Spatial Distribution and possible sources of saline waters in Rodeo Lagoon, Golden Gate National Recreation Area, Marin County, California

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Term Project for Landscape Architecture 222: Hydrology for Planners
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Rodeo Lagoon is an estuarine lake dominated by freshwater, with maximum measured salinity levels less than one-third that of seawater. This project identifies three possible sources for salinity beyond the seasonal input of seawater from the adjacent Pacific Ocean, and evaluates their significance in the early spring season using two data sets: a groundwater study on the barrier beach between the ocean and the lagoon to determine rate and direction of subsurface flow; and a salinity profile in the lagoon at depths of 0, 0.5, 1.5 and 2.5 meters. Groundwater flows through the barrier beach toward the ocean at a Darcy velocity of about 5 meters per day. Salinity declines steeply with proximity to the inlet of Rodeo Creek into Rodeo Lagoon indicating that the effluent is fresh water with low dissolved solid content. Leachate from sediments at the bottom of Rodeo Lagoon are a possible salinity source. The validity of this source could be determined by sampling and testing the bottom sediments. The most significant source of dissolved solids is the seasonal input from the Pacific Ocean when a channel connects the lagoon and the ocean.

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Introduction

Rodeo Lagoon, located in the Golden Gate National Recreation Area, Marin County, California (Figure 1), is a tidal lagoon separated from the Pacific Ocean by a barrier beach that ranges from about 45 to 120 meters in width. Rodeo Creek and its principal tributary Gerbode Creek drain Rodeo Valley, a 3 square mile watershed (Oerter, 2003), and discharge into the lagoon at its eastern end. Strong wave action and increased discharge from Rodeo Creek during winter storms open a seasonal channel across the beach connecting the lagoon to the ocean. The goal of this study is to determine possible sources of salinity in Rodeo other than seasonal influx of seawater from the adjacent ocean.

We have identified three possible sources for dissolved solids in Rodeo Lagoon in addition to seasonal wave and tidal input: elevated salinity levels in effluent from the Rodeo Creek watershed, salt water intrusion by subsurface flow through the barrier beach from the ocean, and leaching of ions entrained in lagoon bottom sediments. To qualitatively assess the contribution of groundwater flow through the beach, we measured the hydraulic gradient between the lagoon and the ocean. We also created a salinity profile of the lagoon in a series of contour maps designed to show salinity distribution at the surface and at depths of 0.5, 1.5 and 2.5 meters.

Site Description and Land-Use History

Rodeo Lagoon is an estuarine lake located on the coastal Marin Headlands, five kilometers northwest of San Francisco. The lagoon is approximately 200 meters wide and 850 meters long, with the long axis running east to west. Rodeo Creek and Gerbode

Creek drain into the east end of the lagoon after passing a small concrete weir. A beach separates the lagoon from the ocean on the west side (Figure 2). This area experiences a Mediterranean type climate with a mean annual precipitation of about 26 inches (Lehre, 1974). Drainage from the hills to the north and south of the lagoon make a minor fresh water contribution to the lagoon, however the strongest freshwater input comes from Rodeo Creek. Figure 3 contains a map of the site showing the locations of Gerbode and Rodeo Creeks and the former military installations in the surrounding area.

The beach on the west end of the lagoon is a transient feature of the landscape. A seasonal channel across the beach allows seawater to enter the lagoon. Gentler waves redeposit sand on the beach closing the channel in the spring. While the channel is closed water exchange between the lagoon and the ocean takes place by subsurface flow. (Snead, 1982) Unless another source of dissolved solids exists in the watershed of the feeding streams or in the lagoon itself, the largest influx of saline water into the lagoon occurs when a channel connects it with the ocean. The presence of either non-marine source would indicate an anthropogenic effect.

Rodeo Valley was used for dairy ranching in the nineteenth and twentieth centuries. Draining wetlands to grow grain for cattle grazing may have contributed to early-stage channel incision in the Rodeo and Gerbode Creek Valleys. (Constantino, 2003) The area was under control of the U.S. Army by 1937. (Luce, 1993) Construction of infrastructure that accompanied the Army's presence in Rodeo Valley also contributes to the anthropogenic influence we see there today. In the 1970s, the National Park Service acquired the Marin Headlands and began converting it into the Golden Gate National

Recreation Area. Fort Chronkite, which is immediately north of Rodeo Lagoon, currently houses the Headlands Institute and National Park Service offices.

Methods

Over a three day period in early April, 2004 we made measurements to ascertain the direction and rate of subsurface flow through the beach and collected salinity data in Rodeo Lagoon to build salinity profiles of the lagoon.

Groundwater Study

To measure the level of the groundwater table through the beach that separates the lagoon from the ocean, we installed five shallow piezometers at the locations marked on the map in figure 4. The piezometers are constructed of 6-, 7-, or 8-foot sections of PVC pipe, perforated in the lower eight inches. Nylon stockings act as effective filter fabric. Using a bucket auger we excavated a vertical hole for each piezometer to a depth sufficient to measure the elevation of the water table at each location. Once the piezometers were in place and capped, we filled the holes with coarse sand. (Figure 5) We chose a placement pattern for the piezometers such that we would be able to calculate elevation head gradients between proximal piezometers. We measured depth to water after two days using a measuring tape and a flashlight, recording the depth and the distance from the top of the piezometer to ground level.

We recorded the map position of each piezometer in Universal Transverse Mercator (UTM) coordinates using a GPS receiver. We logged the elevation of each position using an auto-level and stadia rod. In order to make relative measurements of the water levels in the piezometers, we defined an arbitrary datum, which resides 1000 cm below the elevation of the survey level.

Salinity Distribution Study

To map salinity distribution we entered Rodeo lagoon via canoe, equipped with a weighted line, a conductivity meter and a GPS receiver. Beginning at the easternmost point in the lagoon near the bridge that spans the inlet of Rodeo Creek, we took salinity and temperature measurements from the surface to the bottom at half-meter depth intervals, using a conductivity meter with a probe attached to a weighted line marked with 50 cm graduations. We used the GPS receiver to record the map position of each of a total of 30 sample sites, and a stadia rod to measure the depth of the lagoon at each to gain an idea of the overall bathymetry of the lagoon.

Data Processing and Analysis

Using the following formula we converted the depth-to-water measurements taken from each piezometer to head relative to the arbitrary datum defined above.

$$h = 1000 - z - d + p$$

In this equation, h represents head, z represents elevation change between ground and instrument elevation, d represents depth to water and p represents the height to which the piezometer protrudes above ground. The local hydraulic gradient is obtained by simply dividing the change in head between two piezometers by their separation distance.

Because some of our equipment used English units, and others used metric, the first step in data processing was to convert everything to meters for horizontal measurements and centimeters for vertical measurements. Once the salinity data was converted to the correct units we imported it into Surfer 7, a computer program designed to generate three-dimensional contour plots. Surfer employs a variety of statistical models to fit a surface plot to a data set. To generate the contour plots for salinity in Rodeo Lagoon, we chose the method of ordinary kriging. Kriging is advantageous over simple least-squares regression type statistical models because the kriging method passes its fit lines through all data points, where when using least-squares, the fit line may miss some points, even if they are not outliers. (Rubin, 2003) The results of this computer analysis are the contour plots of salinity discussed below.

Results and Discussion

Aside from seasonal input from the ocean, we have identified three possible sources for salinity in Rodeo Lagoon: leaching of salts from bottom sediments, saline effluent from the Rodeo and Gerbode Creek watersheds, and subsurface saltwater intrusion through the barrier beach.

Groundwater intrusion

We determined the hydraulic gradient in the unconfined aquifer running through the berm along with the direction of subsurface flow (Figure 4). The measured heads are tabulated in table 1. We took two measurements from each piezometer, with the exception of piezometer number 5 which was vandalized and removed from service. These determinations are based on the first set of measurements. Between piezometers 1 and 2, the hydraulic gradient is 0.035, and between piezometers 4 and 5 the hydraulic gradient is 0.025. Both of these gradients are in the direction of the ocean. Groundwater flows from higher head to lower head in the direction of the hydraulic gradient. Therefore, the data collected in these piezometers shows the near-surface water to be flowing from the lagoon through the beach and into the ocean. The groundwater flow regime may change seasonally, but based on our data set subsurface flow is not a source. Employing Darcy's law ($v = -K\nabla h$) and an estimated hydraulic conductivity of $6x10^{-5}$ m/s (from Domenico, Schwartz, 1998), we can estimate the flow rate (Darcy velocity) to be approximately 5 meters per day toward the ocean.

Salinity distribution

We created contour maps of salinity levels in Rodeo Lagoon at: 0 m (the water surface), 0.5 m, 1.5 m, 2.5 m (Figures 6 – 9) using the data in table 2. Examining the salinity contour maps we see that at the surface and at depths of 0.5 m and 1 m, salinity is significantly lower near the creek inlet.

On the surface of the lagoon there is a trend of low salinity at the Eastern end near the weir and bridge with increasing salinity towards the beach. We report salinity values as low as 0.2 parts per thousand (‰) on the surface of the lagoon at the creek inlet. Salinity increases rapidly with distance from the inlet, approaching the lagoonal average of 3.2‰. The contour map at 0.5 m depth shows a similar trend of lower salinity near the creek inlet and increasing salinity towards the beach. The minimum salinity at this depth is greater than that at the surface—2.8‰ at the creek inlet.

At 1.5 m depth, the contour plot still shows salinity to increase with distance from the creek inlet, but the minimum salinity near there is greater than 3.1‰. At this depth, the rapid decline in salinity that occurs near the creek inlet in the lesser depths is not apparent.

In the small area with depth of 2.5 m, we see the same trend of increasing salinity with increasing distance from the creek inlet. The minimum salinity here is 5.0‰. The salinity profile defined by these contour plots shows a trend of increasing salinity with depth even at areas of high freshwater influx. Density increases proportionally with dissolved solid content, and we can see pronounced density stratification in Rodeo Lagoon as the higher dissolved concentration water sinks to the bottom.

We can see a sharp decrease in salinity levels throughout the salinity profile at the inlet of Rodeo Creek into the lagoon. The regulated influx of freshwater from Rodeo Creek is certainly the source of the low salinity waters toward the east end of the lagoon, ruling out the possibility of a significant dissolved solid contribution from the watershed during the spring months.

The size of the plume of freshwater from the creek inlet may be damped by afternoon onshore winds, which were observed on each visit to the site and confirmed to be an almost daily occurrence (D. Fong, National Park Service, personal communication, April, 2004). If onshore winds act as a transport mechanism for surface waters then this may explain why the area of decreased salinity is not larger. As these winds blow from the ocean towards the back of the lagoon they have the ability to carry saline surface waters from near the beach east towards the bridge and weir area, perhaps masking the extent of the freshwater infiltration. Waves generated by this wind may also cause near-surface mixing of the water. This mixing does not seem to reach the deepest parts of the lagoon, most likely because the fetch is not long enough to generate waves that reach that depth. (Horne, Goldman, 1994)

Dissolution of Bottom Sediments

Salinity readings at 2.5 m depth showed the highest dissolved solid concentrations—on the order of 8.5‰. The majority of these high readings are located in the western portion of the lagoon, away from the freshwater input. While the lagoon demonstrates pronounced density stratification due to variant dissolved solid content, the abrupt increase in salinity between 1.5 and 2.5 m depths may suggest that these high salinity bottom waters are not necessarily the result of seawater influx. An alternative explanation for the higher salinity levels near the bottom of the lagoon could be leaching of material entrained in the bottom sediments into the water at the bottom of the lagoon. Such a leachate could be derived from a pollution source that existed when Rodeo Valley was still military controlled or may be a result of the composition of the bottom sediments. Even the highest salinity measured near the lagoon bottom was less than 10‰, far lower than the dissolved solid content of the ocean, which is approximately 35‰. Our data set cannot confirm or occlude the lagoon bottom sediments as a possible source of salinity in the lagoon.

Sources of Error

We have identified three primary sources for error in this project that were introduced during data collection. One source of error is the correlation between salinity measurements and location of sample sites. Windy afternoon conditions made it difficult to remain stationary in the canoe while making measurements in the lagoon. Onshore winds in the afternoon compounded this problem. We threw away three measurements as outliers due to extensive drifting during sampling. Most involuntary movements were small enough to not adversely affect the data quality.

The GPS receiver we used to gather horizontal map coordinates has an inherent error of up to two meters in measurement. Again, this fits in to experimentally acceptable error and does not diminish the quality of the data set.

The third error source occurs in the groundwater study. We measured the water table level relative to an arbitrary datum 1000 centimeters below the elevation of the survey instrument. While this does not effect measurements of hydraulic gradient, since this quantity is relative, it makes it impossible to refer the measured quantities to known elevations, such as mean sea level and the water level of the lagoon.

Further Study

This study is but a starting point for an in depth study of the hydrologic regime and dissolved load transport in and out of Rodeo Lagoon. Our field study took place at a specific time of year on a system that varies seasonally, and even diurnally. This study would benefit greatly from a year round study to observe and determine the significance of seasonal effects on lagoon salinity. Continuous monitoring of the groundwater levels and of salinity at specific predetermined points in the lagoon would allow us to observe any diurnal effects in the groundwater system due to tides, and in the salinity due to wind driven mixing in the lagoon.

A future project might incorporate a more extensive survey tied into existing survey points so groundwater levels can be compared to sea level. A survey of the lagoon edge would add a large amount of data to a water table model and constrain the equipotential surfaces that describe the system.

Finally we are unable to assess the validity of the sediments at the bottom of the lagoon as a source for elevated salinity levels at depth. A sampling expedition followed by laboratory tests could help to determine whether or not the bottom sediments could be a significant source of salinity in the deep parts of the lagoon.

Conclusions

Based on the hydraulic gradients measured near the edge of Rodeo Lagoon, we see that that the spring season salinity distribution of Rodeo Lagoon is not the result of infiltration of salt water from the ocean through the barrier beach. If the salinity of the lagoon were coming from daily intrusion of the ocean into the groundwater table then the hydraulic gradient would slope in the direction of the lagoon. The hydraulic gradient in the groundwater through the barrier beach shows that the direction of subsurface water flow is from the lagoon to the ocean. We know that in the winter season it is possible that intrusion along an opening between lagoon and ocean is possible due to the preferred channel cut by increased discharge from Rodeo creek and increased wave erosion during large storm events. During the drier months however when the lagoon and ocean do not experience open circulation there may be some salinity source that allows the lagoon to remain saline even with the constant influx of freshwater from the surrounding tributaries. One possible explanation for both the maintenance of saline waters during the dry season and repressed freshwater influence would be interaction between bottom waters and the underlying sediments.

Acknowledgements

The authors would like to thank the following people for their contributions and insightful comments on this project: Matt Kondolf, Dave Shaw, Darren Fong, George Brimhall, Chi-Yuen Wang, Erik Oerter, Phoebe Bass, Charles Battaglia

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Figure and Table Captions

Figure 1: Map of the San Francisco Bay Area with the location of Rodeo Lagoon emphasized.

Figure 2: Photograph of Rodeo Lagoon looking west. Note the barrier beach separating the lagoon from the Pacific Ocean.

Figure 3: Site map showing the locations of Rodeo and Gerbode Creeks, Rodeo Lagoon and the surrounding former military installations.

Figure 4: Map of the beach that separates Rodeo Lagoon from the Pacific Ocean showing the locations of shallow piezometers installed as part of this study.

Figure 5: A shallow piezometer installed to measure groundwater flow through the beach at Rodeo Cove. Note the uninstalled piezometer in the background.

Figure 6: Contour map of salinity levels in parts per thousand (‰) on the surface of Rodeo Lagoon. Schematic outline shows approximate location of the lagoon boundaries.

Figure 7: Contour map of salinity levels in ‰ at 0.5 meter depth. Schematic outline shows approximate location of the lagoon boundaries.

Figure 8: Contour map of salinity levels in ‰ at 1.5 meter depth. Schematic outline shows approximate location of the lagoon boundaries.

Figure 9: Contour map of salinity levels in ‰ at 2.5 meter depth. The areal extent of this map is much smaller than that of the other three maps because only a small portion of the lagoon that reaches a depth of 2.5 meters. The parallel horizontal lines show the approximate boundary of this area.

Table 1: Heads measured in five shallow piezometers.

Table 2: Salinity measurements in Rodeo Lagoon.

Figures

Figure 1

Figure 2

Figure 3

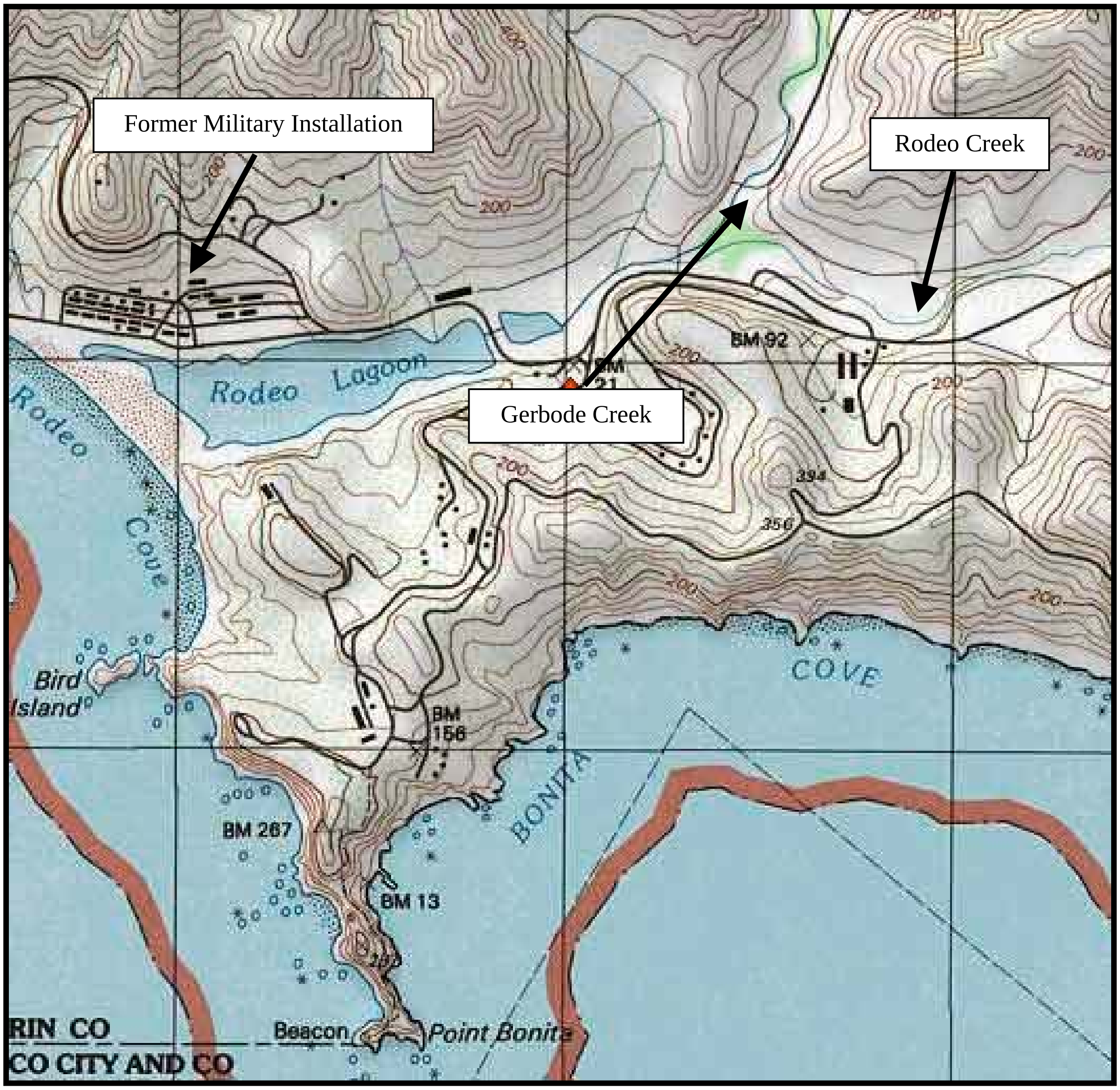

Former Military Installation
Rodeo Creek
Gerbode Creek
Rodeo Lagoon
Rodeo
Cove
Bird
Island
BM 92
BM 156
BM 267
BM 13
394
356
200
COVE
BONITA
Beacon
Point Bonita
RIN CO
CO CITY AND CO

Figure 4

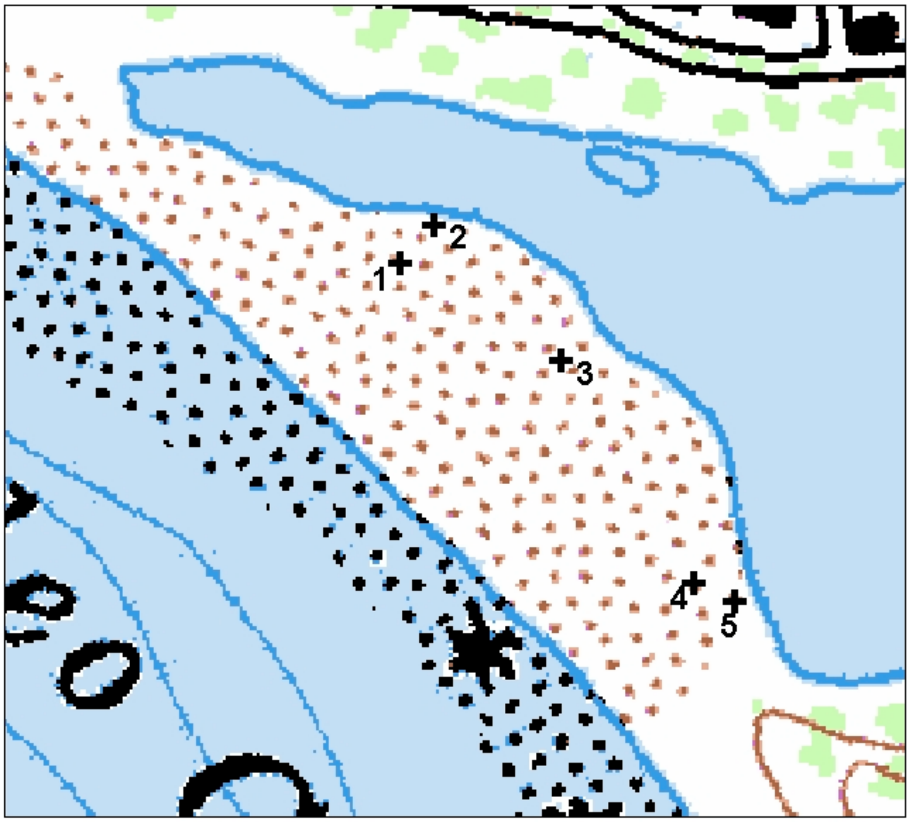
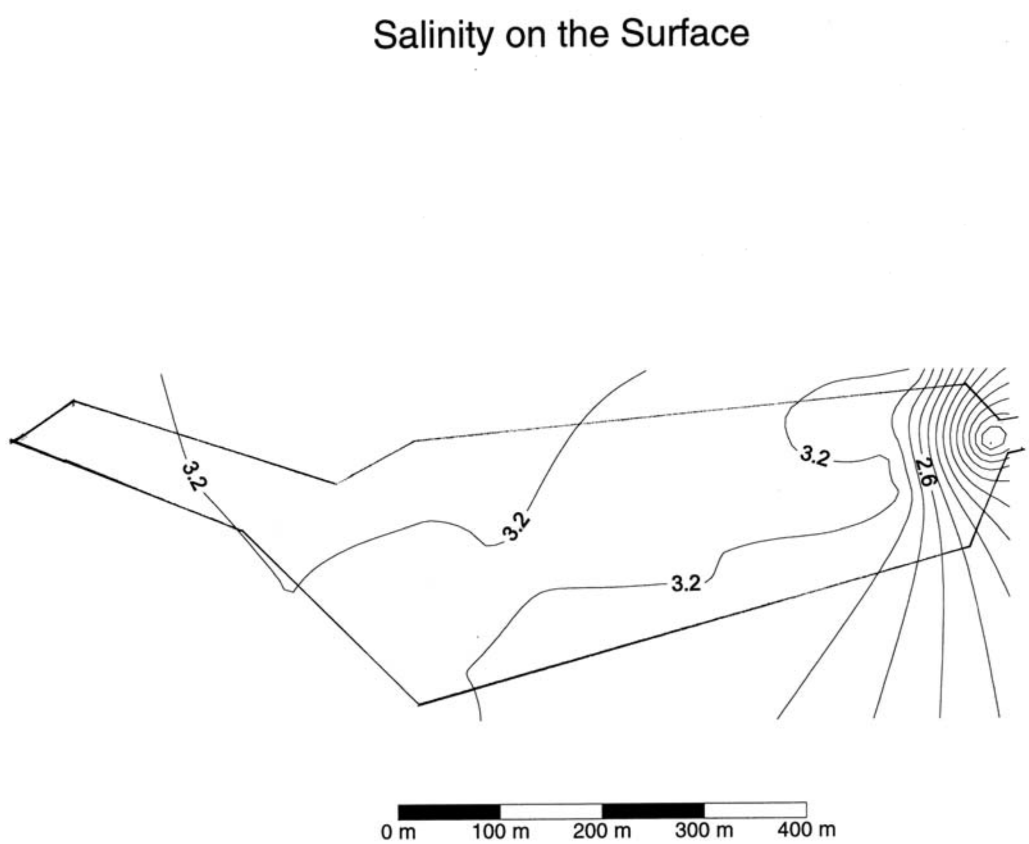


Figure 5

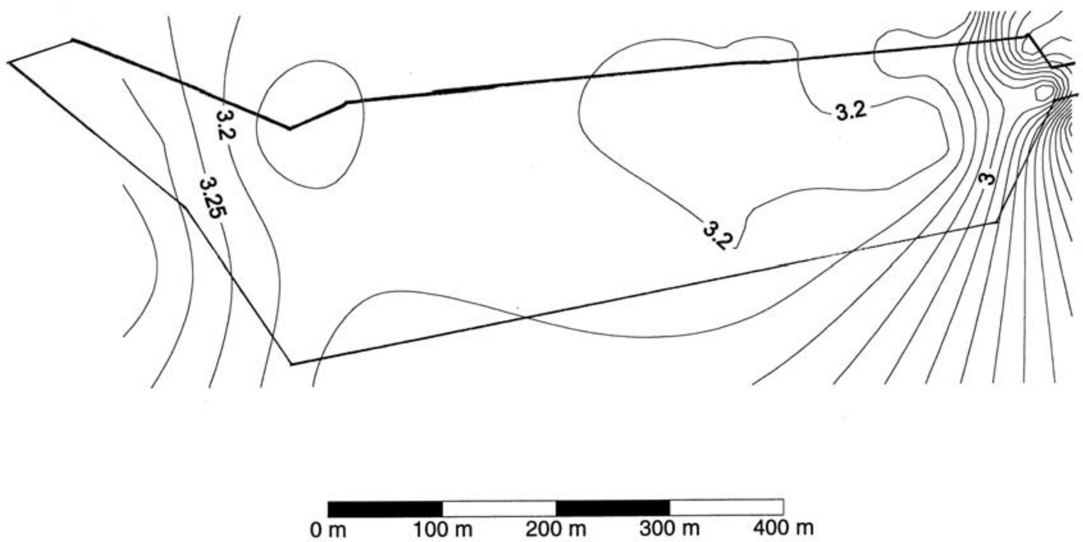
Figure 6



Contour interval is 0.3 ‰.

Figure 7

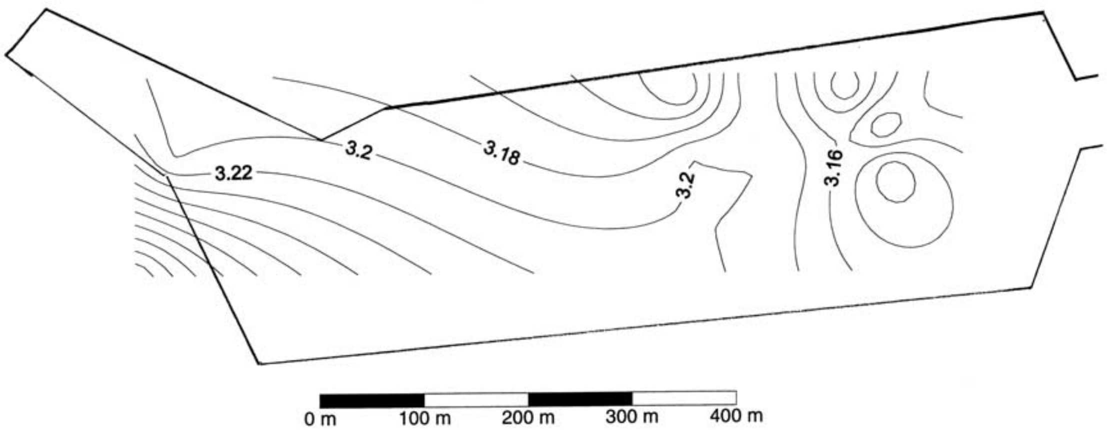
Salinity at Depth = 0.5 m



Contour interval is 0.05 ‰.

Figure 8

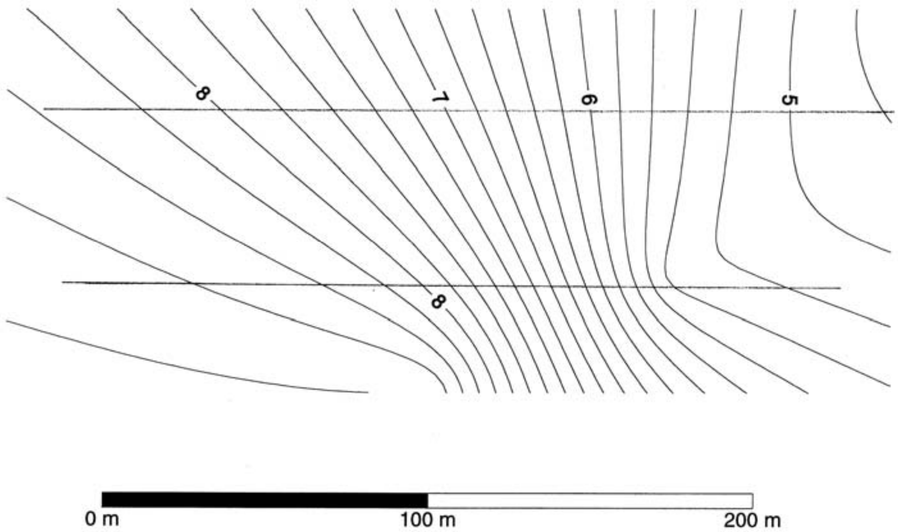
Salinity at Depth = 1.5 m



Contour interval is 0.02 ‰.

Figure 9

Salinity at Depth = 2.5 m



Contour interval is 0.2 ‰

Tables

Table 1

Piezometer	northing (m)	easting (m)	Head (cm)
1	4187075	540854	558.1
2	4187083	540862	597.4
3	4187040	540885	570.8
4	4186978	540926	596.2
5	4186976	540932	644.0

Table 2

Date	Time	northing (m)	easting (m)	Depth to bottom (cm)	Sample depth (cm)	Salinity (‰)
04/07/2004	1220	4187197.96	541729.30	88.4	0.0	1.5
04/07/2004	1220	4187198	541729	88.4	50.0	2.4
04/07/2004	1230	4187225	541710	143.3	0.0	0.5
04/07/2004	1230	4187225	541710	143.3	50.0	3.1
04/07/2004	1230	4187225	541710	143.3	100.0	3.2
04/07/2004	1240	4187259	541692	106.7	0.0	1.5
04/07/2004	1240	4187259	541692	106.7	50.0	2.6
04/07/2004	1240	4187259	541692	106.7	100.0	3.2
04/07/2004	1240	4187259	541692	106.7	150.0	3.2
04/07/2004	1243	4187290	541668	149.4	0.0	2.5
04/07/2004	1243	4187290	541668	149.4	50.0	2.8
04/07/2004	1243	4187290	541668	149.4	100.0	3.2
04/07/2004	1246	4187296	541639	140.2	0.0	3.2
04/07/2004	1246	4187296	541639	140.2	50.0	3.2
04/07/2004	1246	4187296	541639	140.2	100.0	3.2
04/07/2004	1252	4187251	541582	161.6	0.0	3.1
04/07/2004	1252	4187251	541582	161.6	50.0	3.1
04/07/2004	1252	4187251	541582	161.6	100.0	3.2
04/07/2004	1252	4187251	541582	161.6	150.0	3.1
04/07/2004	1253	4187225	541586	189.0	0.0	3.1
04/07/2004	1253	4187225	541586	189.0	50.0	3.2
04/07/2004	1253	4187225	541586	189.0	100.0	3.2
04/07/2004	1258	4187212	541615	186.0	0.0	3.2
04/07/2004	1258	4187212	541615	186.0	50.0	3.2
04/07/2004	1258	4187212	541615	186.0	100.0	3.2
04/07/2004	1258	4187212	541615	186.0	150.0	3.2
04/07/2004	1302	4187173	541625	106.7	0.0	3.2
04/07/2004	1302	4187173	541625	106.7	50.0	3.2
04/07/2004	1302	4187173	541625	106.7	100.0	3.2
04/07/2004	1302	4187173	541625	106.7	150.0	3.1
04/07/2004		4187142	541573	140.2	0.0	3.2
04/07/2004		4187142	541573	140.2	50.0	3.2
04/07/2004		4187142	541573	140.2	100.0	3.2
04/07/2004		4187184	541519	216.5	0.0	3.2
04/07/2004		4187184	541519	216.5	50.0	3.2
04/07/2004		4187184	541519	216.5	100.0	3.2
04/07/2004		4187184	541519	216.5	150.0	3.2
04/07/2004		4187184	541519	216.5	200.0	3.1
04/07/2004		4187267	541493	192.1	0.0	3.2
04/07/2004		4187267	541493	192.1	50.0	3.2
04/07/2004		4187267	541493	192.1	100.0	3.2
04/07/2004		4187267	541493	192.1	150.0	3.2
04/07/2004		4187249	541427	216.5	0.0	3.2
04/07/2004		4187249	541427	216.5	50.0	3.2
04/07/2004		4187249	541427	216.5	100.0	3.2
04/07/2004		4187249	541427	216.5	150.0	3.1
04/07/2004		4187186	541432	216.5	0.0	3.2
04/07/2004		4187186	541432	216.5	50.0	3.2

Date	Time	northing (m)	easting (m)	Depth to bottom (cm)	Sample depth (cm)	Salinity (‰)
04/07/2004		4187186	541432	216.5	100.0	3.2
04/07/2004		4187186	541432	216.5	150.0	3.2
04/07/2004	1329	4187126	541441	201.2	0.0	3.2
04/07/2004	1329	4187126	541441	201.2	50.0	3.2
04/07/2004	1329	4187126	541441	201.2	100.0	3.2
04/07/2004	1329	4187126	541441	201.2	150.0	3.2
04/07/2004	1403	4187087	541438	54.9	0.0	3.2
04/07/2004	1403	4187087	541438	54.9	50.0	3.2
04/07/2004		4187151	541160	228.7	0.0	3.2
04/07/2004		4187151	541160	228.7	50.0	3.2
04/07/2004		4187151	541160	228.7	100.0	3.2
04/07/2004		4187151	541160	228.7	250.0	4.7
04/07/2004	1422	4187124	541215	231.7	0.0	3.2
04/07/2004	1422	4187124	541215	231.7	200.0	6.0
04/07/2004	1429	4187003	541196	137.2	0.0	3.2
04/07/2004	1429	4187003	541196	137.2	0.0	5.8
04/07/2004	1434	4186971	541112	51.8	0.0	3.3
04/07/2004	1434	4186971	541112	51.8	50.0	3.1
04/07/2004	1437	4187069	541094	228.7	0.0	3.3
04/07/2004	1437	4187069	541094	228.7	250.0	5.3
04/07/2004	1444	4187193	541042	88.4	0.0	3.1
04/07/2004	1444	4187193	541042	88.4	50.0	3.1
04/07/2004	1444	4187193	541042	88.4	100.0	3.2
04/07/2004	1452	4187185	540842	228.7	0.0	3.3
04/07/2004	1452	4187185	540842	228.7	100.0	3.4
04/07/2004	1457	4187077	540900	195.1	0.0	3.4
04/07/2004	1457	4187077	540900	195.1	50.0	3.4
04/07/2004	1457	4187077	540900	195.1	100.0	3.4
04/07/2004	1457	4187077	540900	195.1	150.0	3.4
04/07/2004	1457	4187077	540900	195.1	200.0	9.0
04/07/2004	1500	4186956	540990	57.9	0.0	3.3
04/07/2004		4187060	540969	228.7	0.0	3.3
04/07/2004	1511	4187072	541026	228.7	0.0	3.2
04/07/2004	1511	4187072	541026	228.7	300.0	8.6
04/07/2004	1516	4187033	541019	231.7	0.0	3.4
04/07/2004	1516	4187033	541019	231.7	250.0	8.8
04/07/2004	1527	4187143	540889	216.5	0.0	3.3
04/07/2004	1527	4187143	540889	216.5	250.0	8.3
04/07/2004	1530	4187187	540936	122.0	0.0	3.2
04/07/2004	1530	4187187	540936	122.0	50.0	3.3
04/07/2004	1530	4187187	540936	122.0	100.0	3.2
04/07/2004	1530	4187187	540936	122.0	150.0	3.2