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12 Abstract (Purpose, method, results, conclusions)

The conceptual feasibility of storing fresh water in the ocean was investigated using a plastic membrane as the reservoir liner. In the initial phase, two physical hydraulic models were constructed to test the concept. The first was a water-filled, glass-sided box to observe the movement and reaction of the membrane to various simulated effects of currents, waves, and sediment deposition. The second was a 1:400-scale model (6.7 x 6.1 m) of West Loch, Pearl Harbor (a potential field application site), with 1:24 vertical exaggeration for similitude. The curtain method was used because it can enclose a large water body. The effect of wind, waves, tides, and currents on the curtain were simulated and the reactions observed. Although modeling is a useful tool for investigating initial concepts, its direct field application is limited because of scaling. Actual field testing on an initial pilot-stage basis constituted the second phase. Curtains, floating reservoirs, and bags were constructed of polyethylene sheets and deployed. All worked well after modifications were made following initial testing. The bag is the easiest to deploy because it is prefabricated and ready for use. No field attachment of floats and anchors is necessary, as for curtains or floating reservoirs; however, the latter two have certain characteristic advantages which may override this difficulty. Based on this experimental experience, the concept of membrane water-storage appears feasible and further development work leading to operational equipment seems justified. Selection of suitable membrane material is one of the key factors to be explored, along with the effects of weathering and biota. Quiescent waters are essential to the success of this concept.

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STREAM-WATER STORAGE IN THE OCEAN BY USING AN IMPERMEABLE MEMBRANE

Edwin T. Murabayashi
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Technical Report No. 152

May 1983

Final Technical Completion Report
for
Flexible, Floating Membrane Impoundment of Stream Water in a Coastal Embayment as a Means of Water Conservation and Water Quality Control of Waikele Stream Inflows into the West Loch, Pearl Harbor, Oahu

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ABSTRACT

The conceptual feasibility of storing fresh water in the ocean was investigated using a plastic membrane as the reservoir liner.

In the initial phase, two physical hydraulic models were constructed to test the concept. The first was a water-filled, glass-sided box to observe the movement and reaction of the membrane to various simulated effects of currents, waves, and sediment deposition. The second was a 1:400-scale model (6.7 x 6.1 m) of West Loch, Pearl Harbor (a potential field application site), with 1:24 vertical exaggeration for similitude. The curtain method was used because it can enclose a large water body. The effect of wind, waves, tides, and currents on the curtain were simulated and the reactions observed. Although modeling is a useful tool for investigating initial concepts, its direct field application is limited because of scaling.

Actual field testing on an initial pilot-stage basis constituted the second phase. Curtains, floating reservoirs, and bags were constructed of polyethylene sheets and deployed. All worked well after modifications were made following initial testing. The bag is the easiest to deploy because it is prefabricated and ready for use. No field attachment of floats and anchors is necessary as for curtains or floating reservoirs; however, the latter two have certain characteristic advantages which may override this difficulty.

Based on this experimental experience, the concept of membrane water-storage appears feasible and further development work leading to operational equipment seems justified. Selection of suitable membrane material is one of the key factors to be explored, along with the effects of weathering and biota. Quiescent waters are essential to the success of this concept.

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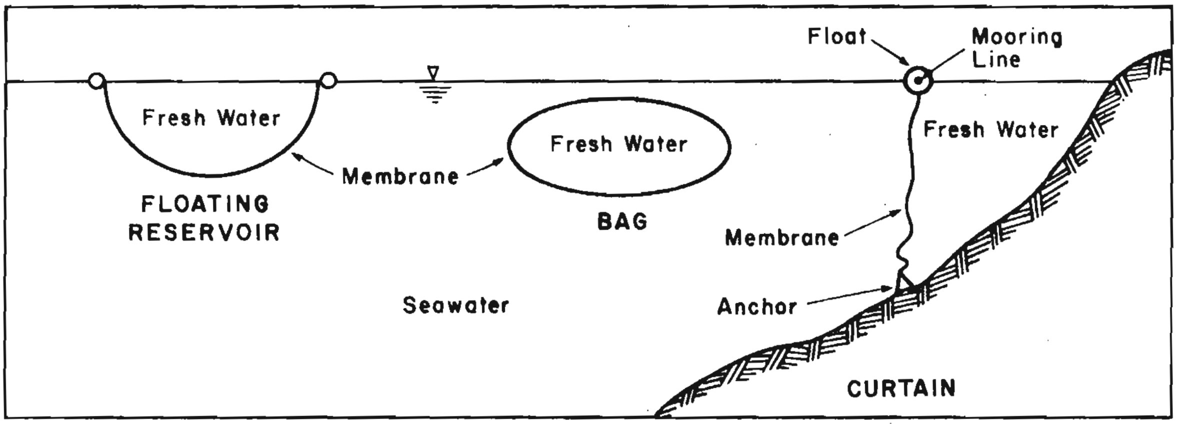
INTRODUCTION

One of the primary factors precluding the use of storm water and other surplus water is the economic cost of storing it until it can be used. The cost of conventional, rigid dams and reservoirs and of land inundated by impounded water are generally too expensive for storing low-quality water, which may be suitable for irrigation or other uses. Thus, a cheaper way to store water would open enormous potential for extending freshwater resources which might otherwise be lost.

This project investigated the possibility and feasibility of using impermeable, plastic membrane liners for storing stream water in the ocean. The advantages of this method are less construction cost than earth reservoirs and it does not take up valuable land area.

Three basic types of membrane enclosures are as a floating reservoir, as a bag, and as a curtain.



Various combinations of these are adaptable to any particular application.

The membrane itself does not need the structural strength of rigid conventional reservoirs because the pressure on both sides of the membrane is in dynamic equilibrium at all points and all depths.

Other applications of this technique are unlimited, necessitating only the imagination to perceive its application. Briefly, two examples are as large aquaculture tanks and as an enclosed bag for shipping water by towing. Similarly, flexible membrane pipes for transporting flowing water underwater from one point to another may prove to be feasible.

There are two aspects to this study, which are intertwined. First is the general concept of storing stream water in the ocean using membrane technology and, second, its possible application in West Loch of Pearl Harbor, an inland embayment. To this end, there were physical model studies of membrane behavior underwater as well as a model study of West Loch. Subsequently, the three storage techniques were field tested.

Overview

An initial overview will help to bring the project in perspective. There are advantages and disadvantages to each of the three basic types which determine its appropriateness to any particular application. Possible ripping of the membrane is a problem common to all the methods, as is the necessity for deployment in calm waters.

CURTAIN ENCLOSURE. In its simplest form, the curtain consists of a flotation system, the membrane, and an anchoring system. The flotation system consists of a buoyant material to hold the upper edge of the membrane at the water surface. Combined with the flotation is a mooring line to strengthen the upper edge and to give lateral control. The membrane is a vertical barrier that extends from the surface to the sea bottom. Slack in the curtain allows movement of the membrane with changing tides, inflow, waves, currents, and wind. The anchoring system seals the curtain to the sea bottom and side-slopes to minimize seepage under the membrane. Such an anchorage should be heavy enough to remain immobile when subjected to natural ocean movements. A flexible weight system which conforms to the uneven sea bottom is necessary. Locations with steep, side slopes should be avoided or modified to minimize seepage under the membrane.

In deployment, the curtain is laid across a bay from shore to shore or as a U-shaped enclosure open on the shoreward side. Incoming stream water displaces the captured seawater, diluting it to the point where it becomes mainly fresh water.

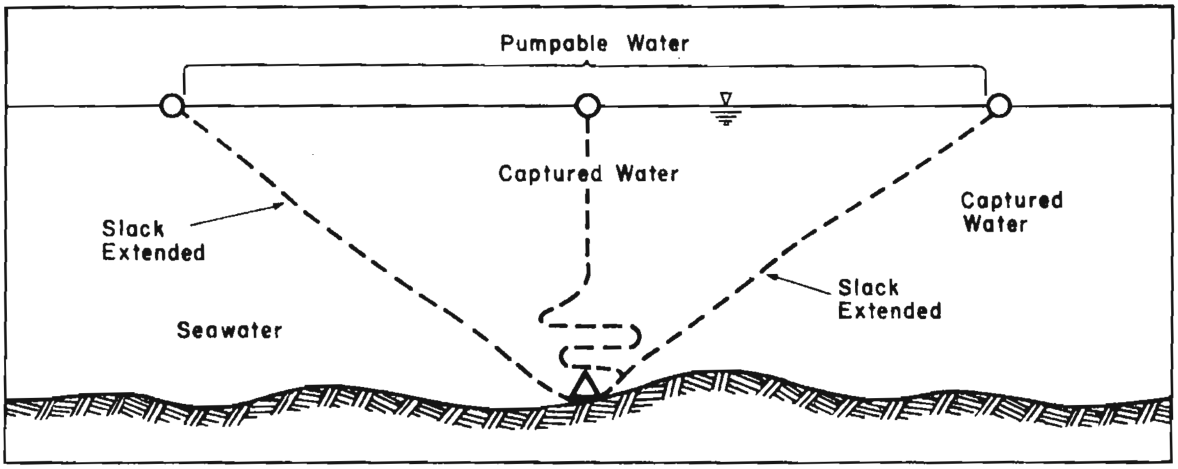
A curtain enclosure has the following advantages.

1. A large body of water can be enclosed. This may be particularly useful in capturing storm runoff too voluminous and difficult to handle by other membrane methods. Rocks, sediments and other debris can be settled out or separated, and thereby not damage the membrane. This method may also be suitable for pollution control by separating contaminated water.

2. Catchment of storm waters is best suited to the curtain method. These flows are too voluminous and precipitous for bags or open reservoirs.
3. A relatively small amount of membrane is used because there is no bottom or top lining to the enclosure.
4. No danger of dam bursting because the placement is in an existing water body.
5. Rainfall can be captured and stored because of its open top.
6. Water from diffused (nonpoint) inlets flowing into the reservoir area can be captured. In the Pearl Harbor aquifer area this includes submarine springs from which fresh water is presently lost to the sea.
7. The curtain can be readily removed, as compared to rigid dams, if the need arises.

The curtain method includes the following disadvantages.

1. The actual quantity of water which can be pumped out for use is dependent upon—or limited by—the amount of slack in the membrane, as shown below.



   Obviously, the captured water cannot be completely pumped out as in a rigid dam.
2. Above water components of the curtain will be subjected to solar radiation and weathering degradation—a problem with many membranes.
3. The stored water is subject to a mean net annual evaporation loss of 782.3 mm (30.8 in.) in the Pearl Harbor area.

4. Waves may overtop the curtain. Sufficient floats and freeboard will handle undulating waves without overtopping in relatively quiet waters; however, whitecaps are difficult to control. The wave force itself is transmitted through the membrane into the captured water even though the waters remain separated. On reaching the other end, the wave force is retransmitted into the main water body, leaving the stored water unaltered if no overtopping has occurred.
5. The two lateral ends of the curtain must be securely moored on shore.
6. The floats and the ballast have to be attached to the curtain in the field which, can be a very cumbersome operation when large curtains are used.
7. Since fresh water floats over seawater, the fresh water will evaporate first. Also, because of this stratification, the seawater becomes trapped below, reducing the freshwater storage. One-way duckbill valves incorporated near the bottom of the curtain may move seawater out since incoming freshwater flow will create a slight hydraulic head. This valve was not tested.
8. Underwater environmental impact will occur in two ways: inside the enclosure the salinity will decrease; and outside the curtain, the salinity will increase because the freshwater outflow is being trapped.

BAG. The experimental work has indicated that the bag method is the simplest to manufacture and the easiest to deploy in the field. The advantages of the bag method are

1. The bag can be pre-made, transported to the site, and filled without any on-site attachment of float or ballast apparatus
2. No evaporation loss occurs
3. No problems with wave overtopping occurs
4. The fresh water can be completely separated from the seawater body
5. Very little if any of the membrane is exposed to aerial weathering
6. Buoyancy can be controlled by leaving a small amount of air in the bag so as not to drag on the bottom and, thus, compensate for any sediments in the stored water
7. The bag can be towed to where it is needed

8. The environmental impact is minimal.

Disadvantages of the bag method are

1. A comparatively larger amount of membrane is needed because the water is fully enclosed
2. The amount of water to be stored is limited by the size and number of bags
3. Only debris-free water can be stored so as not to risk puncturing the membrane
4. Ripping of the bag is possible by underwater snags and obstacles.

FLOATING RESERVOIRS. Floating reservoirs are akin to a half a hemisphere, open at the top and consisting of a membrane with floats around its periphery.

The advantages of floating reservoir are

1. An intermediate amount of membrane is needed because the top is open
2. Having an open top, rainfall can be captured and stored
3. Fresh water can be completely separated from the seawater body
4. Very little environmental impact occurs.

Disadvantages of open reservoirs are

1. The stored water is subject to evaporation loss
2. Weathering of above water parts will occur
3. There is a possibility of overtopping waves contaminating the stored water
4. Floats must be attached in the field before deployment. This can be a cumbersome operation
5. The amount of stored water is limited by the size and number of reservoirs.

Objective

This project addresses the problem of increasing usable water supply by capturing and storing runoff for later use. For example, low quality water so captured can be used for irrigation, thus supplanting potable quality water which is presently used for irrigation. The captured water could also conceivably be treated to upgrade it to potable quality if the need arises.

Therefore, the objective of this study is to explore the possibility of catching and storing freshwater runoff which would normally be lost to the sea. The method is by membrane separation technique to store the water in the ocean itself. West Loch of Pearl Harbor, an inland embayment, is envisioned as a potential site for the curtain technique, particularly since it has been previously examined (Chang 1973) as a possible reservoir by damming its mouth.

LITERATURE REVIEW

Marine biologists have pioneered the use of flexible, impermeable membrane enclosures for holding water within another water body. Such enclosures were developed to isolate biota under observation from uncontrollable aspects of their environment while still being influenced by them (Gust 1977; Menzel and Steele 1978). Large bags were used by Controlled Ecosystem Pollution Experiments (CEPEX) in their studies in Puget Sound (Case 1978). Partial membrane enclosures have been used to retain nutrient-rich waters around kelp planted on experimental, open sea, floating kelp-platforms (Global Marine 1981).

In an assessment of national water resources policy, Ackerman et al. (1968) proposed the use of flexible "sausages" to increase water supply. Kii (1978) suggested that a 1 609 m (1 mile) long cylindrical rubber bladder might be a practical way to transport fresh water. He also reported that the U.S. Navy is developing 67 m (220 ft) long bladders made of tough rubber-coated fabric for oil storage and transporting. The bladder would slip through the water with very little resistance and would be undisturbed by wind.

A novel concept was explored by Mortimer (1975) in England. Water is pumped from a river into a stilling basin for primary treatment, then pumped to a flow-balancing tank for secondary treatment, and finally fed into undersea storage bags. The main objective was to use the sea bed, rather than land, for water storage. The suggested size of each bag was 25 m (82 ft) high, 150 m (492 ft) wide, 1 000 m (3281 ft) long with an expected life of 15 to 20 years.

In terms of material, Kii (1978) and Mortimer (1975) reported that rubber-coated fabric and cord, treated polyester fabric, polypropylene, or polychloroprene rubber could be used. Ackerman et al. (1968) suggested rubber, nylon, or polyester membrane. New materials are constantly entering the market, offering diverse possibilities for using plastics not only for water storage but for many engineering applications (Bares 1982). In any event, for potable water storage, the membrane should not contaminate the water with deleterious pollutants.

In many ways, non-rigid, air-supported structures are similar to water membrane containers. As impervious membranes have been developed, an entirely new spectrum of air structure construction and materials have emerged. Many of them may have direct and indirect application in the water field. Koerner and Welsh (1980) classified three major application of membrane construction as air supported, tension, and water-filled structures. They recognized the advantages of membranes as the infinite variety of geometric configurations possible, their relatively low cost, and rapid construction time. The Silver Dome in Pontiac, Michigan, spanning 40 470 m^2 (10 acres) is one of the world's largest membrane structure. Utilizing Teflon-coated fiberglass, it cost two-thirds less than the original still-vaulted roof design and the membrane is guaranteed for 20 years (Morrison 1980).

Stiffer, semirigid membranes have been used for many years as land-based reservoir liners. Similar types of materials have been used for coffer dams and aquaculture tanks with varying amounts of supplemental support (Rankilor 1981). These semirigid materials may have application for shallow depth curtain enclosures.

A freshwater reservoir was created at sea level by damming off a bay in the Hong Kong Plover Cove Project (Hong Kong Government Information Services 1968). The High Island project was similarly conceived, using rigid conventional dams (Vail 1975). Although the cost was very high, it was still cheaper than desalinization. The curtain method investigated in this report is aimed at a similar application, hopefully at considerably less cost.

In Hawai'i Chang (1973) in an unpublished report explored the feasibility of damming West Loch, Pearl Harbor, to store fresh water. The same idea was expressed later by Watson (1977) and the State Water Commission (1979).

LABORATORY PHYSICAL MODEL

Two physical models were used in this study to investigate underwater membrane movement and behavior. A glass-sided box was used for three dimensional observations and a model of West Loch was used to primarily test the curtain method, which appears to be the most suitable for West Loch.

Glass-Sided Box

A water-filled glass-sided box 1.2 x 1.2 x 0.14 m deep (4 x 4 x 1½ ft) was used for preliminary analysis of membrane behavior under water. Basic principles and concepts were tested, observations noted, and photographs taken to document the effects and possible problem from inflow, tides, winds, waves, and currents on the membrane. In the preliminary analysis to examine basic membrane behavior under water, no attempt at scaling was made.

A relatively thin (3 mil or 0.076 2 mm) polyethylene membrane sprayed black to enhance observation, was used in this phase. A thin membrane was desirable because it would flex easily and not resist movement, thereby lessening the observable effects of water movement on the membrane. In all of the experiments, the membrane tensile strength to contain the stored water was never in jeopardy.

FLOATING RESERVOIR. In testing the floating reservoir, a square polyethylene sheet, cut large enough to allow a 0.3 m (12 in.) sag when filled was used. It was fitted along its periphery with floats consisting of styrofoam pieces strung together with nylon line. The string of floats was shorter than the membrane perimeter so that when the membrane edge was gathered, an open-top bag would be formed. The membrane was wrapped and secured around the floats so that there was about a 0.03 m (1 in.) watertight freeboard completely around the periphery.

This liner was then placed on the water and slowly filled with inflow. As filling progressed the floating edge became increasingly circular, as compared to the original square membrane. When the reservoir was completely filled, the floats formed a perfect circle. In side-view, the underwater part of the membrane gradually tautened and smoothed out as filling progressed, forming a flat-bottomed balloon when completely filled. This fitted perfectly the theoretical mode. The filled volume was about 0.14 m^3 (5 ft^3).

When surface waves were generated, the circle of floats was pushed inward at the point of initial contact, causing the circle to first flatten out, then to indent into the enclosure as the waves continued. The membrane below the surface followed the inward movement of the floats, but to a lesser extent, and retained much of its original shape, although the bottom of the membrane gradually sank as the floats flattened inward.

A single burst of underwater current generated by hand movement caused a ripple to pass along the membrane bottom in the direction of the current. After its passage the bottom flattened once again. The surface floats retained the circular configuration. A continuous underwater current caused a flattening of the side facing the current and a compensating sagging of the bottom occurred on the opposite side to maintain a constant volume. A continuous rippling of the membrane bottom also occurred. As the current continued, the floats deflected slightly inward and the entire reservoir began moving with the current. When the current was suddenly stopped, the bottom flattened out at a lower position than originally sustained. The exact reason for this is not known, but the current forces probably exerted a negative pressure, thereby pulling the membrane down after its passage.

The floating reservoir rose and fell with tidal changes. The only problem was in keeping the membrane from touching bottom. The configuration of the reservoir remained static for all intent and purposes.

To test the effect of excess inflow, water was gradually added. The entire reservoir began sinking, thus pulling down the floats until it was overtopped, bringing outside water into the reservoir.

The effect of sediment in the inflow was also investigated. Small quantities of sand dropped into the reservoir caused the membrane bottom to sink and increasing amounts of sediment made it touch bottom. When the sand was evenly distributed in quiet waters, the deposition was evenly spread on the bottom and less-sloping sides of the membrane. However, any movement of the membrane by waves or underwater current action caused all the sand to funnel to a central point, pulling the membrane into a cone. With additional sediment load, the membrane touched bottom. It is highly undesirable to have the reservoir bottom in contact with the ocean bottom because of possible abrasion, snagging, and tearing. Excessive sediment deposition will eventually exceed the flotation capacity and force the membrane below water level. Thus, sediment-free inflow is desirable.

Simulated wind conditions were not tested because an adequate fan was unavailable at the time. However, based on the other conditions tested, several things can be expected. The higher the above-water freeboard, the greater the direct effect of wind on the reservoir. Since winds also generate waves, an effect similar to that caused only by waves can be anticipated. An additional concern is that in designing a flotation system with low freeboard to minimize wind deflection, the possibility of wave overtopping is increased. Floats having high buoyancy and low vertical profile may be able to bob up and down without wave overtopping and to minimize wind deflection.

In simulated towing of the filled, open reservoir, a single attachment point pulled outward, the circle of floats, putting stress at that point. To reduce this stress, it may be desirable to distribute the load by using a multiple-line, towing system attached at several places on the floats. Similarly, several attachment points may be desirable when anchoring the reservoir in place. The stored water was well-contained and did not flow out during the towing.

In this model study, the open reservoir concept worked very well, without any significant problems arising.

CURTAIN. The curtain method was tested by clamping the membrane to the glass side and to the opposite side. The bottom was sealed with weights, and floats attached to the top. Enough slack was provided in the top edge and in the middle to allow the membrane to flex on filling.

The curtain was tested for the effects of inflow, tides, underwater currents, surface waves, wind, sediment loading, and overfilling.

On initial filling the membrane was vertically suspended as viewed from the side. As inflow continued the membrane bulged slowly outward taking on a fuller shape. When filled to capacity, the deflection was about 0.4 m (15 in.).

As would be expected, a rising tide deflected the membrane inward, whereas a dropping tide moved it outward in response to equalizing water level. The curtain therefore needs sufficient slack to take tidal changes without exerting excessive stress.

Underwater currents seemed to have less effect on the curtain than on the floating reservoir. This may be attributable to the anchoring and mooring of the curtain as compared to a free-floating reservoir. When the enclosure in only partially filled, thereby allowing the curtain to hang vertically, the currents cause only a rippling of the membrane. When the enclosure is near capacity and the curtain is round and taut, the current will slightly flatten the membrane at its contact point and then deflect sidewards. Since currents can have considerable latent force, the curtain should be strongly moored on shore and anchored adequately to the bottom. In West Loch the current moves shoreward at lower depths; thus, the bottom half of the curtain will tend to be pushed inward.

With respect to wave action, the greater the amount of water stored within the curtain, the less effect waves had on it. When the enclosure is full, the taut curtain merely bobs up and down; waves will override the floats only if they have a crest or are wind-driven and choppy. If the enclosure is only partially filled, allowing considerable slack, the waves pushed the floats shoreward to the extent that the slack would allow. Obviously, surface waves directly affect the upper part of the curtain, but in doing so other portions are affected to maintain equilibrium. Waves were observed to transmit through the curtain into the enclosed water.

Wind, and the waves created by it, would also affect the curtain. As discussed earlier, wind force per se has a direct effect only on the above-water components of the curtain. But in doing so, it moves the attached below-water components. In many respects the action and reaction of the curtain is similar to that caused by surface waves.

Inflow sediments have less effect on the curtain than on the floating reservoir because there is no membrane bottom on which the sediment settles. Conceivably, sediments could settle on the slack or on the fully extended membrane, and eventually pull down the floats. However, the constant flexing and movement of the curtain will more likely continually cause the sediments to simply slide off. This was observed in the sediment loading of the floating reservoir where evenly distributed sand slid to a central point with the slightest movement of the membrane. At West Loch the stream inflow point is at a considerable distance from the proposed curtain site. Therefore, there is less likelihood of sediments settling on the curtain.

If the enclosure is overfilled, the weakest component will fail. The failure will undoubtedly occur either at the surface or at the bottom. If the bottom is securely anchored, the line reinforcing the upper edge of the curtain may break. Or, the on-shore mooring may give way. Or, the reservoir water may override the floats and flow out. In the model studies, the latter occurred. Conversely, if the flotation-mooring components are secure, the bottom edge will be pushed outward, dragging the anchorage system. That the submerged membrane will burst is unlikely because pressure on it is in equilibrium at all points. Any membrane failure will probably occur near the water surface where differential stresses occur.

Three possible solutions to the overfilling problem are (1) to incorporate duckbill valves near the bottom of the curtain, as discussed earlier regarding bleeding to the outside, and seawater trapped at the bottom of the reservoir; (2) to construct a spillway on shore where the curtain comes ashore; and (3) to place a spillway on the curtain. If the latter is done, placement should be at the center of the curtain length, where, in one of the experiments, overtopping occurred.

West Loch Scale Model

CONSTRUCTION. Based on the scaling calculations (App. A) a 6 x 9-m (20 x 30-ft) model of West Loch was constructed within the confines of an existing model. The horizontal scale was 1:400 and the vertical scale 1:24.

Bottom contours were derived from a bathymetric map and transferred to parallel templates 0.3 m (1-ft) apart, cut from 6.35-mm (1/4-in.) plywood. The templates were vertically placed and sand packed between them to within 0.025 m (1 in.) from the top. A sand-cement mortar placed over the packed sand subsequently brought the model to grade. The concrete embayment was waterproofed with fiberglass resin and below water level areas painted silver, while the dry land was painted light green. The actual shoreline was painted dark green to accentuate it in photographs (Fig. 1).

To maintain a consistent and constant inflow for the model stream, the water was first fed by hose into a 0.09 m^3 (25 gal) open top, equalizing tank having an overflow assembly. By putting in more water than that being drawn out through a valve at the bottom, a constant head could be maintained. The regulated outflow from the tank entered a stilling basin to dissipate wave forces before flowing into the embayment through the model stream.

To simulate tidal changes, a moveable hinged plank extending along the seaward end permitted variation in water level. Because the top of the plank was level, the overflow was even throughout its length. The height could be varied as much as 0.038 m (1½ in.), corresponding to an actual 0.91-m (3-ft) tide.

Single- and double-wall curtains were constructed from 1.5 mil thick

NOTE: Mottling in bay from paint discoloration.

Figure 1. Top view of West Loch model with membrane curtain in place

black polyethylene sheets 0.91 x 2.13 m (3 ft x 7 ft). Sleeves about 0.04 m (1½-in.) diameter were formed along both edges of its length by folding over and heat sealing. For the single-wall curtain, a combined flotation and mooring system, consisting of 0.025 m diameter styrofoam cylinders strung together with 20.4 kg (45 lb) steel fishing leader, was inserted into the upper sleeve. Sand inserted into the bottom sleeve comprised the anchorage system. Excess slack was removed from both ends near the shoreline to give a more streamlined rather than baggy appearance. For the double-wall curtain, the styrofoam-wire flotation-mooring system was inserted into both of the curtain sleeves and folded into a "U" in cross section, with floats at the top of each end. A separate sand-filled membrane tube was then laid at the bottom of the U to serve as anchorage.

Ends of the curtain were moored to opposite shores by lead weights, which allowed flexibility in membrane positioning while remaining immobile during testing. The single- and the double-membrane curtains were tested for each environmental factor.

TEST PROCEDURE. Curtain testing was emphasized on the West Loch model because it appeared to be best suited for the site conditions. The selection of a specific site for its deployment hinged on several restrictions imposed by the U.S. Navy, the owner of West Loch. Ideally, a short span which encloses the greatest amount possible would be most economical. This would be the narrow channel leading into West Loch, but channel blocking is prohibited. Also, the curtain could not be placed within the "blast zone" of the nearby naval shore magazine, nor in any way interfere with naval ship traffic.

The curtain site selected to meet these restrictions stretched from the mouth of Kapakahi Stream on Waipio Peninsula, across West Loch to the peninsula near Honouliuli (Fig. 2). The curtain spanned a scale distance of approximately 1 220 m (4000 ft) with a maximum depth of 3.05 m (10 ft).

The curtain was tested for the effects of varying inflow, tidal change, surface waves, and wind loading. Testing focused on the reaction of the curtain when subjected to recorded normal loadings, while maximum loading was determined by the capability of the laboratory equipment. The mixing pattern of the inflow with the bay water was also simulated by coloring the inflow with red rhodamine B dye at 10 mg/ℓ concentration.

Three flow rates each were run on the single- and double-membrane cur-

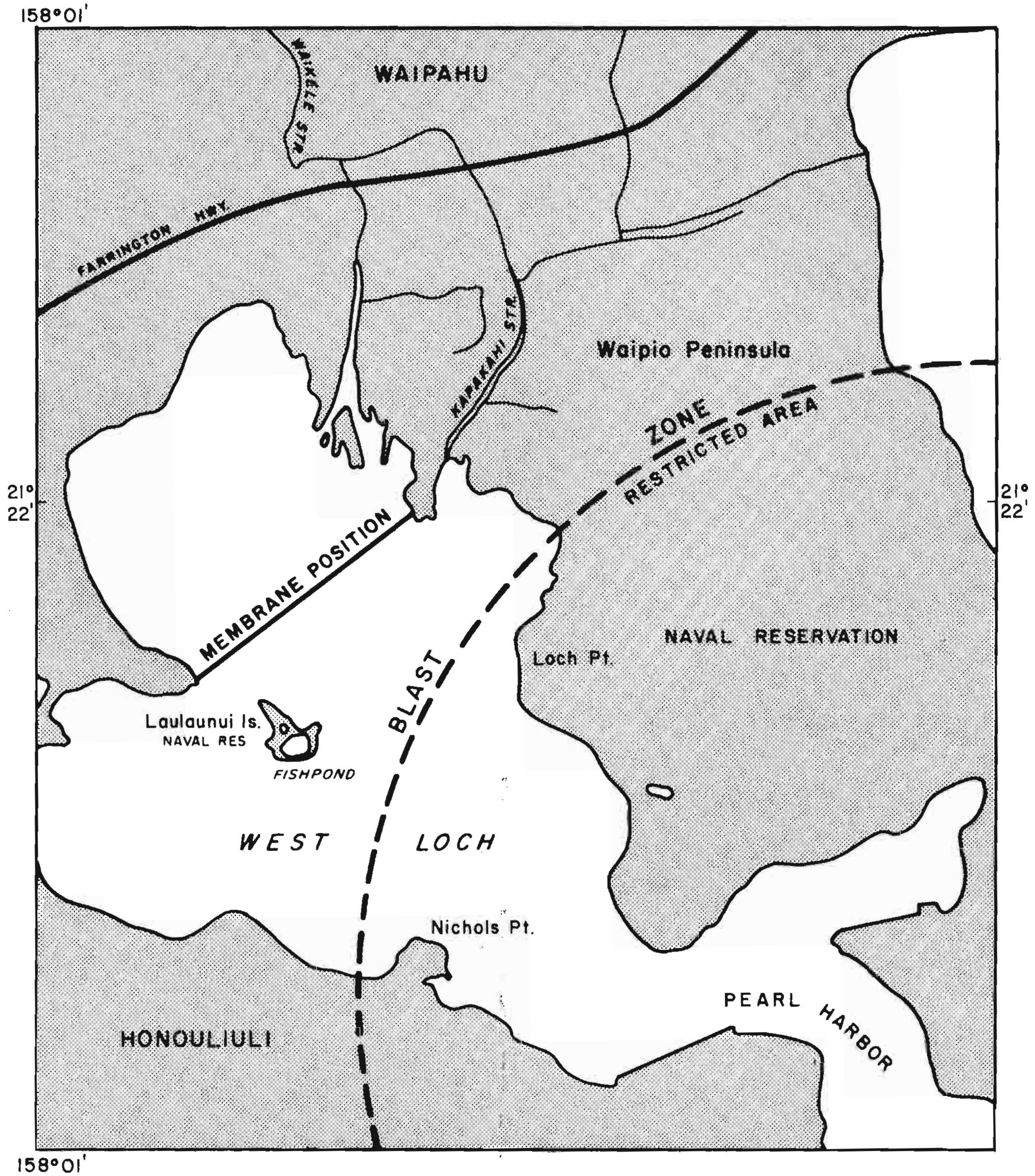


Figure 2. Proposed location of prototype membrane and limits of restricted "blast zone" area, West Loch, Pearl Harbor

tains' reaction to varying inflow. Using an inflow scale of 47,030:1 (App. A), the minimum recorded inflow of 0.56 m^3/s was converted to 0.714 ℓ/min for the model. Similarly, the average streamflow of 1.63 m^3/s was scaled to 2.08 ℓ/min. The maximum recorded flow of 385.56 m^3/s converts to 491.9 ℓ/min. This maximum flow rate could not be attained on the model apparatus. The maximum attainable was about 35 ℓ/min, equivalent to 1.67×10^{-5} m^3/s in the field. Details of the conversion factors used are in Appendix A, and a brief structural analysis of the curtain at the maximum inflow of 385.56 m^3/s is given in Appendix B.

The maximum tidal change of about 0.6 m (2 ft) in West Loch or about 0.025 m (1 in.) on the model was used in the testing. Tests were run from high to low tide and from low to high tide.

Surface waves were hand generated at 2-s intervals, using varying pieces of plywood, large pieces for large waves, and smaller ones for smaller waves. This method was superior to a mechanical wave generator which caused return waves from shore runup.

Wind loading was simulated with two variable speed 0.51 m (20 in.) diameter fans, each driven by a 1/6 hp motor. Wind direction was based on prevailing northeasterly trade winds (App. D) and storm-related southwesterly Kona winds occurring during the winter. Scale velocities up to 35.76 m/s (80 mph) were estimated and measured by an anemometer positioned in the middle of the embayment at a 10 m scale height, the standard used for hydrologic measurements (U.S. Department of Agriculture 1979).

At the beginning of each test the curtain was aligned straight across the embayment. And to document the movement of the curtain during testing, sequential photographs were taken from a platform 4.57 m (15 ft) directly above the model. A 0.30 m (1 ft) square grid system was installed to serve as fixed reference points. This consisted of dark-colored string, to contrast with the lighter bay bottom, pulled taut and affixed to the model frame so that it was about 0.15 m (6 in.) above the bay.

Aside from the curtain, the feasibility of using the bag and open reservoir was examined. They were tied at the stream mouth from which water flowed directly into the models.

Only fresh water was used both in the bay and for the inflow. Seawater could have damaged the pump and other equipment.

RESULTS AND DISCUSSION

Curtain Method. The major element influencing curtain movement was attributable to changes in water volume as affected by tidal fluctuation and inflow variation. As expected the membrane moved in the direction of lower hydraulic gradient. That is, with regard to tides, the curtain moved seaward in a receding tide and shoreward on an incoming tide. Similarly, as stream inflow progressed, the increasing volume within the enclosure pushed the curtain outward.

The key to the usefulness of the curtain is sufficient slack to absorb these volume changes. When the slack capacity is exceeded, problems develop.

In a test using the single-membrane curtain, the effect of high to low tide and back to high tide was examined. As the tide was lowered, the water within the enclosure first caused the curtain to billow and to tauten. Then with nowhere for the water to go, the bottom anchorage system was pushed outward and did not return to its original position when the tide was raised to its original level. A similar type of response can be expected with inflow and out-pumpage variations in the enclosure. A structural analysis of the curtain using the maximum recorded field inflow of 385.15 m^3/s (13,600 cfs), or a worst possible event, is given in Appendix B.

In the model testing, tidal changes caused the greatest deflection, followed closely by inflow variation. Again, this is related to the amount of slack in the curtain. If inflow is small, the slack is absorbed slowly and the curtain is deflected slowly. Conversely, if the inflow is large, the curtain will deflect more rapidly. Although the maximum recorded inflow equivalent of 8.2×10^{-3} m^3/s (491.9 ℓ/min) could not be duplicated, the 5.83×10^{-4} m^3/s (35 ℓ/min) attainable was enough to cause overtopping of the curtain. This occurred at the deepest section of the bay near the middle of the curtain length. Based on photographic scale measurements, the overtopping flow covered 61 m (200 ft) of the curtain. The possibility of such a large flow causing damage or failure of the curtain emphasizes the need for protective measures.

The main effect of the wind was on the protruding flotation system, with very little effect on the structure as a whole. With the predominant northeasterly trade winds and southwesterly storm winds being mainly parallel to the curtain alignment, even the 35.8 m/s (80 mph) scale winds had minimal effect. The wind generated waves were not of sufficient height to overtop the floats.

Similarly, the effect from the hand-generated waves was insignificant. Even when the waves hit the curtain broadside, the flotation system merely bobbed up and down, and the wave force was transmitted through the membrane into the enclosure. Again, the amount of slack is the key to the curtain's performance. If the membrane is taut and the floats are unable to rise with the wave, overtopping will occur. Cresting waves could not be generated at scale heights in the model.

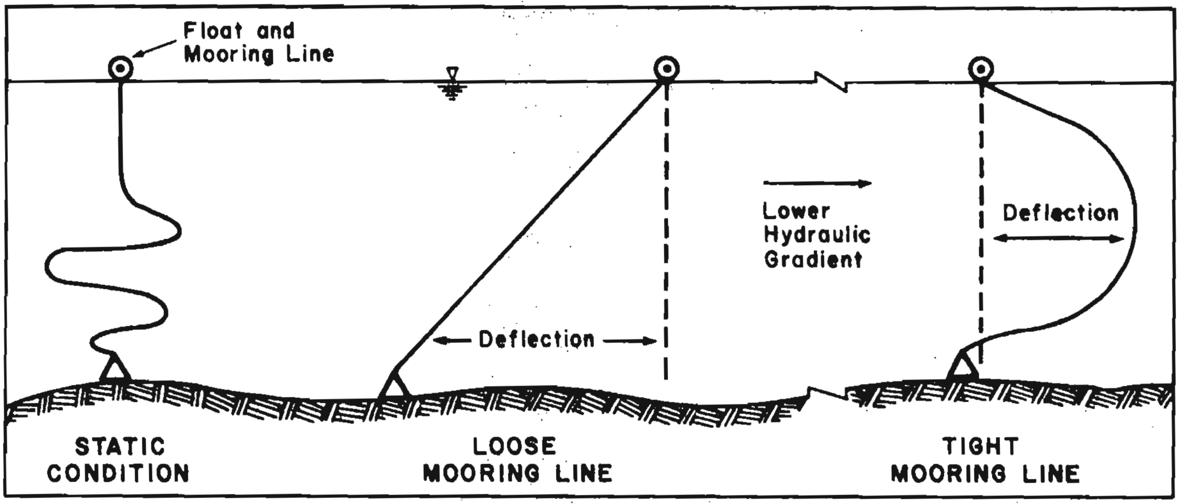
A double-membrane curtain was also tested and subjected to the same factors as the single-membrane. The addition of another membrane and float system suppressed and lessened the effects of the factors. The partitioned central section seemed to absorb and dissipate much of the energy transmitted to the curtain and the additional float system was not affected by as much wind as expected, even at high speeds.

Two cases of severe conditions were simulated on the single- and the double-membrane curtains. The first consisted of minimum inflow with high tide which was subjected to 35.8 m/s (80 mph) scale southeasterly Kona winds and surface wave action. The second condition was maximum inflow at high tide with 13.4 m/s (30 mph) scale northeasterly trade winds. The single- and double-membrane curtains functioned well, but the latter was superior.

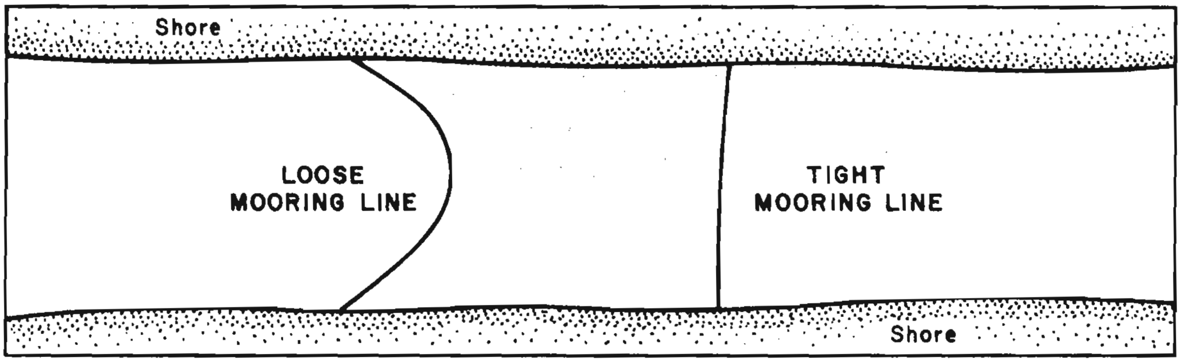
The overhead photography did not work as well as expected. The two dimensional photographs could not adequately capture the three-dimensional movement of the curtain. However, gross deflection of the black curtain, which contrasted against the lighter bay bottom, was readily discernible in the photographs.

Attempts to find actual scale deflections of the curtain proved to be impossible because of its high variability and inconsistent movement. Overhead photographs of different runs of the same test were overlaid on a light table and examined. The location and amount of deflection were not even relatively consistent. This poor reproducibility is attributed to such factors, as (1) insufficient weight in the anchorage system, so that the curtain could slip on the bottom anywhere along its length when subjected to a hydraulic gradient; (2) seepage loss beneath the curtain; (3) inadvertent varying tension of the top mooring line; and (4) bunching of the membrane when changing shape from concave to convex and vice versa.

Basically, the curtain slack is deflected in two ways: both are dependent on the tension of the top mooring line. If the mooring line is loose, the curtain slack will take a linear profile on filling. On the other hand, if the mooring line is tight, the deflection will be curved. Viewed from the top, these curtain deflections are reversed: the linear slack is curved and curved slack is linear.



CROSS SECTION



PLAN VIEW

Red dye added to the inflow water simulated the circulation within the enclosure. On entering the bay, the inflow moved first along the curtain and returned in a clockwise manner. Seepage under the bottom anchorage system was also observed but could not be seen in the photographs. Color photography may have been advantageous.

Bag and Open Reservoir. Testing of the bag and open reservoirs in the West Loch model was not feasible because of the shallow depths despite the vertical exaggeration. The membrane dragged on the bay bottom, which is undesirable.

FIELD PILOT TESTING

After completion of model testing, the second phase pilot field testing commenced. Field-scale curtains, floating reservoirs, and bags were constructed and tested.

Fabrication

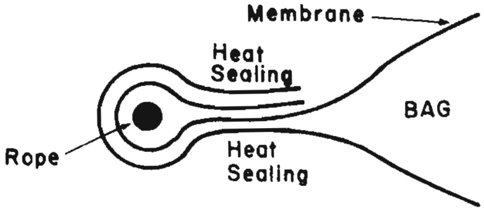
Fabrication begins with the selection of a membrane. Some of the criteria for a suitable membrane include non-degradation on exposure to water and weathering (particularly ultraviolet rays), resistance to puncture and tearing, nontoxic to water or biota, easily handled, easily seamed or glued together. Selection of a suitable membrane can be an ardous task given the myriad of membranes and their modifications, such as reinforcement and sandwiching. A brief discussion of membrane selection is presented in Appendix C. New membranes are constantly being introduced; therefore, it is imperative that the most up-to-date materials be sought.

Since the main objective of the study is the determination of proof of concept, no priority was given to selection of a permanent membrane. In stead, 6 mil black polyethylene sheets 6.1 x 9.1 m (20 x 100 ft) were used. With a density of approximately 0.92, nearly that of water, polyethylene has almost neutral buoyancy. The advantage of polyethylene is its ready availability locally and low cost; therefore, design changes would not be excessively costly. The design derived from the polythylene models can be adapted to fabricating production models using appropriate membranes. Black, rather than clear, membrane was used because it can be seen in the water, and is more resistant to ultraviolet (sunlight) degradation to which polyethylene is particularly susceptible.

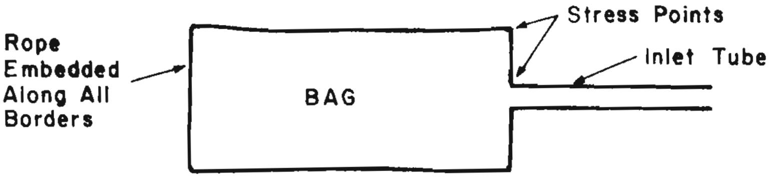
Aside from the selection of membrane material, even load distribution is the crucial consideration in membrane structural design and fabrication. Stress points created where load is unevenly distributed are to be avoided. Coupled with this is the attainment of strong and leak-free joints and seams.

Heat seaming is the only means of joining polyethylene sheets; there is no glue that adheres to it. After trying several methods, the best seams were derived from the simplest, which was heating the plastic sheets with a teflon-sheathed clothes iron. The desired joint (seam) is placed over an aluminum sheet then pressed with the heated iron. Immediately after the desired melt is reached the seam is cooled with a damp cloth to stabilize the polyethylene, thereby preventing wrinkling and giving a strong, smooth, water-tight joint.

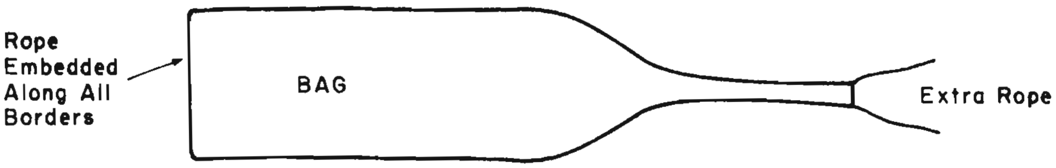
BAG. The bag is essentially flat membrane sheets seamed together to form a sack. The edges of the bag were reinforced with 9.55 mm (3/8 in.) polypropylene rope embedded with the membrane as shown below. This allows the load to be evenly distributed along the rope.



A small membrane tube attached to the bag facilitates filling from the stream mouth while the main body sits in deeper water. Field testing showed that the right angles at the inlet end of the body were stress points, subjecting the membrane to possible tearing.



INITIAL MODEL— PLAN VIEW



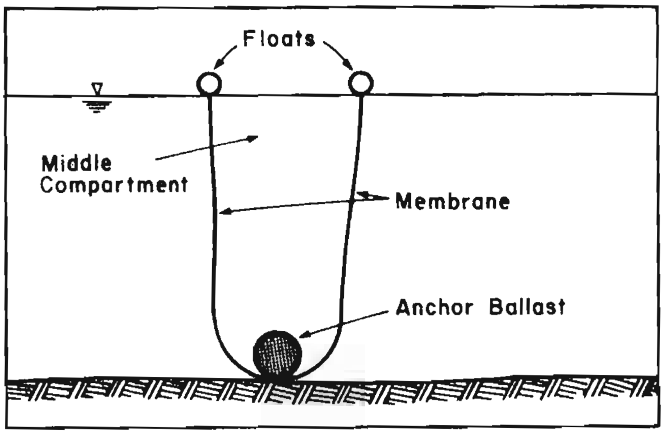
FINAL MODEL— PLAN VIEW

Consequently, the final design derived was more bottle-shaped, which worked well. The extra rope at the inlet is for handling and securing the bag to shore or to an anchor. It can also be used for towing the water-filled bag.

The initial design incorporated an opening in the middle of the bag to remove trapped air. But field testing showed that the air could be purged through the inlet opening; consequently, subsequent models did not have this feature. The opening consisted of a "Zip-loc" bag seamed into the main bag. The Zip-loc could be opened to remove air, yet provide a watertight seal when closed.

The bag was 6.1 x 15.2 m (20 x 50 ft), with a capacity of 177.9 m^3 (47,000 gal).

CURTAIN. As mentioned previously, the curtain method required flotation, mooring, and anchorage systems to position the membrane. For ease of field deployment a U-shaped (in cross-section) double-membrane design was adopted, as shown below.

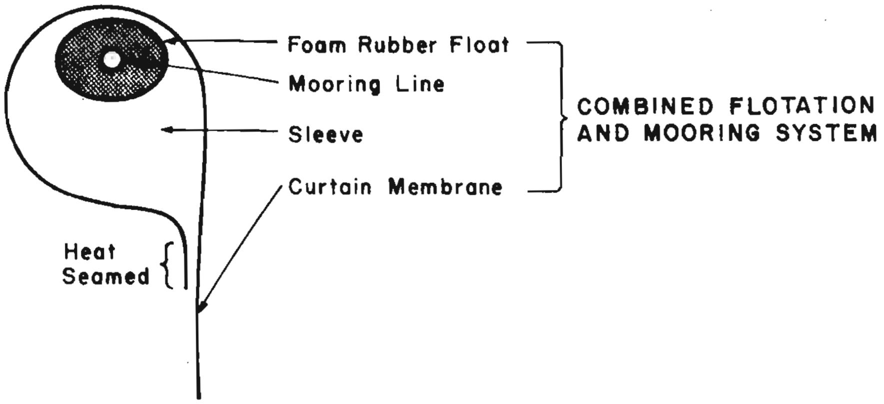


CROSS SECTION

The anchoring system seals the curtain to the bottom of the bay and side-slopes. Such a system should minimize seepage under the membrane and be strong enough to remain immobile when subjected to normal ocean movements. A flexible weight system which conforms to uneven bottoms is necessary and locations with steep side-slopes should be avoided or modified to make it less sloping.

The anchoring ballast consisted of sand-filled, 0.1 m (4 in.) diameter cylindrical membrane tubes in 0.91- to 1.22-m (3-4 ft) lengths, laid end to end. This simple technique allowed easy placement of the ballast after the membrane had been deployed on the water, and met the need for even anchor distribution to effect bottom sealing. The U-shaped curtain allows placement of additional ballast if the need arises. The alternative of pre-assembling the anchor with the curtain makes the whole unit very heavy, and attaching anchors while deploying the membrane is very cumbersome in the field. The U-shaped method also gives double-membrane separation of the waters.

The flotation system consisted of standard 0.1 m (4 in.) diameter x 1.8 m (6 ft) long foam rubber pipe insulation. The insulation was strung together with nylon parachute strap pulled through the center hole. This was placed in a membrane sleeve formed at the edge of the membrane as shown below:



The membrane sleeve through which the float passes is made sufficiently large to allow additional strings of floats to be added if necessary.

The foam rubber pipe insulation makes an ideal float because (1) it has good buoyancy and does not waterlog easily; (2) the circular shape distributes the load evenly on the membrane, whereas square corners will tend to cut through; and (3) the softness and flexibility throughout its length allows easy bending without stress points where they are joined. With rigid floats, the membrane tends to wear out where the floats are connected because this is the only point where flexing can take place. (4) The center hole allows the floats to be strung together by pulling a line through it, thereby combining the flotation and mooring control system. (5) The insulation is light and easy to handle.

The parachute strap used for the mooring system also strengthens the floating edge of the curtain. Moored to opposite shores, the strap holds the curtain in place. The parachute strap used was soft and pliable, thereby resisting any tendency to cut into the foam rubber.

One polyethylene sheet, 6.1 x 30.48 m (20 x 100 ft) was used for the curtain. With allowances for the sleeves on both edges, this gave an effective usable height of about 2 m (7 ft) in double membrane configuration and length of 30.48 m.

FLOATING RESERVOIR. The floating reservoir is essentially a flat plastic sheet with its edges gathered to a smaller perimeter thereby forming a bag. In this experiment a sheet 12.2 x 15.2 m (40 x 50 ft) was used with a float perimeter of 30.48 m (100 ft), giving a 238.46 m^3 (63,000-gal) capacity when filled. The flotation system is similar to that on the curtain. Sleeves were seamed into each edge but the corners were left open to allow the floats to be more readily pulled through. Following this, the corners were pinned in place over the float to provide a water-tight seal.

To fill the reservoir a membrane tube 0.91 m (3 ft) in diameter by 15.2 m, similar to that used on the bag is seamed into the main body just below the flotation system. The tube is reinforced with rope around its inlet and two sides of its length and ties into the flotation system of the main body.

Deployment, Testing, and Discussion

Field deployment and testing was done in the quiescent waters of a small boat harbor. A small stream entering the harbor supplied freshwater inflow and a small beach and a shallow area adjacent to the stream mouth provided space for assembling and deploying the structures. Deeper harbor water (over 1.5 m [5 ft]) immediately offshore enabled floating the reservoir and the bag. It was an ideal site. The inflow water was relatively clean with very little sediments.

The structures were left in the water for only one or two hours. Long-term storage was not attempted because the test objective was proof of concept and the development of a design that works in the field.

BAG. In deployment, the plastic bag is first spread on the sea surface then stream water is introduced through the inlet tube.

Three separate field tests were made with the bag. Design refinements were made between tests. As mentioned earlier, the initial model was very angular, causing stress points to develop and subsequent membrane failure. The second model was bottle-shaped to alleviate the problem but the inlet tube was too short making it difficult to catch the inflow above sea level.

The third model was bottle-shaped with a 15.2 m (50 ft) inlet tube, which was clamped shut to prevent leakage after filling. This bag design worked very well. It was easy to deploy as well as to retrieve. When towed by hand it moved easily and smoothly after the initial inertia was overcome. The deployed bag is shown in Figure 3.

FLOATING RESERVOIR. The membrane liner for the floating reservoir is first spread on the water, then a string of floats is inserted into the sleeve of each of the four edges. The floats are subsequently tied together at each of the four corners, thus forming a complete loop. The reservoir is then filled through the inflow tube.

The basic concept worked well from the beginning, but there were problems where the inlet tube was attached to the body. The inflow tube was initially connected at the same level as the floats, which caused tearing of the membrane by the excessive loading. In a subsequent model the tube was fastened below the floats, which worked well (Fig. 4).

One string of floats was found to be insufficient in preventing overtopping by even small waves. By incorporating another set of floats, this

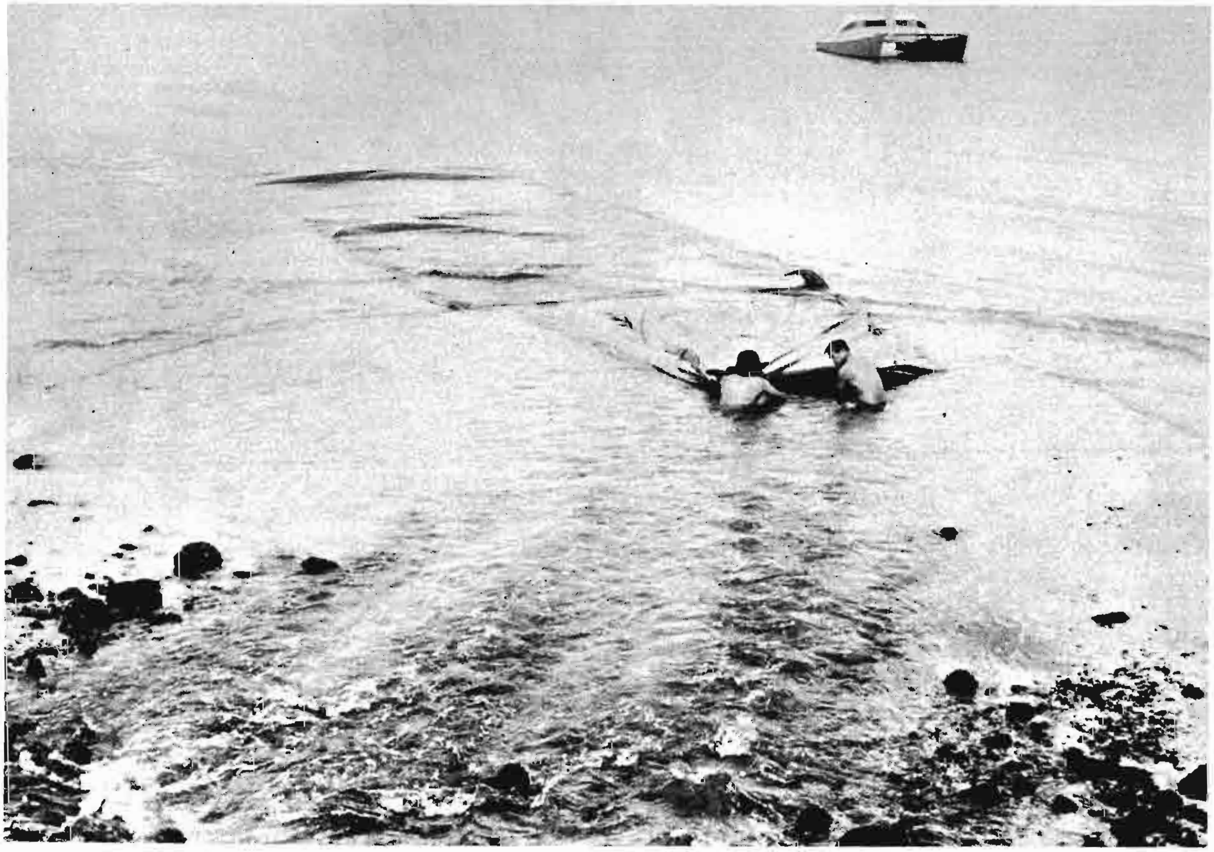


Figure 3. Stream-water filled bag floating in seawater

Figure 4. Floating reservoir being filled through inlet tube

problem was solved. Outside waves are transmitted through the membrane into the contained water and on out the other end as though there was no membrane. Air trapped beneath the membrane on initial deployement escapes as the reservoir fills.

CURTAIN. The curtain was first laid open on the sea surface and the string of floats inserted into the sleeves on both edges. This insertion proved to be difficult; therefore, vertical slits had to be cut in the sleeve about every 6.1 m (20 ft) in order to pull the floats through. The slits were cut on the outside edge so that seawater could not enter the enclosure. Thus the integrity of the curtain to separate the waters was unaffected.

Subsequently, the curtain was maneuvered in place in water about 1 m (3 ft) deep and brought up on shore at each end. The mooring straps were tied to rocks onshore. The sand ballast was then placed near the middle of the curtain, thereby sinking it and providing the bottom seal. The floats were then readjusted to attain a double-membrane curtain. A theoretical U-shaped configuration is difficult to attain because getting water in the middle compartment is difficult. Nevertheless, a double-membrane curtain is produced without compromising its performance. The deployed double-membrane curtain is shown in Figure 5.

Since the storage concept is that inflowing fresh water will dilute the seawater captured within the enclosure, outflow must occur past the curtain. This was best accomplished by allowing it to escape around the sides at the shoreline. Attempts at keeping the water from leaking around the ends caused either the outflow to override the floats or the ballast to be swept seaward, which was predicted by the model studies.

Water samples taken from within the enclosure at the end of the 2-hr

Figure 5. Double membrane curtain in place
(stream inflow is from left)

test to measure the amount of dilution were inconclusive.

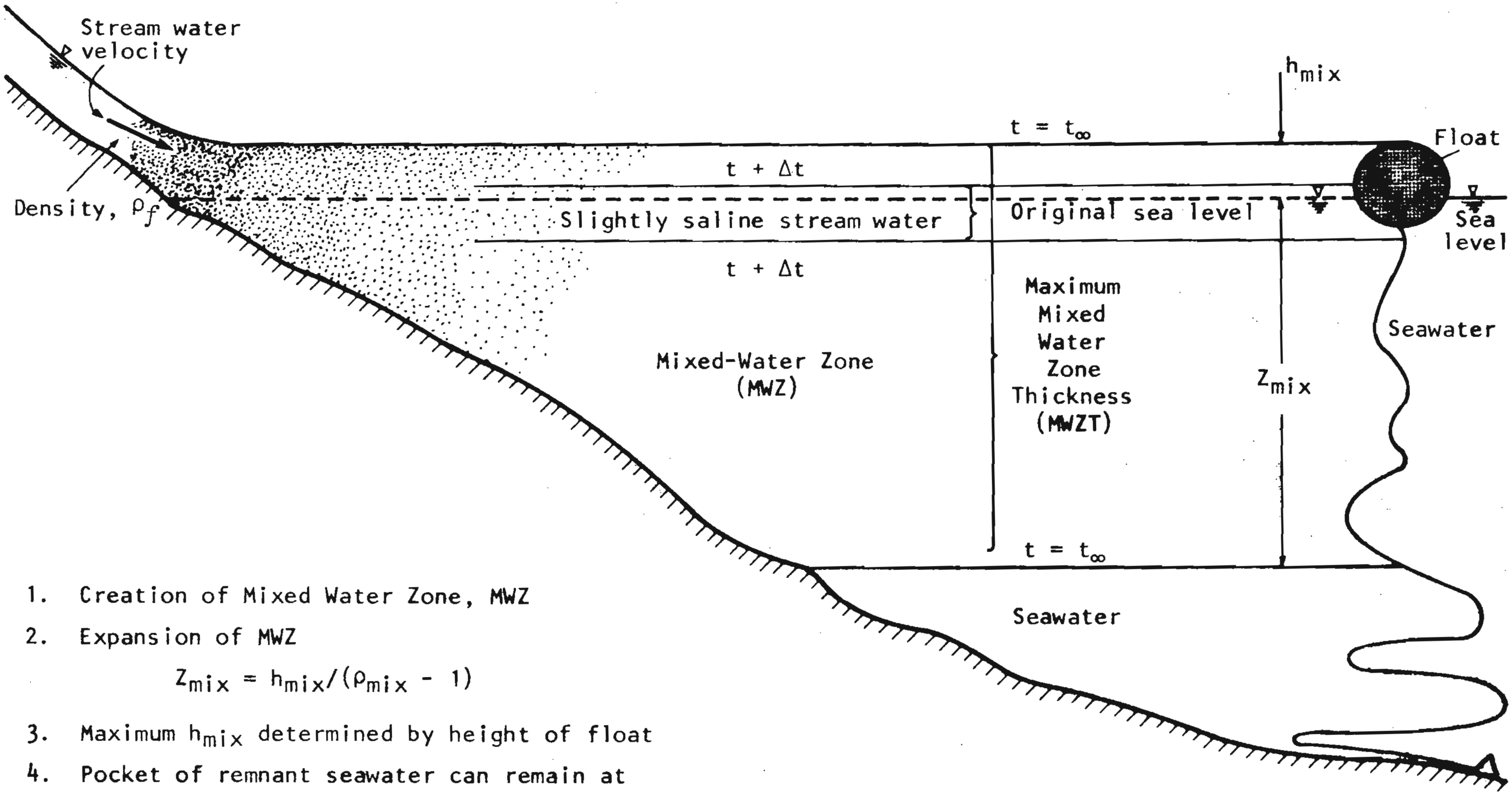
While the curtain worked well in this test, of the three methods examined in this study, the curtain is the most difficult to deploy in the field. For application in West Loch a much sturdier, and thereby heavier and stiffer, membrane will probably be needed as well as larger floats and heavier ballast. The design and logistics of doing this will require considerable study. The concept works, but its actual application will be much more difficult.

As mentioned previously, the curtain will be laid in a marine bay; thus, initially, the water on both sides of the membrane will be similar. Subsequently, fresh water flowing into the enclosure will gradually dilute the captured seawater. However, fresh water, which is slightly lighter than seawater, will tend to float over the heavier seawater. Thus, a gradient or stratification will occur (Fig. 6). In addition to the freshest water at the top, there will be a mixed zone grading to nearly seawater at the bottom. And if there is sufficient depth, a pocket of remnant seawater will remain at the bottom. To maximize freshwater storage, seawater should be purged as much as possible from the storage area. To do this a simple one-way valve which operates at very low pressure differentials would facilitate the purging. Although it was not tested, membrane duckbill valves open to the seaward side and incorporated into the curtain near its bottom may function properly. The pressure differential would be provided by the inflowing fresh water.

There is a very important and practical consideration to this stratification problem. Based on pan evaporation and rainfall data available for the West Loch proximity, about 784 mm (30.8 in.) of net evaporation loss can be expected per year. This loss will come from the uppermost and freshest water layer.

MATERIALS SELECTION AND DESIGN CONSIDERATIONS

The selection of suitable materials and the utilization of appropriate design considerations is crucial to the success of an operational membrane structure. While it is beyond the scope of this project to make specific recommendations, some discussion of criteria is appropriate.



1. Creation of Mixed Water Zone, MWZ
2. Expansion of MWZ

$$Z_{mix} = h_{mix}/(\rho_{mix} - 1)$$

3. Maximum h_{mix} determined by height of float
4. Pocket of remnant seawater can remain at bottom depending on bottom topography and max h_{mix}

Assume 1. continuous streamflow with constant density
2. mixing by turbulence occurs at stream mouth

Figure 6. Cross-sectional diagram of freshwater-seawater stratification in a curtain enclosure

Obviously, all components (floats, membrane, and anchorage system) must be able to withstand prolonged exposure to adverse marine environmental conditions without being physically or chemically degraded and to require minimum maintenance. The U.S. Navy (1977) evaluated various materials for use in containing oil spills, which may be useful in materials selection. In general, nonmetallic materials are preferable because they are generally unaffected by corrosion. Possible biological damage by marine biota are not investigated in this study.

As stated earlier, aside from selection of appropriate materials, the single most important design consideration is even load distribution. For construction and material selection, the use of rigid materials should be avoided as much as possible because stress points are concentrated where connections to flexible components occur.

Flotation-Mooring System

The float system, which also incorporates the mooring line, developed for the field pilot study can be considered nearly ideal, although the actual material used can vary. The foam-rubber pipe insulation combined (1) good buoyancy, (2) even load-distribution on its cylindrical shape without corners to cut into the membrane sleeve, (3) flexibility throughout its length, and (4) protection of the membrane from abrasion and cutting by the mooring line.

The need for a wave fence to provide additional freeboard above the floats is still largely unanswered. From the experimental observation, a non-cresting wave poses no problems. And a cresting wave lower than the floats may also not be a problem. It must be pointed out that a wave fence will increase wind deflection. And a fence strong enough to stop waves will probably be heavy, thereby needing additional flotation.

Air filled bags or sausages are too prone to leakage and, thus, were discarded early in the study. Similarly, loose unconsolidated materials such as styrofoam chips can escape through holes in the retaining casing, thereby deflating the float and littering the surroundings.

Anchoring System

The design requirement for the anchoring system is that (1) it must be heavy enough to hold the curtain immobile to the bottom, thereby minimizing seepage under the membrane; and (2) it must be flexible enough to conform to bottom and side-slope contours. The basic concept of using sand-filled membrane tubes worked well in the model and initial pilot field testing; however, the ease with which it can be deployed under full scale field use is uncertain. Anchoring the single-membrane curtain was the most difficult to do in the field. Preassembly to the curtain would make it very heavy and cumbersome to handle and field assembly would be difficult.

Membrane

The membrane is the element common to the bag, open reservoir, and curtain. There is a wide diversity of potential materials and combinations incorporating reinforcing and sandwiching. New materials are constantly being introduced; therefore, an up-to-date search should be conducted before a selection is made. Appendix C contains some materials presently available. Some properties to consider in the selection of an appropriate membrane are discussed below.

Tensile Strength. The material must have sufficient tensile strength to withstand various loads during operation, such as wind, wave, currents, tides, and inflow. The required strength should be incorporated in the membrane and in any reinforcement.

TEAR RESISTANCE. The material should not continue to tear after being cut, snagged, or punctured. Tears may be caused by snagging on debris, biota, or improper handling. If a tear remains small, very little mixing will occur before repairs can be made. If total failure occurs, complete flushing of the enclosure may be required.

PUNCTURE RESISTANCE. Punctures can occur during all phases of operation, including handling and installation. The membrane must be able to resist punctures.

ABRASION RESISTANCE. The membrane material must withstand any abrasion such as rubbing, scraping, dragging or erosion, that weakens the membrane surface. Abrasion damage weakens the structural strength, chemical resistance, and water absorption, thereby increasing maintenance costs and decreasing the membrane life.

FLEXIBILITY. The membrane material must be flexible enough to conform to waves, swells, and currents, and to have sufficient slack and flexibility when the membrane is moved outward by the inflow.

Flexibility is also required for storage and handling. The material must be capable of being wrapped or folded in a relatively small bundle for prolonged periods without cracking, tearing, or creasing permanently.

STRETCH RESISTANCE. The membrane should not stretch excessively when subjected to operational loads, and should return to its original shape after the loads are removed. The material should be dimensionally stable without stretching or shrinking under any conditions, including loading, moisture, temperature, light, or chemicals. Under these conditions, the material should retain its shape and operate under normal design conditions.

A relatively low total elongation of a fabric, characterized by a steep stress-strain curve and high (100%) modulus, and recovery from stretching are desirable in the curtain material to prevent it from losing its shape when subjected to uneven load distribution.

LOW DENSITY. A low density material is easier to handle, requiring less men and machinery during installation. However, the material still has to meet the tensile strength requirements. A lighter material will also decrease the buoyancy required for the floats.

NONPOROUS. The material used for the membrane must separate fresh water from seawater and therefore be impervious to seepage.

HIGH TEMPERATURE RESISTANCE. The material should not appreciably change when exposed to high temperatures, and its flexibility, strength, and imperviousness should remain the same. The material also should not become tacky or block under high temperatures as a result of exposure to the sun on the float system and membrane above the water surface.

LOW TEMPERATURE RESISTANCE. The material should not stiffen, crack, or become brittle when subjected to cold temperatures. In Hawai'i and similar climatic regions, this should not be a problem, but may be significant in colder climates.

WEATHER AND WATER RESISTANCE. No appreciable change should occur in the structural, physical, or chemical resistance properties of the membrane material after prolonged exposure to ultraviolet light, ozone, freshwater, or seawater. The high amount of ultraviolet light in Hawai'i may cause a premature deterioration of the material above the water surface. These effects on the membrane and float system must be seriously considered in design and operation practices.

RESISTANCE TO PETROLEUM AND CHEMICAL PRODUCTS. The material should not be adversely affected by the presence of oil and other chemical products.

COLORABILITY AND COLORFASTNESS. The material should have a highly visible color, such as orange or yellow, and be resistant to discoloration and fading when exposed to heat, cold, light, and chemical products. The flotation system must be visible to boats in the area to avoid damage to the floats and membrane.

FLAME RETARDANCY. The material should be self extinguishing and not continue burning once the source is removed. A flame to the material should not cause the membrane or floats to burst into flames. This requirement is more of a safety precaution and is not a structural requirement.

RESISTANCE TO WATER ABSORPTION. The membrane and floats should not absorb moisture while in the water. Absorption will increase the weight of the membrane and exert a greater force on the floats.

RESISTANCE TO MARINE GROWTH, FUNGUS, AND MILDEW. The material should be resistant to the growth of marine organism because the membrane will be in constant contact with water. Fungus and mildew may also grow on the float system. The added weight and possible deterioration effect pose problems to the system. Antifouling coatings are usually applied on the materials, preventing growth, but the leaching-off of the chemicals may pose a pollution problem. Resistance to such growth reduces the maintenance required to clean the membrane and improves the life of the membrane.

REPAIRABILITY. Tears, breaks, and punctures, must be easily repairable underwater as the membrane cannot be removed for repairs. The adhesive must therefore work underwater, cure quickly, and develop a strong bond.

CLEANABILITY AND MAINTENANCE. Oil products, marine growth, and other chemical contaminants that may accumulate on the membrane must be easily and inexpensively removed from the membrane without damage to the surface. Periodic cleaning will help to increase the life of the system.

WEST LOCH SITE

West Loch is part of Pearl Harbor, an inland marine embayment (Fig. 7) which also consists of the East and Middle Lochs, connected by a main channel leading to the sea. The harbor has been carved by natural forces into the surrounding calcareous sedimentary materials. The entire harbor is part of a U.S. Navy base and under its jurisdiction, although primary naval activity is confined mainly to the East and Middle Lochs. By comparison, West Loch is relatively unused and relatively shallow, and the upper reaches are not dredged.

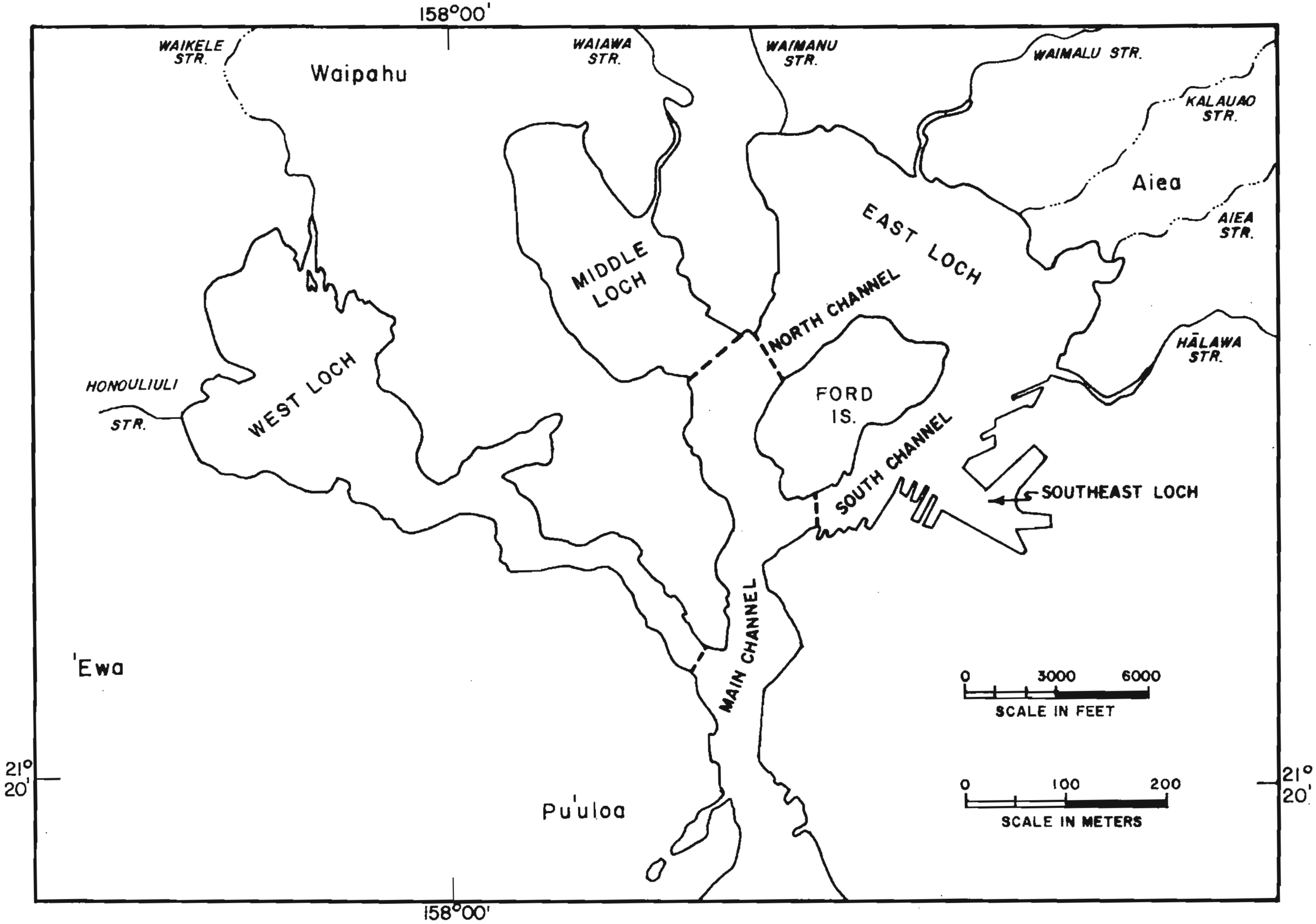
The Pearl Harbor basin, consisting of the harbor and its drainage basin as shown in Figure 8, is the most important groundwater basin on O'ahu. The basin supplies irrigation, military, and municipal needs. In recent years, however, the aquifer has been developed to near capacity. The Honolulu Board of Water Supply in a recent study (Mink 1980) showed that the heads of all the well groups in the Pearl Harbor basin have steadily declined in recent years. During the 1977 drought the Governor, responding to widespread concern over the adequacy of water supplied, appointed a State Water Commission to assess Hawai'i's water situation and to recommend administrative and legislative actions needed. After an extensive investigation, the Commission (1979) submitted a report that included fourteen recommendations, one of which was "the prudent development of surface sources by stream diversions and impoundment."

In an unpublished 1973 report, Chang explored the feasibility of developing West Loch into a freshwater lake and estimated the cost of conventional damming at more than $12 million. The same idea was also expressed in a Water Resources Research Center seminar by Watson (1977), who urged the development of one of the bays in Pearl Harbor as a reservoir to store water for irrigating agricultural lands. Thus, a membrane curtain may be a less expensive alternative method for utilizing West Loch.

To this end, appropriate background information relating to West Loch is presented below.

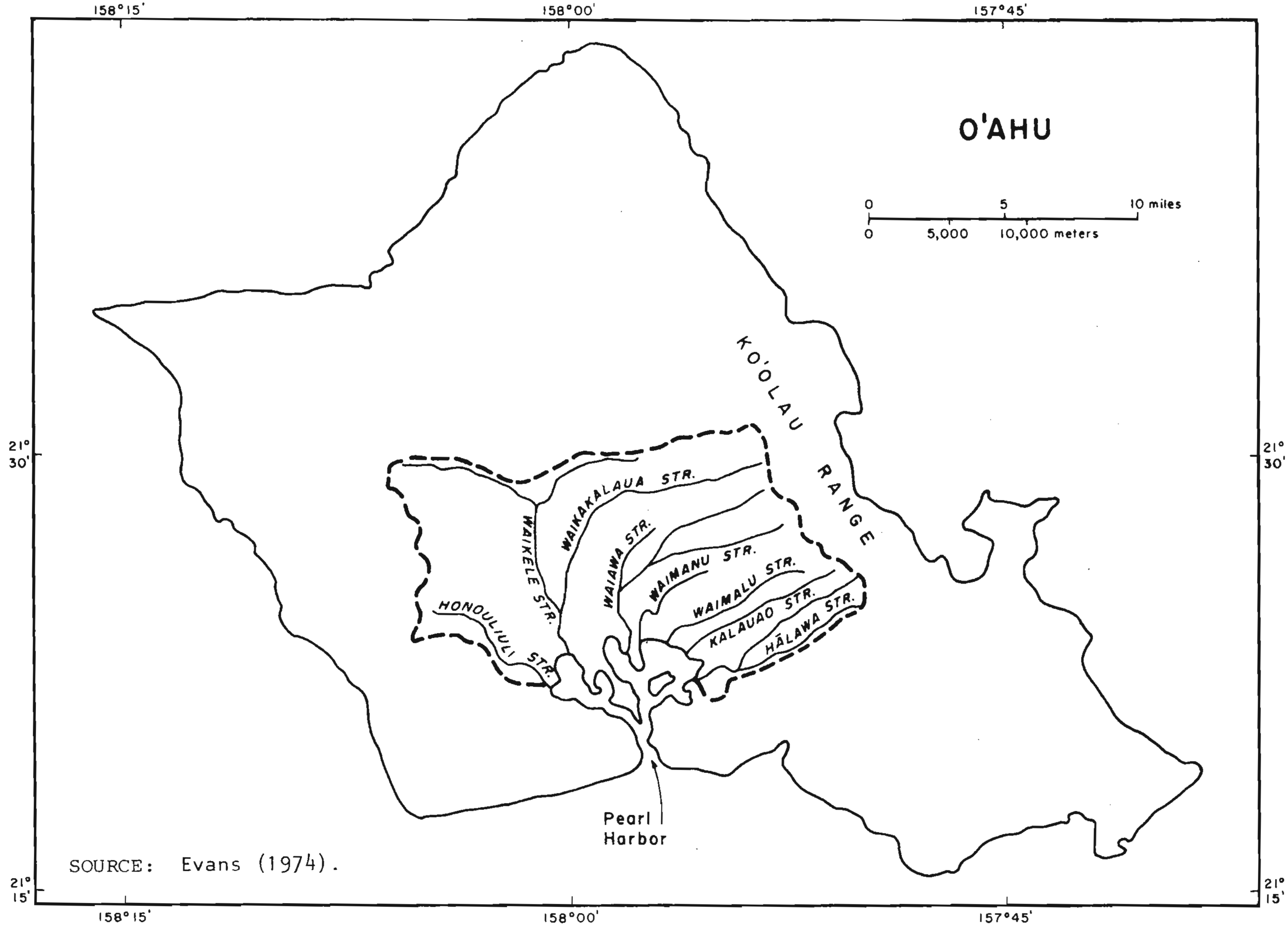
Hydrology

West Loch is an estuary with freshwater inflow from springs along its inland periphery as well as surface water. Waikele Stream is the primary



SOURCE: Evans (1974).

Figure 7. Major divisions and fresh water sources of Pearl Harbor, O'ahu, Hawai'i



SOURCE: Evans (1974).

Figure 8. Pearl Harbor drainage basin and major streams discharging into Pearl Harbor

surface water source flowing into West Loch. The Waikele Stream watershed is the second largest watershed on O'ahu. Of the 73 531.3 m (45.7 miles) of drainage area, about one-third is zoned forest reserve, one-third agriculture, and one-third military and urban uses.

The 25 yr average discharge (water years 1953-1959, 1961-1978) is 1.07 m^3/s (37.8 ft^3/s). The maximum discharge was 385.15 m^3/s (13,600 ft^3/s) on 28 November 1954, and the minimum flow was no flow for part of 25 February 1978.

Waikele Stream originates in the Wai'anae Range at an elevation of 784.86 m (2575 ft) above mean sea level, flowing eastward for about 12 872 m (8 miles) where it is joined by Waikakalaua Stream. The Waikakalaua Stream starts from the Ko'olau Range at an elevation of 817.17 m (2681 ft) above mean sea level and flows westward for approximately 25 744 m (16 miles) before joining Waikele Stream. From this juncture it flows southward an additional 16 090 m (10 miles) to its mouth at West Loch. A third tributary, Kīpapa Stream joins it within this segment.

A U.S. Geological Survey gaging station is located 804.5 m (½ mile) from the mouth of Waikele Stream entering West Loch and the area below the gaging station is called Waikele Spring. The average spring flow (June 1973-March 1978) is 0.56 m^3/s (12.7 mgd). The average chloride load was 68 to 120 ppm for the same period. Although there is no recent data, it can generally be assumed that the lowering of the head in the Pearl Harbor basin aquifer would greatly reduce the spring flow in this region.

Representative rain gage stations in the vicinity of West Loch were selected for review from the Division of Water and Land Development (DOWALD 1973*a*) report. The three stations were 746 (Apokaa), 747 (Field 62), and 752 (Waipio), whose average median was 587.50 mm (23.12 in.), maximum 1 108.20 mm (43.63 in.), and minimum 196.34 mm (7.73 in.) (Table 1).

Pan evaporation data (DOWALD 1973*b*) from eight stations adjacent to West Loch (Table 2) indicate that the mean annual evaporation is about 1 958.34 mm (77.1 in.). This cannot be directly applied as the potential evaporation from a large water body, such as West Loch. There is evidence that the pan coefficient of a Class A pan is about 0.7 (Winter 1981; Hounam 1961; USGS 1954; Kohler et al. 1955). Thus, the potential evaporation from West Loch is 1 370.84 mm (0.7 of 1 958.34 mm [53.2 in.]).

With annual evaporation of 1 371 mm and 587 mm annual rainfall, the

TABLE 1. MEDIAN, MAXIMUM, AND MINIMUM ANNUAL RAINFALL, WEST LOCH, PEARL HARBOR VICINITY

STATION NO.	RAINFALL Median (mm)	(in.)	Maximum (mm)	(in.)	Minimum (mm)	(in.)
746 (Apokaa)	541.02	21.3	1 140.46	44.9	198.12	7.8
747 (Field 62)	568.96	22.4	1 066.80	42.0	167.64	6.6
752 (Waipio)	652.78	25.7	1 117.60	44.0	223.52	8.8
Total	1 762.76	69.4	3 320.84	130.9	589.28	23.1
Average	587.50	23.13	1 108.20	43.63	196.34	7.73

SOURCE: Taliaferro (1959).

TABLE 2. ANNUAL MEAN PAN EVAPORATION, WEST LOCH, PEARL HARBOR VICINITY

STATION NO.	PAN EVAPORATION Annual Mean (mm)	(in.)	YEARS OF RECORD
732 (Reservoir 6)	2 290.32	90.17	1963-1968
737 (Reservoir 9)	2 120.39	83.48	1963-1968
738.4 (Field 155)	1 850.90	72.87	1964-1967
740.3 (Field 200)	2 035.81	80.15	1960-1963
740.4 (Kunia Sub-Sta.)	1 777.75	69.99	1963-1969
740.5 (Kunia Sub-Sta.)	1 608.07	63.31	1964-1969
741 (Ewa Mill)	1 890.27	74.42	1961-1968
751.2 (Rock Pile)	2 087.12	82.17	1963-1968
Total	15 660.62	616.56	
Mean Annual	1 957.58	77.07	

NOTE: Based on DOWALD (1973*b*) data.

net evaporation loss per year is 782.32 mm (30.8 in.). Thus, although unsuited to the characteristics of West Loch, a bag reservoir appears to be better suited to areas where evaporation exceeds precipitation.

The effects of brackish irrigation water on tropical soils has been investigated by El-Swaify et al. (1977) who found that the soils tested exhibited less tendency to accumulate detrimental sodium ions on the exchange complex than is known for temperate arid soils. The soils tested were representative of the area around West Loch, the primary irrigation area of the proposed project. The report concludes that the potential is promising for the supplemental use of saline waters for irrigation of tropical soils.

A study of water conditions in East and Middle Lochs (Evans 1974) may give insight into probable conditions in West Loch (App. D).

SUMMARY

The concept of storing fresh water in the ocean was investigated using a flexible impermeable membrane as the separating liner. Three basic methods examined were as a curtain, bag, and floating reservoir. Preliminary behavioral tests were first conducted in a glass-sided tank where underwater movements of the membrane could be readily observed.

Subsequently, a 1:400 scale model of West Loch, Pearl Harbor, a possible application site, was constructed to further test the methods. Various tests were run on the model, with emphasis on the single- and double-membrane curtain which seemed to be best adapted to the site. Simulated variables included the effects of inflow, tide, wind, and wave, and their various combinations. The double-membrane curtain appeared to be best suited for the West Loch application.

It should be emphasized that each method has particular advantages and disadvantages, listed in the report, which determines its applicability to any specific situation.

The second phase of initial pilot field testing was also conducted. Large bags, floating reservoirs, and curtains were constructed and deployed. After some modifications and refinements were made, they all functioned well. The bag was shaped like a bottle with a long inlet tube. This eliminated right angle stress points at the "shoulders" and "neck". The floating reservoir is a hemisphere with an inlet tube attached in the side. A U-shaped double-membrane curtain, containing a middle water-filled compartment was deployed in the field testing.

RECOMMENDATIONS

The possibility of storing stream water in the ocean using flexible, impermeable liners has been demonstrated. Based on the information derived from this study, the following recommendations are made.

1. A continuing systematic research and development plan needs to be formulated and implemented to attain the full potential usage of membrane water storage.
    a. In this R & D work, membrane selection should be done carefully. It is the key to the longevity of the structures.

   b. Low cost water transport using the bag should also be investigated in conjunction with storage.

2. With respect to West Loch as a possible reservoir site, the curtain appears to be the most appropriate of the three basic methods. It is able to capture and store normal flow and storm runoff from Waikele Stream as well as diffused submarine spring outflow along the bay's inland perimeter. The other methods cannot do this. There are, however, three important disadvantages:
   a. The potential evaporation loss is about 457 mm (18 in.) per year
   b. The amount of stored water which can be pumped out at any time is dependent on the amount of slack in the curtain, but the reservoir cannot be completely pumped out
   c. Considerable environmental impact will occur if West Loch is converted from its existing estuarine condition to a freshwater body.

CONCLUSIONS

The experimental evidence indicates that the bag, open reservoir, and curtain methods have potentials for field application. Each has its advantages and disadvantages which determine their applicability to any given situation. All require quiescent water bodies for deployment.

The bag is simple to fabricate and easy to deploy in the field. No flotation or anchoring system is required and there is complete water separation with no evaporation loss. The bag is limited by the need for unobstructed access to the inflow source for filling and sufficiently deep water directly offshore to preclude bottom dragging. Relatively little environmental impact occurs.

The open reservoir requires a flotation system but no anchoring device as the curtain method, making it intermediate in complexity between the bag and curtain. This method is simple to fabricate but more difficult to deploy than the bag because floats must be attached in the field. There is separation of water, but outside water can enter by wave overtopping. Also, evaporation losses will occur, but it can also catch rain falling into the enclosure. Like the bag, unobstructed access to inflow water is necessary, as well as to deeper water directly offshore to preclude bottom dragging. Relatively little environmental impact occurs. However, for most applications the bag appears superior to the open reservoir.

The curtain is the most difficult to fabricate and deploy, but has the greatest potential for application at West Loch because of prevailing conditions. The curtain can best capture and store storm runoff and diffused flows from submarine springs in the area, which the other methods cannot do. An obstructing mangrove growth at the Waikele Stream mouth and shallow nearshore water depths preclude the use of bags or open reservoirs. The major limitation of the curtain is that the quantity of water which can be pumped out of the reservoir at any time is governed by the amount of vertical slack in the curtain, an inherent characteristic of the structure. Underwater environmental impact is substantial because the seawater in West Loch will be displaced by fresh water. Despite its drawbacks, from a technical viewpoint, the curtain appears best suited for West Loch.

Selection of suitable membrane material is crucial to the success of a project. Since new materials are constantly being marketed, an up-to-date search is essential.

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APPENDIX CONTENTS

Figures

Tables

APPENDIX A. DETERMINATION OF MODEL SCALE FACTORS

Because the Pearl Harbor West Loch area is so vast, a geometrically distorted model (larger vertical scale than a horizontal one) was used for practical and economic reasons. Thus, accuracy in measurements, such as water surface elevations which would otherwise be immeasurable, could be obtained.

In establishing the model parameters, the length and depth scales were based on the available space in the laboratory. All other parameters were in proportion to these scales.

Since the dominating forces are due to gravity, the Froude number **Fr** in the model and prototype will produce a good approximation for dynamic similitude, as

$$Fr = V^2/gd$$

$$Fr_{model} = Fr_{prototype}$$

$$(V^2/gd)_{model} = (V^2/gd)_{prototype}$$

where

V = velocity (ft/s)
g = gravity (ft/s^2)
d = distance (ft).

The length scale (length and width) is proportioned by $R_l = H_p/L_m$. The depth scale is distorted because the depth is very shallow in comparison to its length, and therefore is proportioned by $R_h = H_p/H_m$.

Since the gravity g is the same for the model and the prototype, it can be eliminated from the reduced scale. Thus,

$$(V^2/d)_{model} = (V^2/d)_{prototype}$$

$$d_p/d_m = V_p^2\ V_m^2$$

$$V_p/V_m = (d_p/d_m)^{\frac{1}{2}} = (R_h)^{\frac{1}{2}} .$$

APPENDIX TABLE A.1. DERIVATION OF SCALING FACTORS

Parameter	Symbol	Equation
Length (width)	L	$L_p/L_m = R_L$
Depth	H	$H_p/H_m = R_H$
Surface area	S	$L_p/L_m = (R_L)^2$
Cross-sectional area	A	$\{[(L_p)(H_p)]/[(L_m)(H_m)]\} = (R_L)(R_H)$
Volume	Vol	$\{[(L_p)(L_p)(H_p)]/[(L_m)(L_m)(H_m)]\} = R_L^2 R_H$
Velocity	V	$V_p/V_m = \surd d_p/d_m = \surd R_H = R_H^{0.5}$
Discharge	Q	$VA = (R_H^{0.5})(R_L)(R_H) = R_L R_H^{1.5}$
Time	T	$T_p/T_m = (L_p/V_p)(L_m/V_m) = (L_p V_m)/(L_m V_p) = R_L R_H^{-0.5}$
Force (weight)	F	$F_p/F_m = [(\gamma_p H_p L_p)^2/(\gamma_m H_m L_m)^2] = R_H R_L$
		since $= \gamma_p = \gamma_m$
Pressure (head)	P	$P_p/P_m = H_p/H_m = R_H$
Roughness coefficient	n	$n/n = R_L^{-\frac{1}{2}} R_H^{\frac{2}{3}}$

where

R_L = length ratio

R_H = height ratio

subscript p = prototype dimension

subscript m = model dimension

SOURCE: Murphy (1950).

APPENDIX TABLE A.2. HYDRAULIC MODEL SCALE FACTORS

Parameter	Symbol	Scale (ft)
Length	L	1:400
Width	W	1:400
Depth (height)	H	1:24
Surface area	S	1:160,000
Cross-sectional area	A	1:9,600
Volume	Vol	1:3,840,000
Velocity	V	1:4.899
Discharge	Q	1:47,030
Time	T	1:81.65
Force (weight)	F	1:3,840,000
Pressure (head)	p	1:24
Roughness	n	1:0.416

APPENDIX B. STRUCTURAL CALCULATIONS

A. Data

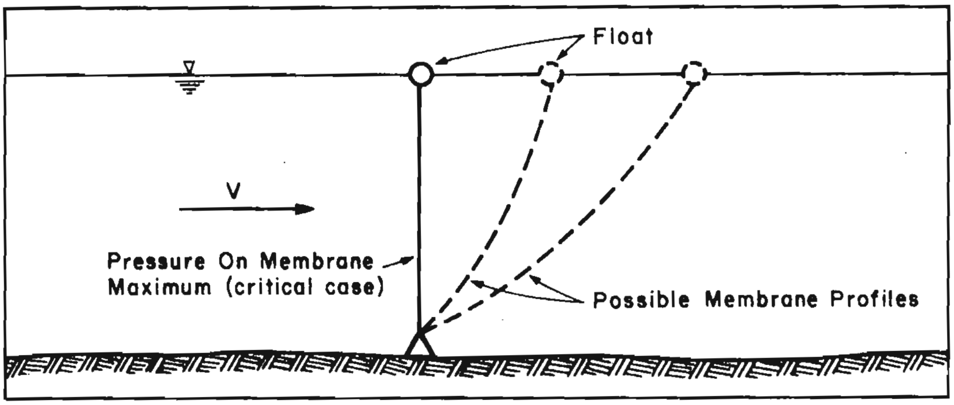
Maximum design inflow into reservoir	13,600 cfs
Volume of enclosure	66,800,000 ft^3
Surface area of membrane	20,000 ft^2
Span between abutments	3,500 ft

NOTE: Measurements based on positioning of membrane (App. Fig. B.1) and use of maximum recorded stream discharge.

B. Design Procedure

Since the discharge into the reservoir and the surface area of the membrane are known, the velocity of water at the face of the membrane may be approximated by

$$V = \frac{Q}{A} = \frac{13,600}{20,000} = 0.7 \text{ ft/s}$$



Appendix Figure B.1. Membrane curtain profile

To find the pressure on the surface of the membrane use the Bernoulli equation based on the following assumptions:

1. No change in the potential energy of the flowing water
2. No frictional losses.

The Bernoulli equation is

$$V^2/2g + P/w + z = V_1^2/2g + P_1/w + z_1$$

where as assumed previously, $z = z_1$ and $V_1 = 0$ since the velocity at the membrane face will be zero for the most critical case, and $P = 0$ since this is an open channel flow.

Thus, the equation reduces to

$$V^2/2g = P_1/w$$

$$P_1 = 1/2\ w/g\ V^2$$

where

$$V = 0.7\ \text{ft/s}$$

$$w = 64.0\ \text{lb/ft}^3\ \text{(seawater)}$$

$$g = 32.2\ \text{ft/s}^2$$

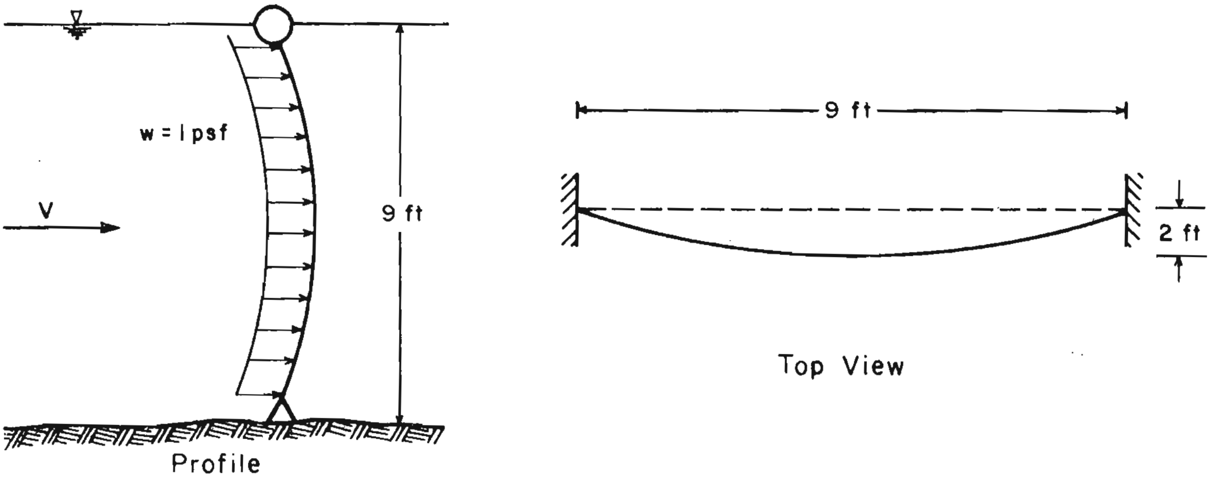
and therefore,

$$P_1 = 0.5\ \text{lb/ft}^2,\ \text{say } 1.0\ \text{lb/ft}^2.$$

This pressure will be assumed to be uniformly distributed over the entire membrane for ease of calculation.

C. Membrane analysis

Analysis of the membrane should be done at the maximum depth (i.e., about 2.7 m or 9 ft) in both directions, much as a cable structure subjected to an even, vertical dead load of 1.0 lb/ft^2 (App. Fig. B.2).



Appendix Figure B.2. Profile of vertical loading on 9 ft deep membrane and top view of 9 ft wide membrane

Since the height of the membrane is very small compared to its length, the stresses will be assumed to be acting principally in the direction of the length. Tension in the membrane can then be solved by treating it as a cable.

The height of the top and bottom ends of the membrane are assumed to be aligned and the maximum sag approximately 0.60 m (2 ft).

Solution:
$$y = a \cosh x/a$$
$$x = 4.5 \text{ ft}$$
$$y = 2 + a$$

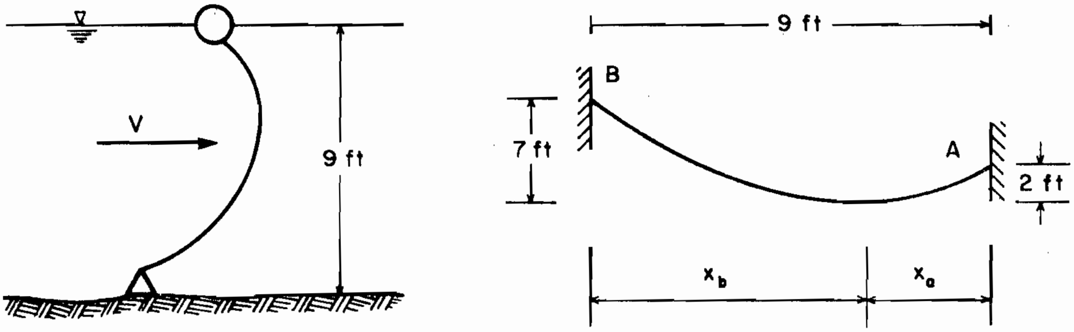
where "a" is constant found by trial and error.

$$(2 + a) = a \cosh 4.5/a$$
$$a \cong 5.35 \text{ ft}$$
$$y_c = 2 + 5.35 \text{ ft} = 7.35 \text{ ft}$$
$$T_{max} = w \times y = (1.00)(7.35) = 7.35 \text{ lb, say } \underline{8 \text{ lb}}$$

Length of membrane section

$$s^2 = y^2 - a^2 = (7.35)^2 - (5.35)^2 = 25.4$$
$$\text{Length} = 2\sqrt{25.4} = 10.1 \text{ ft}$$

Another case to be considered is when two ends of the membrane are not aligned (App. Fig. B.3).



Profile

Top View

Appendix Figure B.3. Profile and top view of a membrane with unaligned upper and lower edges

As an illustration, a typical case is when the top of the membrane attached to the float moves back 1.52 m (5 ft) relative to the bottom end and the sag is 0.61 m (2 ft) from the top end.

Solution:
$$y_a = 2 + a$$
$$y_b = 7 + a$$
$$x_a = 9 - x_b$$

from the catenary equation,

$$y = a \cosh x/a$$
$$(2 + a) = a \cosh x_a/a = a \cosh (9 - x_b)/a$$
$$\text{and } (7 + a) = a \cosh x_b/a$$

or $\cosh^{-1} (2 + a)/a = (9 - x_b)/a$

and $\cosh^{-1} (7 + a)/a = x_b/a$.

Combining the two yields

$$9/a = \cosh^{-1} (2 + a)/a \cosh^{-1} (7 + a)/a$$

and "a" again found by trial and error is about 3.1.

$$T_{max} = w(y_b) = 1(3.1 + 7) = 10.1 \text{ lb, say } 11 \text{ lb (at bottom end).}$$

Thus, by allowing the top end of the membrane to move relative to the bottom end, the tension in the membrane increases.

Length of membrane section:

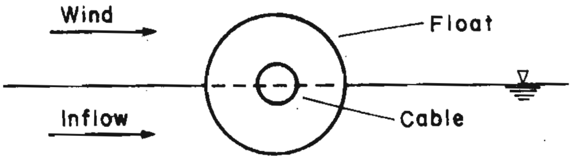
$s = (10.1)^2 - (3.1)^2 + (5.1)^2 - (3.1)^2 = 11.7$, say $\underline{12 \text{ ft}}$

D. Stresses on Main Cable Support

Load on cable due to flow of water

$$(9 \times 1)/2 = 4.5 \text{ lb/1in. ft}$$

For maximum effect of an 80-mph wind, direction is assumed to be in the same direction as the inflow (App. Fig. B.4).



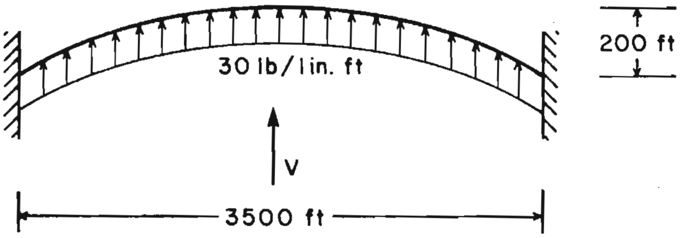
Appendix Figure B.4. Cross section of a float and cable subjected to wind and inflow from the same direction

A drag coefficient of 1.5 is assumed along with "1 ft^2" of float exposed over the surface per linear foot.

$P = 0.00256 V^2 = 0.00256 (80)^2 = 16.4 \text{ lb/ft}^2$

$F = C_D \times P \times A = (1.5)(16.4)(1) = 24.6$, say 25 lb/1in. ft

Total load on cable = 25 + 4.5, say 30 lb/1in. ft



Appendix Figure B.5. Top view of load distribution subjected to stress and drag forces

Solution: $y = a \cosh x/a$

$$x = 3500/2$$

$$y = 200 + a$$

$$200 + a = a \cosh 1750/a$$

$$a \cong 7675 \text{ ft}$$

$$Y_c = 200 + 7675 = 7875 \text{ ft}$$

$$T_{max} = WY_c = (30)(7875) = 236{,}250 \text{ lb}$$

$$\cong 236 \text{ k}$$

Length of cable: $S^2 = Y^2 - a^2 = (7875)^2 - (7675)^2$

$$= 3{,}110{,}000$$

$$\text{Length} = 2\sqrt{3{,}220{,}000} = \underline{3528 \text{ ft}}$$

E. Comments

Although the tension in the membrane was determined to be only 5 kg (11 lb), this should not be the only membrane strength requirement for the following reasons:

1. The computations are based on static loading conditions only and since the water will be continuously moving, a safety factor of 3 is recommended
2. Since the type of flotation system is not specified, additional buoyant forces will be transferred to the membrane
3. The type of shore and sea-bed anchors will greatly influence the buildup of stress concentrations at these points
4. Whatever the material, the membrane will creep or stretch with time under continuous loading; therefore, the creep rupture relationship for the material should also be considered.

SOURCES: ASCE (1979), Merritt (1976), Parcel and Moorman (1955), Streeter and Wylie (1975).

APPENDIX C. SOME EXISTING MEMBRANE MATERIALS

PVC (Polyvinyl Chloride). Offers good chemical resistance, sealability, and serviceability in unexposed applications; has performed satisfactorily as liner for recreational lakes, canals, evaporation ponds, sewage lagoons, and brine ponds. A provision for earthen cover is recommended for PVC to maximize service life.

OR PVC (Oil Resistant Polyvinyl Chloride). Provides additional resistance to petroleum products by a special formulation of PVC.

CPE (Chlorinated Polyethylene). Features excellent weatherability, sealability, chemical resistance and long term durability; does not require a cover material for most applications.

CPER (Reinforced Chlorinated Polyethylene). Offers all of the desirable characteristics of CPE and, in addition, provides greater strength and resistance to creep, sagging, and puncture where conditions of use are severe, such as steep slopes or other high stress applications.

Hypalon (Chlorosulfonated Polyethylene). Provides excellent resistance to weathering and chemical attack; has been used for potable water containment; is available only as a reinforced membrane and does not require a protective cover for most applications.

EPDM (Ethylene Propylene Diene Monomer). Used for many years for roofing and lining applications; most widely used single-ply roofing membrane in the United States because of superior weathering and elongation characteristics.

EPDM R (Reinforced EPDM). Has the superior weathering characteristics of the nonreinforced EPDM with additional strength and tear resistance required by some applications; many potable water reservoirs rehabilitated with EPDM R or Hypalon.

NYLON/NEOPRENE (Dupont). High-strength nylon fabric coated on both sides with Dupont Neoprene synthetic rubber (fabric acts as strength member while Neoprene makes it impervious and offers protection against deterioration); fabric specifically woven to offer high resistance to penetration by foreign objects; Neoprene resists weathering, temperature changes, ozone, chemical fumes, and abrasions, and inhibits growth of fungus and algae, is fire resistant, and usually not edible by animals; remains flexible, shock resistant, and durable.

APPENDIX D. WATER AND WIND CONDITIONS AT PEARL HARBOR

Pearl Harbor can be described as a two-layer-flow estuary with vertical mixing. Circulation between individual lochs and the main channel varies greatly. Thus, Pearl Harbor is considered as three very different embayments connected to a common main channel that leads to the Pacific Ocean. Where ship traffic is heavy, extensive channel dredging has carved rectangular bathymetric profiles 11 to 15 m deep. Other water areas are not maintained to such depths and some nearshore areas are shoaling with mangrove stands established. Heavy sedimentation of over 0.1 m/yr have been recorded, with materials transported primarily by streams draining the adjacent upland agricultural and urban areas.

The temperature and salinity characteristics are quite stable and similar to ocean values when below the thermocline. Streams and springs bring fresh water into Pearl Harbor, with about 30% of the total freshwater volume entering the harbor from the head of West Loch. The main thermocline and main halocline are normally at 1.5 to 5.5 m depths. The freshwater outflow of West Loch causes estuarine profiles along the western side of the main channel. Diurnal temperature ranges may exceed 2°C in the undisturbed shoal areas. Oil films in the harbor may also influence the net radiation balance and heat budgets.

The major mechanisms driving the circulation in Pearl Harbor include: tide, freshwater influx, mixing processes, wind stress, and the spatial and temporal derivatives of wind stress. Other factors are considered negligible or unable to obtain. Tides increase water depths in the harbor by about 0.6 m (2 ft) and cause oscillatory currents under a generally constant surface outflow caused by freshwater inflow. Tidal current reversals occur when the tide peaks at high and low tides. Currents in Pearl Harbor are generally almost parallel to the shoreline.

The winds tend to follow the channels. Under prevailing northeasterly tradewind conditions, wind-induced currents in North Channel, in the entrance to Middle Loch, and in the South Channel are normally strongest and set toward the harbor entrance. The high relief of the harbor shorelines cause marked cross-channel differences in wind velocity and induced current

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SOURCE: This material from Evans (1974).

velocity. Currents on the upwind side of the channel are often opposite to those on the downwind side. With a continuous cross-channel wind, the surface water moves across the channel and outward. Cross-channel flows are usually about 20% of the outward surface flows. With a high enough wind velocity, the continuous wind stress can tilt the thermocline and halocline such that the boundary between the two water layers may contact the water surface. Surface flows are compensated by upwelling along the upwind side of the channel. The mean maximum surface current is about 0.2 m/s and the mean maximum lower layer current is about 0.05 m/s.

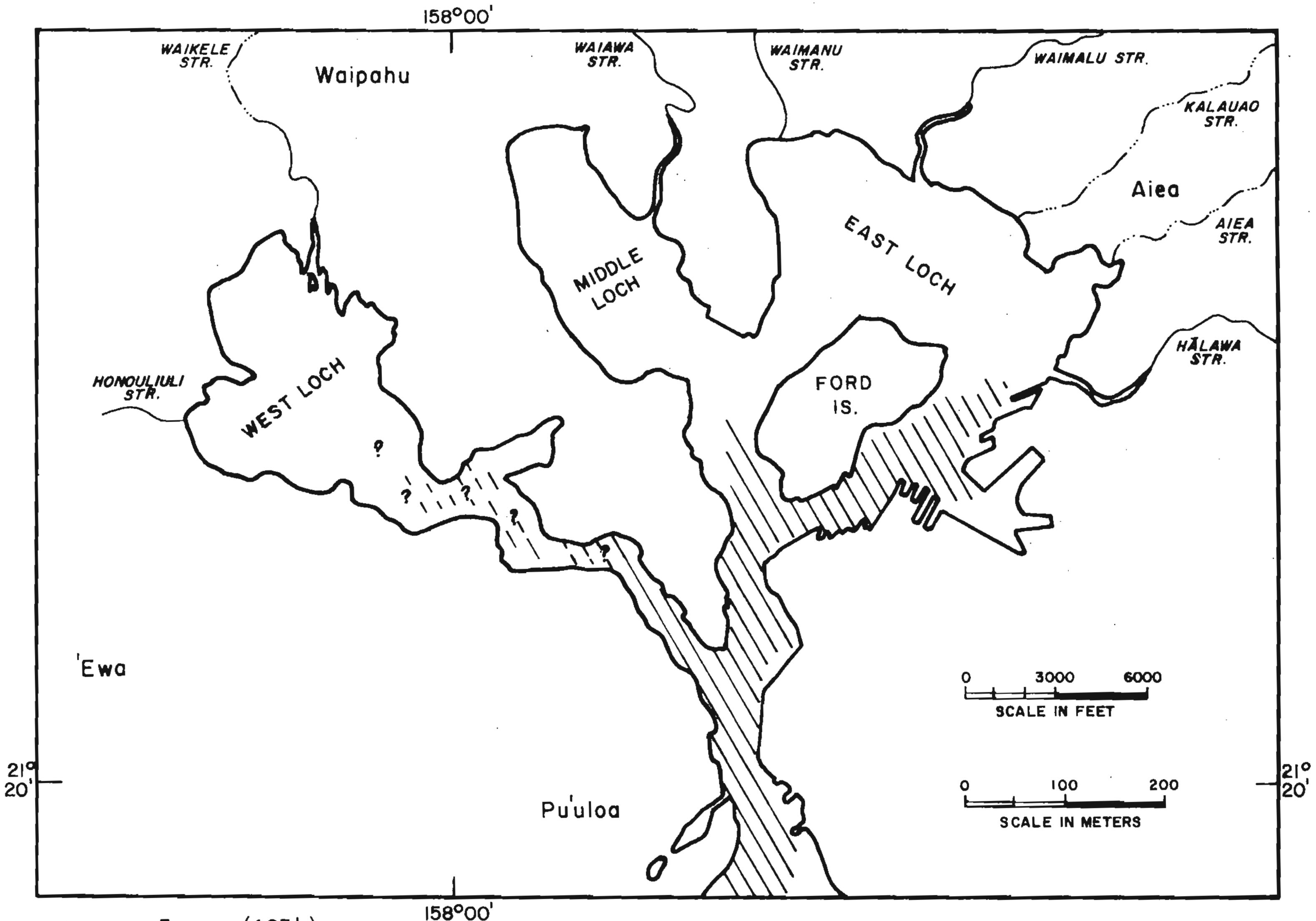
With decreased vertical stratification, usually during the winter, wind derived currents (caused by changes in wind speed or velocity differences between two locations) can be several times stronger than tidal or normal wind stress currents. Wind derivative current velocities as high as 0.3 m/s have been recorded.

The mixing in Pearl Harbor is determined by the vertical stability of the water column, winds, tides, and the movement and positioning of surface craft. The water column stability determines the mixing efficiency of the various driving mechanisms. The elevated temperatures and freshwater influx in the surface layers generally increase the stability. However, winter solar heating of the upper layer decreases the stability of the water column when the cooler stream inflow interacts with the warmer harbor water. Tides and winds result in classical estuarine mixing, but ship movements cause mixing in areas of heavy ship traffic. Wind driven upwelling may also be an important mixing device.

Driving Mechanisms

Pearl Harbor is affected by several major forces: tide, freshwater influx, seawater influx, various mixing processes, wind stress, and temporal and spatial derivatives of wind stress. Other factors include net radiation balance and heat budget for the harbor, surface water evaporation, and wind build-up on the shelf off the harbor entrance. Factors such as tsunamis and hurricanes may be important on very rare occasions.

TIDE. Very little tidal action occurs throughout most of Pearl Harbor and tidal flushing is appreciable only near the harbor entrance (App. Fig. D.1). Thus, tidal variation is projected to be rather insignificant within the confines of West Loch.



SOURCE: Evans (1974).

Appendix Figure D.1. Region of major tidal currents

FRESHWATER INFLUX. The inflow of fresh water into a semi-enclosed body of water results in a special kind of estuarine circulation. With moderate mixing effects, a seaward flow occurs in the surface water layer (App. Fig. D.2), which has a relatively low salinity; and a landward flow occurs in the bottom layer, which contains ocean water of higher salinity. This two-layer flow with vertical mixing is caused by the more buoyant freshwater layer floating on the seawater layer. The force of the inflow carries the floating surface water out to sea. Tidal currents bring in the bottom, lower layer. Considerable mixing between the layers may occur depending on the wind, waves, temperature, and ship activity.

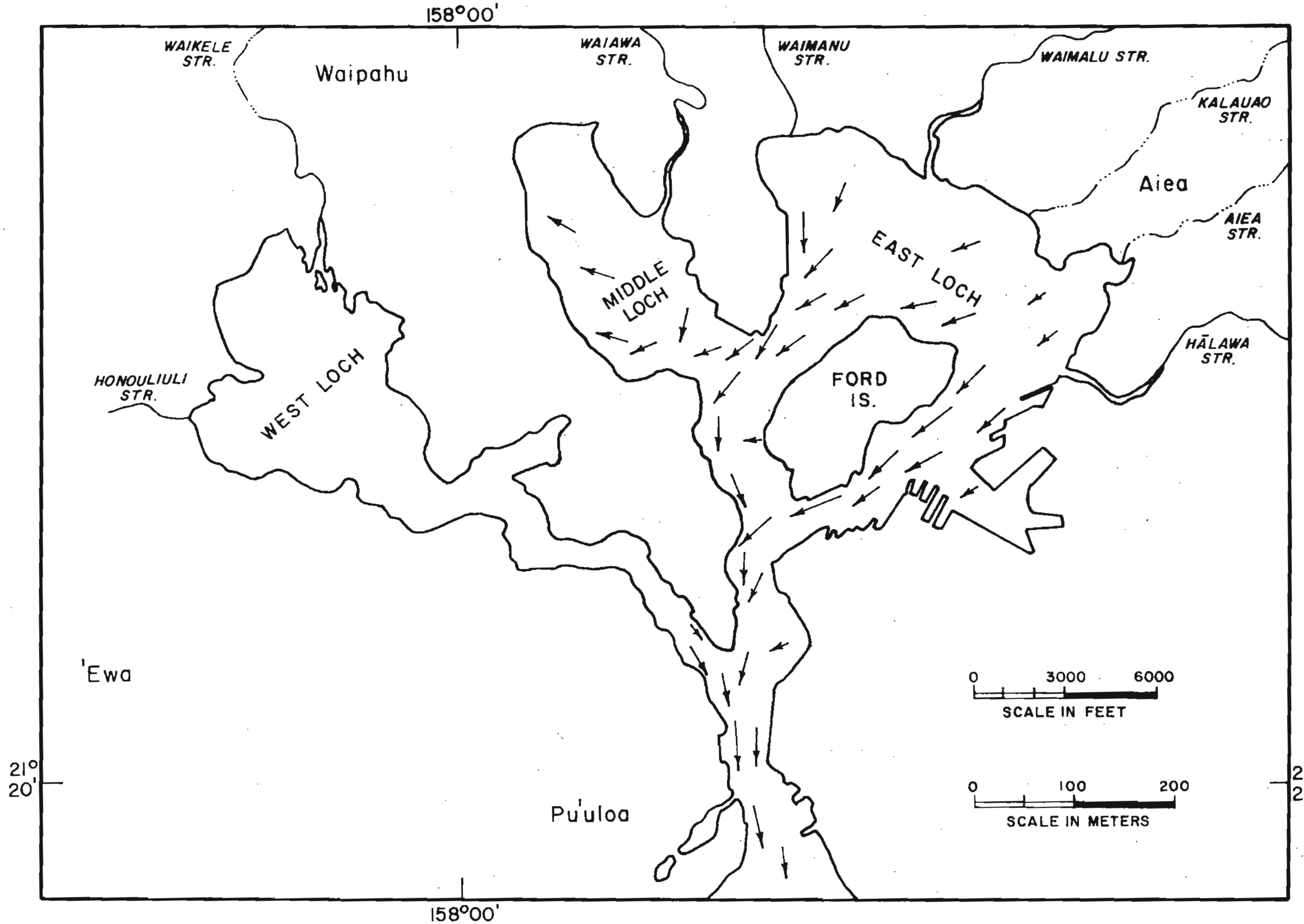
SEAWATER. Seawater and mixing processes are important driving forces in characteristic estuarine circulation. The seawater entering Pearl Harbor originates from the upper, mixed layer of the North Pacific Ocean. During 1972 to 1973 surveys, the maximum values of temperature and salinity of the seawater (associated with fall heating and evaporation) were respectively about 26.6°C and 35.2‰; mean values were about 24.5°C and 34.5‰.

By the conservation of water mass for a harbor, the volume rate of seawater inflow is calculated to be the outflow of the surface layer minus the freshwater influx. For a normal year, the influx of seawater into Pearl Harbor would be about 200 m^3/s.

The seawater moves in the bottom layer towards the lochs, where it is diluted with the fresher surface water layer by vertical mixing. While this is occurring, the surface water layer, containing the freshwater streamflow and some seawater that has mixed into the surface layer, is flowing out to sea. There are basically two layers: the upper layer, containing mostly fresh water; and the lower layer, containing mostly seawater. Mixing occurs between the layers, with the surface layer being diluted with salt water, and the lower layer being diluted with fresher water. This mixing depends on the mixing mechanisms of wind, waves, temperature, and ship activity.

MIXING. The presence of fresh and seawater, a set of driving forces, mixing, and solid boundaries which contain the interactions determine the physical properties of an estuary. The mixing processes include both processes which act as driving forces, i.e., ship-induced mixing, and processes which stem from primary driving forces, i.e., tidal mixing.

The effects of tides, winds, waves, and ship movements produce verti-



SOURCE: Evans (1974).

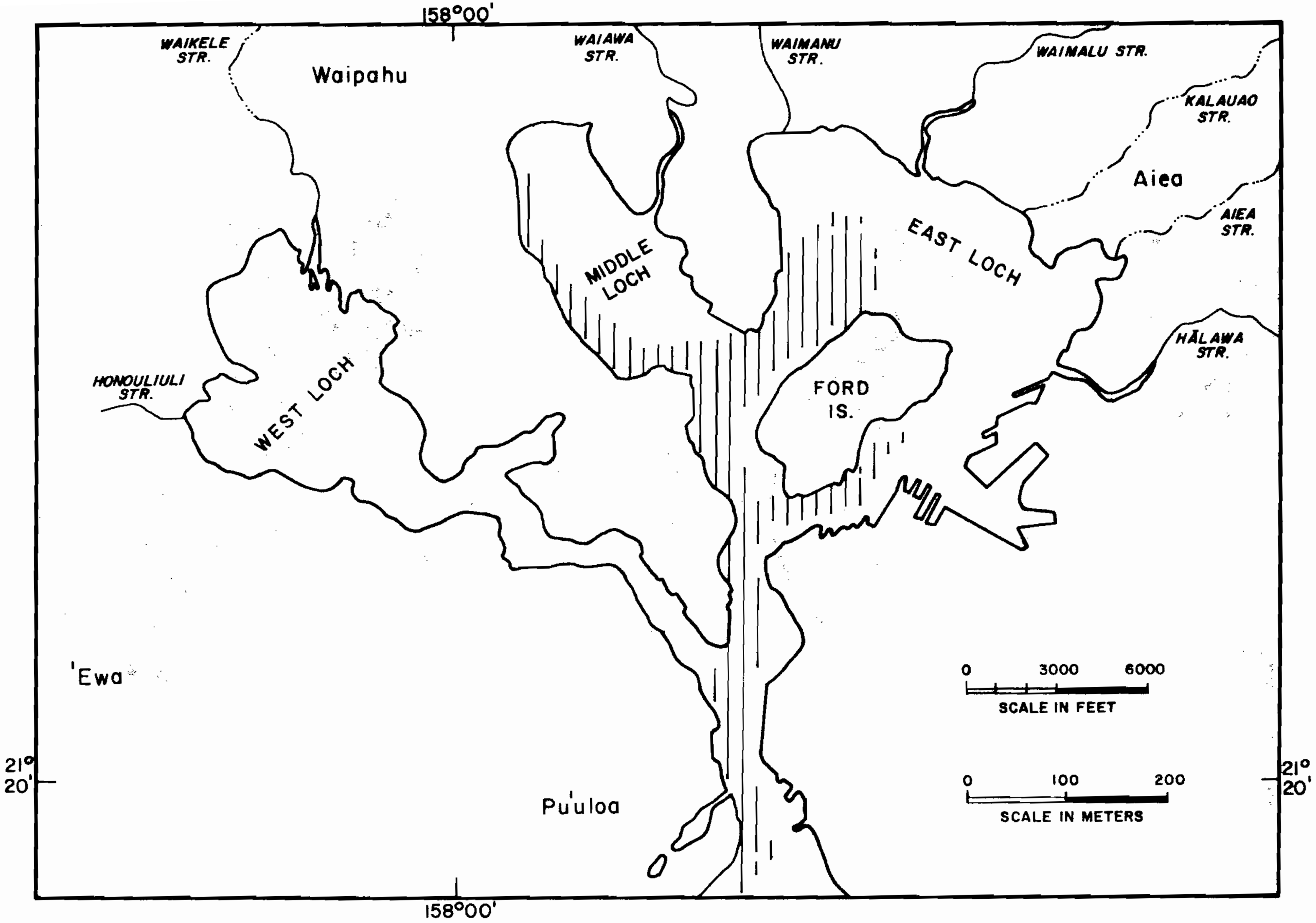
Appendix Figure D.2. Surface water circulation pattern cal and horizontal mixing. Ship traffic is important in some areas of Pearl Harbor which include the Main Channel and East Loch; some areas such as West Loch are only minimally affected. The tide produces classical mixing through out most of the harbor. The northeast trade winds, with the wind stress acting on the water surface, produces a surface movement, vertical mixing, and a possible tilt of the interface between the surface and lower layers. Wave action is at a minimum because of refractive losses at the entrance to the harbor. Local wind-generated waves are present at heights of less than 0.3 (1 ft) and periods of less than 5 s.

WINDS. Wind stresses and their variations acting on the water surface cause most of the vertical mixing and some horizontal circulation in Pearl Harbor (App. Figs. D.3, D.4). The normal trade winds of 4.0 m/s from 70° east-northeast produce a wind-induced current in the surface layer in the direction of the wind, and a weaker return circulation in the lower layer opposite the wind.

The channels and loch of Pearl Harbor are surrounded by abrupt shores, trees, and buildings which affect the velocity and direction of the wind. Therefore, surface-wind velocities vary greatly, especially in channels and areas close to shore (App. Fig. D.5). Wind stress is great in large spans of water surface. Wind also tends to follow the narrow channels because of the corridor formed by the shoreline. Wind stress in short spans of water have a lesser influence.

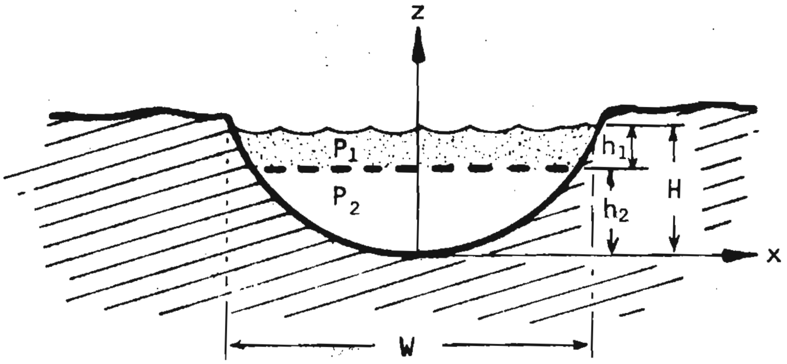
The dominant spatial variation in wind is associated with the development of a sea breeze in the afternoon on sunny, warm days. These usually light sea breezes only weaken the trade winds near the harbor entrance. However, the sea breezes occasionally develop sufficiently to overcome the trade winds entirely near the harbor entrance. This causes the trade winds to prevail in the upper reaches of the harbor and produces southerly winds near the entrance.

Wind stress causes the thermohalocline (the boundary between the upper and lower water layers) to tilt (App. Fig. D.4). If the wind is coming from the northeast, the southwest end of the harbor will show a deepening of the thermohalocline, with the northeast side showing a rising of the thermohalocline. As the degree of thermohalocline depression increases, a compensating buoyant force, which opposes further convergence of the lighter upper-layer water, is developed. When the winds and breezes stop, a reverse

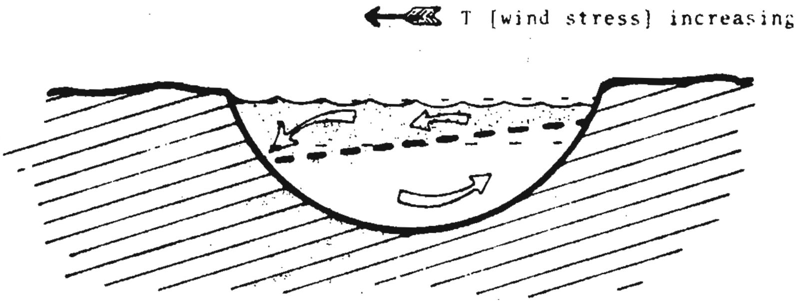


SOURCE: Evans (1974).

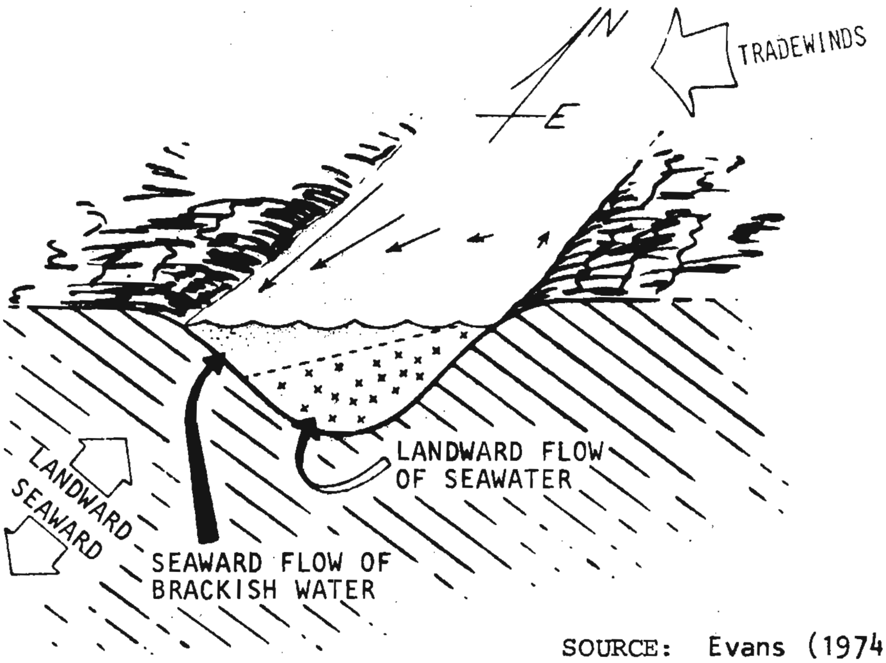
Appendix Figure D.3. Region of major wind-driven currents, Pearl Harbor, O'ahu, Hawai'i



Simple basin with two liquids, no wind stress

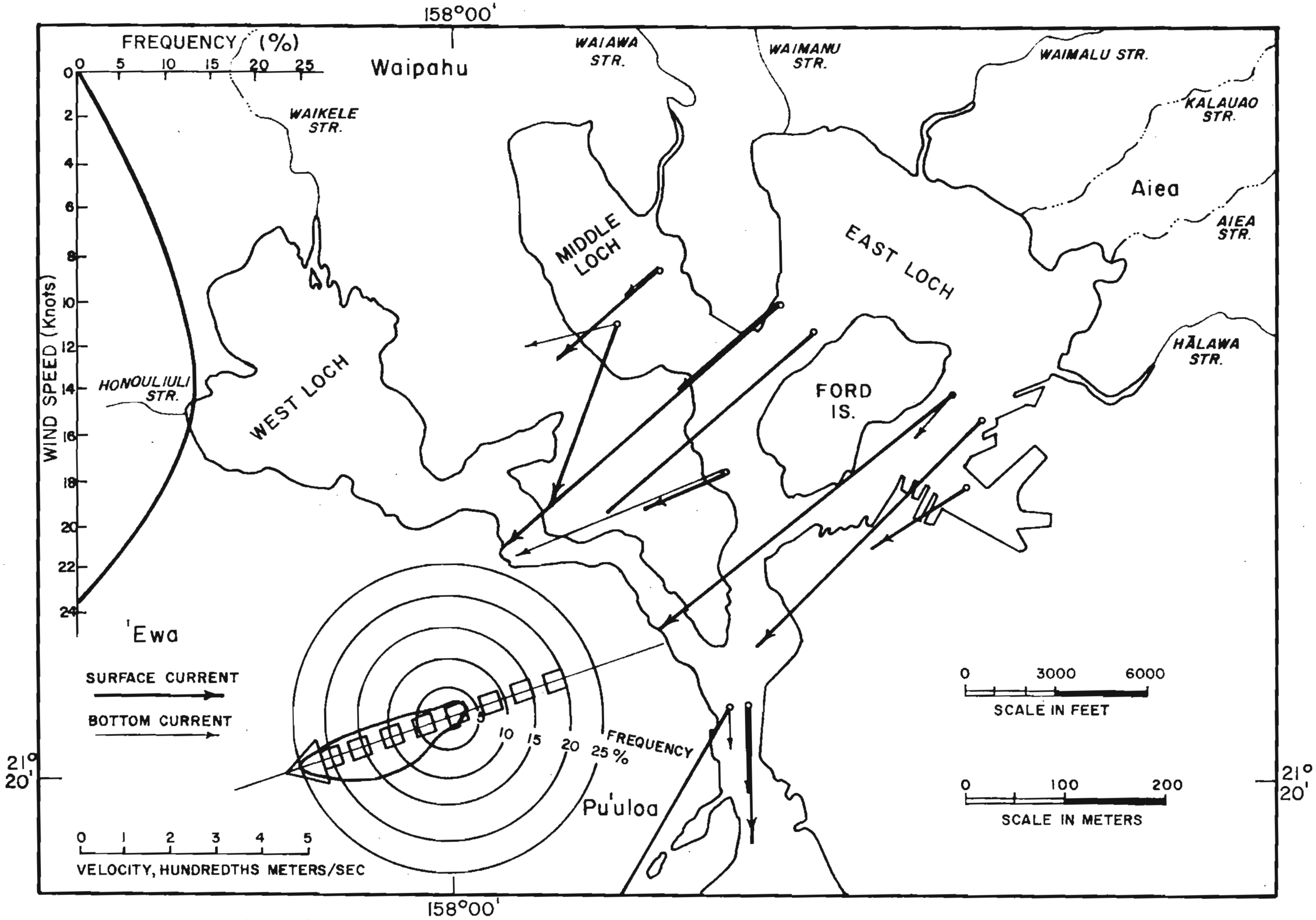


Case of increasing wind stress; arrows indicate circulation; light dashed lines indicate levels of free surface and interface



SOURCE: Evans (1974).

Appendix Figure D.4. Typical flow pattern in main channel under tradewind conditions; arrows indicate directions and intensities of currents at 1 ft depth



SOURCE: Evans (1974).

Appendix Figure D.5. "Wind-driven" model circulation of Pearl Harbor, O'ahu, Hawai'i flow is encountered to level off the thermohalocline again.

WATER MASSES. The waters of Pearl Harbor are a mixture of fresh water from runoff and rainfall with that of seawater. The Ghyben-Herzberg principle applies, wherein the lighter freshwater surface layer floats over the denser seawater bottom layer. Mixing occurs between the two layers with increasing salinity with depth. Within Pearl Harbor, there are generally two layers: a mixed upper layer, and a lower layer which resemble nearshore ocean waters. The lower layer moves inward from the ocean and the upper layer moves outward to sea.

The various springs in the upper reaches of the harbor also contribute fresh water to the harbor; however, because of the recent decline in the aquifer's freshwater head such contribution may be diminishing.

General Conclusions

1. The circulation of Pearl Harbor is driven by wind stress, temporal changes in wind stress, tide, ship-induced turbulence, and freshwater influx. The effect of these driving forces depend on the location in Pearl Harbor.
2. The currents in the upper layer of the harbor are generally directed oceanward, with speeds ranging up to about 0.3 m/s (0.6 knot). The circulation of the lower layer is more variable and weaker, usually moving inwards. Tidal currents are strongest at the entrance to the harbor and decrease farther in the harbor. The mean tidal current speeds are less than 0.5 m/s. Flows in Pearl Harbor tend to be cyclonic (anticlockwise).
3. Residence times indicate that contaminants in the surface sediment layer will be eliminated most rapidly from Pearl Harbor.
4. The general appearance of the water in Pearl Harbor is improved by moderate ship activity which enhances the mixing processes and thus reduce the residence times for the bottom layer waters. South Channel and Southeast Loch, areas of heavy ship traffic, have improved water conditions caused by the stirring up of the bottom layer and sediments. However, West Loch has limited ship movement and therefore limited mixing by this means. Areas with little mixing will have a fresher upper layer with less salinity.