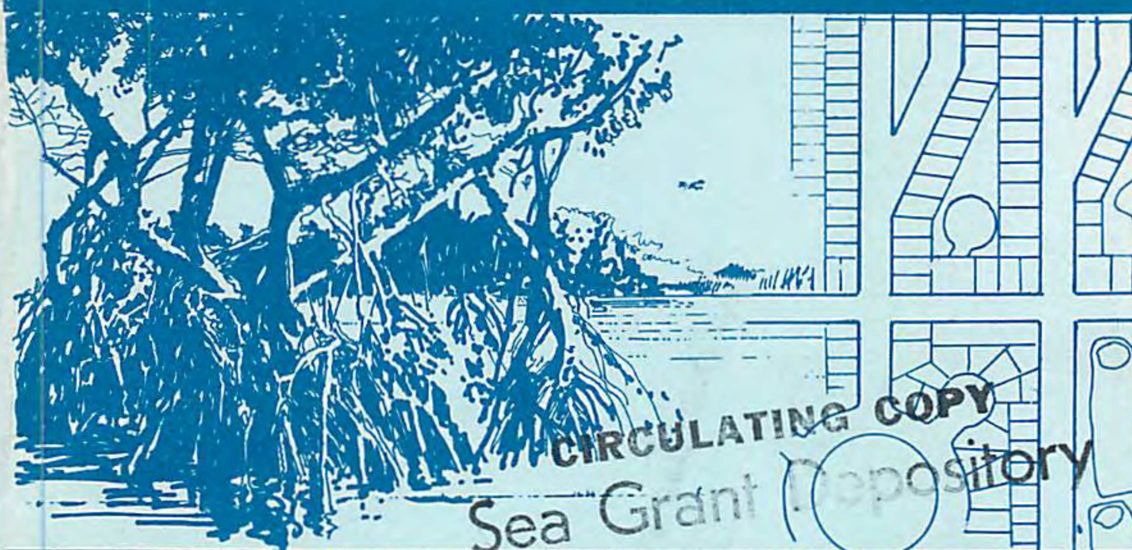
COASTAL ZONE MANAGEMENT SERIES



Water Movements in Shallow Coastal Bays and Estuaries

Thomas N. Lee and Claes Rooth

Bulletin Number 3

UNIVERSITY OF MIAMI SEA GRANT PROGRAM

January 1973

Sea Grant

Coastal Zone Management Bulletin #3

Water Movements in Shallow Coastal Bays and Estuaries

Thomas N. Lee
and
Claes Rooth

Cover Photo: William M. Stephens

University of Miami Sea Grant Program (NOAA Sea Grant No. 2-35147)
Miami, Florida 1973

The University of Miami's Sea Grant Program is a part of the National Sea Grant Program, which is administered by the National Oceanic and Atmospheric Administration of the U. S. Department of Commerce.

University of Miami Sea Grant Program
10 Rickenbacker Causeway
Miami, Florida 33149
1973

TABLE OF CONTENTS

FOREWARD

The Sea Grant Coastal Zone Management Bulletin Series is being offered as a method of acquainting the public with advances in the fields of coastal zone engineering and research.

Further expansion of human population into the coastal zone is assured. As this happens, conflict over the uses of this limited area's natural resources will increase inasmuch as all uses are not compatible.

The purpose of the Coastal Zone Management Bulletin Series is to summarize new research results in the management context and to stimulate discussion of new management techniques which appear to offer possible solutions to complicated socio-environmental problems.

A further aim of this Series is to present sometimes complex thoughts and concepts in a semi-technical publication which can be used by planners, developers and persons in public office.

This Bulletin is published by the University of Miami Sea Grant Program in the belief that its contents will be helpful to those concerned with the problems of the coastal zone.

WATER MOVEMENTS IN SHALLOW COASTAL BAYS AND ESTUARIES

INTRODUCTION

Perhaps the most urgent requirement in order to increase the flow of useful products from the sea is to develop some rational program for multiple use. An indispensable prerequisite is that information must be made available to allow decisions to be made as to which areas must be put aside for one use or another, or which areas can serve for several purposes. The pressures imposed by a rapidly increasing population demand intelligent control and management of estuaries and other coastal regions. In order to accomplish this, a thorough knowledge is required of the physical and chemical characteristics and the ecology of the region.

Recently there has been a tremendous demand for reliable information about estuaries which will serve as the basis for important decisions on their effective management and control. There are a large number of conflicting demands on shallow water areas which makes it difficult to serve all interests to the degree demanded by concerned groups. For example, between 80 and 90 percent of the sea food harvested in the United States consists of animals that depend to a greater or lesser extent on the shallows at the edge of the sea, including the brackish estuaries. The filling of these estuaries for urban development and their use by industry, causing various states of pollution, has already reduced the potential of the country to produce more food from the sea and this process is going on at an accelerated rate. To some extent the changing and destruction of the edge of the sea areas is inevitable; in other cases it can be prevented if the public and government officials are aware of the principles involved.

Important physical factors which decide the pollution sensitivity of a coastal or estuarine water mass are its residence time, and its degree of stratification. In very shallow water, the latter is less important. When one is studying water mass exchange with reference to pollution problems, a hierarchy of problem scale arises. The need of water hygiene at a marina, for instance, depends on the local circulation and vertical mixing conditions. But county-wide planning must take into account the combined impact of perhaps several dozen construction projects along the shoreline. It then becomes necessary to understand the circulation in the bay as a whole, and the rate of exchange between the bay, and outlying waters. Only where this is known can one begin to estimate the biological consequences of a certain level of nutrient efflux, or the effects on gross water quality of the addition of known amounts of degradable wastes.

A Modular Approach for Understanding Estuarine Water Movements

Historically, studies of estuarine circulation have been conducted in deep openings to the ocean with large river outflows. Exchange processes which control the residence time were considered to be governed by the relative volumes of fresh water outflow vs. tidal prism. Unfortunately, mathematical determinations of circulation have led to the belief that solutions obtained for a particular estuary are not applicable to other areas, thus requiring a complete study of each estuary of interest. Much of this complexity of estuarine circulation models arises from the necessity to cope with different flow regimes in different parts of any specific estuary. It is often possible, however, to divide an estuary into subregions, each with different but simpler flow characteristics. A set of models for such subregions can be looked upon as a kit of building blocks. Suitably combined, these building blocks will yield a qualitative model for any specific estuary. The practical advantage of this method is that identification of flow regimes can be accomplished with a minimal observational program. Preliminary estimates of exchange rates and assessments of water quality can thus be made with modest efforts and expenditures. Where more precise information is needed, the method supplies an effective base for detailed studies.

Estuarine exchange processes are typically controlled by the forces of tides, winds, river run-off, evaporation and precipitation. These forces display large variations in time and space between different estuaries and within any given estuary due to the geographic locations and complexities of shapes. The modular approach separates an estuary into characteristic regions as shown in FIGURE 1. The building blocks consist of regions of direct exchange between an estuary and the coastal waters (A), interior basins (B), the regions of exchange between basins (C), and the region of river influence (D). There is a large amount of literature on inlet hydraulics and effects of river run-off; therefore, the emphasis of this paper will be on mixing processes within the interior of estuaries.

Application of Method

Segmentation of an estuary can be approximated at first by using existing depth and tidal charts if available and any other forms that may exist, such as temperature or salinity charts. Since estuaries are traditionally drainage basins for the surrounding land mass, they will usually display large salinity variations within the estuary and sharp contrasts from the coastal waters. During the periods of low run-off, estuaries with weak exchange with the ocean will produce high salinities by evaporation. During high run-off periods, the interiors of estuaries will display low salinities. The net result is that salinity is a very useful tracer of estuarine interaction. Therefore, salinity measurements can be used to separate an estuary into characteristic flow regimes. Salinity measurements should be conducted as rapidly as possible at maximum and minimum run-off and wind stress conditions. Local airports and weather stations can be used to obtain historical meteorological data which will aid in selection of observational periods.

Southeast Florida's Biscayne Bay Estuary Example

Biscayne Bay and Card Sound (FIGURE 2) are excellent locations to initiate a modular approach to understanding estuarine mixing processes, due to the

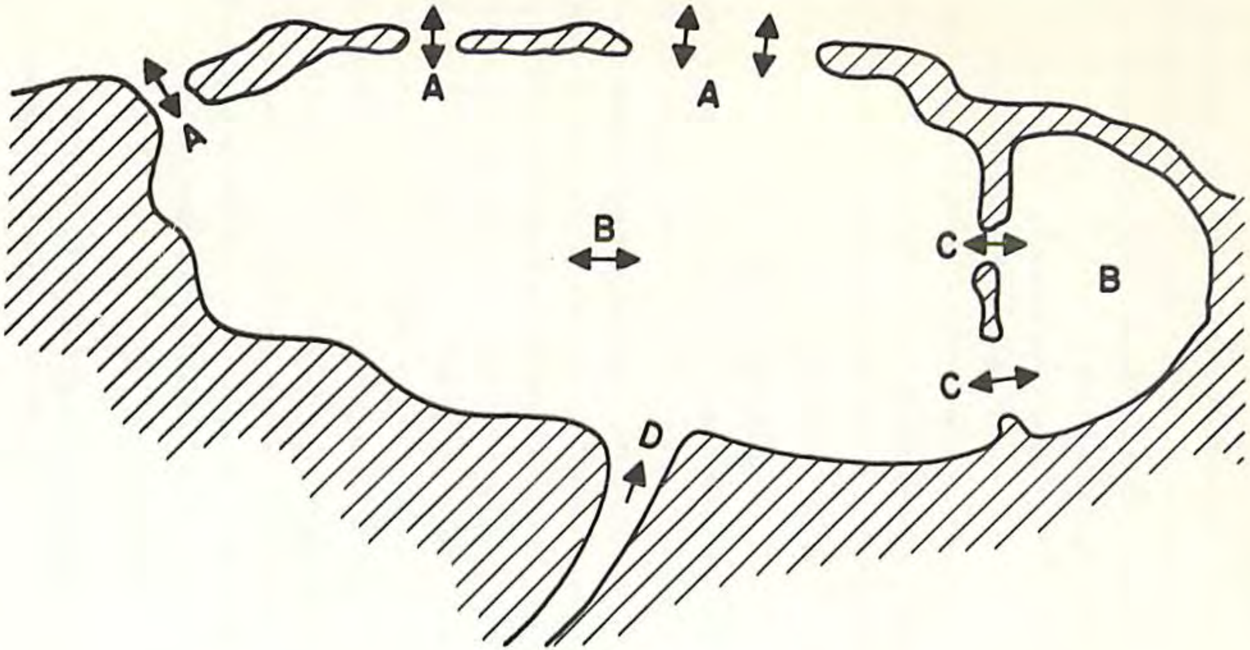


FIGURE 1 - Estuarine Model

FIGURE 2 - Biscayne Bay and Card Sound

diversity of flow regimes present. North Biscayne Bay represents a highly polluted region where man's impact has been intense. The Miami River discharges into this region with a heavy load of industrial and domestic wastes. Dredge and fill operations associated with Miami Harbor's deep water port, land development, and construction of causeways have greatly altered the bottom topography. The creation of bulkhead lines and construction of seawalls have completely inundated the natural low-lying shoreline. Middle Biscayne Bay, South Biscayne Bay, Card Sound, Little Card Sound, and Barnes Sound are still relatively unspoiled. This system of basins separated from each other by shallow shoals and from the ocean by the northward extension of the Florida Keys extends approximately 45 miles along its major axis, with widths ranging from 3 to 8 miles. Water depths in the interior of the basins vary from 6 to 10 feet. The embayments communicate with each other across shallow shoals and through dredged navigational channels. Exchange with the ocean takes place through a complicated network of tidal inlets and across a broad shoal ("Safety Valve"), honeycombed with narrow flow channels.

Semidiurnal tidal forcing at the seaward entrances to the embayments is approximately in phase because the length of the major axis is small in comparison to the tidal wave length. The wave that enters the interior of North Biscayne Bay progresses south with decreasing amplitude and increasing lag due to frictional dampening by the shallow shoals (Schneider 1969).

Climatologically, wind forcing occurs mainly from the passage of winter cold fronts with accompanying strong northerly winds. Salinity conditions are forced by the pronounced wet-dry seasons of southeast Florida. The rainy periods are usually in late May and September, with dry conditions prevailing during the winter.

Tidal Exchange in the Vicinity of Inlets

The regions of direct coastal-estuarine interaction are confined to the vicinities of the seaward openings, coupling the estuary to the sea. Flow through these openings will normally be dominated by tidal forces. The astronomical tidal wave progressing through the coastal waters produces a slope in the water surface through the opening. The magnitude of the resulting flow will be directly dependent upon the height of the slope. The volume of fluid that can be exchanged through an opening depends also on its width and depth. The shapes of openings can vary from narrow inlets to broad shallow flats.

The region of the estuary which undergoes direct exchange with the ocean will depend upon the shape of the seaward opening. Theoretical analysis indicates that in the vicinity of inlets narrow enough to produce a noticeable jet of coastal water into the estuary on flood tide, the region of direct tidal exchange will correspond to a semicircle with a radius approximately 500 times the mean depth of the inlet.

FIGURE 3 clearly shows the penetration of a low salinity jet of coastal water (shaded areas) into Card Sound from the Broad and Angelfish Creek inlet complex. The observations were made at the start of ebb tide and therefore represent the maximum estuarine region of direct tidal exchange with the ocean during low wind periods. The theoretical analysis predicts the penetration distance of this region to be approximately 6000 feet, which corresponds quite well with FIGURE 3.

The residence time of water within the inlet exchange region will depend greatly on the magnitude of the longshore coastal current seaward of the inlet. If, on ebb tide, the estuarine discharge intersects a strong coastal current flowing parallel to the shoreline, then a large portion of the discharge will be removed from the vicinity of the inlet, thus reducing the residence time of this region to about one day. If, on the other hand, the coastal currents are weak as is often the case off Biscayne Bay and other coastal lagoon systems of Florida, then a large portion of the ebbing discharge will return to the bay on the flood tide. The residence time in the vicinity of the tidal inlet during this case will be on the order of several days to a week.

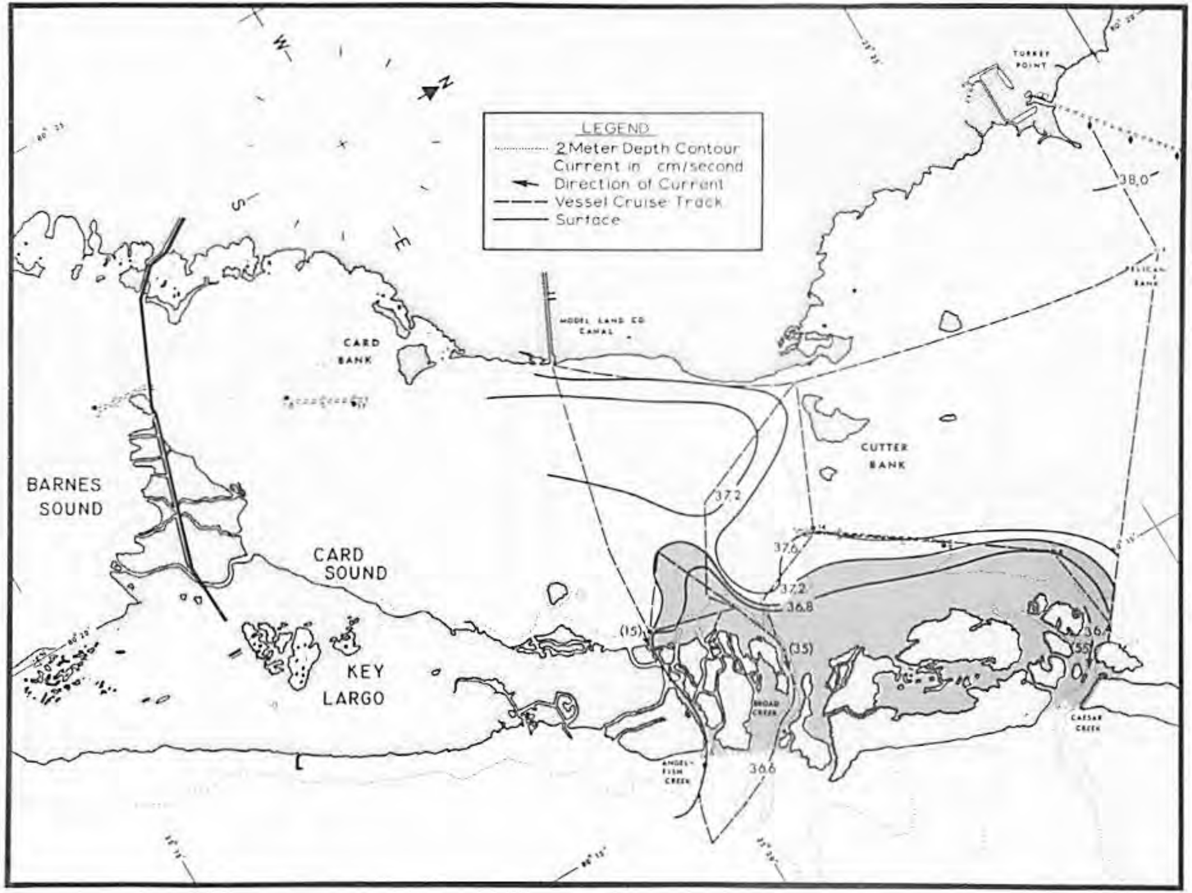


FIGURE 3 - Penetration of a low salinity jet of coastal water (shaded areas) into Card Sound

Tidal Exchange in the Interior of Estuaries

Tidal currents in the interior regions of estuaries will normally show a simple reversing pattern aligned with the major axis of the basins. Theoretical tidal analysis suggests that this simple tidal flow should result in substantial asymmetric mixing conditions, with mixing being enhanced in the direction of flow.

If an estuary consists of several interconnected basins, then due to the preferred direction in tidal mixing, exchange of interior water will be predominantly between the different basins. Direct exchange with the ocean will be restricted to the regions in the vicinity of the tidal inlets.

The tidal currents and tidal-induced mixing in South Biscayne Bay and Card Sound are shown in FIGURE 4. This figure shows the result of surface salinity mapping in the interiors of South Biscayne Bay and Card Sound with low wind effect. The fall wet season is evident in the low salinities along the western sides of the basins (shaded area). Synoptic measurements of surface currents were conducted on a tidal time scale by aerial photography of dye releases. Tidal currents in the interior show a simple reversing pattern aligned with the major axis of the basins with peak speeds of about 20 cm/sec (0.4 knots). In agreement with our previous analysis which suggests a preferred mixing in the downstream direction, the salinity patterns are found to be aligned in the direction of the flow.

As a result of the simple reversing tidal current pattern, the interiors of the basins in Biscayne Bay will exchange with the adjacent north and south basins with very little direct exchange with the ocean by tidal mechanisms. This results in very long tidal residence times for the water within these central basins. We estimate that the tidal residence time of the interior waters of Biscayne Bay is on the order of one year.

A striking demonstration of the weakness of tidal exchange in Biscayne Bay is provided by the seasonal salinity contrasts between the different basins and the ocean, which develops in response to the pronounced wet-dry

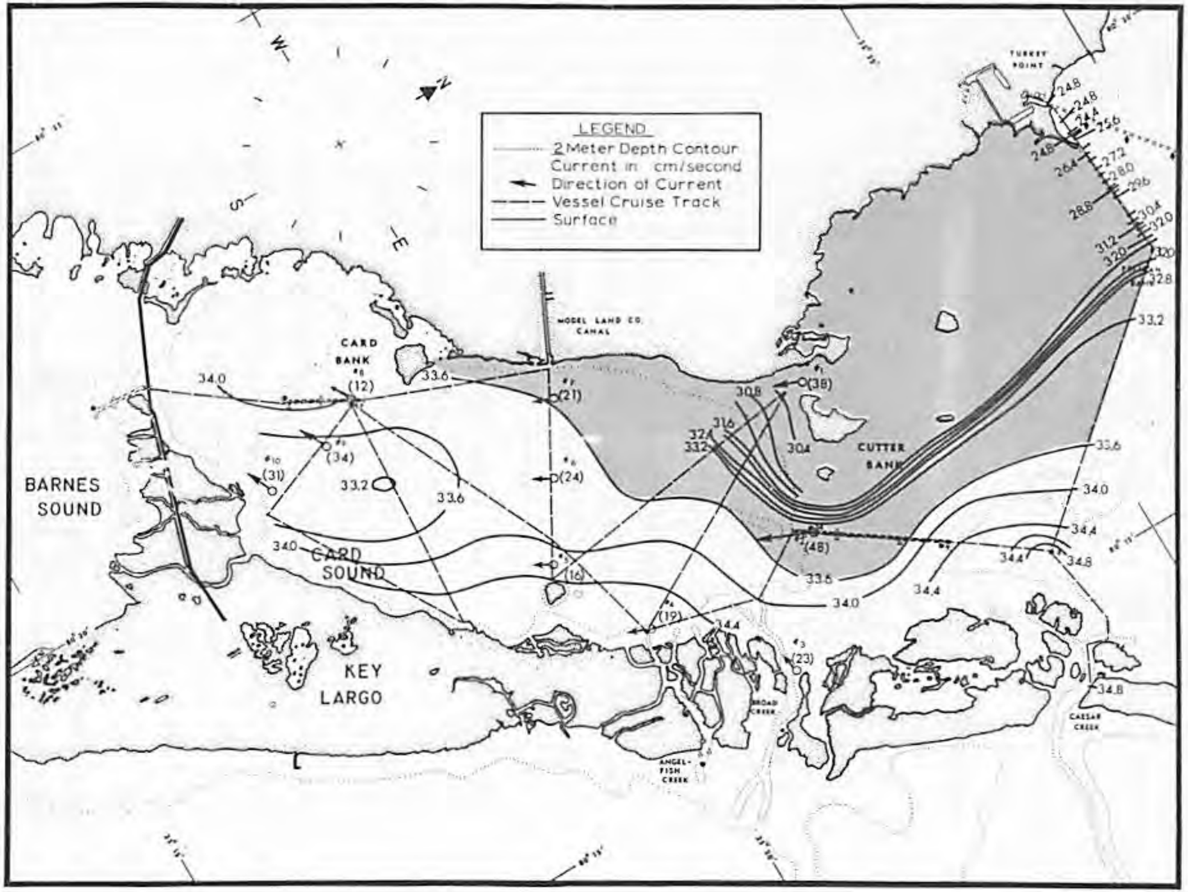


FIGURE 4 - Tidal currents and tidal-induced mixing in South Biscayne Bay and Card Sound

seasons of southeast Florida. A comparison of salinities taken in Bear Cut, which opens into Middle Biscayne Bay, with samples from South Biscayne Bay are shown in FIGURE 5. Station SE 5 is located near the western side of South Biscayne Bay where land run-off would have a greater influence than Station D which is located near the eastern side of South Biscayne Bay. RSMAS Dock is the University of Miami's dock located in Bear Cut. The high tide salinities at RSMAS Dock are indicative ofthe coastal water salinity changes and the low tide values indicate bay salinities. The two annual salinity minima of the bay waters are clearly shown at the time of rainfall maxima in spring and late summer. However, after the wet periods, the bay salinities do not tend to stabilize with the coastal waters as would be the case for a well-flushed estuary but rather continue to increase, indicating poor coastal-estuarine exchange.

Wind Influence on Estuarine Exchange

The importance of wind stress on estuarine exchange cannot be over-emphasized. As indicated previously, shallow estuaries are very poorly flushed by tidal mechanisms alone. Wind influence can greatly reduce the residence time by setting up a mean circulation which can transport interior water into the vicinity of tidal inlets where direct exchange with the ocean takes place. We estimate that a wind-induced current with a magnitude of 1/300 of the maximum tidal current will flush the estuary in a similar time span. If one assumes the wind stress at the water's surface as equal to the bottom stress, then the maximum surface drift velocity induced by local wind is about 3% of the wind speed. If a 10 knot wind produced a 0.3 knot drift current in Card Sound, then the residence time of the estuary would be 2.2 days. However, in most estuaries, a slope in the water surface develops soon after the onset of wind. A sustained circulation will then arise, either due to partial sheltering by the adjacent land boundaries, or due to irregular bottom topography, and thus not likely to amount to more than a modest fraction of the simple estimate above. If one assumes a 10% value for the

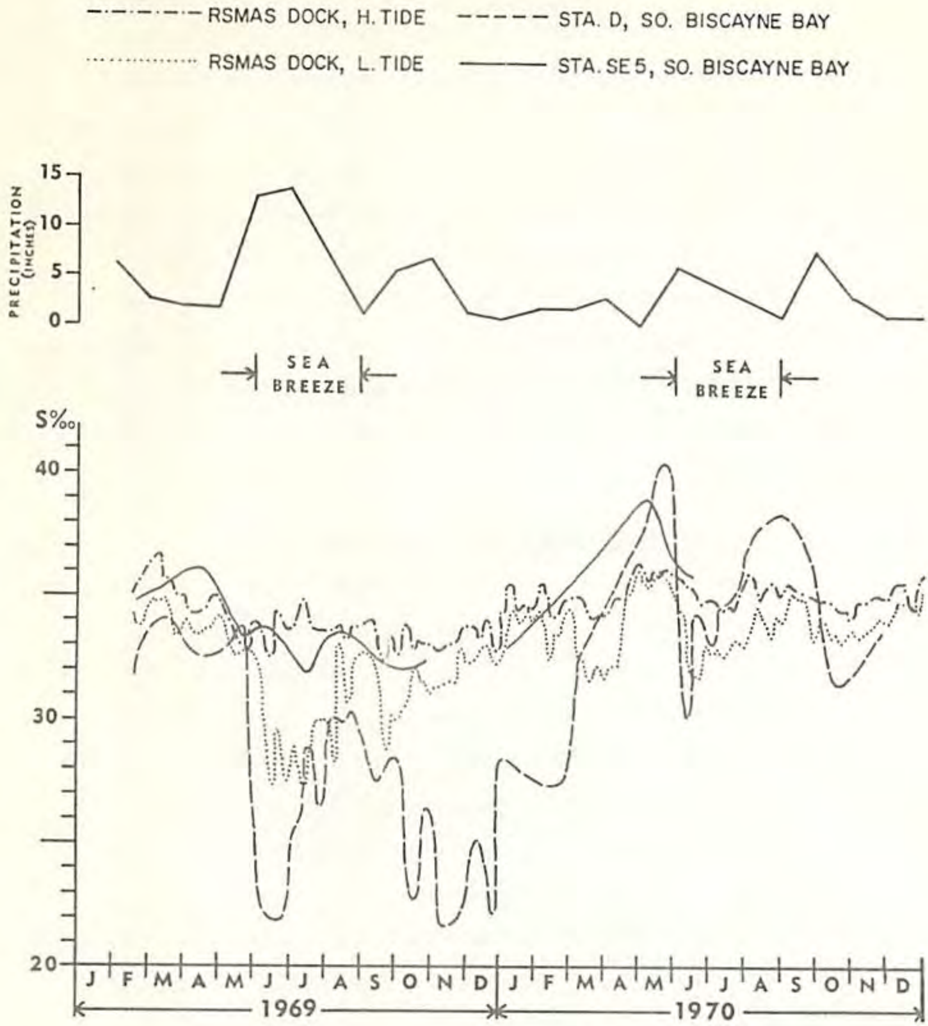


FIGURE 5 - A comparison of salinities taken in Bear Cut with those taken in South Biscayne Bay

ratio of wind-induced circulation velocity to maximum drift velocity, our quantitative example above would yield an exchange time with a 10 knot wind of 22 days. If a wind-induced circulation becomes as much as 50% of the maximum drift velocity, then the exchange time reduced to 4.4 days, showing that the tidal exchange time is nearly two order of magnitudes greater than wind exchange time.

Direct wind forcing in tidal inlets can usually be neglected due to the small surface areas involved. However, a wind-induced slope of the water surface in the interior can bias the head across the inlet, thus biasing the transport to sea and further augmenting the estuarine exhcange with the ocean.

In regions of exchange between basins of an interconnected estuary, the effect of wind will be due to the surface slope within the basin. The slope will behave as in the tidal inlet to bias the head between basins, producing a pressure gradient flow that may be of comparable magnitude to the tidal flow.

The wind influence on exchange in Card Sound can be seen in FIGURE 6. A cold front with wind speeds of 20 knots out of the north passed through the area one day prior to the field observations. The low salinity jet which is apparent in FIGURE 3 has disappeared even though both observations were made at a similar stage of the tide. Also the interior or Card Sound is well-mixed and the salinities in Broad and Angelfish Creeks have increased 0.4°/oo to be comparable to estuarine salinities. The above differences in the two figures suggest a mean wind-induced circulation which is transporting interior water to the region of direct exchange with the ocean, thereby biasing the flow from the inlets.

Summary

A modular approach to the analysis of mixing and flow characteristics in shallow tidal estuaries is presented using as an example the South Florida Biscayne Bay estuary. The method depends on isolating relatively simple characteristic flow regimes in different parts of an estuary. These can be

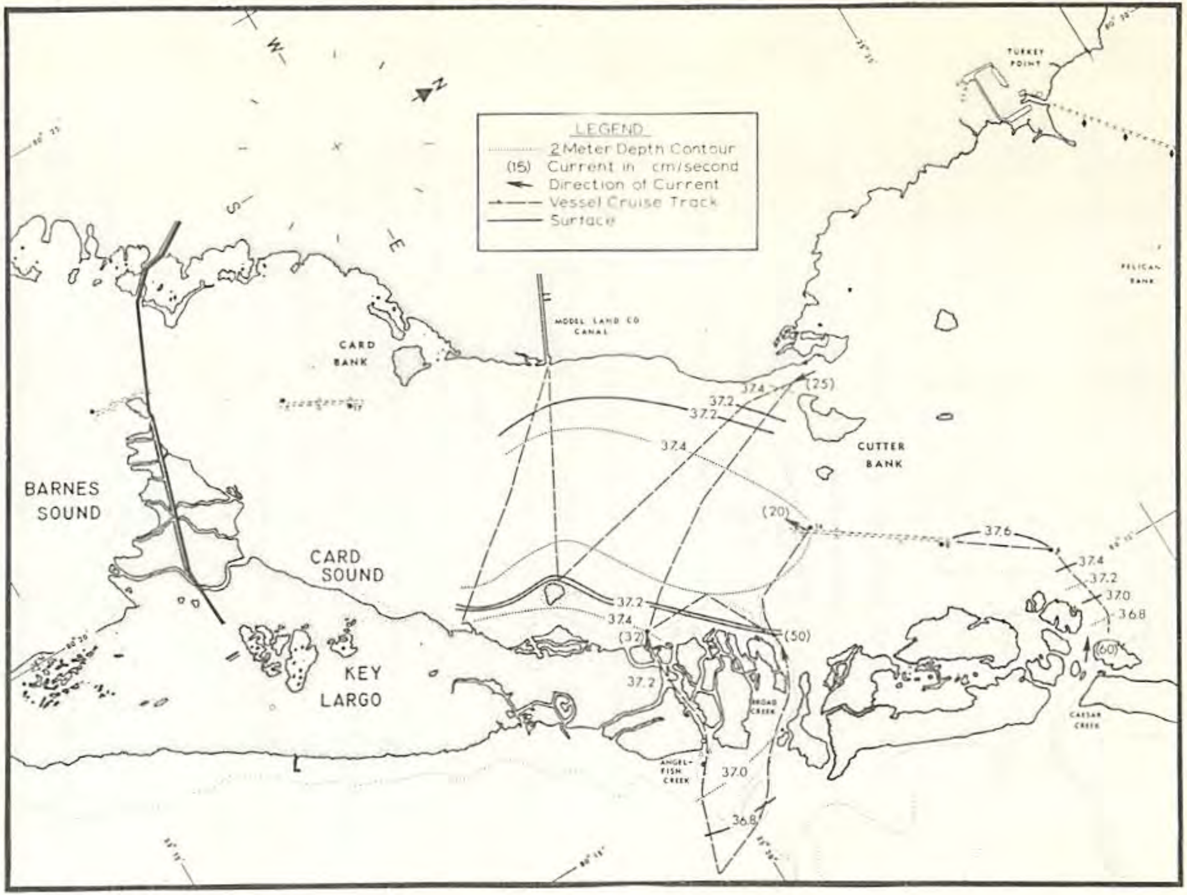


FIGURE 6 - Wind influence on exchange in Card Sound

considered as building blocks which, when recombined in different configurations, are capable of yielding a qualitative model for any specific estuary. In Card Sound and South Biscayne Bay, tidal-induced mixing is separated into two flow regions: the interior of the basins and the regions in the vicinity of the tidal inlets. Asymmetric, reversing tidal flow in the interior produces a preferred mixing in the direction of flow which enhances downstream diffusion, resulting in salinity patterns aligned with the direction of flow. This effect inhibits direct exchange with the ocean, producing very long residence times in the interior. Direct exchange between the basins and the ocean takes place in a region near the inlets defined by a semicircle with a radius approximately 500 times the depth of the inlets. Wind effects were found to have a great influence on exchange processes in shallow estuaries. Wind effects mix the estuary horizontally and vertically and can set up a mean circulation that transports interior water into the direct exchange region of the tidal inlets, thereby substantially decreasing the basins residence time.

The generalization of this approach to other specific estuaries is straightforward. One would begin by considering the gross geometry of basins and their connections, attempting to identify á priori the dominant processes in each. Such identification serves to facilitate planning of an efficient minimal observation program. The resulting qualitative model can be of immediate value in preliminary assessments of estuarine water quality and can become a useful tool for management in planning for multiple use estuaries.

Conclusions and Implications

The water quality of coastal bays and estuaries is controlled by a complicated balance between the rates of influx and removal of pollutants. The rate and quality of the effluent entering the estuary is a function of our planning and water management. Therefore, in order to protect or restore our inshore environment, community planners and enforcement agencies must be supplied with reliable estimates as to a particular water body's ability to remove pollutants. An exact quantitative determination of the removal rate is extremely complicated due to the dependence on many chemical, biological, and physical processes which vary both in time and space. However, the problem can be simplified if one considers the removal rate to be primarily a physical process and therefore dependent on the flushing rate or residence time of the receiving water body with biological and chemical processes considered as secondary effects.

The residence time of shallow bays and estuaries with weak river runoff, similar to the embayments along the coast of the southeast and Gulf states, is primarily dependent on tide and wind-induced motions. We have shown previously, using Biscayne Bay as an example, that shallow bays are very poorly flushed by tidal mechanisms. The tidal residence time of interior waters is estimated to be on the order of one year. Wind-induced circulations were found to be capable of reducing the residence time by a factor ranging from 10 to 100, depending on the magnitude, direction, and duration of the wind. The major wind flushing occurs in the winter during the passage of cold fronts and accompanying strong winds up to 20 knots. The residence time of coastal bays during this period (December through March) is the time duration between the passage of cold fronts with the intensity to flush the bay or the cumulative effect of flushing action of lesser fronts and is estimated to be on the order of several weeks. However, during the remainder of the year, winds are predominately weak in intensity and in an onshore direction (sea breeze effect or trade winds), with the result that interior waters do not exchange with the ocean. The effect on pollutants being discharged into the bay will be to accumulate pollutants along the mainland shore with very little removal except during periods of intensive meteorological activity.

The impact of pollutants discharged into a bay with long residence time is clearly evident in North Biscayne Bay (FIGURE 1) which receives a variety of industrial and domestic wastes from the Miami River, water drainage canals, and marinas. These waters which were once renowned for their clarity have, in two decades, become extremely turbid, with high concentrations of organic material, nutrients, and *E. coli* bacteria. These effects are reaching into middle Biscayne Bay, especially along the mainland shore. South Biscayne and Card Sound are still relatively unspoiled; however, south Miami is growing at an extremely rapid rate with new facilities being built to handle the waste products of this growth. A centralized sewage treatment plant is under construction in south Dade County. The final effluent from this plant is planned to be discharged into South Biscayne Bay. Although this effluent will conform to a recent 90% treatment law, it will still contain high levels of nutrients and possibly harmful viruses which will degrade the water quality due to the long residence time of the receiving waters. The only way to insure the protection of poorly flushed estuaries is to stop using them as sinks or to purify the effluent to a degree that can be absorbed by the receiving water body. The purification can be accomplished by new and better treatment methods or the use of coastal interceptor waterways, such as those described by Tabb and Heald (1973).

References

Schnieder, J. J. 1968: Tidal relations in the south Biscayne Bay area, Florida. Open File Rep. U.S. Geol. Surv. Mimeo Rep., 16 pp.

Tabb, D. C. and E. C. Heald 1973: The Coastal Interceptor Waterway. University of Miami Sea Grant Program, Coastal Zone Management, Bulletin No. 1, 11 pp.

Acknowledgments

This manuscript is based on work partially supported by the University of Miami's Sea Grant Program under National Oceanographic and Atmospheric Administration, U. S. Department of Commerce, contract no. 2-35147; U. S. Atomic Energy Commission (AT(40-1)-3801-4); and Florida Power & Light Company.