WIND-DRIVEN CIRCULATION OF WATER IN CANALS OF FLAMINGO PARADISE N.V.

by

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for

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1. INTRODUCTION

Flamingo Paradise, a resort development proposed for the island of Bonaire in the Netherlands Antilles, features an inland canal system which is joined to the Caribbean Sea by means of a narrow entranceway (see Figure 1). Concern has been expressed over the possibility of problems in maintaining acceptable water quality in the canal system if the water circulation within the system and the exchange with clean sea water were to prove to be inadequate after completion of the development. In the light of the knowledge that the site is subjected about 95% of the time to east-northeast trade winds ranging from eleven to seventeen knots, a study was undertaken to determine the effect of wind on the nature of the flow patterns within the inland canal system.

A scale model of the site, including the canal system and a portion of the adjacent sea coast, was constructed and placed in the Industrial Wind Tunnel at Colorado State University (see Figure 2). The model was filled with water and a simulated natural wind was imposed in the approximate direction of the prevailing trade-winds.

Flow patterns within the canal/sea system were observed by means of dye injection and were recorded on sketches, color still photographs and color motion pictures. The still photographs and motion pictures of all model tests have been provided apart from this report to Edward D. Stone, Jr. & Associates, and are on file at Colorado State University.

After initial testing, modifications were made to the modeled canal system in an attempt to improve the wind-driven circulation and exchange processes. In order to assess the effectiveness of these modifications, empirical estimates were made of the time required to completely exchange the water in the modified system with clean sea water. These estimates are contained in an appendix to this report.

In a preliminary phase of this study, the effect of the proposed condominium units on surface winds (hence on pedestrian comfort) was investigated briefly. Scale building models were placed in the Industrial Wind Tunnel and a simulated natural wind was imposed. Wind flow patterns for various building orientations were then observed by means of smoke tracer releases. An exploratory investigation of natural ventilation of the buildings was conducted by observation of smoke tracers through the buildings. The models were constructed with transparent walls for the purpose.

2. STUDY METHODOLOGY

The objective of this study was to determine, by means of physical modeling, the effect of the prevailing winds on the circulation of water within the Flamingo Paradise canal system and on the exchange of water between the canal system and the ocean. Strict kinematic and dynamic similarity of these processes cannot be practically achieved in the wind tunnel. However, comparisons of circulation and exchange can be made among several cases (keeping the simulated wind speed and direction constant and varying channel geometry parameters, for example) to determine the best means of preserving water quality in the canal system. This comparative approach was therefore adopted and wind-tunnel tests were conducted in three phases, as described below.

Phase I

- canal system completed as proposed
- no buildings or vegetative cover present

Phase II

- addition of all significant buildings and vegetation, approximately as proposed

Phase III

- modification of canal system to improve circulation and exchange with ocean

Relative circulation rates were determined by injecting slightly negatively buoyant dye (Rhodamine) near the bed at several canal locations and by releasing small buoyant particles (styrofoam) on the water surface. Dye movement, indicating near-bed velocities, was recorded by a periodic sequence of still color photographs and by means of vector-diagram sketches. For the final canal configuration determined for Phase III, dye and styrofoam movements were recorded on color motion-picture film.

3. DESCRIPTION OF MODEL AND TEST PROCEDURE

A 1:500 model scale was selected in order to provide complete site coverage within the confines of the Industrial Wind Tunnel at Colorado State University. However, channel depths were scaled at 1:250 in order to minimize the additional flow resistance in the model due to viscous effects. The model islands and the surrounding topography were cut from 3/4-inch plywood and placed in a tray, also of plywood construction, which acted as a container for the model canal system and the adjacent "ocean". Ramps were installed to provide a gradual transition between the wind-tunnel floor and the edge of the tray. All water-exposed surfaces were coated with epoxy paint to prevent warping, waterlogging or dye absorption. Silicone sealant was applied around the edges of islands, etc., to prevent flow under the islands (i.e., between the tray and the bottoms of the islands). The tray was made sufficiently long that its downwind (west) end did not interfere significantly with the local circulation near the marina entranceway. In addition, a strip of fibrous material was attached to the downwind end of the tray to prevent the reflection of wind-generated waves into the entranceway region.

Buildings, where required, were scaled at 1:500 and were constructed of styrofoam. Building clusters were assembled approximately as shown on the Flamingo Paradise Master Plan, Sheet No. 4. Vegetation was simulated at critical locations with fibrous packing material.

With the model in place in the wind tunnel and the tray filled with water, a gradient wind speed of ten feet per second was imposed. After a sufficient length of time for the wind-drive circulation to have reached a steady-state condition, dye was injected at three selected locations through small tubing connected to syringes located outside the wind tunnel. Still color photographs were then taken at thirty-second intervals for a duration of thirty minutes. Sketches were made, in the form of vector diagrams, of the direction and relative magnitude of the near-bed water flow. Once the photography was completed, buoyant particles were distributed on the water surface and relative surface velocities were sketched on the vector diagrams.

In addition to these data, color motion pictures were made of the test for Phase III (with channel improvements) at the rate of five frames per second for a thirty minute duration.

4. TEST RESULTS

Phase I (No Buildings). The observed circulation was primarily confined within "cells" consisting of straight reaches of channel. (See Figures 3 and 4.) That is, in a particular straight reach, the flow circulated (downwind near the water surface and upstream near the bed) much as though it were a closed system. A weak vortex developed near the marina area and another in the entranceway. Little, if any, exchange was visible between the canal system and the ocean. Due to the "internal" circulation described above, vertical mixing of the dye occurred as the test progressed, giving the appearance that the near-bed velocities were greater than they actually were.

Phase II (Buildings Present). With buildings and vegetation present, the circulation patterns became even more localized than in the Phase I test. (See Figure 5.) "Dead" zones in the lee of islands tended to isolate the circulation "cells" to an even greater extent. The vortices near the marina and entranceway were stronger than in the previous case, and again no significant exchange was evident between the inland canal system and the ocean. The local circulation and vertical mixing were intensified somewhat in those fetches still exposed to the wind after addition of the buildings. As in the previous case, the spread of the dye due to vertical mixing and subsequent advection in the upper layers could be misinterpreted from the photos in regard to the magnitude of near-bed velocities. That is, the photographs of the late stages of the test imply near-bed velocities which were greater than actually observed velocities.

Phase III (With Channel Improvements). Subsequent to the previous tests, it was concluded that the exchange of water between the canal system and the ocean could be significantly improved if some means could be provided for the direct return of sea water to the upwind end of the canal system, thus eliminating the two-layer flow regime in the canals and its inherent vertical mixing problem. Therefore, a covered channel or conduit was added to the canal system to directly convey sea water to the upwind end of the system. As the water in this covered channel was not subjected to wind stress, the return flow was driven by the differential head (over the length of the canal system and ocean to the channel inlet) created by wind set-up on the exposed canals.

In a test conducted in a similar manner as the tests for Phases I and II, it was observed that the exchange between the canal system and the ocean was significantly improved as a result of the through-flow from the conduit. (See Figure 6.) In nearly all of the channels, the entire vertical profile of longitudinal velocity was oriented in the downwind direction. The distribution of the flow into the canal system from the conduit may not be optimal in that the distribution of dye among the channels at the upwind end of the system did not appear equal. However, it was determined that the establishment of wind-driven through flow was feasible; the precise distribution of the conduit outflow is a relatively minor problem which can be accommodated during a later stage of design.

The "dead" zones in the lee of the model islands were still somewhat in evidence in the Phase III test. If necessary, it may be possible to modify the shapes of two or three islands in order to increase the effective fetch near the zones in question. In addition, culverts through the "peninsulas" which jut out into the canal system might be investigated as a means of increasing the circulation in the areas between the islands and the mainland. However, these steps were not undertaken as part of this study due to the significant flow improvement which resulted from the addition of the conduit, and also due to the conflict with the objective (stated in the Master Plan) of minimizing fetch length and wave chop within the canal system.

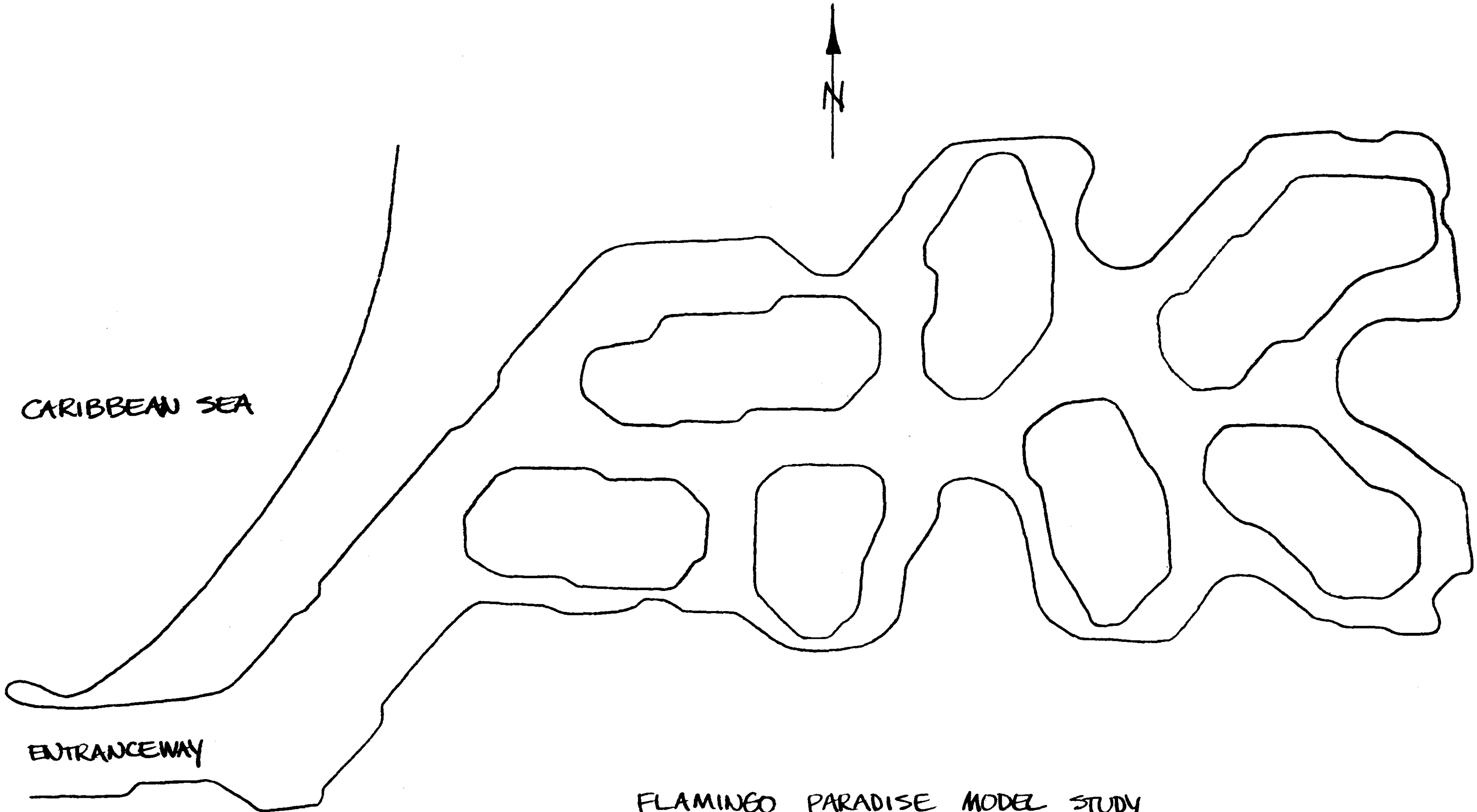
5. CONCLUSIONS

1. The wind-driven circulation within the inland canal system as proposed is primarily confined to "cells" consisting of finite reaches of channel. Vertical mixing is noticeable but exchange between the canal system and the ocean is poor.

2. The wind-driven exchange of water between the canal system and the ocean can be significantly improved by the addition of a covered channel or conduit to directly convey sea water to the upwind (east) end of the canal system.

3. The circulation may be subject to improvement by means of modifying island shapes, but any improvement would be associated with increases in effective fetch and would likely also result in increased wave chop within the canal system.

4. The test results are qualitative in nature. Inferences may therefore be drawn regarding relative improvements in circulation by certain conceptual modifications; however, the determination of the required hydraulic design parameters is beyond the scope of the present study.



FLAMINGO PARADISE MODEL STUDY

PROPOSED LAYOUT OF INLAND CANAL SYSTEM

APPROX SCALE 1 : 4000

FIGURE 1

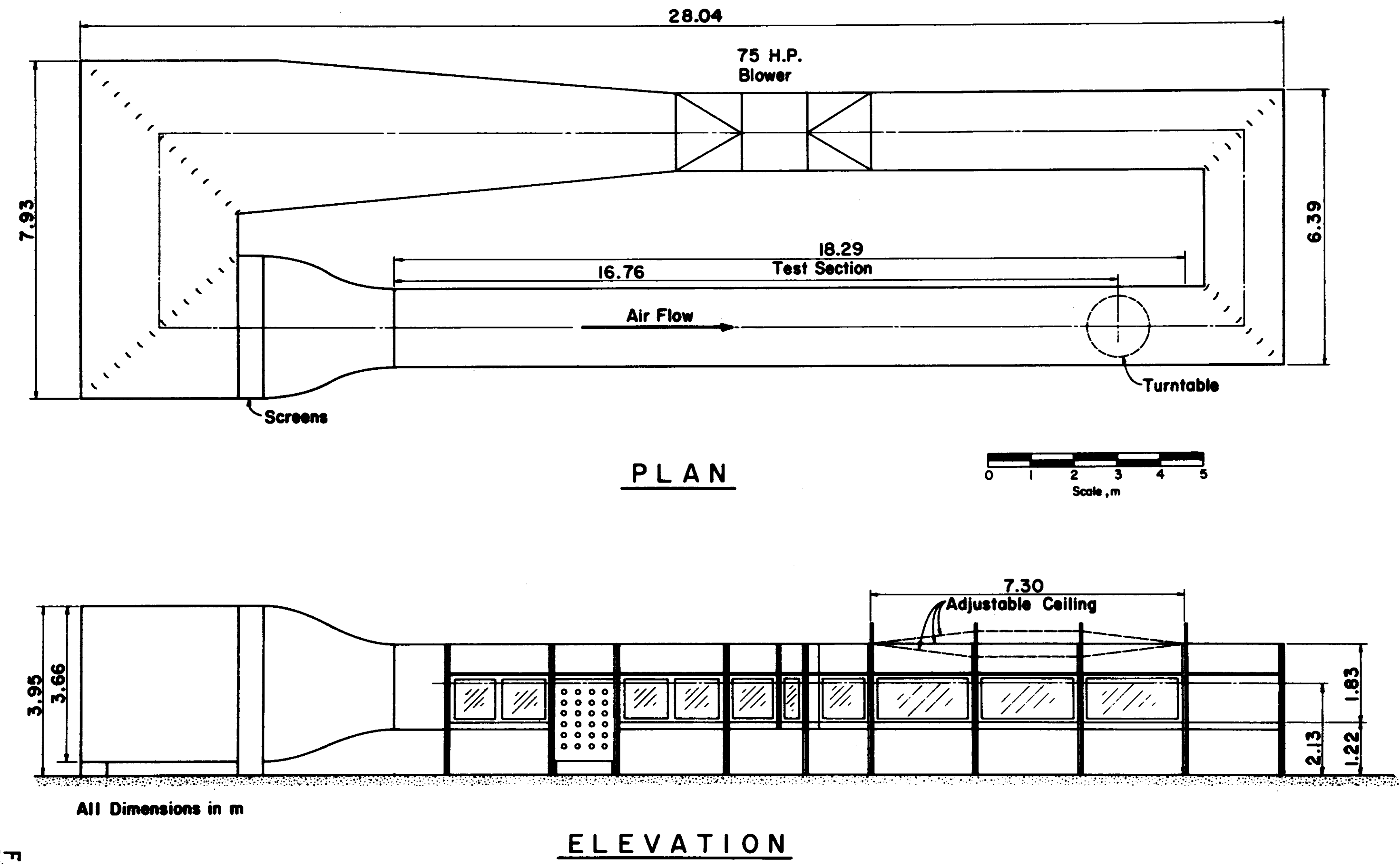
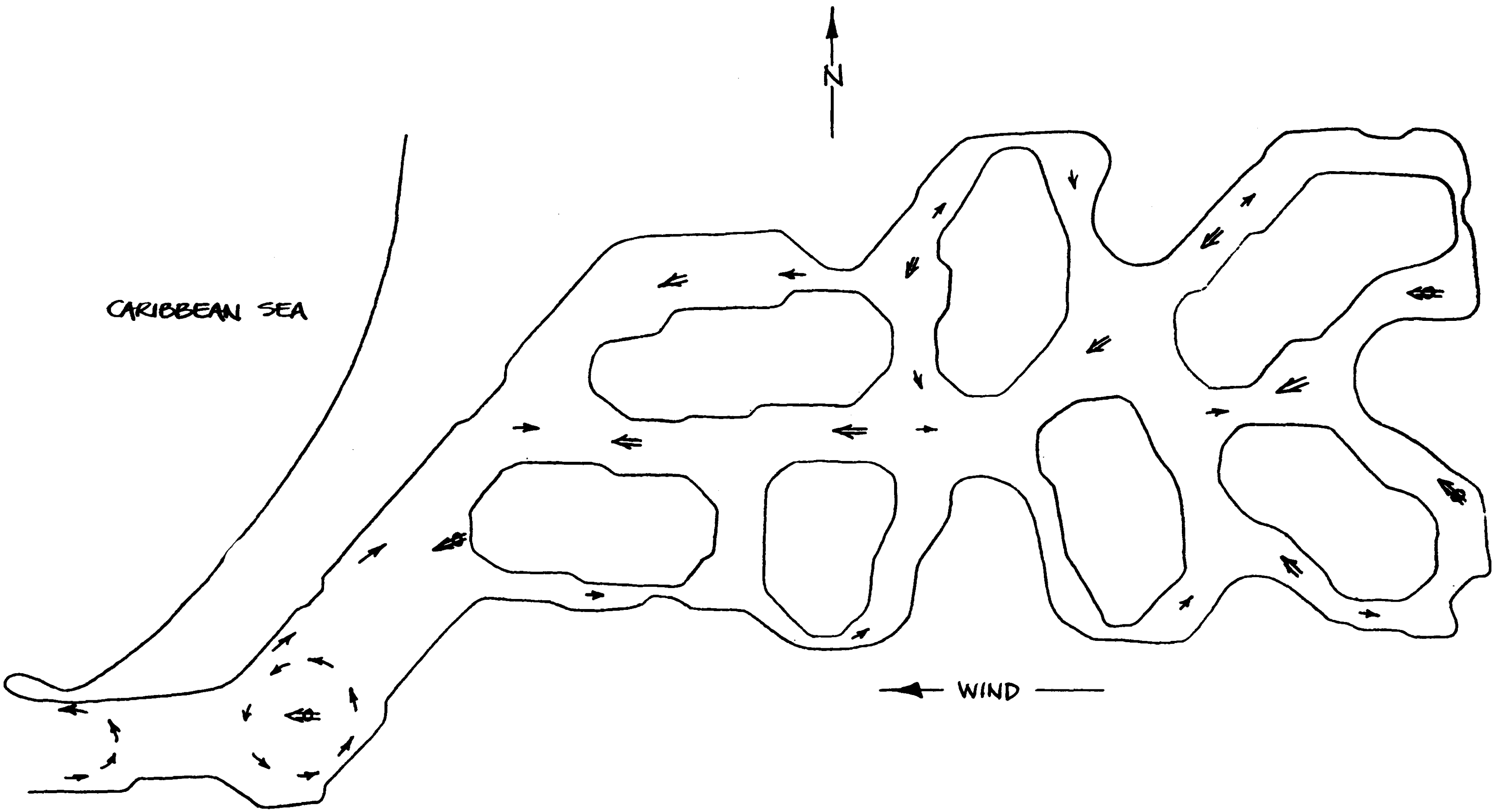


FIGURE 2

INDUSTRIAL AERODYNAMICS WIND TUNNEL
FLUID DYNAMICS & DIFFUSION LABORATORY
COLORADO STATE UNIVERSITY



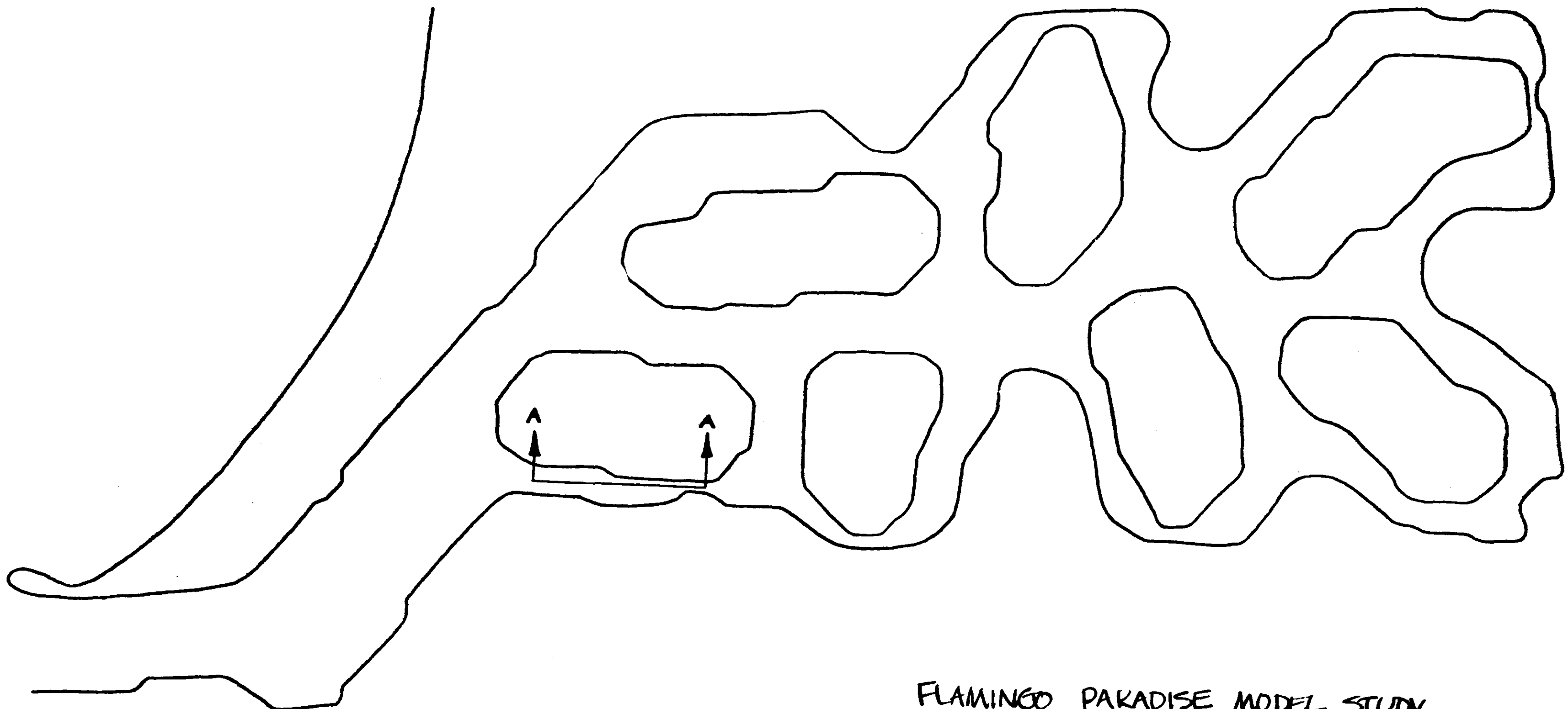
FLAMINGO PARADISE MODEL STUDY

PHASE I : NO BUILDINGS

LEGEND

SURFACE VELOCITY
NEAR-BED VELOCITY
NO MOTION

FIGURE 3



FLAMINGO PARADISE MODEL STUDY

CIRCULATION IN TYPICAL "CELL"

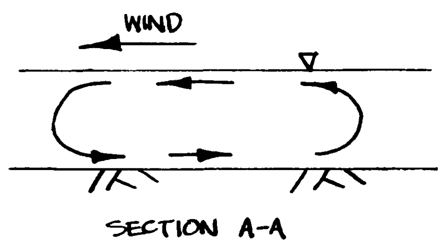
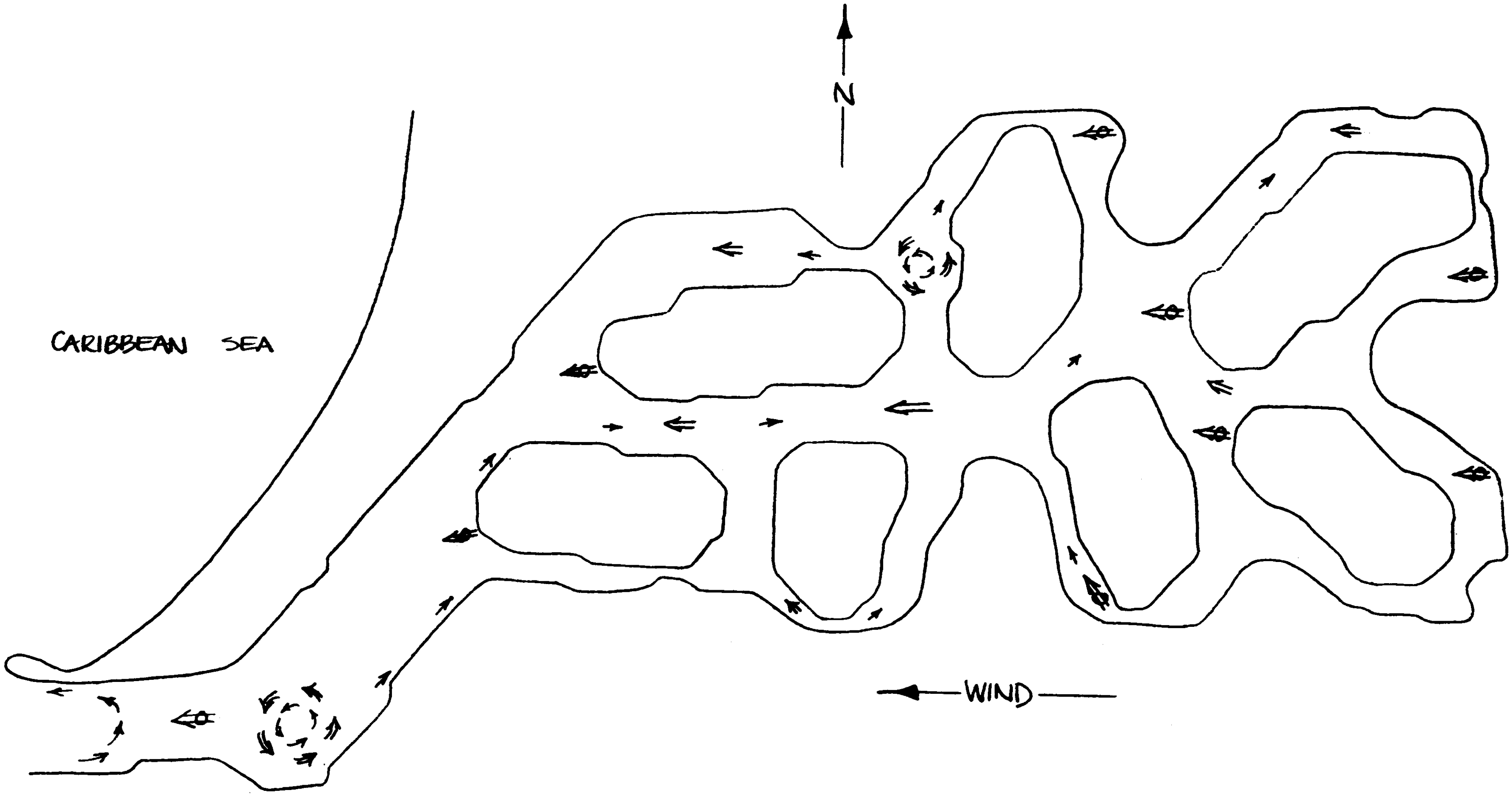


FIGURE 4



FLAMINGO PARADISE MODEL STUDY

PHASE II : BUILDINGS PRESENT

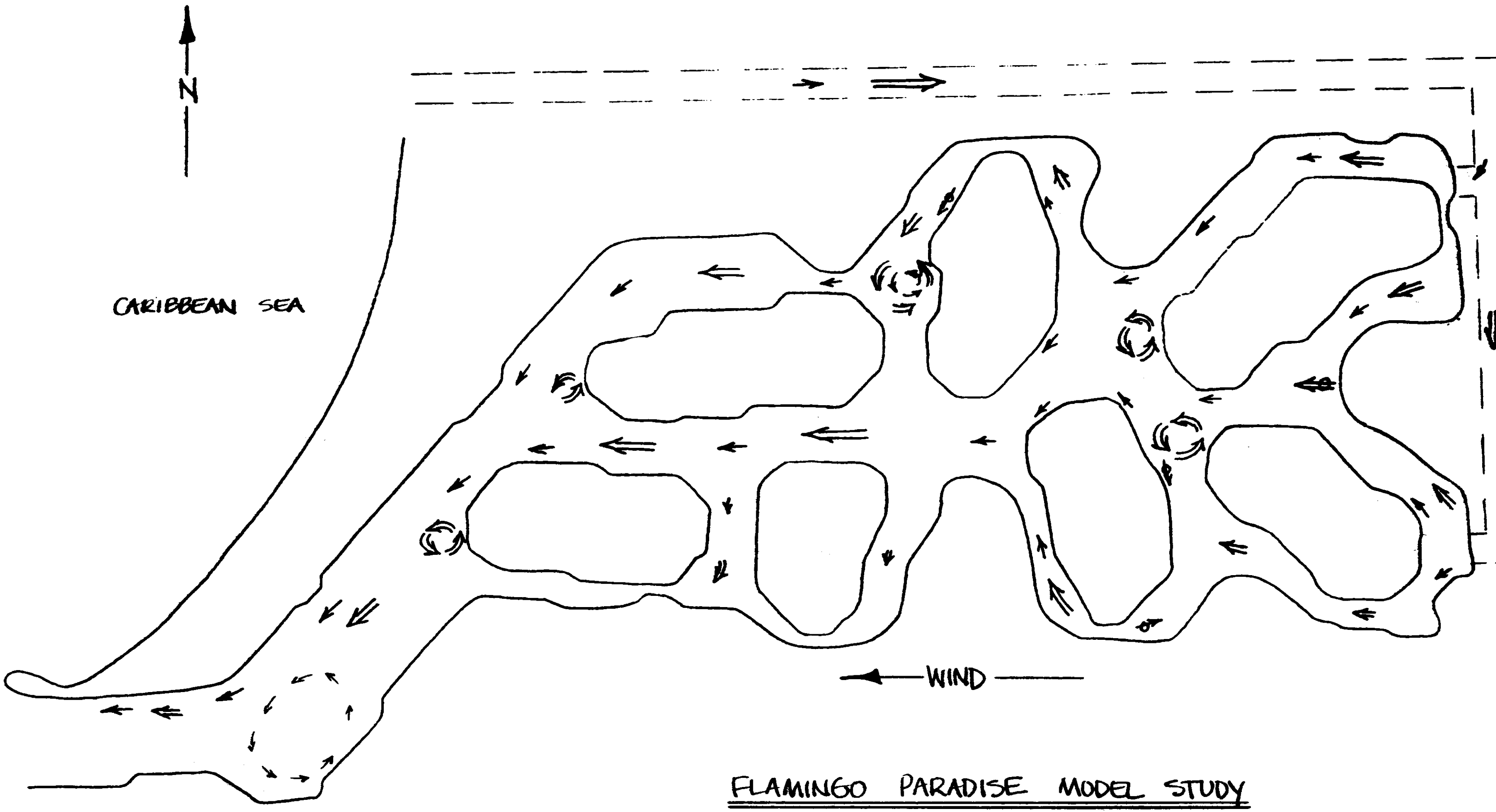
LEGEND

SURFACE VELOCITY

NEAR-BED VELOCITY

NO MOTION

FIGURE 5



FLAMINGO PARADISE MODEL STUDY

PHASE III: CHANNEL IMPROVEMENTS

LEGEND

SURFACE VELOCITY

NEAR-BED VELOCITY

NO MOTION

FIGURE 6

APPENDIX

ESTIMATE OF EXCHANGE TIME FOR TYPICAL MODIFIED CANAL SYSTEM CONFIGURATION

- ASSUMPTIONS

  - wind speed, $U = 15$ mph (= 22 ft/sec = u)
  - canal depth, $d = 5.5$ ft
  - exposed fetch, $F = 4200$ ft (= 0.80 mi = f)
  - canal volume, $V = 7 \times 10^6 ft^3$

- METHODOLOGY

  - estimate total wind set-up over length of canal system from following empirical formulae:

    1. Sibul (Ref. 1): $S \simeq 4.9 \times 10^{-5}\, d\left(\frac{F}{d}\right)^{1.66}\left(\frac{u^2}{gF}\right)^a = 0.018$ ft

       where $a = 2\left(\frac{F}{d}\right)^{-0.077}$

    2. Zuider Zee (Ref. 2): $S \simeq \frac{U^2 f}{700d} = 0.047$ ft

  - assume that return (conduit) flow does not significantly affect wind set-up, and that the set-up represents the differential head available to drive the return flow.

  - calculate the discharge in the conduit (assuming a typical size and material) corresponding to the available head, by conventional methods.

  - determine the time required to replace the volume of the canal system once at the calculated discharge rate.

- RESULTS

	Estimated Set-Up	
Conduit Dia.	0.047 ft (method 1)	0.018 ft (method 2)
5 ft	Q = 7.5 cfs t = 11 days	Q = 4.7 cfs t = 17 days
3 ft	Q = 1.9 cfs t = 42 days	Q = 1.2 cfs t = 67 days

NOTES:

- conduit assumed circular concrete, $\varepsilon = 0.01$ ft.
- Q = conduit discharge
- t = time for complete exchange of canal system

- REFERENCES

1. Sibul, O., "Laboratory Study of Wind Tides in Shallow Water", U.S. Army Corps of Engineers, Beach Erosion Board, Technical Memo 61, 1955.

2. Davis, C.V. and K.E. Sorensen, Handbook of Applied Hydraulics, Third Edition, McGraw-Hill, 1969.