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A STRATEGY TO MAINTAIN TIDAL FLUSHING IN SMALL COASTAL LAGOONS

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Abstract

A strategy of minimal, but frequent tidal inlet and channel maintenance dredging, coupled with seasonal flows of freshwater runoff, can be successfully harnessed to maintain tidal flushing in certain small southern California coastal lagoons. We have applied this technique to three lagoons in San Diego County. The results of our studies strongly suggest that it is feasible to maintain tidal flushing in many small lagoons without massive enlargement and deepening to increase the tidal prism, and without intrusive and costly structures.

Introduction

San Diego County's watersheds are drained by 29 major and minor creek and river systems (Simon, Li & Associates, 1988). These terminate in a variety of river mouths, estuaries, marshes, lagoons and bays (Boland and Zedler, 1996). There are 7 lagoons along the coast of San Diego County relevant to this study (Figure 1). Each receives varying amounts of ephemeral flows of freshwater, depending on the watershed size, which ranges from 18.8 to 1724 mi^2. The strong seasonality in stormwater runoff imposes unique hydrological and ecological conditions on these lagoons, which range in size from 246 to 1320 acres of wetlands.

Buena Vista Lagoon is a freshwater lagoon isolated from the ocean by a weir adjacent to the beach. Three lagoons, Batiquitos, Agua Hedionda, and Tijuana Estuary, are open to year-round tidal flushing. The ocean inlets at Batiquitos and Agua Hedionda lagoons are sustained by jetties and occasional maintenance dredging. Tijuana Estuary is open naturally, due to its large tidal prism, configuration, and large watershed area.

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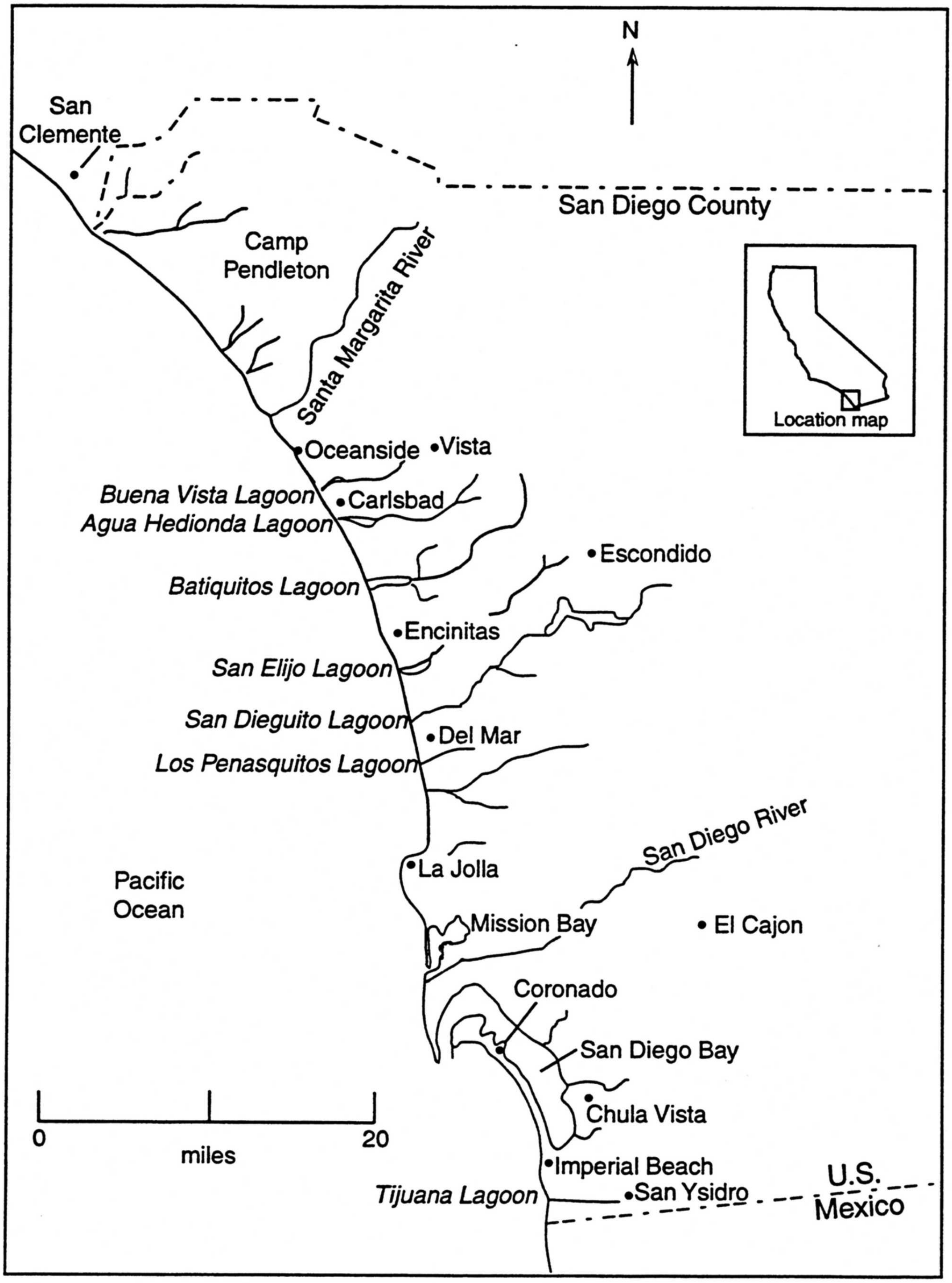


Figure 1. Map showing major lagoons and bays along San Diego County coast.

The remaining lagoons, San Elijo, San Dieguito, and Los Penasquitos, are open only intermittently and require maintenance dredging of the inlet and main channel to sustain tidal flushing. This paper describes studies that have been conducted in these three lagoons.

Factors Controlling Lagoon Conditions

Three physical factors control the conditions in San Diego's (and many other) coastal lagoons: tidal flushing, seasonal fluvial runoff, and the deposition of sediments.

Tidal Flushing

Coastal lagoons will stay open to the ocean if the tidal prism is large enough to facilitate scouring of flood tide deposited marine sediments from the channel bed. Since most of San Diego's lagoons have relatively small tidal prisms and ebb flows are constricted by bridges, their inlets are dominated by flood tides, accumulate marine sands, and tend to close.

When tidal flushing ceases, seasonal stormwater runoff accumulates, fresh or brackish, eutrophic water conditions prevail, and plant biomass and sediments accumulate within the lagoon. If rainfall runoff is low, the lagoon inlet may open briefly or may remain closed. During summer, high water temperatures, low dissolved oxygen, and large changes in lagoon water salinity (2 to 50 ppt) may occur. The long term outcome is that the marine communities degenerate and fresh/brackish water plants such as cattails (*Typha spp.*) and bulrushes (*Scirpus spp.*), colonize and expand.

On the other hand, when the lagoon inlets are open, the accumulated organic and fine sediment burden and associated eutrophic conditions will be reduced, the benthos, fisheries and salt marsh habitat will be enhanced, species abundance, diversity and trophic complexity will increase, human health conditions will improve and the potential impacts from any contaminant spills will be reduced. When tidal flushing is sustained, secondary productivity is enhanced and develops linkages with the nearshore ocean environment, e.g. production of juvenile fishes, like California halibut (*Paralichthys californicus*).

Stormwater Runoff

The historical record of rainfall from 1850 to 1994 recorded at Lindbergh Field (near downtown San Diego, CA) shows that there are large variations from year to year (Elwany et al., 1995). A plot of the cumulative residual rainfall, r_t, calculated for each successive year t shows that there are long term cycles of wet and dry periods Figure 2). The value r_t is a running departure from the mean annual rainfal calculated according to the following equation:

$$r_t = \sum_{i=t_o}^{i=t} (r_i - \bar{r}),$$

where $\bar{r}$ is the mean rainfall over the entire record.

The ascending parts of the curve reflect above average rainfall, and the descending parts reflect below average rainfall. For example, the years between 1945 and 1977 were the third period of semi-drought in the record, with an average yearly rainfall of about 8.5 in. We are currently experiencing a wet period. Between 1978 and 1994 the average annual rainfall was approximately 11.3 in, 14% above normal. During wet periods, stormwater runoff is more likely to assist in scouring the ocean inlet and facilitate tidal circulation than during dry periods. However, the recurrence rate of major stormwater runoff events is not high enough to keep the lagoon ocean inlets open for any prolonged period of time.

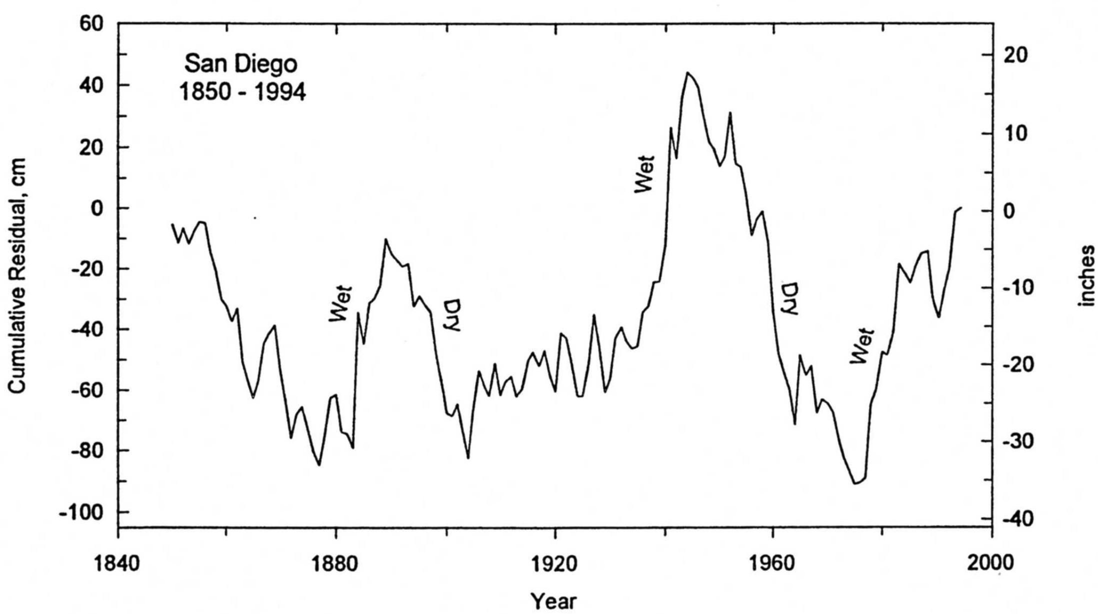


Figure 2. Cumulative residual rainfall in San Diego, CA, illustrating wet and dry periods.

Sedimentation

Since stormwater runoff is highly seasonal in southern California, river sediment discharge is also episodic. Discharge is limited by the presence of dams, urbanization, channelization, and soil type within the watershed. In fact, dams control 51.5% of the entire 4530 mi^2 of watershed that drain to the ocean in San Diego County. Simon, Li & Associates (1988) investigated the delivery of river sediments to the coast in the San Diego region and concluded that for the rivers that discharge into lagoons, nearly 100% of the sediments greater than 0.063 mm were deposited within the lagoons. Only suspended silts and clays transit the lagoons and are discharged to the ocean. Four lagoons, San Elijo, San Dieguito, Los Penasquitos, and Tijuana Estuary, showed the largest rates of sediment deposition.

Ocean Inlet Opening and Closure Processes

Inlet closure is a complex process that is poorly understood, because it involves numerous variables that may interact to different degrees depending on the time course of events. These variables include waves and beach characteristics, lagoon hydrology, inlet configuration, channel morphology, sediment characteristics, presence of cobbles, and adjacent shore morphology. Beach width is of particular importance because of its effect on the length of the inlet channel and volume of beach sediment available for resuspension and transport into the inlet and lagoon channels during flood tides. Consequently, changes in beach width may have an important influence on inlet dynamics. For example, a long inlet channel that crosses a broad sand beach during summer will be more sensitive to closure processes than a channel that crosses a narrow sand beach during winter. Deposits of beach cobbles may also contribute to inlet closure. Waves may cause the cobbles to migrate into the inlet, restrict tidal exchange, and reduce ebb flow scouring of the channel sand bed.

The duration of inlet closure events varies. Short term closures result from periods of high ocean wave activity that cause substantial sediment suspension, transport, and redeposition. A beach berm barrier can be established across a lagoon inlet in a few hours. Since minimal sediment is deposited within the adjacent lagoon channel, the inlet may reopen under the right conditions. Long term closure events lasting months to years that emerge from cumulative deposition of sediment in the inlet as well as the adjacent lagoon channel, are more difficult to reverse, because they typically require major stormwater runoff to blow out the beach berm and to scour the channel bed. As the long term closure process matures, there may be brief episodes of limited tidal exchange, for example, during spring tides.

When tidal flushing has ceased, seasonal stormwater runoff may accumulate and increase the lagoon water level and pressure head. Fresh or brackish water conditions may prevail for many months, or blow out the barrier beach berm, scour the channel bed, and restart tidal flushing. The extent to which the channel is scoured is a significant factor in the duration of tidal flushing. The tidal flushing may continue briefly or continue for many months until depositional processes close the lagoon inlet once again.

Lagoon Restoration

Several of the coastal lagoons in San Diego County have undergone significant long term degradation from construction of dams, urbanization, periods of drought, lack of tidal flushing, conversion of salt marsh habitat to brackish water marsh, and invasion of exotic species. As a result, there is renewed interest in restoring these lagoons (Boland and Zedler, 1996). However, these lagoons are complex ecosystems and our ability to successfully create, restore, or enhance them is limited and largely experimental.

Although the federal government recommends that restoration be given precedence over creation of wetlands habitat (US Government, 1995), California government agencies seem to recommend creation over restoration or enhancement projects due to the historical losses of wetland acreage and their desire to add new wetland acreage. This policy plus the desire for self-sustaining mitigation projects has led to applying hydrological solutions to lagoon problems. Hence, increasing the tidal prism and construction of jetties at the ocean inlet have dominated approaches to rehabilitating these lagoons. These two elements necessarily result in risky destruction/conversion of one habitat to another and incurring high costs for dredging and jetty construction. In turn, since the increased tidal flows may affect the stability of the older highway bridges and railroad trestles, these structures may also have to be replaced or protected; increasing the project cost even further. Also, depending upon the characteristics of lagoon sediments, the dredged materials are not always easily disposed.

Inlet Maintenance Strategy

Earlier plans for restoring coastal lagoons in southern California were based on the view of maximizing the tidal prism so that the inlets would sustain themselves through increased tidal flushing. The tidal prism needed was determined by using hydraulic modeling data and the results of classical studies on the stability of lagoon inlets by O'Brien (1931), Escoffier (1977), and Bruun (1978). These studies emphasized the roles of the tidal prism and longshore sediment transport in governing the stability of tidal inlets. The net result has been the assumption that massive enlargement and deepening of the lagoon basin by dredging was required to increase the tidal prism of the wetland enough for the inlet to become stable.

The main drawbacks to this approach are the high costs of dredging, disposal of sediments, the ecological disruptions during the construction phase, the fact that one system of habitats is often replaced by another, and the need for cross-beach jetty structures to help stabilize the inlet. In addition, the outcome of this approach is unpredictable, ecological success is not guaranteed, and the mitigation credit that should be awarded is difficult to estimate beforehand. Results of our studies suggest that it is feasible to maintain tidal flushing in small lagoons without resorting to large scale dredging. We propose an alternative strategy of inlet maintenance that is more economical, and less intrusive.

The proposed plan consists of two small scale tidal inlet and channel dredgings per year. The plan coupled with scouring from seasonal flows of stormwater runoff, can be successfully used to maintain tidal flushing in small coastal lagoons. Maintaining the inlet according to this plan will greatly reduce the frequency of inlet closures, but may not prevent rapid storm wave induced closures. The plan calls for prompt reopening if the lagoon does not reopen naturally within a few days. Development of this approach is the result of a five year tidal inlet monitoring study conducted at San Elijo, San Dieguito, and Los Penasquitos Lagoons located in San Diego County, California.

A one-time restorative dredging would be carried out to return the inlet and main channel to a near-equilibrium configuration. Subsequent maintenance dredging efforts would remove newly deposited marine sediments from the inlet channel before it migrates farther into the lagoon. Dredging with conventional earth-moving equipment, which can work in water depths up to three feet, or with a small barge-mounted pump and slurry pipeline is more economical and can be deployed more frequently than use of large scale dredgers. This approach does not require jetties to stabilize the inlet, and fosters continued recreational use and public access to the beach.

Inlet Maintenance Methodology

Three proven dredging methods were evaluated for their usefulness in maintaining inlets to small coastal lagoons as follows: conventional earth-moving equipment, cutterhead suction dredge, venturi pump dredge (Creek & Sagraves, 1995). Each dredge method was assessed for its ability to: 1) Complete entire scope of work, 2) Work within the constraints of the work site and on short notice, 3) Conduct both large and small maintenance jobs 4) Compete cost effectively. Other methods are discussed by Inman & Harris (1970) and Jenkins et al (1980).

The greatest constraint to dredging operations is the access problem created by presence of road and railroad bridges that traverse the lagoon inlet and main channel. The dredge method or combinations of methods must be able to dredge beneath these bridges and to transport sediments to the beach disposal site. Typical dredging rates for each method are summarized in Table 1.

Table 1. Estimated dredging capabilities of excavation equipment

Dredge type	**Dry Capacity (yd^3)**	**Wet Capacity (yd^3)**	**Dredging Rate (yd^3/hr)**
Front end loader	7	5	150-250
Scrapper	22	16	300
Backhoe excavator	3.5	3	250-350
Cutterhead Dredger (12 - 14 inch)	–	–	up to 875
Eddy Pump (12 - 14 inch)	–	–	330

Conventional Earth-moving Equipment

Most earth-moving vehicles are capable of working in 2-3 ft of water during periods of low tide. Earth movers, front end loaders, and tractor excavators have been used successfully to maintain the ocean inlets at Los Penasquitos, San Dieguito, and San Elijo Lagoons. Depending upon haul distance, a single earth mover can move about 150 - 250 yd^3 of wet beach sediment per hour. The mobilization and demobilization time for this equipment is minimal. There is no slurry pipeline involved. There is no de-watering runoff or turbidity plume generated at the disposal site and disposal incorporates grading.

Successful operation of these vehicles in the marine environment requires operators experienced in operating safely on sand beaches, in sea water, and under tidal conditions. These vehicles can work in lagoon channels that pass under most highway bridges, but not under railroad trestles. A disposal route must be accessible in order to be able to transport and dump the excavated sediments. The excavation effort must be scheduled around workable tide levels and ebb flows, otherwise flooding tides can rapidly undo previous progress. The inlet channel is opened temporarily and the lagoon is allowed to drain during ebb tide to lower the water level so that the vehicles can work in the channel. The inlet is then closed off again by construction of a temporary berm. The inlet is then reopened during a low spring tide, after the excavation is completed.

<u>Cutterhead Suction Dredger and Slurry Pipeline</u>

This is one of the most common dredgers and represents a proven technology. Typical dredger units are capable of dredging at rates of 150 yd^3 per hour and pumping a sediment slurry of 15% to 20% at 15 - 20 ft/sec. It operates by differentially winching forward by alternating lowering and raising it port and starboard spuds and by using anchors. The slurry pipeline is sensitive to wave motion and may have to be submerged or routed over land. The dredger should be operated in an upriver direction, particularly if there is a possibility of excessive stormwater runoff and may have to be redirected into the flooding tidal currents. A two knot current is thought to be maximal for safe operation since the spuds may slip in fast currents. Similarly, waves in excess of 2 - 3 ft can damage the ladder supporting the cutterhead. Consequently, this dredger would probably have to operate when the lagoon is closed. So opening of the inlet would have to be done by conventional earth-moving vehicles. Presence of cobbles may be a problem for a system that depends on pumping. Initial launching requires a body of deep water adjacent to the shore and several launchings may be required if it can not pass under certain bridges. The mobilization period may be lengthy.

<u>Venturi Pump and Slurry Pipeline</u>

The Eddy pump (Creek & Sagraves, 1995) is a relatively new high velocity, submersible pump dredging technology that offers a 50% energy savings and an ability to pump a sediment slurry of up to 70% solids. The pump is mounted on a small barge, lowered over the side to the dredge depth, and used to dredge the sediments by suction without the aid of a cutterhead. It has a maximum pumping rate of 10,000 gpm and can pump 250 ft of head. The 12 in pump can pump up to 560 yd^3 of sand per hour. Alternatively, the pump could be operated via a crane boom from shore. These attributes, including increased maneuverability and ability to pump cobbles, offers some significant advantages in terms of efficiency and in minimizing discharge of slurry water on the open beach. The pump requires operation of a slurry pipeline and would be difficult to operate in the ocean inlet.

Application of the Maintenance Plan

Three experimental dredgings were undertaken at San Elijo Lagoon between 1994 and 1997 (Elwany et al., 1997). Conventional earth-moving equipment was used during the three experiments for dredging the inlet and the lagoon inlet channel. Figure 3 shows the equipment used for these experimental excavations. The first experiments was conducted in April 1994 and resulted in an open inlet for 4 months (22 April 1994 - 23 August 1994). The second experiment was conducted in June 1995, and the lagoon remained open until the end of October 1996 (4 months). The third experiment was conducted in winter 1996-97 and kept the lagoon open intermittently from the end of September until 1 March 1997 (5 months). Figure 4 (A) gives time periods of lagoon open or closed conditions at San Elijo Lagoon from 1986 to 1 March 1997.

At San Dieguito Lagoon, our studies (Elwany et al., 1994) show that the typical inlet opening and closing sequence that is observed begins when a major flood scours the inlet channel bed below the equilibrium depth sustainable by the maximum available tidal prism. The inlet recharges with littoral sand, rapidly filling the entrance and exterior portions of the lagoon channels to a near-equilibrium depth. This condition has repeatedly been observed to remain semi-stable for up to several years. However, the inlet and channels slowly fill, building sills which choke off the inlet over a period of 2 to 5 years, eventually leading to inlet closure and deterioration in lagoon water quality. The lagoon remains closed until a large enough flood again scours the inlet and interior channel, or until the inlet is opened artificially. If a major flood occurs, the cycle starts over. This sequence of events implies that the inlet will remain open naturally as long as sufficiently large floods occur every 2 to 5 years. When there are no floods, the lagoon remains closed.

Based on our understanding of the physical and dynamical processes controlling San Dieguito Lagoon an inlet maintenance plan was developed. A one-time restorative dredging of about 25,000 yd^3 would be carried out to return the inlet channel to a near-equilibrium configuration. Subsequent maintenance dredging would remove an average yearly volume of about 15,000 yd^3 of sand from the inlet channel. Dredging with conventional earth-moving equipment, which can work in water depths up to three feet, or a small barge-mounted pump and slurry pipeline has been examined (Elwany et al., 1994), and found to be economical and far less disruptive than massive dredging. This approach requires no structures to stabilize the inlet, leaving recreation and lateral access along the beach area unaffected.

The plan discussed above has also been applied with good success to Los Penasquitos Lagoon by the Los Penasquitos Foundation from 1990 until present. The lagoon was dredged annually using earth-moving equipment. Figure 4 (B) shows time periods of lagoon opening and closing before and after adopting the maintenance

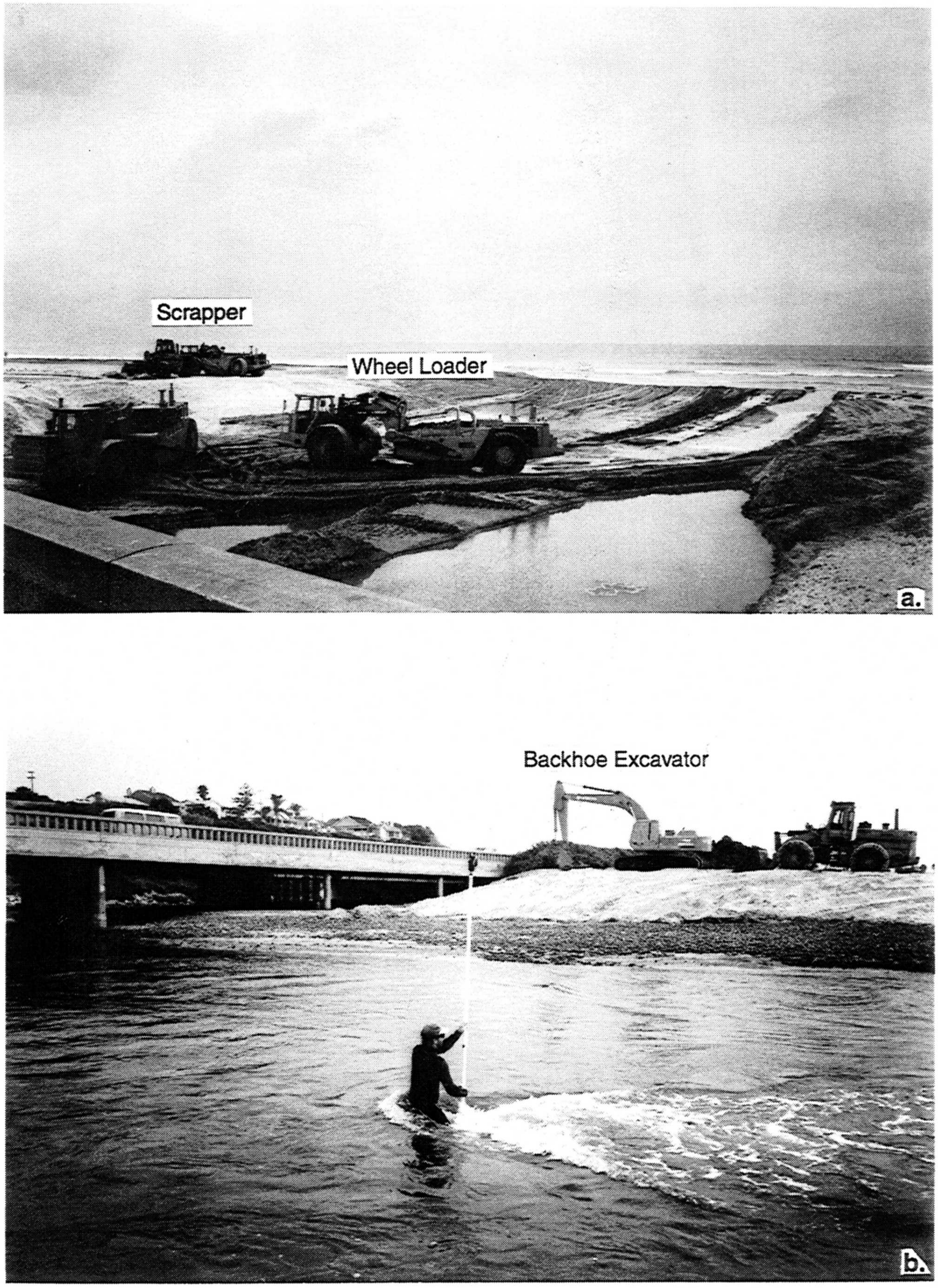
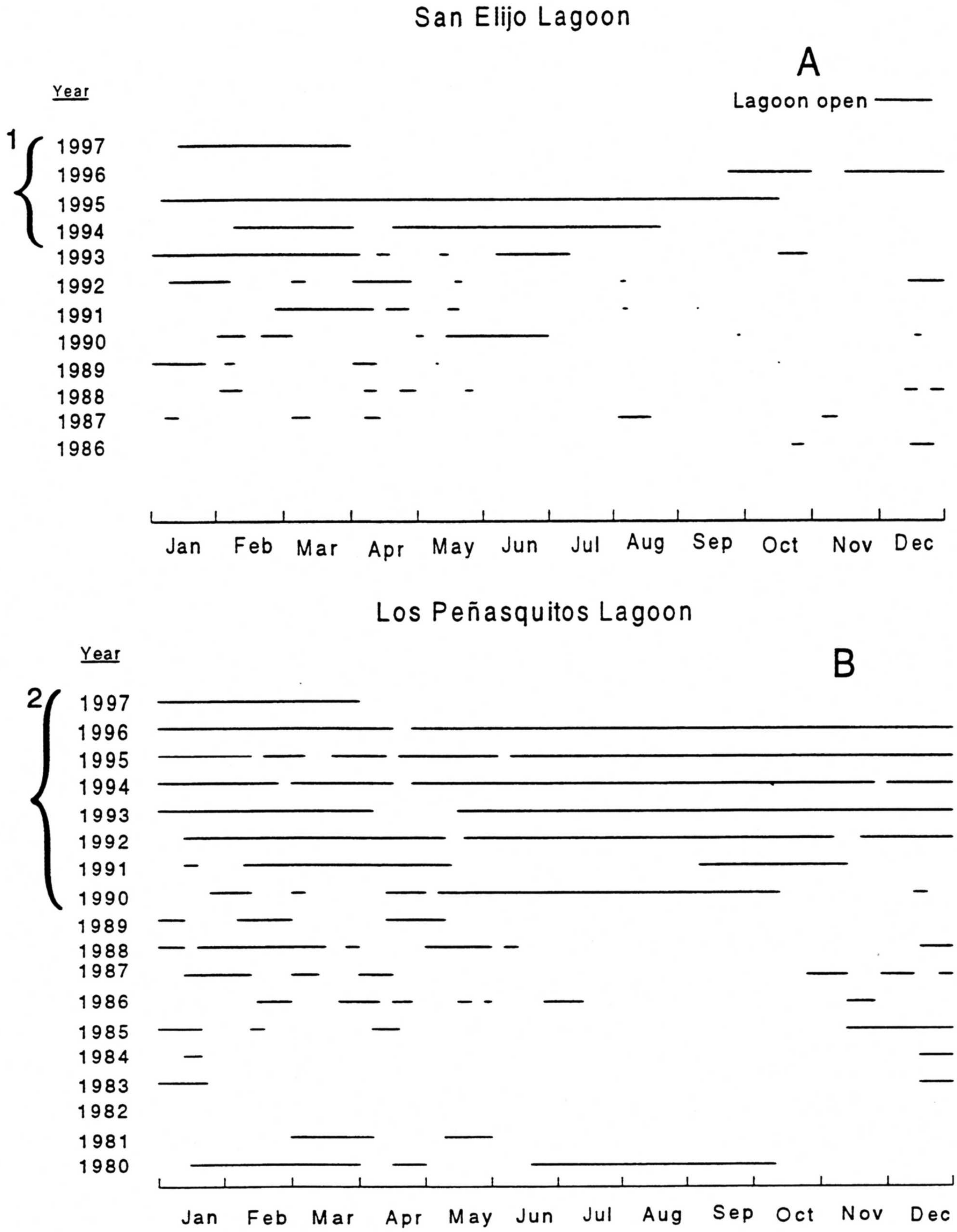


Figure 3. Conventional excavation equipment used to dredge San Elijo Lagoon.



1 Results of Experimental Dredging

2 After Implementing Inlet Maintenance Plan.

Figure 4. Inlet status (open or closed) at San Elijo and Los Penasquitos Lagoons to March 1, 1997.

plan. Between 1980 and 1989 the lagoon was open only 22% of the time, while from 1990 onward it has been open 80% of the time.

Conclusions

Southern California coastal lagoons are small, shallow, and subject to closure of the inlet. These lagoons are backed by rivers or streams. Episodic stormwater runoff contribute to scouring deposited marine sediments and restarts tidal flushing. Active dredging maintenance of the ocean inlet and main channel is required in order to sustain tidal flushing.

A site specific dredging maintenance plan should be designed on the basis of monitored marine sedimentation rates and changes in lagoon water quality conditions. On the basis of costs and flexibility in scheduling and deployment, conventional earth-moving vehicles are the best method for carrying out inlet maintenance programs in small coastal lagoons in San Diego County, California. The discussed maintenance plan was applied successfully to San Elijo and Los Penasquitos lagoons in San Diego County.

Acknowledgements

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