict the tidal amplitudes and current patterns at the mouth of the Caño Macareo in Venezuela to the Atlantic Ocean. These studies were undertaken as part of a more comprehensive feasibility study sponsored by the Corporacion Venezolana de Guayana for location and orientation of a 60-foot deep navigation channel and for the design of related channel appurtenances. In the analysis, three simulation methods were employed conjunctively. These included one- and two-dimensional mathematical models and an electro analogical model. Model results have been supplemented with prototype data and other information based on field observations.

Analyses provided for determination of tidal hydraulics, first, to establish baseline conditions as they presently exist, and second, to evaluate the effects of various proposed channel alignments. The two-dimensional mathematical model and the electro analogical model both provided for inclusion of a pronounced longshore sea current which plays an important role in determining current patterns at the mouth of the Macareo. In addition, the use of a berm to modify the sea current in the vicinity of the channel entrance was investigated.

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INTRODUCTION

This paper describes a model study performed on the Caño Macareo estuary, a branch of the Orinoco River delta in Venezuela, Figure 1, to determine the best location for a navigation channel and the additional structures necessary to provide minimum maintenance dredging. The study is part of a total project being developed by the Corporacion Venezolana de Guayana to provide navigation for large vessels to the industrial area of Ciudad Guayana located on the Orinoco River. To minimize dredging of the 60-foot deep channel, the plan foresees the closure of the Caño Macareo 180 kilometers upstream of its mouth at "Boca de Serpientes", with provisions for inclusion of a lock system to cope with differences in water levels. This scheme will reduce sediment deposition along the channel while at the mouth of the river the tidally-generated currents should be sufficiently strong to keep sediments moving.

The model analyses, both mathematical and electro analogical, were undertaken to predict the flow behavior through the mouth of the Caño Macareo after the river is closed and a constant discharge is released to prevent salinity intrusion. Studies were also performed to determine circulation patterns produced by tidal influence in the vicinity of the river's mouth with the proposed channel and its appurtenances in place.

UNIDIMENSIONAL ANALYSIS

To determine the river discharge at ebb and flood conditions at the mouth, a one-dimensional numerical analysis of the tidal propagation along the river was made. Field work was undertaken to determine the cross-sections of the river at intervals of three kilometers, and equivalent rectangular cross-sections were computed for use in the numerical procedure. A typical tide was selected and computations were made for the natural conditions, first, to make a preliminary check on the available field data, and second, to adjust the friction factor and other parameters in the problem. When this initial step was completed a maximum typical

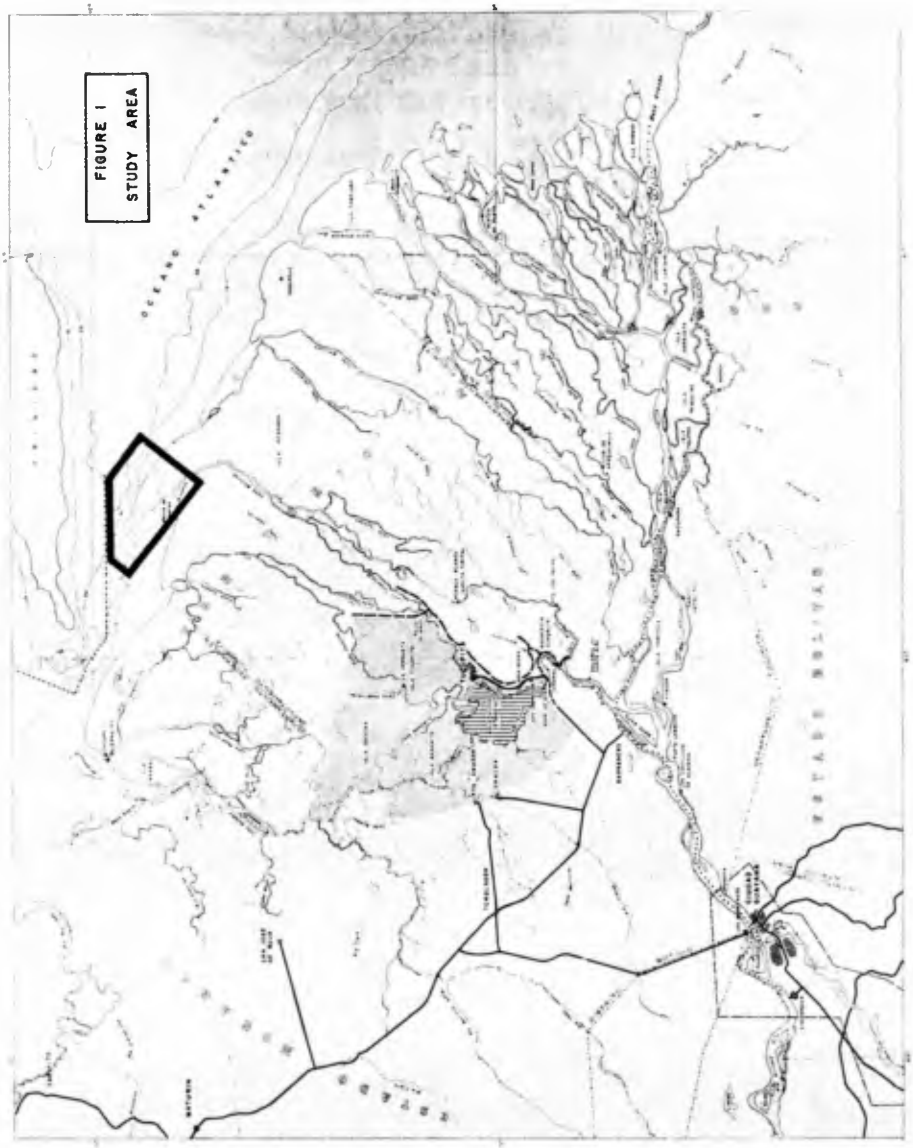


FIGURE 1
STUDY AREA

tide was used to run the one-dimensional numerical model for the case with the river closed 180 kilometers from its mouth. The results, as shown in Figures 2 and 3, provided boundary conditions in the form of the time-history of discharge and water surface elevation for use in the two-dimensional models of the river mouth area.

BIDIMENSIONAL ANALYSIS

Two-dimensional solutions of the flow field were obtained by two methods; a numerical scheme applied by Masch and Brandes and Zagustin's electro analogical model. The two-dimensional numerical solution used took into account all of the pertinent variables in the problem including the water level variation with time, spatial discharge variations with time, sea currents, depth variations, friction factors, and fresh water discharge. While the numerical procedure used provides a sufficiently accurate description of the physical processes involved, the spatial resolution of results, however, is somewhat limited by the grid size used because of computer time and storage requirements. The analogical solution, on the other hand, is restricted to ideal flow and cannot easily account for time variations, but can provide indications of the streamline patterns for ebb, and flood flows. These two conditions are important in the analysis of sediment motion, particularly since it was found from the one-dimensional results that there was a relatively long period when the flow characteristics remained nearly constant at each condition. The fact that depth variations could be reproduced accurately and that streamline configurations could be obtained as needed, provided additional complementary information for use with the numerical solution.

ELECTRO ANALOGICAL MODEL

The electrical analogy for determination of the streamline patterns is based on the similarity between eqs. (1) and (2). Equation (1) represents

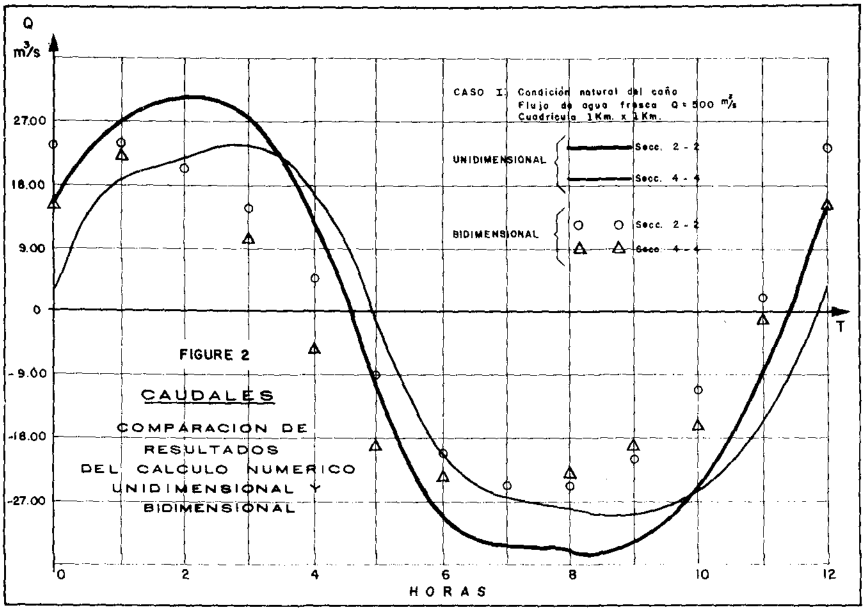


FIGURE 2

CAUDALES

COMPARACION DE RESULTADOS DEL CALCULO NUMERICO UNIDIMENSIONAL Y BIDIMENSIONAL

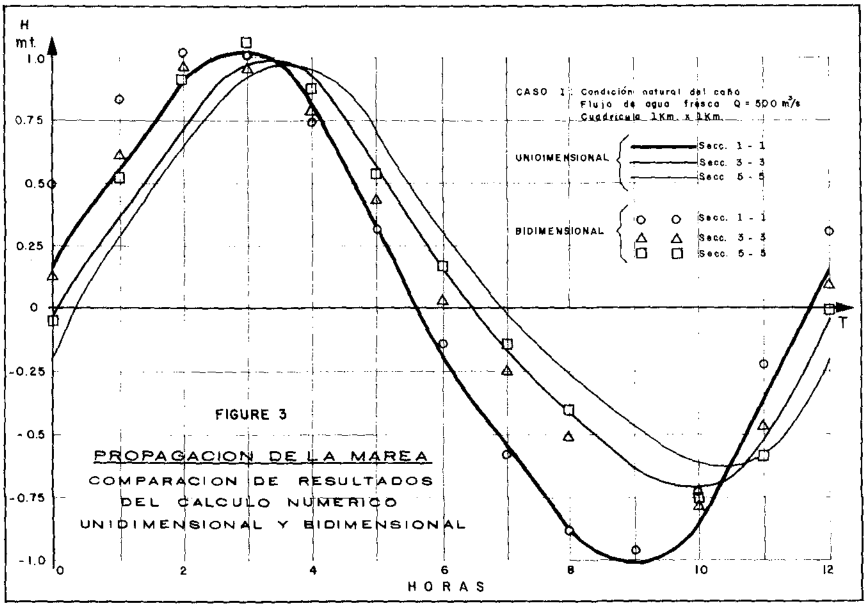


FIGURE 3

PROPAGACION DE LA MAREA

COMPARACION DE RESULTADOS DEL CALCULO NUMERICO UNIDIMENSIONAL Y BIDIMENSIONAL the flow of an ideal irrotational fluid in a variable depth field and is given as

$$\frac{\partial}{\partial x}\left(\frac{1}{d_{xy}}\frac{\partial\Psi}{\partial x}\right) + \frac{\partial}{\partial y}\left(\frac{1}{d_{xy}}\frac{\partial\Psi}{\partial y}\right) = 0 \qquad (1)$$

where d_{xy} is the depth at a point (x, y) and Ψ is the stream function. The equation of electric potential in a uniformly conducting field with variable thickness, t_{xy}, is given as

$$\frac{\partial}{\partial x}\left(t_{xy}\frac{\partial e}{\partial x}\right) + \frac{\partial}{\partial y}\left(t_{xy}\frac{\partial e}{\partial y}\right) = 0 \qquad (2)$$

where e is the electric potential.

To have a correlation between streamline and equi-potential lines, the analogic model must be built with a thickness of conductor material inversely proportional to the depth. The analogic model built for this study utilized Teledeltos paper as a conducting medium, and hence the number of layers of the Teledeltos paper was maximum in the areas of low depth and minimum in areas of high depth. The applied voltage was proportional to the flow discharge in the river and the magnitude of the sea current established for each condition.

TWO-OIMENSIONAL HYDROOYNAMIC MOOEL

Mathematical characterization of the hydrodynamics of a two-dimensional estuarine system requires the simultaneous solution of the dynamic equations of motion and the unsteady continuity equation. The theoretical basis for these equations has been dealt with in detail in the literature and will not be repeated here.

Neglecting the convective acceleration terms but including wind stresses and the Coriolis acceleration, the equations of motion applicable to tidal flow can be written as

$$\frac{\partial q_x}{\partial t} - \Omega\, q_y = - g\, d \frac{\partial h}{\partial x} - f\, q\, q_x + K\, V_w^2 \cos \Theta \qquad (3)$$

$$\frac{\partial q_y}{\partial t} + \Omega\, q_x = - g\, d \frac{\partial h}{\partial y} - f\, q\, q_y + K\, V_w^2 \sin \Theta \qquad (4)$$

The equation of continuity for unsteady flow can be expressed as

$$\frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} + \frac{\partial h}{\partial t} = 0 \qquad (5)$$

In eqs. (3), (4) and (5), q_x and q_y are the vertically integrated flows per foot of width at time t in the x and y directions, respectively (x and y taken in the plane of the surface area); h is the water surface elevation with respect to mean sea level (msl) as datum; d is the depth of water at (x, y, t) and is equal to (h - z) where z is the bottom elevation with respect to msl; $q = (q_x^2 + q_y^2)^{1/2}$; V_w is the wind speed at a specified elevation above the water surface; Θ is the angle between the wind velocity vector and the x-axis; K is the non-dimensional wind stress coefficient; and Ω is the Coriolis parameter equal to $2\,\omega \sin \Phi$ where ω is the angular velocity of the earth taken as 0.73×10^{-4} rad/sec and Φ is the latitude. The bed resistance coefficient, f, is computed from the Manning equation as $[gn^2/2.21\ d^{7/3}]$ where n is the Manning roughness coefficient. The Manning coefficient can be estimated either from the Stickler Formula knowing spatial and point distributions of sediments or it can be determined empirically from comparisons of measured and computed tide and velocity histories.

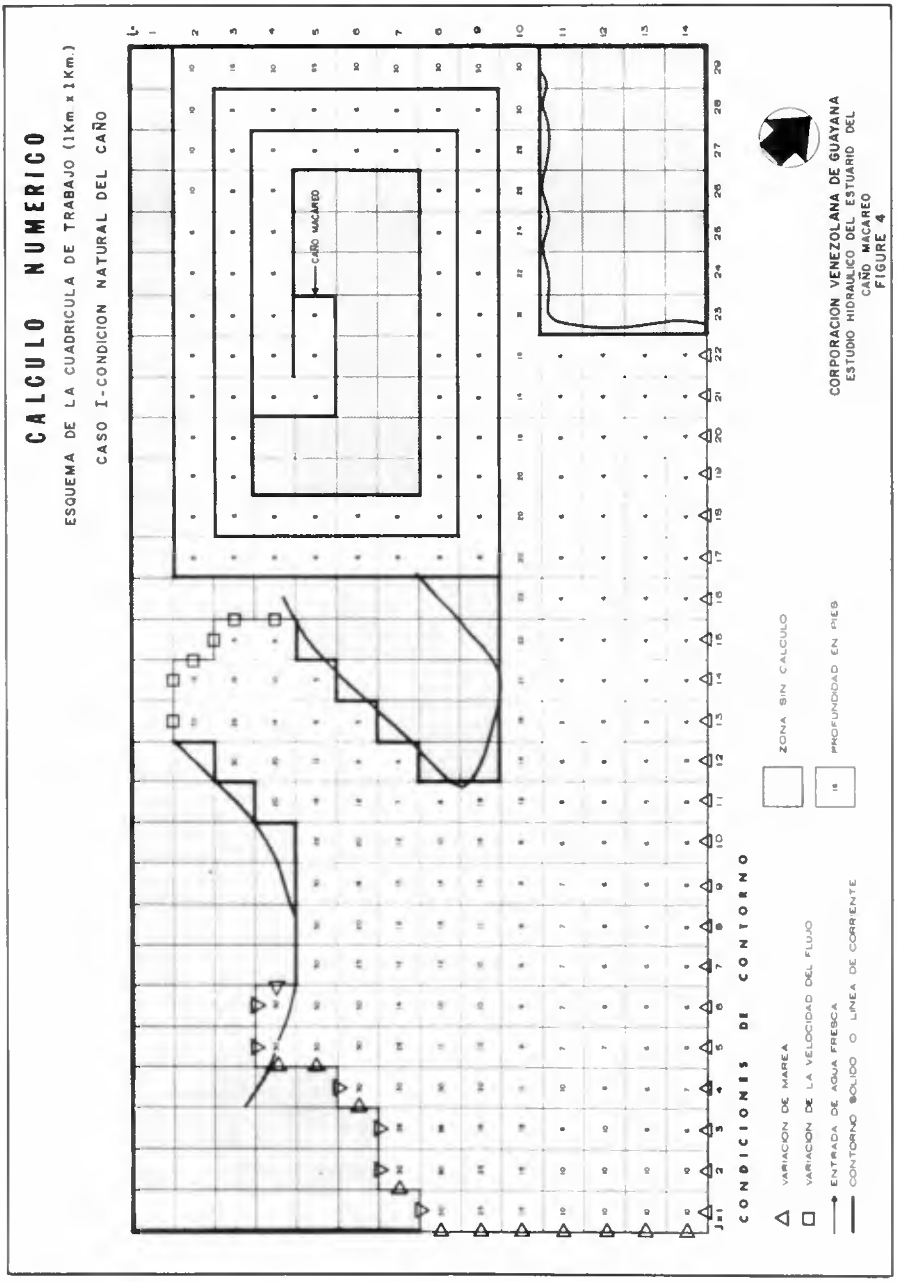
The numerical solution involved an explicit computational scheme in which the two-dimensional vertically integrated equations of motion and the unsteady continuity equation were solved over a rectangular grid of square cells used to represent the physiography of the system and to specify boundary conditions. Two different grid networks were used to describe the study area at the mouth of the Caño Macareo. Resolutions of one and one-half kilometers were used in representing the area from deep water up to the point of river closure, Figures 4 and 5, respectively. The models were excited with representative tides in deep water, a longshore sea current over the continental shelf, and a constant release at the most upstream reach of the river.

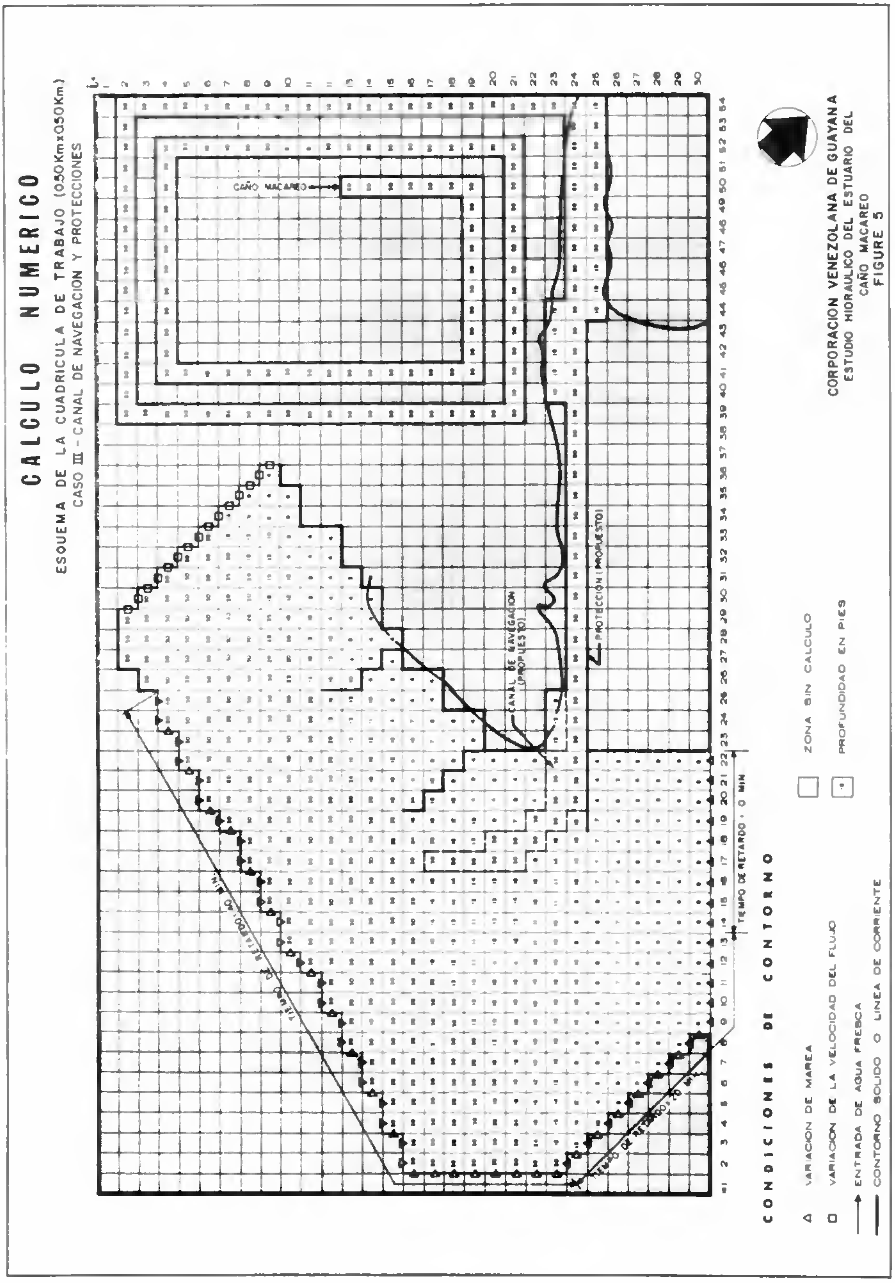
The time histories of water surface elevation and component velocities for one tidal cycle were obtained for each water cell in each of the grid representations including the adjacent shallow areas subject to flooding at high tide. By scanning these results, velocities in each cell were resolved into vectors and then plotted at flood, ebb and slack conditions and compared with results of the electro analogical model.

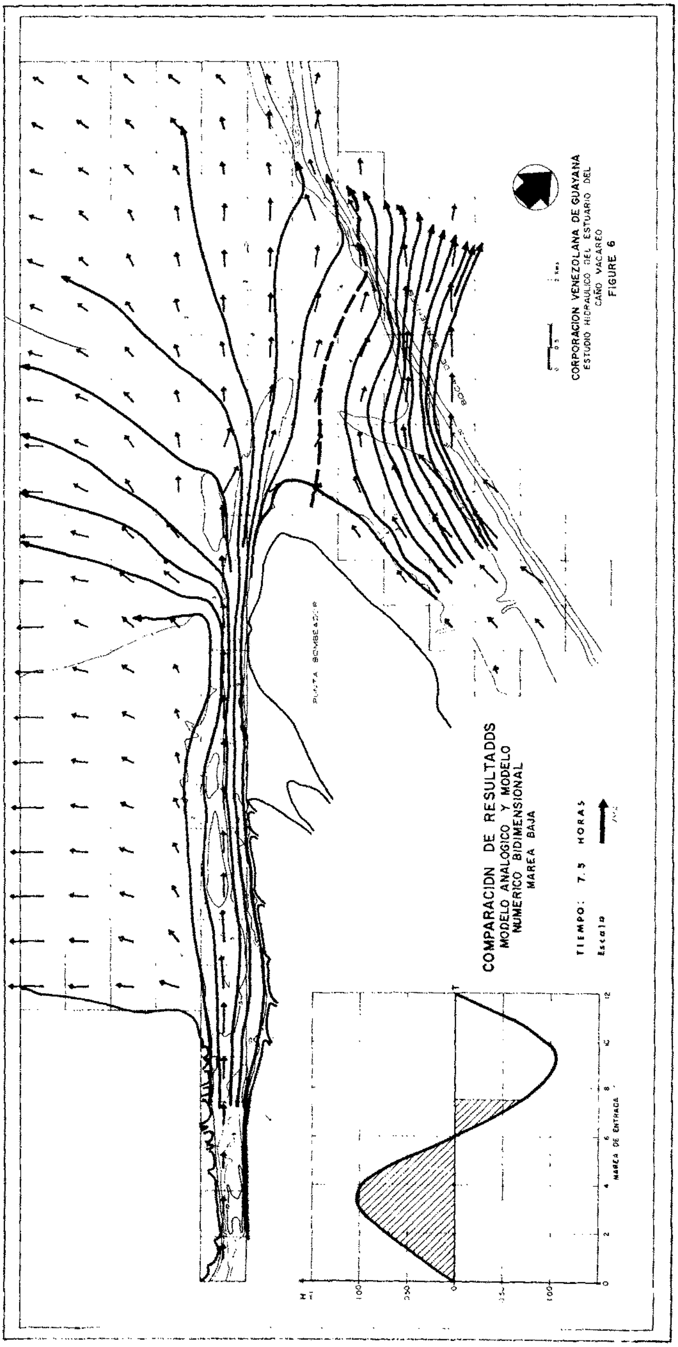
DISCUSSION

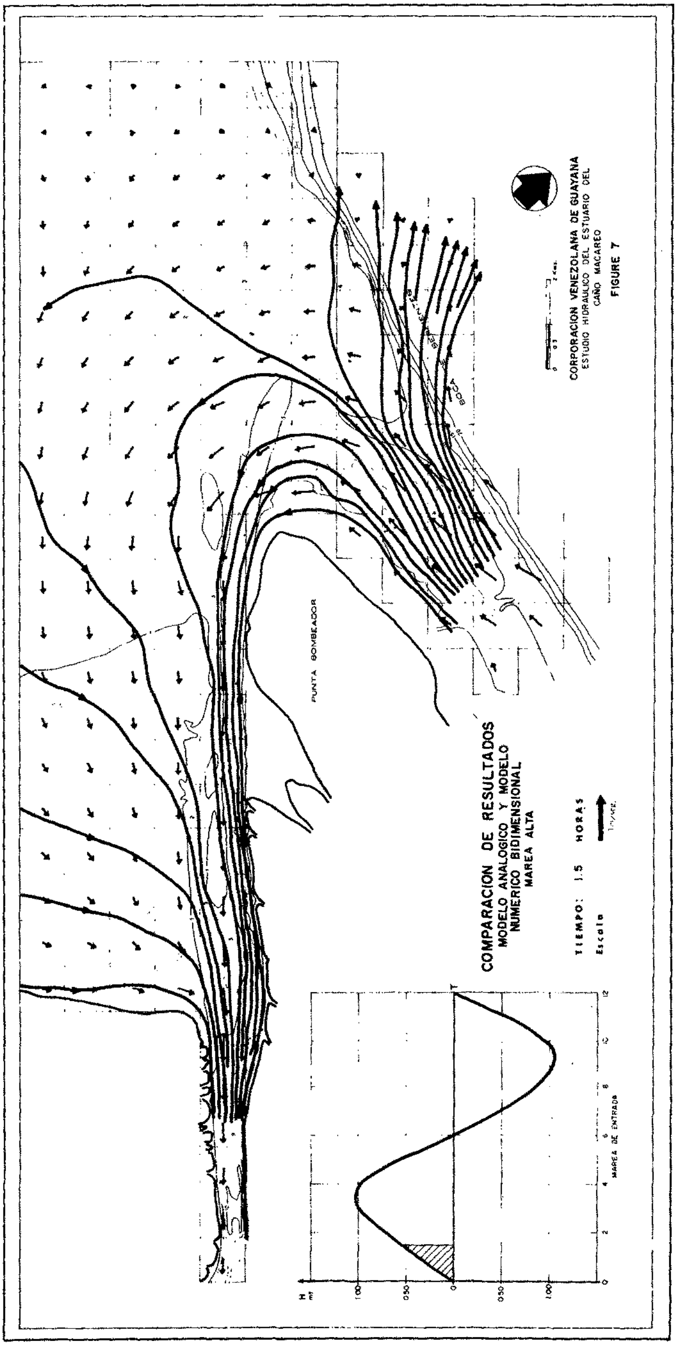
The two-dimensional solutions of the tidal hydrodynamics with the numerical and the electro analogical procedures were carried out initially for natural conditions without channel improvements using boundary conditions determined from the one-dimensional analysis, Figures 2 and 3, and the available field data on the longshore sea current. The results obtained, also shown in Figures 2 and 3, compared satisfactorily with the field measurements of velocity magnitudes and directions at selected cross sections.

For the numerical solution with the one kilometer grid, a spiral type channel was included to take into account the storage effects of the river up to the point of closure. The depth and length of the spiral part of the channel was obtained by trial using the one-dimensional results as a reference. The magnitude of the sea current was divided into three parts and a variation of each magnitude with time was specified. In Figures 6 and 7, the comparison of Masch and Brandes' numerical computations and Zagustin's analogical results is presented for ebb and flood tide conditions.


CALCULO NUMERICO
ESQUEMA DE LA CUADRICULA DE TRABAJO (1Km x 1Km.)
CASO I-CONDICION NATURAL DEL CAÑO
CAÑO MACAREO
ZONA SIN CALCULO
PROFUNDIDAD EN PIES
CONDICIONES DE CONTORNO
VARIACION DE MAREA
VARIACION DE LA VELOCIDAD DEL FLUJO
ENTRADA DE AGUA FRESCA
CONTORNO SOLIDO O LINEA DE CORRIENTE
CORPORACION VENEZOLANA DE GUAYANA
ESTUDIO HIDRAULICO DEL ESTUARIO DEL
CAÑO MACAREO
FIGURE 4


CALCULO NUMERICO
ESQUEMA DE LA CUADRICULA DE TRABAJO (0.50 Km x 0.50 Km)
CASO III - CANAL DE NAVEGACION Y PROTECCIONES
CAÑO MACAREO
CANAL DE NAVEGACION (PROPUESTO)
PROTECCION (PROPUESTO)
TEMPO DE RETARDO = 0 MIN
CONDICIONES DE CONTORNO
VARIACION DE MAREA
VARIACION DE LA VELOCIDAD DEL FLUJO
ENTRADA DE AGUA FRESCA
CONTORNO SOLIDO O LINEA DE CORRIENTE
ZONA SIN CALCULO
PROFUNDIDAD EN PIES
CORPORACION VENEZOLANA DE GUAYANA
ESTUDIO HIDRAULICO DEL ESTUARIO DEL
CAÑO MACAREO
FIGURE 5


CORPORACION VENEZOLANA DE GUAYANA
ESTUDIO HIDRAULICO DEL ESTUARIO DEL
CAÑO MACAREO
FIGURE 6
COMPARACION DE RESULTADOS
MODELO ANALOGICO Y MODELO
NUMERICO BIDIMENSIONAL
MAREA BAJA
TIEMPO: 7.5 HORAS
Escala
PUNTA BOMBEADOR
MAREA DE ENTRADA


CORPORACION VENEZOLANA DE GUAYANA
ESTUDIO HIDRAULICO DEL ESTUARIO DEL
CAÑO MACAREO
FIGURE 7
COMPARACION DE RESULTADOS
MODELO ANALOGICO Y MODELO
NUMERICO BIDIMENSIONAL
MAREA ALTA
TIEMPO: 1.5 HORAS
Escala
PUNTA BOMBEADOR
BOCA
MAREA DE ENTRADA

Partially as a result of the initial runs, it was decided that a lateral protection was required to maintain most of the channel length in the estuary free of sediment. Several combinations of barriers were tested to protect the channel at its exit to the sea. In these tests, the one-half kilometer grid was used with the numerical computations and a more detailed electro analogical model was also built. In both cases a more exact representation of the sea current was taken into account. Figures 8 through 11 show velocity patterns at flood, ebb and slack tide conditions as obtained from the models for a given geometrical configuration of the proposed barriers and channel alignment. After studying several combinations of berms, sea current barriers and channel alignment, a recommended layout, Figure 12, was selected based on minimizing sediment transport problems but still maintaining manageable velocities from the standpoint of navigation.

CONCLUSIONS

The numerical and analogical simulation models described in this paper have been shown to provide the capability for analyzing estuarial circulation patterns resulting from alternative channel configurations. The models which have been applied to the Caño Macareo, an estuary of the Rio Orinoco, were calibrated using data collected in the field and results obtained from a one-dimensional method of analysis. Several geometric configurations of channel alignment were investigated as well as different berm lengths and locations parallel to the channel and alongshore. For each configuration, velocity vectors were determined and then evaluated to select a recommended configuration to minimize sediment problems.

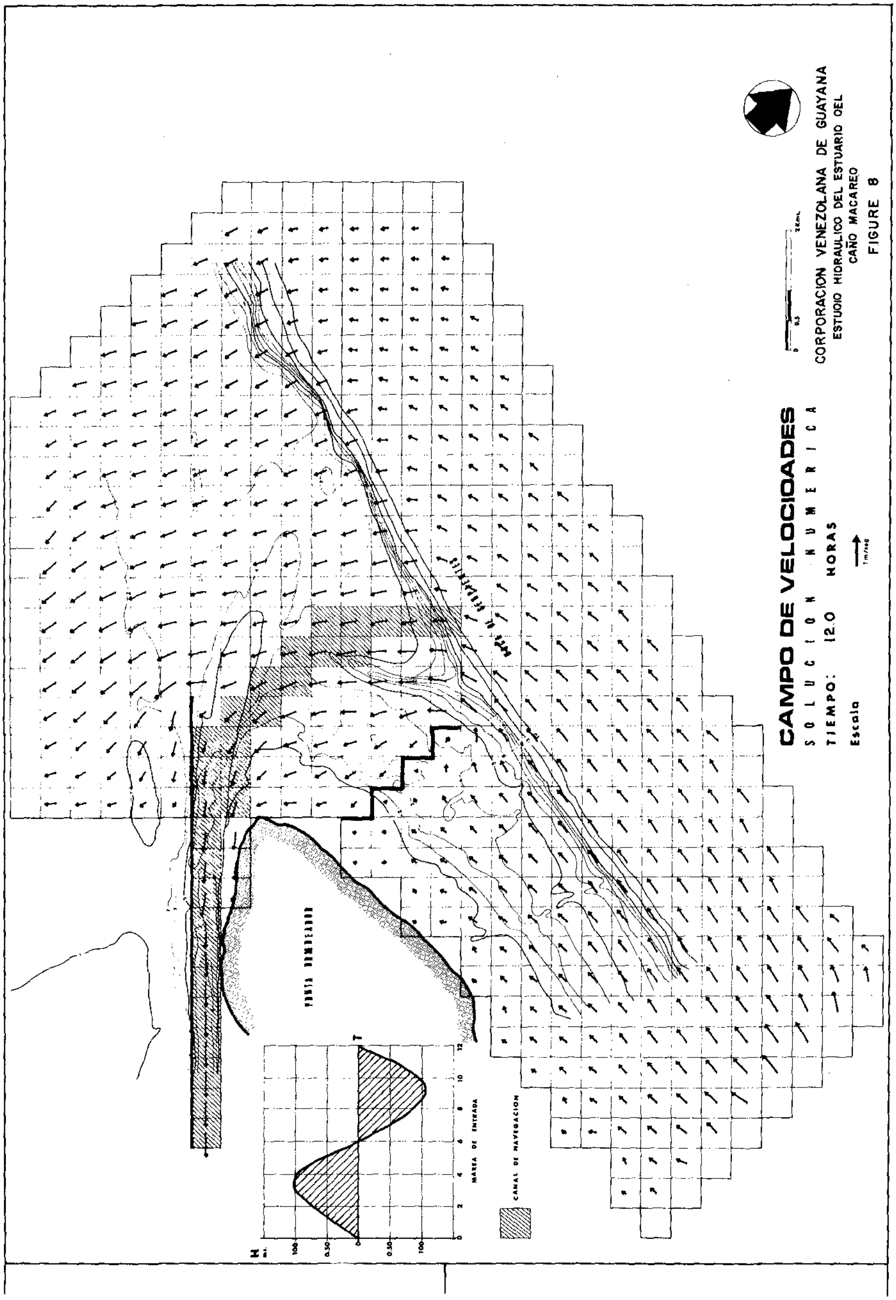
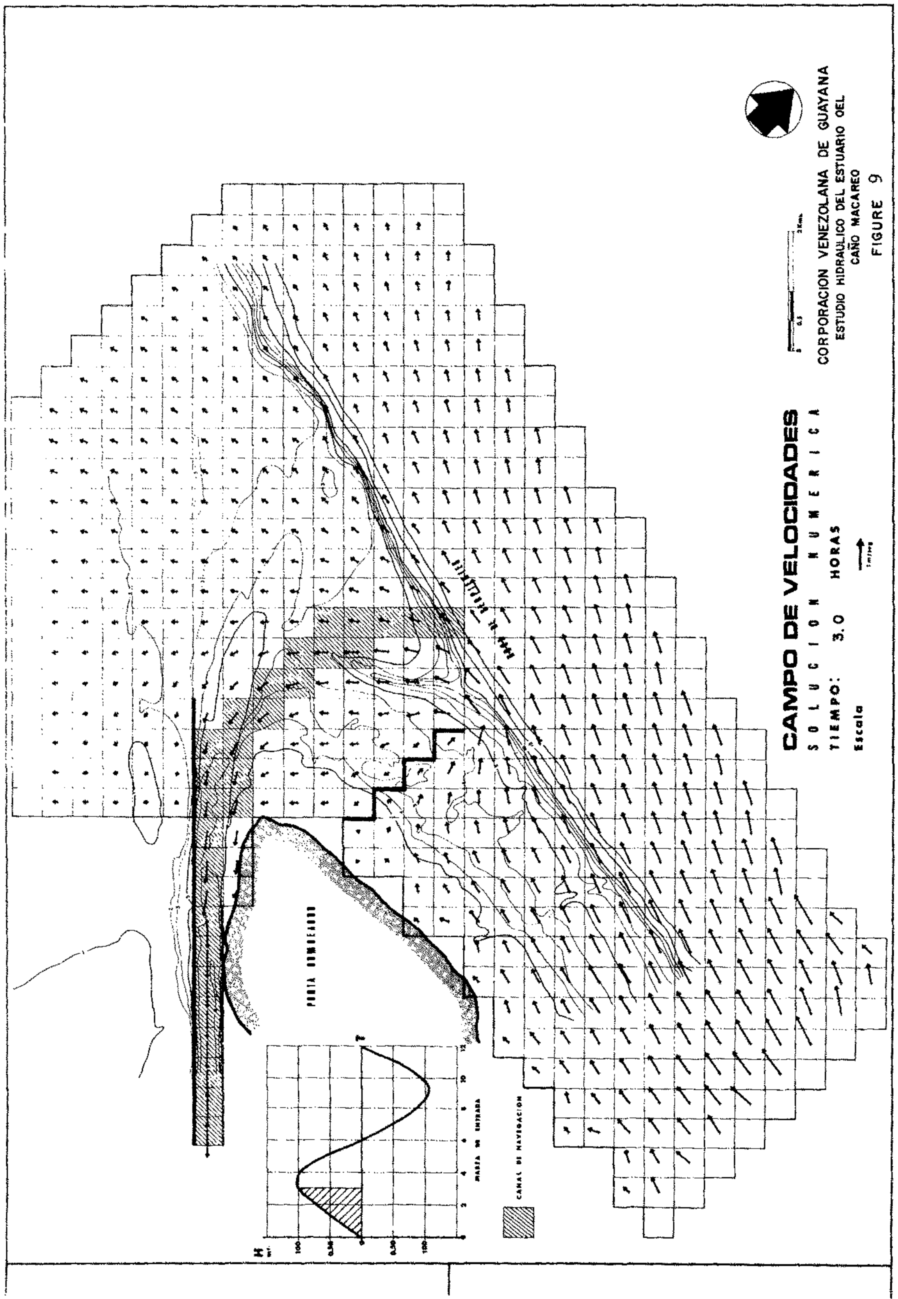

CAMPO DE VELOCIDADES
SOLUCION NUMERICA
TIEMPO: 12.0 HORAS
Escala
CORPORACION VENEZOLANA DE GUAYANA
ESTUDIO HIDRAULICO DEL ESTUARIO DEL
CAÑO MACAREO
MAREA DE ENTRADA
CANAL DE NAVEGACION

FIGURE 8


CORPORACION VENEZOLANA DE GUAYANA
ESTUDIO HIDRAULICO DEL ESTUARIO DEL
CAÑO MACAREO
FIGURE 9
CAMPO DE VELOCIDADES
SOLUCION NUMERICA
TIEMPO: 3.0 HORAS
Escala

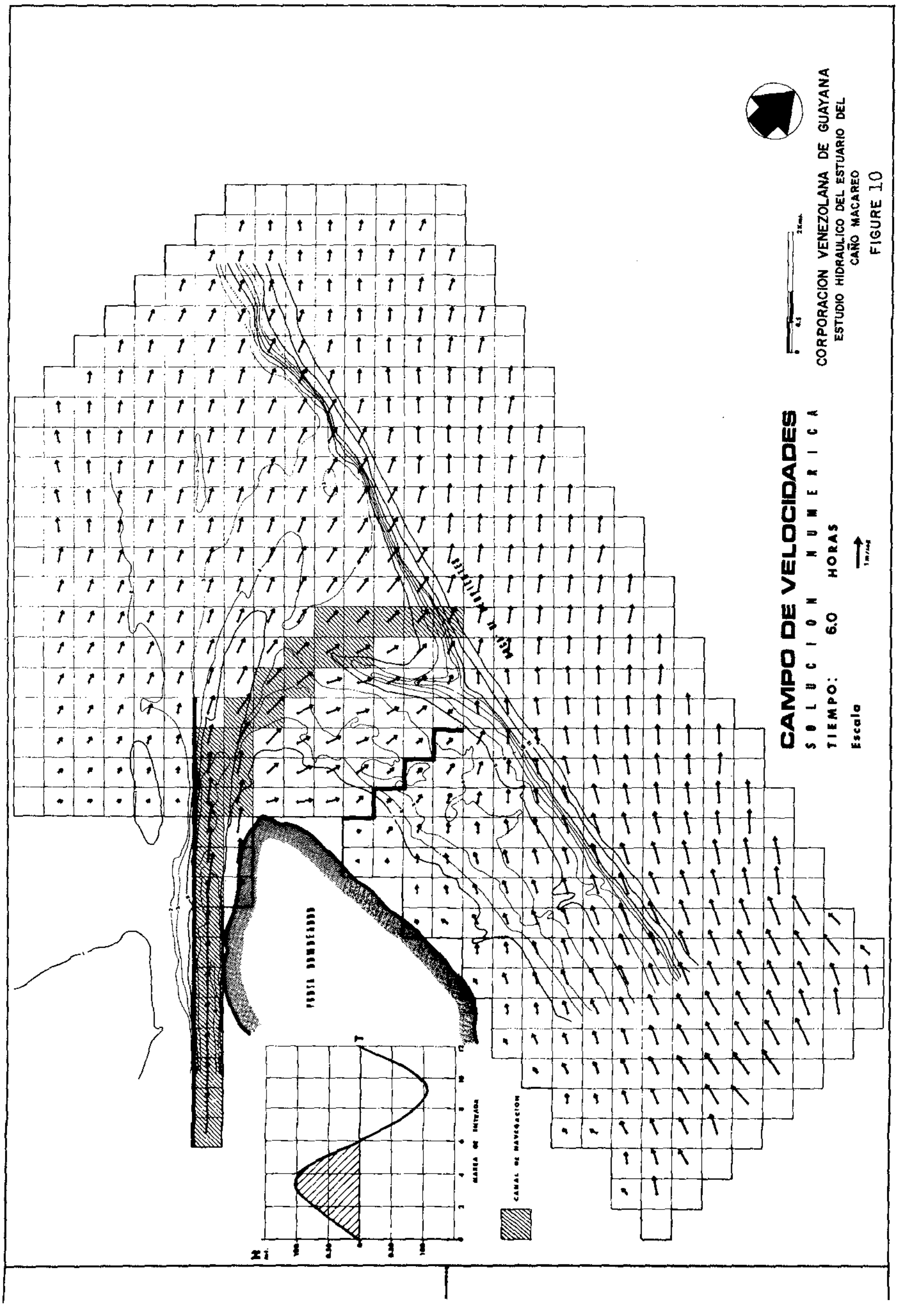
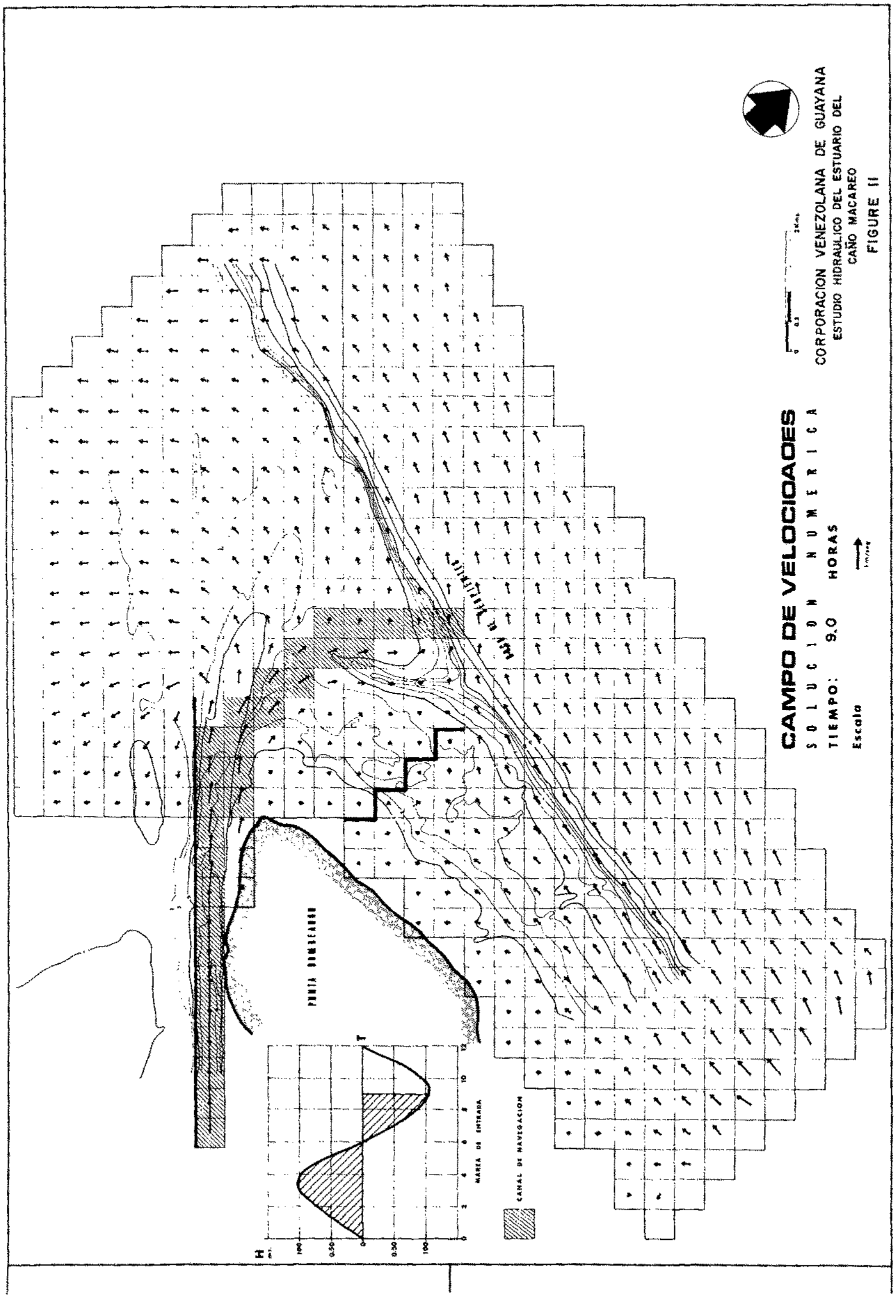

CAMPO DE VELOCIDADES
SOLUCION NUMERICA
TIEMPO: 6.0 HORAS
Escala
CORPORACION VENEZOLANA DE GUAYANA
ESTUDIO HIDRAULICO DEL ESTUARIO DEL
CAÑO MACAREO

FIGURE 10


CAMPO DE VELOCIDADES
SOLUCION NUMERICA
TIEMPO: 9.0 HORAS
Escala
CORPORACION VENEZOLANA DE GUAYANA
ESTUDIO HIDRAULICO DEL ESTUARIO DEL
CAÑO MACAREO
FIGURE 11
CANAL DE NAVEGACION
MAREA DE ENTRADA

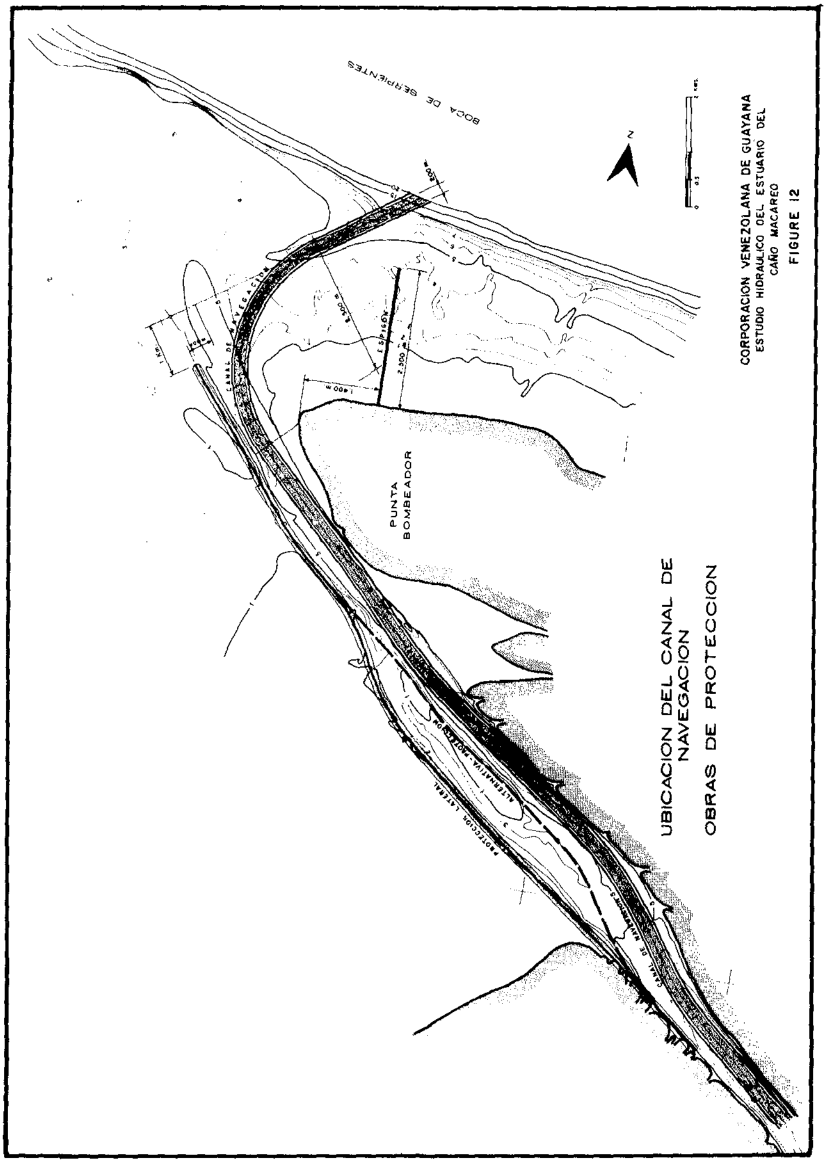

UBICACION DEL CANAL DE NAVEGACION
OBRAS DE PROTECCION
CORPORACION VENEZOLANA DE GUAYANA
ESTUDIO HIDRAULICO DEL ESTUARIO DEL
CAÑO MACAREO
PUNTA BOMBEADOR
BOCA DE SERPIENTES
ESPIGON
CANAL DE NAVEGACION
N

FIGURE 12