The Water Balance Relationship Among Rodeo Tidal Lagoon, its Watershed, and the Ocean

Rodeo Lagoon is located ten miles north of San Francisco in the Golden Gate National Recreation Area. The 35-acre lagoon is separated from the ocean by a 500 foot wide beach for most of the year. In a normal year, Rodeo lagoon is joined to the ocean for three or four weeks during the winter, when floods in the watershed cause the lagoon to overtop its barrier beach. At this point an inlet channel forms, bringing water in and out of the lagoon with the tide until waves again build up the barrier beach. This breaching is critical to maintaining the health of the lagoon because it flushes the lagoon water out, keeps the temperature and salinity of the water at appropriate levels, and allows fish passage (Madej 1989).

The water quality in the lagoon is currently poor. This is of concern for three main reasons: several endangered species live in or around the lagoon, it is an important stop for migratory birds, and thousands of visitors come in contact with the lagoon each month. It is probable that the poor water quality in the lagoon can be partially attributed to the lagoon breaching less often than it did historically (Brown 1993). This phenomenon is not uncommon along the California coast. According to Goodwin (1996), alterations in the watershed as well as the diking off of regions of the lagoon have compromised the stability of many inlet channels along the coast of California over the last century. As a result of development in the area by the military during World War Two, both of these conditions are present at Rodeo lagoon.

According to Ranasinghe (1998), the major influence governing the stabilization of inlet channels is the streamflow through the lagoon. In order to understand the current hydrologic situation in Rodeo lagoon better, I have characterized the water balance in the lagoon during the dry season when the lagoon is isolated from the ocean. I used the volume of inflow to the lagoon from the watershed above (2, 856.7 ft2/6hrs, measured by Oerter 2003), estimated the volume lost to evapotranspiration (2,618 ft2/6hrs), and estimated the volume seeping through the beach (between 2,071.6 ft2/6hrs and 2,071,600.0 ft2/6hrs). In these late dry season conditions, where the rate of outflow from the lagoon exceeds the rate of inflow, pollutants are progressively concentrated in the lagoon as its volume decreases until the beach is breached and tidal exchange with the ocean through the inlet channel restores water quality in the lagoon. The information gathered in this project may be used to investigate further the potential for establishing a stable inlet channel.

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Problem Statement

Rodeo tidal lagoon is located ten miles north of the city of San Francisco along the Pacific Coast. It is part of the Golden Gate National Recreation Area. The National Park Service has identified Rodeo Lagoon as a site in need of restoration primarily due to poor water quality in the lagoon. Studies conducted by the USGS (1989) have identified silt, algae blooms, and heavy metals as the primary pollutants. Elevated temperatures and changes in the salinity of the water also contribute to the poor water quality. The health of the lagoon is of particular concern because it is home to a number of rare and endangered species and is an important stop for migratory birds. Additionally, thousands of visitors a month come in contact with the lagoon and the beach that separates it from the ocean (See Fig. 1 for a photo of the site and Fig. 2 for a map of the site).

The 35-acre lagoon is cut off from the ocean by a 500-foot wide beach for most of the year. In a normal year, it is joined to the ocean for three to four weeks during the winter, when floods in the watershed cause the lagoon to overtop its barrier beach (Zucher 2003). At that point, an inlet channel forms, bringing water into and out of the lagoon with the tide until the flood subsides and waves again build up the beach, isolating the lagoon from the ocean. This breaching of the beach is critical to maintaining the health of the lagoon because it flushes the lagoon water out, keeps the temperature and salinity of the water at healthy levels, and allows fish passage.

It is probable that the poor water quality in the lagoon can be partially attributed to the lagoon breaching less often than it did historically. This phenomenon is not uncommon along the California coast. According to Goodwin (1996) alterations in the watershed as well as the diking off of regions of the lagoon have compromised the stability of many inlet channels along the coast of California. As a result of development in the area, both of these conditions are present in Rodeo lagoon. During WW2, the area was developed by the military because of its strategic location near the mouth of San Francisco Bay. Over the years, development of the site included the construction of roads back and forth across the watershed that drains to Rodeo lagoon and the installation of a weir cutting off a region of the upper lagoon from the lower. This body, called Rodeo Lake, was constructed to provide a reservoir of fresh water for emergencies (Brown 1993).

However, Rodeo Lagoon is in keeping with many tidal inlets along the California Coast, which are only open seasonally. They are a common feature in wave-dominated regions where streamflows are highly seasonal. According to Ranasinghe (1998), the major influence governing the stabilization of inlet channels is the streamflow through the lagoon. In assessing restoration opportunities at Rodeo Lagoon, it is necessary to resolve to what extent the poor water quality is attributable to the afore mentioned alterations to the watershed and diking off of Rodeo Lake, and to what extent the pollution would be present without these changes.

To that end, it is necessary to develop an understanding of the natural physical processes specific to this site. The result of this study will be incorporated into a larger thesis project being undertaken by David Shaw to develop a comprehensive assessment of the factors contributing to the poor health of Rodeo lagoon and the watershed that drains into it. The objectives of my study were to characterize the dynamics of the water balance among Rodeo Lagoon, the base-flow runoff from its watershed, and the Pacific Ocean as they exist in October, during the late dry season.

I have chosen the late dry season as an appropriate time for this study because it represents the hydrologic system during its most static period, before the winter storms, which is when the pollution is most concentrated. At this time, the two creeks draining the watershed, Rodeo Creek and Gerbode Creek, are at their baseflow levels and the inlet channel is closed. I have further limited the factors influencing the hydrologically dynamic relationship between a tidally influenced body and one that is not by limiting my calculations to a six- hour period, which is meant to represent one out-going tide cycle.

Methods of Analyzing Water Balance in Rodeo Lagoon

Backround Research

I began my investigation of the character of Rodeo Lagoon by surveying the existing literature on the matter. I found several helpful papers in a special edition of *The Journal of Coastal Research* (1996) devoted to the subject of "Understanding Physical Processes at Tidal Inlets". Because the site is under the auspices of the National Park Service, I also found useful information from several investigative reports conducted by various government agencies specifically about the current state of Rodeo Lagoon. Most applicable to my calculation of the water balance in the lagoon was a bathymetric survey of the lagoon (Zembsch, 1993). I also gathered information from David Shaw who conducted a personal interview with Dan Zucher, who works at the Marin Headlands Institute office on the site. From him, I learned valuable information about the conditions in the watershed and lagoon over the course of the year. Finally, I studied a USGS

1:24,000 topographic map of the area to understand the extent of the watershed and the extent of the development in the watershed.

Gathering Data at the Site

I spent day one of my field-work walking around the Rodeo Creek Watershed with two other classmates whose projects are closely related to mine. The work of my classmate, Eric Oerter, was directly related to mine. He measured the volume of flow in the two creeks that flow into Rodeo Lake, Gerbode Creek and Rodeo Creek. I considered this combined volume, as Eric determined it with a flume and flow meter, to be the total inflow to Rodeo lagoon, assuming that the flow into Rodeo Lake was equal to the flow out the other side of the lake through the weir. Another classmate, Raymond Constantino's project was to estimate the amount of sediment lost because of erosion resulting from road construction. His study is of tangential relationship to mine because it involves one of the factors contributing to the poor health of the lagoon: silt. I also scouted out the places that would be most appropriate to survey in order to obtain a good estimate of the dimensions of the beach.

On the second day of fieldwork I surveyed the beach, including the dry inlet channel (See Fig. 3 for photos of the survey). For this I used an automatic level and rod, establishing a dummy benchmark on a large rock perched on the terrace just above the sandy beach. I took four cross-sections along a tape laid along the length of the beach between the two headlands that clearly flank the beach. Because the beach is only 1705 feet long, I was able to use only one turning point throughout the survey (See Fig. 4 for a diagram of the cross section locations. See Fig. 5 and Fig. 6 for the cross sections).

For consistency, the water surface of the ocean, designated as zero feet on the cross section, was roughly estimated to be at the point the waves rushing up the beach met the waves rushing down the beach. The other major factor complicating the cross sectional survey of the beach was the fact of the tide moving out during the course of the survey. When I began the survey at noon, the tide was at the day's highest. By the end of the 6-hour survey the tide was reaching its low point. I chose to use this low tide condition to establish the difference in head between the surface level of the lagoon and that of the ocean.

I applied Darcy's equation,

V=k(h2-h1)/ L, where k equals the hydraulic conductivity of sand, h2-h1 equals the change in head, and L equals the distance the distance of travel

to determine the rate of flow out of the lagoon through the beach. The distance between the lagoon and the ocean was taken from the survey of the cross sections, dividing the beach into sections assigned a given width according to extrapolation from the cross sections applied in conjunction with an ariel photograph showing the edge of the lagoon and sketches and notes taken during the survey. To apply this equation it was necessary to look up the hydraulic conductivity of sand (Driscoll 1986). I applied the calculations for both fine grain and coarse grain sand to account for the range of conductivity and presented my findings as a range.

The next step I took in arriving at the volume of water leaving the lagoon through the beach was to analyze the bathymetric survey to determine the average depth of the lagoon, which I multiplied by the width of the beach, as I had determined in my survey (See Fig. 7 for the bathymetric survey). I then divided this area up according to the different areas I had designated when applying Darcy's equation. Finally, I multiplied the results of Darcy's equation by the various areas. I then added these results together to arrive at the total volume water seeping through the beach.

In order to account for the other major loss of water from the lagoon, I looked up the average rate of evapotranspiration as given on a web site, (www.cimis.water.ca.gov). I designated the exact location of Rodeo Lagoon on a map of the bay area showing different zones of evapotranspiration rates. The map was specifically for the month of October. I then multiplied this rate, 2.48 inches per month, by the surface area of the lagoon, which I determined by overlaying the scaled bathymetric survey on a grid and counting the squares at or below the surface level of the lagoon (See Fig. 7 for the bathymetric survey).

In order to simplify the dynamic element of the fluctuating tide when assessing hydrology near the ocean, I calculated all of my volumes over a six-hour time frame in which I assumed the tide was going out (See Fig.8 for a diagram of the water balance).

Results and Discussion

- From Erik Oerter's study (2003), I know that 2, 856.7 cubic feet per six-hour period were flowing into Rodeo Lagoon.
- I estimated that 2, 618.2 cubic feet per six-hour period were being lost from the lagoon through evapotranspiration.
- I estimated that between, 2,071.6 and 2,071,600 cubic feet per six-hour period were seeping out of the lagoon through the beach.

(See Fig. 8 for a diagram of the water balance in the lagoon)

Because the focus of my project changed somewhat between when I gathered the data and applied the data to draw conclusions there are several things I would have done differently if I had it to do over in order to obtain data more suited to my analysis. Firstly, I would have focused less on the geometry of the inlet channel and more on getting a more complete survey of the width of the beach between the lagoon and the ocean. At the time I gathered the data it was my thought that I would go beyond describing the water balance to determining the ideal stabilizing geometry of the lagoon and channel in order to keep the channel open to the ocean for most of the year. It became clear in the course of the project that figuring that out required more of an understanding of tidal hydrology than I have and also that I would need a bathymetric survey of Rodeo Lake to determine how it would alter the situation were it reconnected to the lagoon.

Considering the vastness of the range between the hydraulic conductivities of sand, it would have been very useful to come to a more specific understanding of the sand in the beach by performing a percolation test or taking core samples or some other means.

Recommendations

For future work at this site, I have several recommendations. Firstly I would recommend a bathymetric survey of Rodeo Lake and an assessment of the sediments in it along with an assessment of the weir to determine how soon and what effect the removal or failure of the weir will have on the lagoon. In that event, I think it is important to asses how damaging the contents that have been trapped behind the weir will be when they are released into the lagoon. Even the concentration of fresh water could act as a pollutant to the flora and fauna accustomed to the brackish water of the lagoon (Madej 1989).

Along that same line, I think an analysis of how that added volume in the lagoon, were the weir to be removed, would affect the time the channel stayed open in the winter would be interesting. It seems likely that the weir between the upper lagoon and the lower has dampened the surge of fresh water flowing down the watershed during rain events, thereby robbing the lower lagoon of the volume it requires to breach the beach.

Ultimately, it is likely that establishing a stable inlet channel to ensure regular flushing of the lagoon by the tide could improve the health of the lagoon. The information gathered in this project may be used to investigate further the potential of restoring the conditions in the lagoon to achieve a stable inlet channel.

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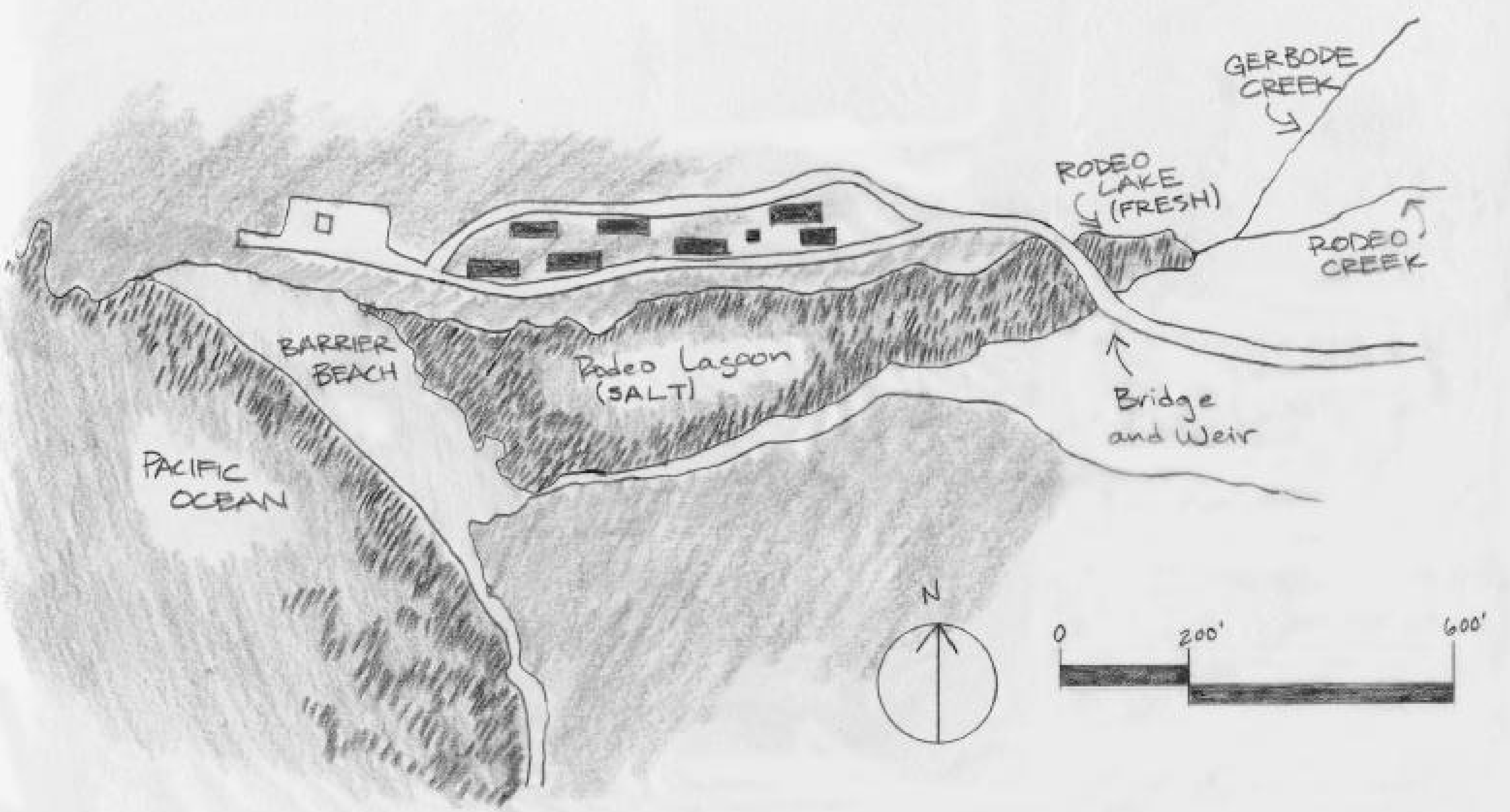
Fig. 1: Overview picture of Rodeo Lagoon (looking north). Inlet channel periodically forms across furthest section of beach. Cross section surveys start at that end, the fourth cross section being at the foot of the hill I am standing on.

Fig. 2: Map of site.

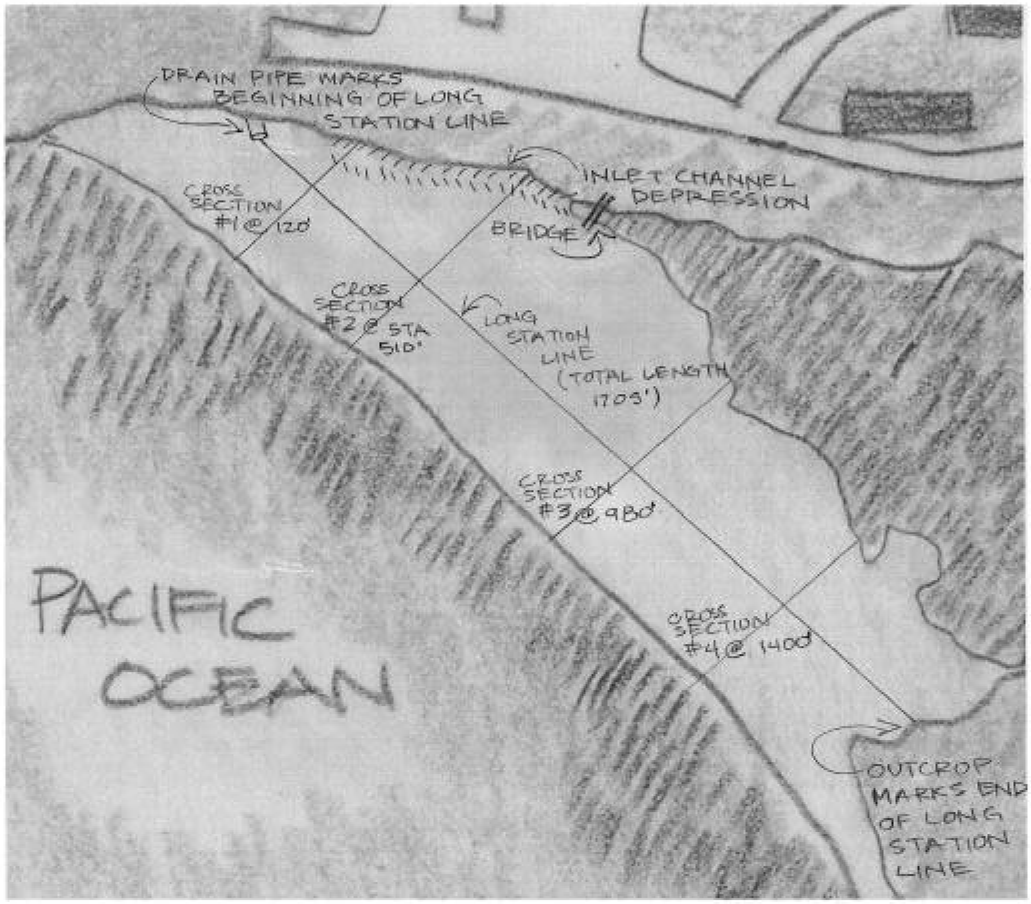


Adapted from USGS topographic 7.5 minute map (2001).

Fig. 3: Surveying third cross section from turning point on ridge of beach. Lagoon and watershed in background.

Dave Shaw holding surveying rod for first cross section (bridge over inlet channel in the background, military foundation remnant in the foreground). Depressed remains of inlet channel evident to the left of Dave and winding towards the right-front of the picture.

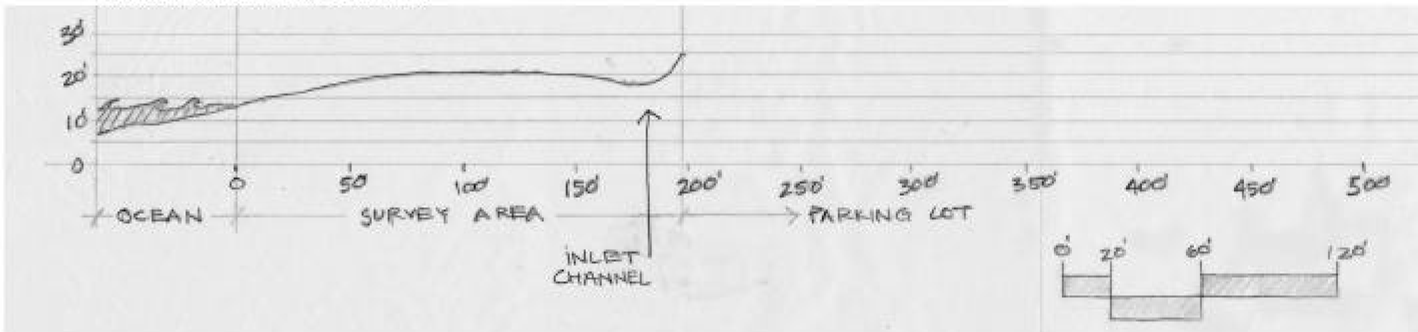
Fig. 4: Map locating cross section surveys.



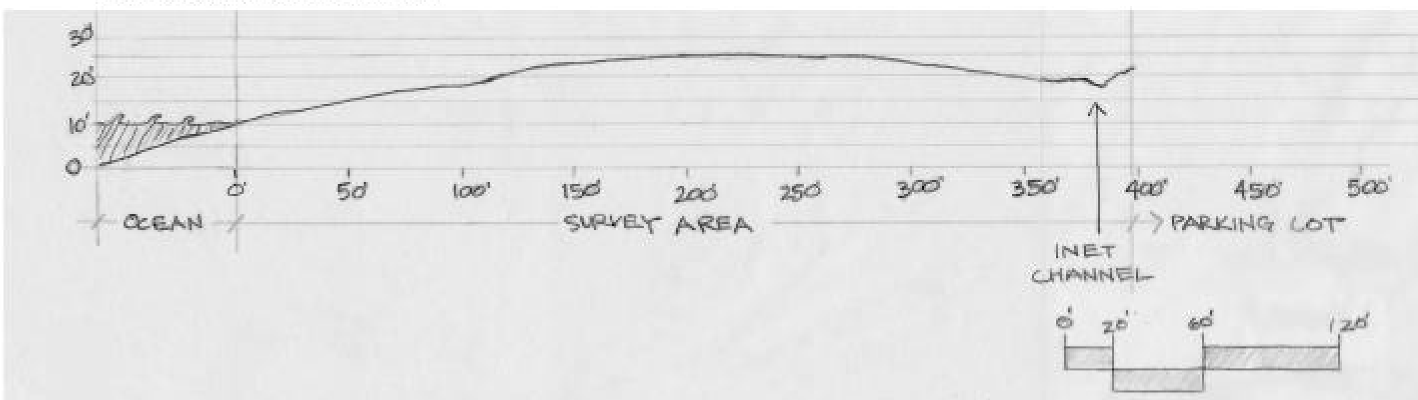
Note: For all cross sections, measurement bagan at the point where the waves rushing out met the waves rushing in. Cross sections one and two end at the top of the first terrace above the beach. Cross sections three and four end at the edge of the lagoon.

Fig. 5: Cross sections one and two.

Cross section #1 at STA 120'



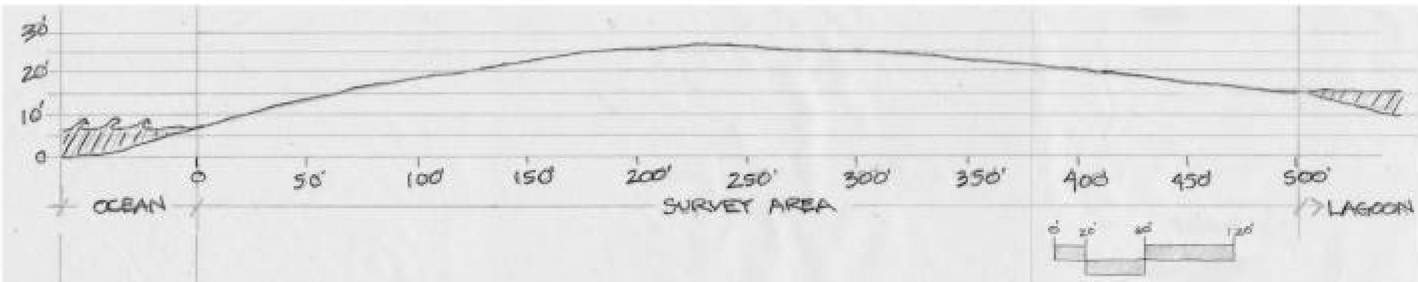
Cross section #2 at STA 510'



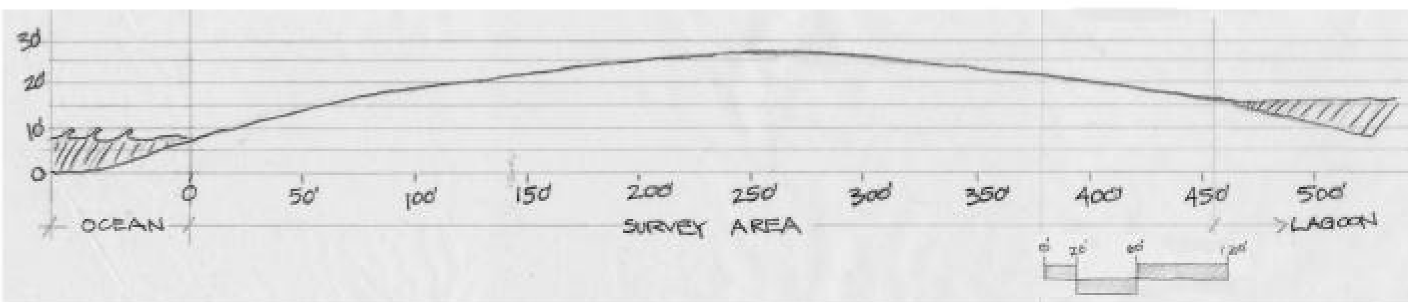
Note: All cross sections exaggerated twice in vertical direction.

Fig. 6: Cross sections three and four.

Cross section #3 at STA 980'

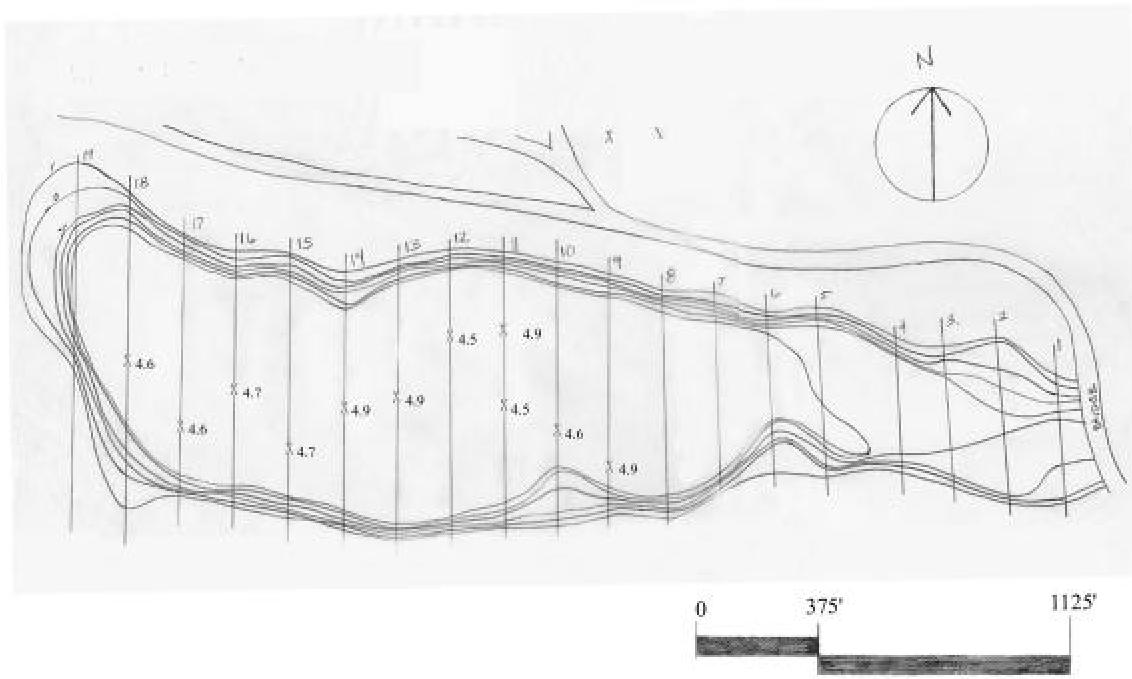


Cross section #4 at STA 1400'



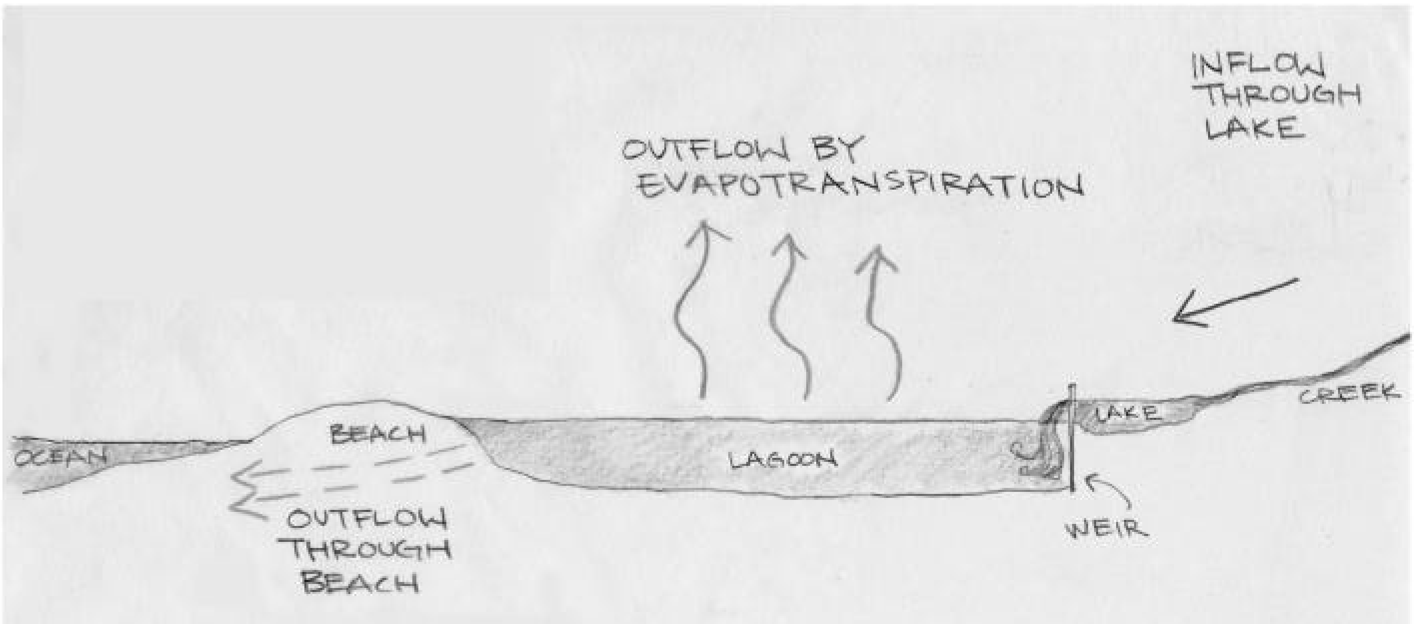
Note: All cross sections exaggerated twice in vertical direction.

Fig. 7: Bathymetric survey of Rodeo Lagoon published by Zembsch, 1993.



Adapted from Zembsch, 1993.

Fig. 8: Water Balance Diagram



Inflow from lake through weir: 2.856.7 ft3/6 hrs

Outflow...

by evapotranspiration: 2,617.2 ft3/6 hrs

through the beach: 2,071.6 to 2,071,600.0 ft3/6 hrs