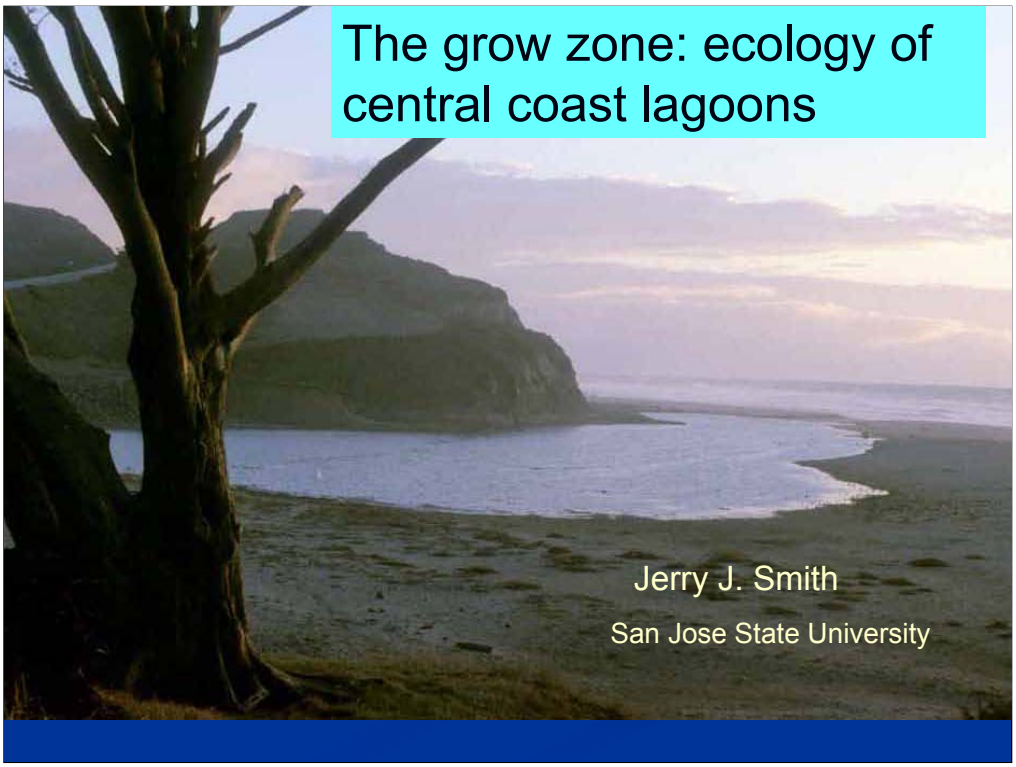
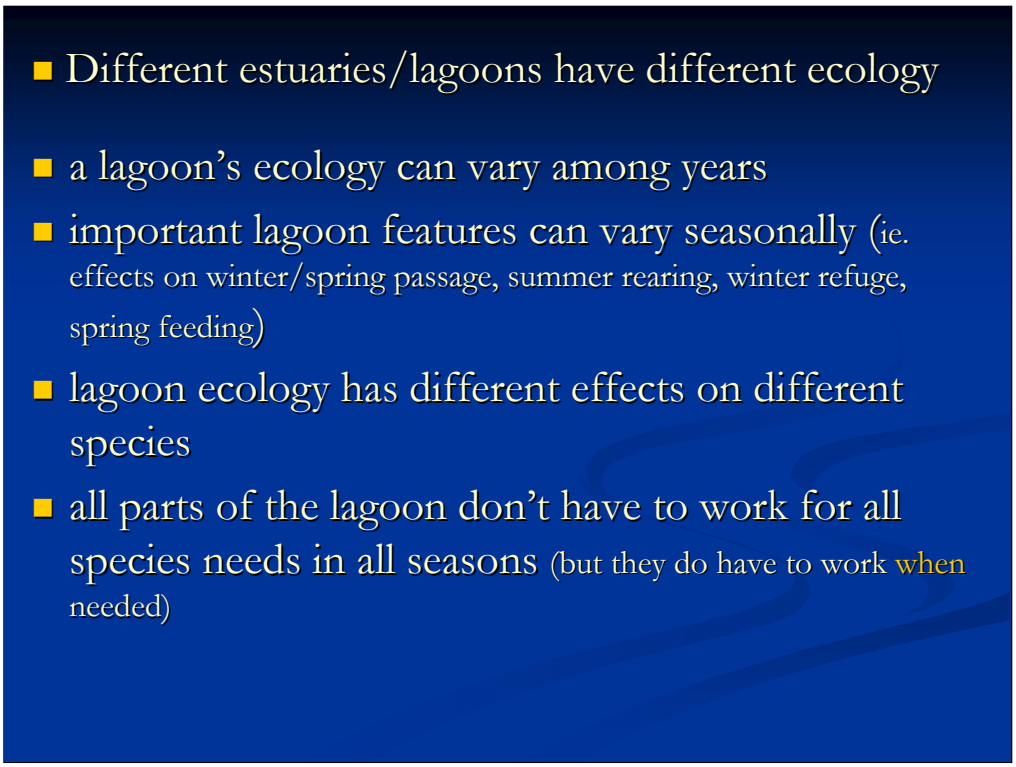


Oral presentation at Salmonid Restoration Federation Conference, March 2009

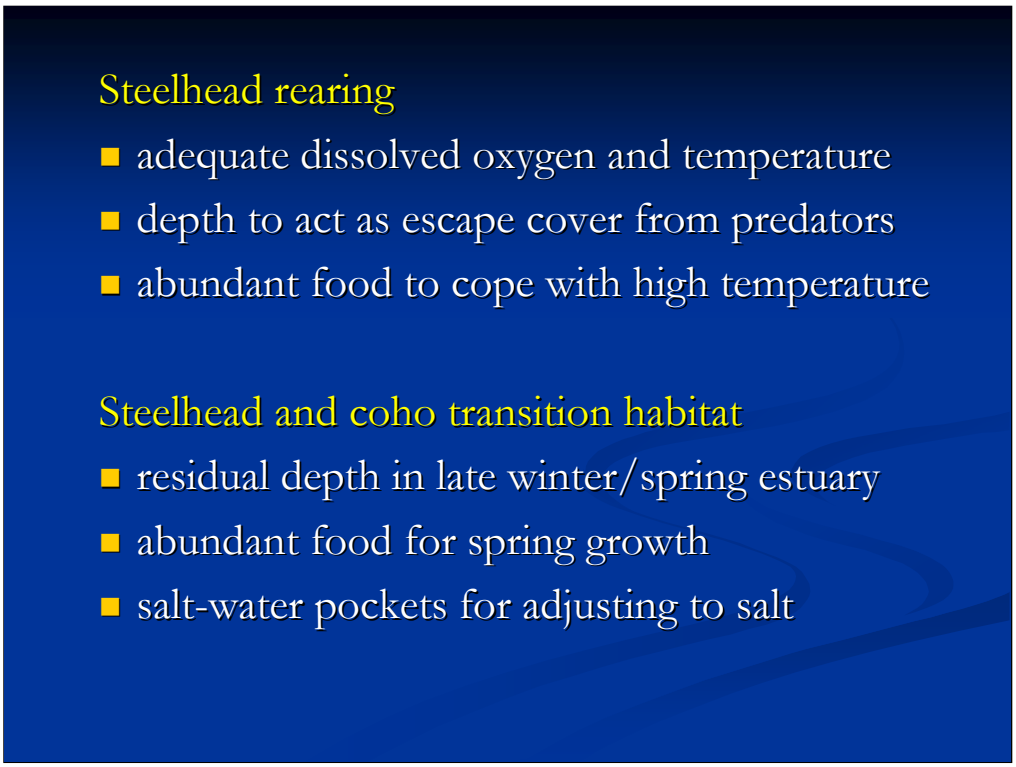


Lagoons differ depending upon size (area, depth), whether and when they develop a sandbar, the amount of freshwater inflow after bar formation, primary production, wind, etc.

Ecology can vary among years due to changes in timing of bar formation (usually later in wet years) and amount and timing of summer inflows.

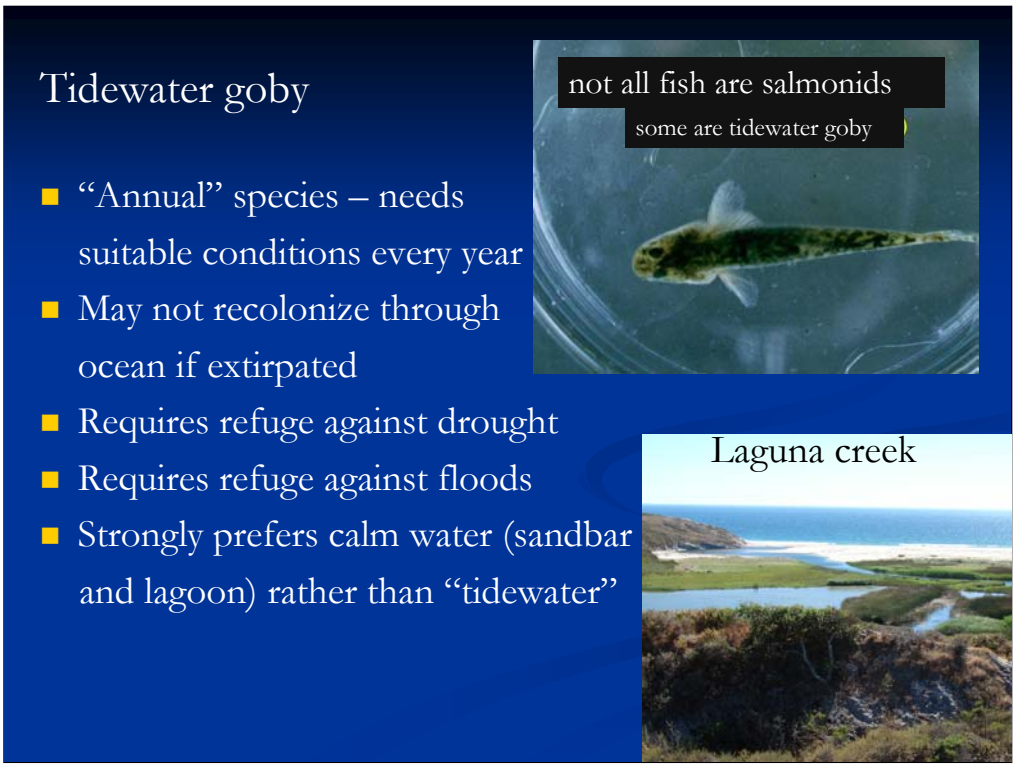
Estuary configuration and size/depth can affect summer rearing, and based upon residual depth at low tide when the bar is open, can affect winter refuge, spring feeding and spring brackish transition habitat.

Steelhead can use the estuary lagoon in some or all seasons depending upon conditions. Some systems provide only summer rearing (Scott, Laguna, Soquel) and lack spring feeding and brackish transition habitat. Others may not rear fish in summer because of insufficient inflow or summer breaching, resulting in dry or brackish/warm conditions, but provide spring feeding or brackish transition habitat. Tidewater goby must have suitable conditions within the estuary complex all year; this includes summer calm lagoon condition (behind sandbars), flood refuges in winter, and refuges in dry years. Red-legged frogs may use seasonal (winter-spring) or backwater freshwater habitat for breeding.



Recent interest and emphasis in estuary/lagoons has been on summer rearing habitat for steelhead. Despite (or because of) the warm conditions, abundant food can produce habitat capable of support abundant fast-growing steelhead that can smolt after 1 summer. This will be one focus of this talk.

However, the role of the estuary in potentially providing feeding conditions for upper watershed smolts of both coho and steelhead in spring and also in providing a brackish water transition zone to aid adaptation to salt water should also be recognized. A system with sufficient residual depth at low tide, areas of salt water for adjustment and abundant invertebrate food from marsh or marine detritus or from phytoplankton blooms can dramatically increase upper watershed smolt size and ocean survival.

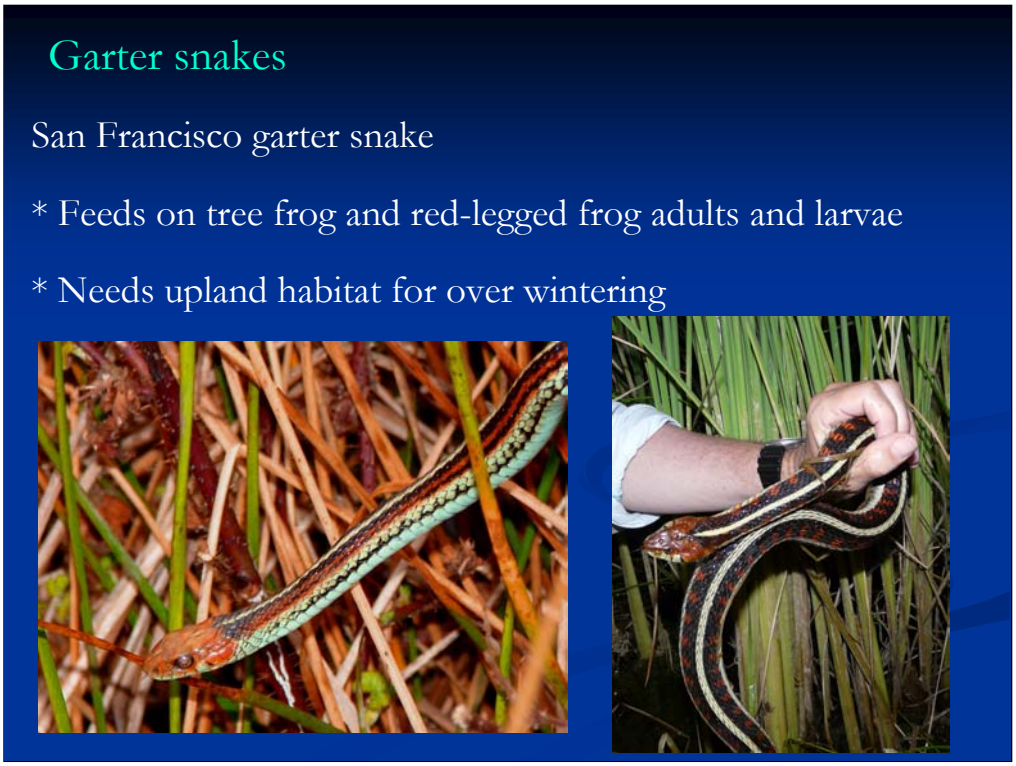


Because they mostly live less than 1 year, conditions have to be suitable every year—there is no multi-year population carryover. In addition, since they travel poorly between watersheds more than 1-2 km apart there is little chance of recolonization. Most coastal populations show substantial genetic differences (including unique allele and haplotypes), reflecting lack of recent gene flow among populations.

Maintaining the independent populations requires refuges against droughts and floods and usually a calm embayment behind a sandbar for best population growth in summer. Tidewater gobies should be renamed "lagoon gobies" to reflect their dependence upon calm lagoon conditions and avoidance of strong "tidewater."

Laguna Creek in Santa Cruz County barely had residual pool habitat when most of the lagoon dried in the in the droughts of 1987-1991. In winter the off-channel pond provides a flood refuge that the main stream channel fails to provide. A sandbar forms in summer, but is often breached artificially by beach goers. The population has persisted, but it's biggest recent threat was a "restoration" proposal that would have eliminated the off-channel pond (which is also red-legged frog breeding habitat), and the structure that produced the residual pools in favor of "restoring hydraulic connectivity" and producing a large, simple summer lagoon for steelhead rearing.

At Waddell Creek in Santa Cruz County red-legged frogs breed in a seasonal pond in the marsh at the mouth, which is subject to occasional salinity problems that kill eggs and/or tadpoles. Fortunately breeding doesn't have to successful every year since the frogs there have been found to live long to enough to breed in several years (and live up to 12 years old). The breeding period is brief (mostly 2-3 weeks) and usually early (January to February) because the pond dries early in summer, providing successful tadpole metamorphosis in only wetter years.



At Waddell Creek and in San Mateo County endangered San Francisco garter snakes (left) are present in estuarine marshes, where then depend tree frogs and red-legged frogs as a dominant food source. If conditions for frogs are degraded, snakes also suffer. Santa Cruz (aquatic garter snakes), red-sided garter snakes (right) and terrestrial garter snakes are also present in coastal marshes.

Western pond turtle

- Tolerant of moderate salinity
- Basking habitat very important
- Long-lived (30+ years)
- Lagoon turtles over-winter in seasonal or perennial wetlands or in upland habitats (flood avoidance)
- Nest in sunny, sparsely vegetated habitats (grasslands, non-irrigated agricultural fields) above flood plain
- Hatchlings may over-winter in the nest

Western pond turtles as indicated above, also require of variety of habitat types at different times of the year to maintain healthy populations. Because of their longevity a turtle population may persist for some time after suitable nesting habitat has been eliminated.

Pescadero and San Gregorio lagoons in San Mateo County have been intensively studied in average, wet and dry years.

Pescadero has an extensive lagoon/marshland complex that is flooded when the bar is in place (left photo); most of the complex is drained when the sandbar is open.

The sandbar at Pescadero formed in late spring/early summer until levee modification and Highway 1 bridge replacement in the early 1990's. Now it remains open until fall and most of the complex is dry in summer (right photo). Low inflows after bar formation now produce stratified conditions that that persist through fall vegetation dieback; bottom hypoxia/anoxia result in fish kills when the bar is breached and surface and bottom hypoxic waters mix.

A debate about whether it is better for the lagoon to stay open or closed in summer for steelhead continues, but ignores the devastating effect of the loss of aquatic habitat in North Marsh in summer (left side of the right picture) when the sandbar is open. This was a/the major habitat of the red-legged frog, San francisco garter snake, western pond turtle and tidewater goby.

San Gregorio has relatively little marshland that is flooded when the sandbar is in place because of an incised stream channel at the estuary.

It is subject to frequent (illegal) breaching in summer due to beach access issues (when the configuration moves to the cliff to the north (left)) and due to upstream agricultural concerns.

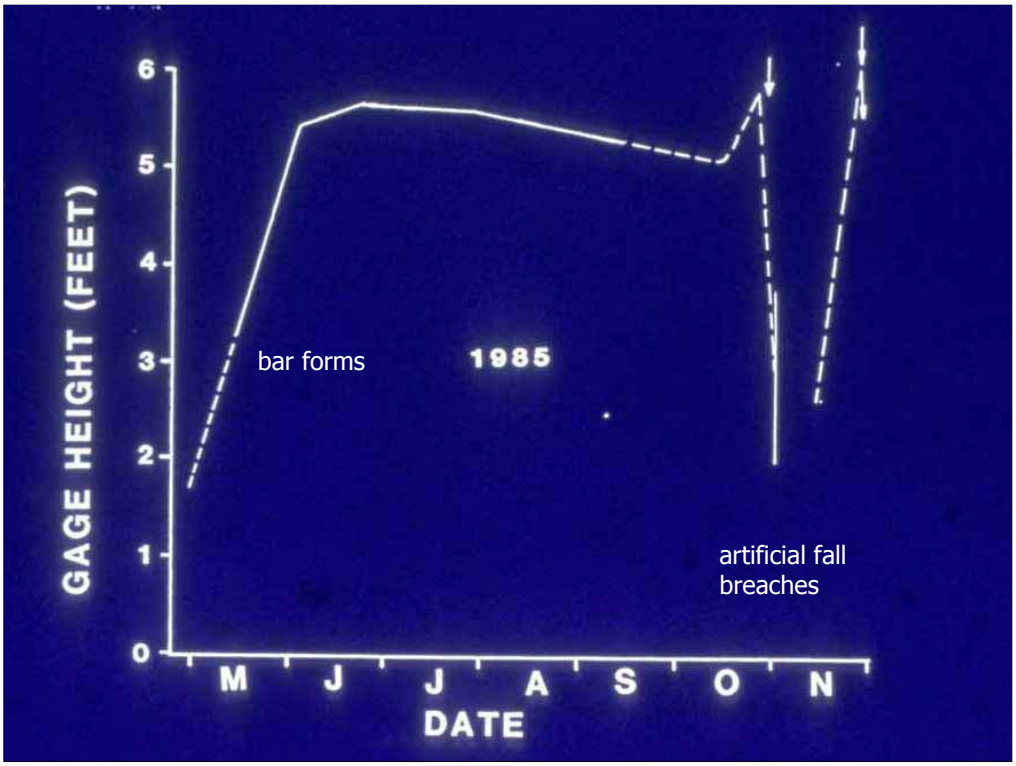
The mouth of lagoons is opened in fall or winter by overtopping or wave erosion of the bar.

Storm flows and wave erosion further open the bar and erode and also narrow and lower the beach. This erosion is greater in wet winters.

In late spring and summer low energy waves deposit sand and rebuild the beach and the sandbar.

Lower stream flows allow easier sandbar formation, but even with high (100-200 cfs) outflows due to stream or tidal flow the bar can be plugged by wave action.

Greater winter erosion of the bar and beach delay bar formation. In addition, offshore sand supply, tidal prism of the estuary, and scour patterns of tidal flows affect timing of sandbar formation or whether a sandbar fully forms.



After the sandbar formed on Pescadero Creek in mid-May 1985 the lagoon depth rapidly increased by about 3 feet (compared to only about 3 feet deep in the deepest spots at low tide prior to bar formation).

The lagoon level maintained most of its depth despite declining inflows until mild rains in October raised the depth about ½ foot.

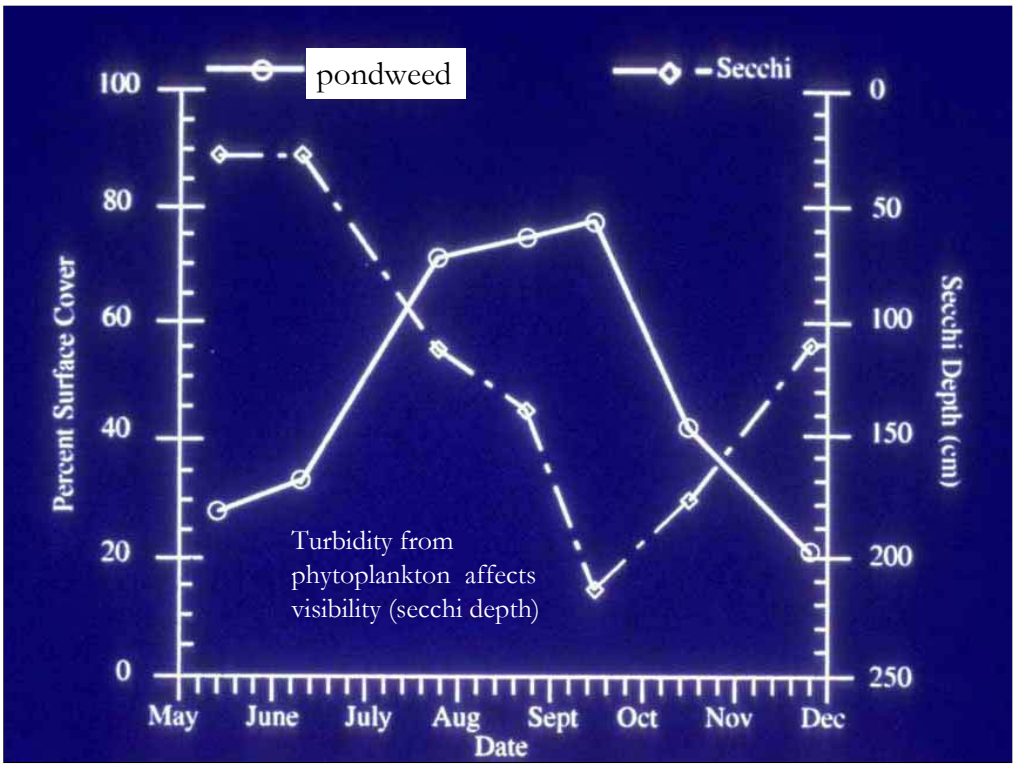
The sandbar was breached on 31 October by farmers concerned about lagoon flooding of agricultural fields. The bar re-formed and was breached again on the day after Thanksgiving.

The raised lagoon levels behind the sandbar increased lagoon area by about 3-4X and flooded marshlands bordering the estuary.

Invertebrate abundance exploded in the flooded marshlands. Steelhead foraged in channels in the flooded marshlands, although water quality (dissolved oxygen) was sometimes a problem at night or during prolonged foggy periods because of decomposition and plant respiration.

Primary production in the main embayment included filamentous algae that supported abundant amphipods and isopods as food for steelhead and other fish.

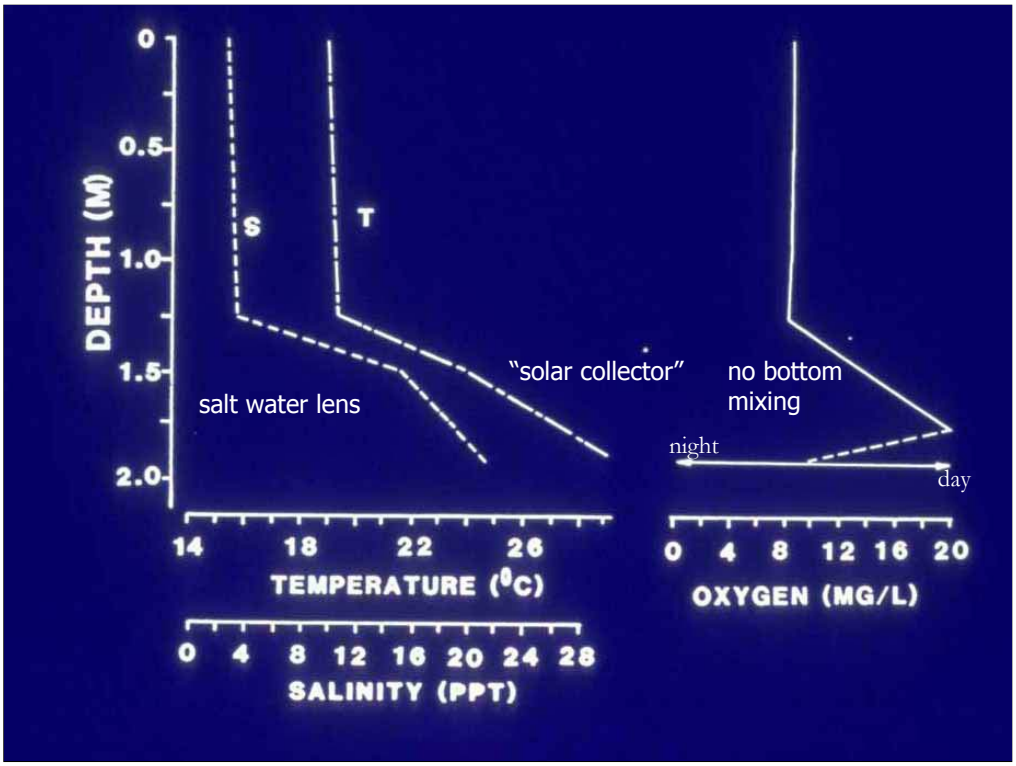
Dissolved oxygen levels sometimes dipped at night or during foggy periods due to plant respiration, but wind mixing in unstratified areas was usually sufficient to maintain adequate DO.



The third form of primary production can be phytoplankton, which results in turbid water conditions. As the pondweed develops it removes nutrients from the water column and becomes dominant, reducing phytoplankton and clearing the water. In fall, when the pondweed dies back, phytoplankton again becomes important.

Either rooted aquatics or turbidy can be important hiding cover elements, reducing predation on steelhead.

Neomysis shrimp, a preferred steelhead food, can be very abundant feeding on phtyoplankton or particulate organic matter. The pondweed is a substrate for epiphytic algae and supports abundant amphipods, isopods and also freshwater insects when the lagoon becomes fresh.

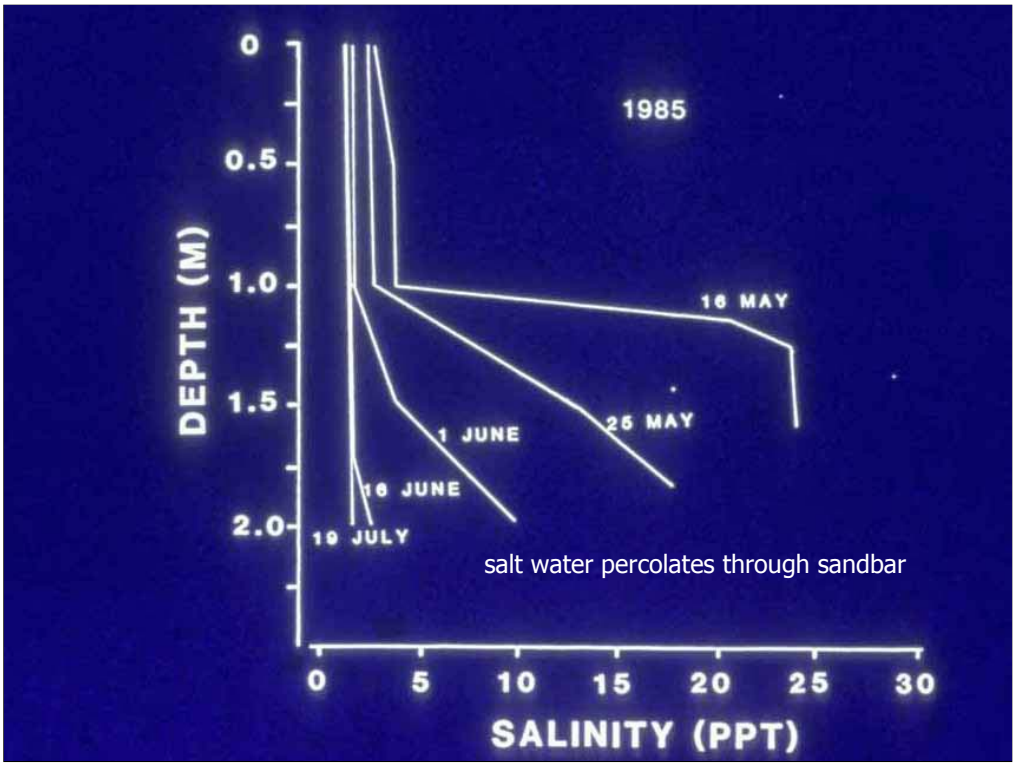


The driving feature for water quality and steelhead suitability in a closed lagoon is usually stratification of the water column by salinity, with the denser salt water on the bottom. These data are from Pescadero lagoon after recent sandbar closure in July 1984.

Stratification by salinity prevents mixing, and in shallow (most) lagoons the bottom layer heats during the day and can't lose its heat because mixing is blocked—the bottom becomes much warmer than the surface, which is able to cool at night. In deep lagoons (Russian River) the warm saline layer may actually be in the middle of the water column, because sunlight can't penetrate to the bottom.

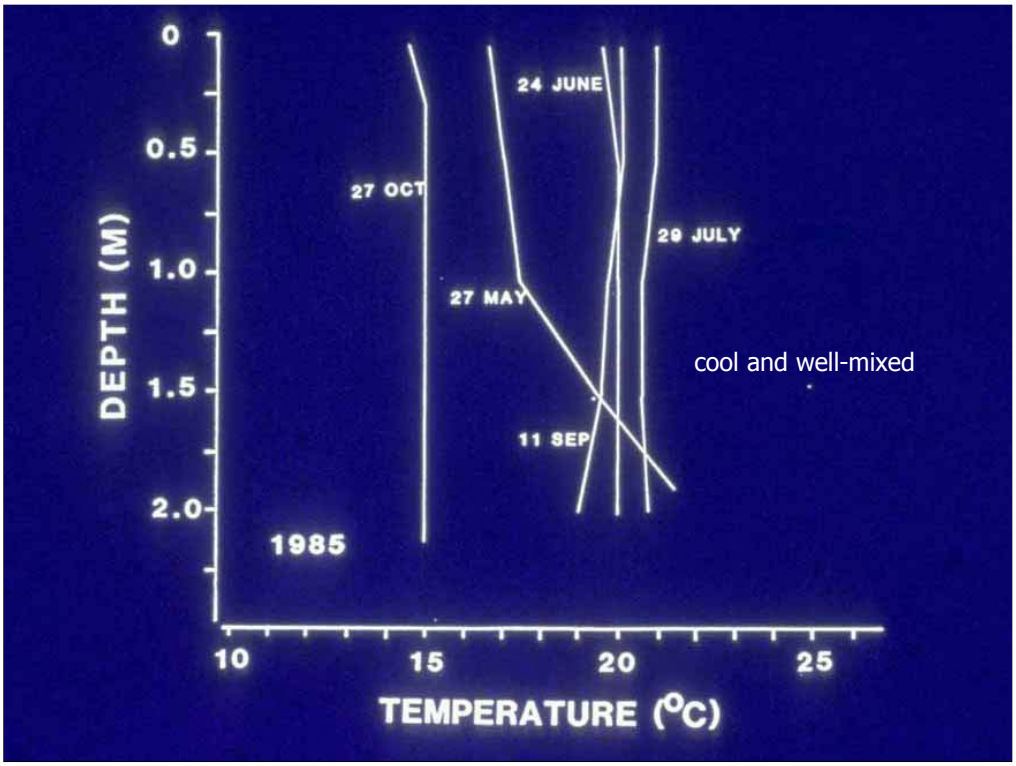
Because of lack of mixing the bottom layer cannot recharge with dissolved oxygen from the surface; the bottom layer may become anoxic due to decomposition of organic matter or (as shown here) fluctuate radically with daytime photosynthesis and nighttime respiration by abundant algae or pondweed.

Water quality monitoring of the relatively stable temperature and salinity profiles can easily detect stratification, which usually indicates potential water quality problems for steelhead and/or their invertebrate food. Monitoring of profiles for dissolved oxygen is sensitive to time of day or weather—the "problems" with dissolved oxygen may occur only episodically.

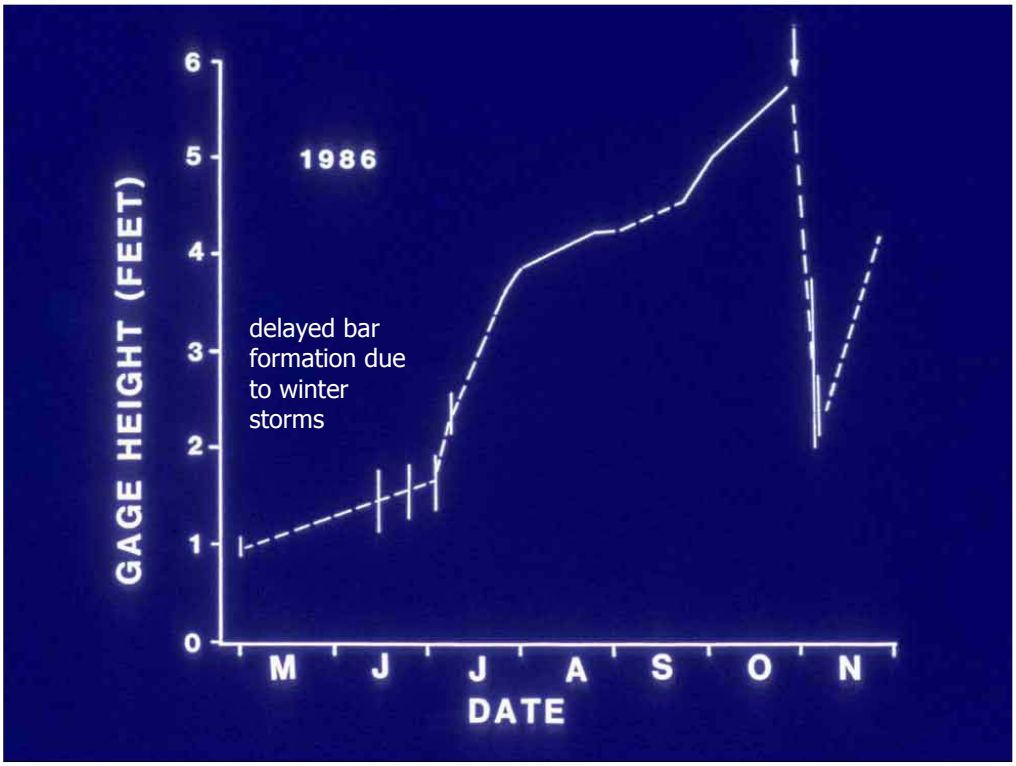


In most systems the lagoon bottom generally slopes towards the sandbar, with most of the deepest water against the bar. With raising lagoon levels, due to adequate freshwater inflow, the bottom salt water is gradually percolated through the bar eliminating the saltwater lens throughout most of the lagoon.

Isolated saltwater lenses may exist in deeper holes in upstream portions of the lagoon.

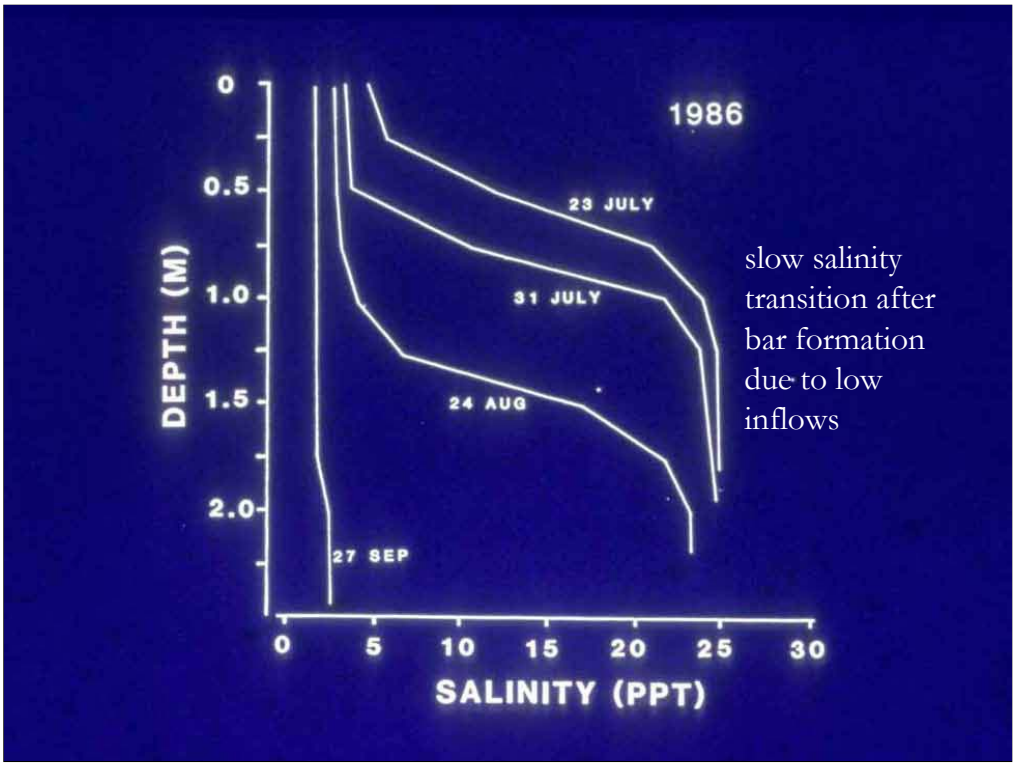


After conversion of the lagoon to fresh water the destratified system can mix easily and water temperatures tend to be relatively cool throughout the water column and dissolved oxygen levels are also generally good. Invertebrates and steelhead can be very abundant.

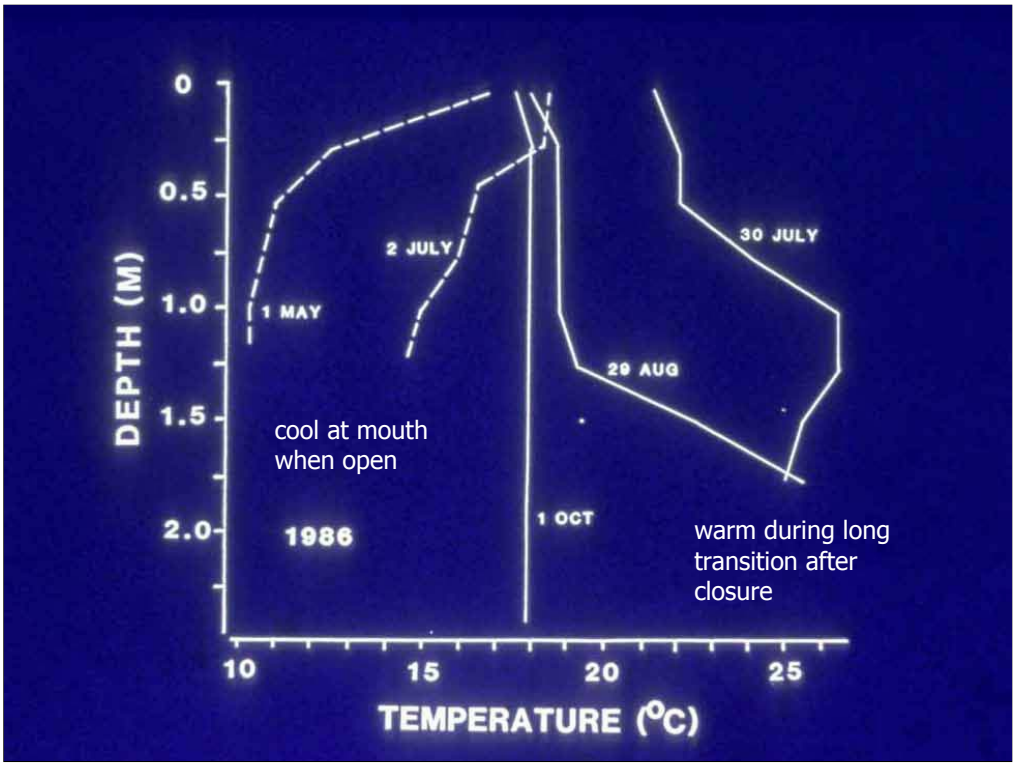


In 1986 the sandbar at Pescadero Creek formed late (mid-July) due to severe erosion of the beach by February storms; it took longer for the beach to re-form and for the sandbar to develop.

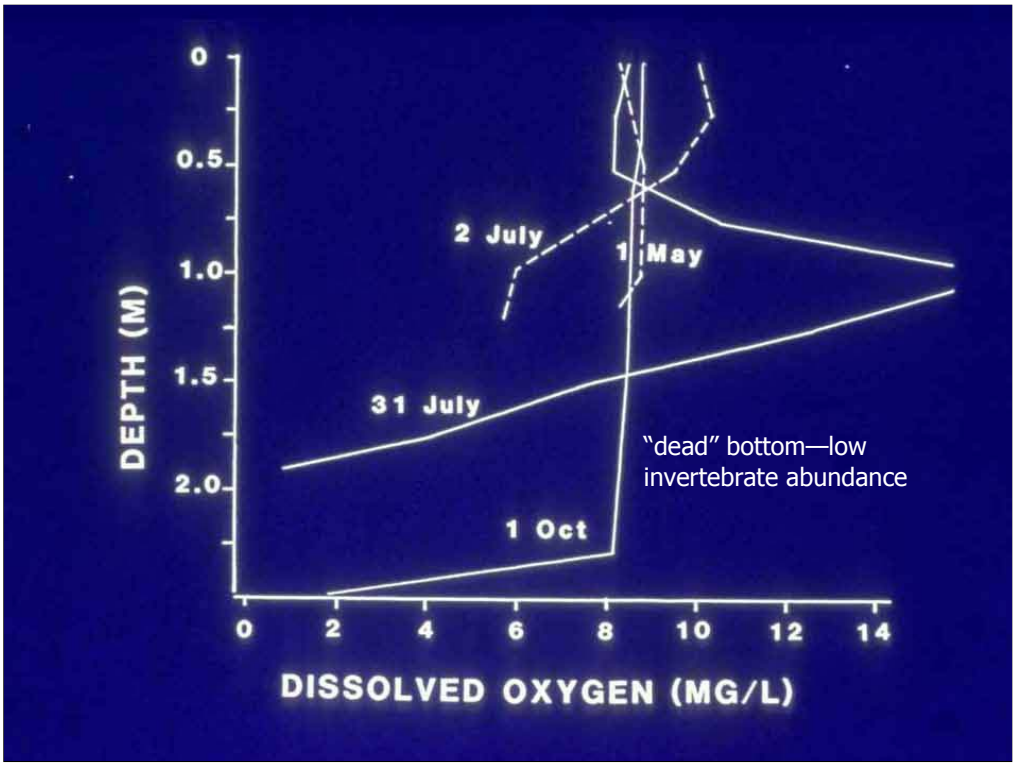
By the time of bar formation, inflows to the lagoon were quite low (due to diversions upstream) so the lagoon only slowly increased in depth behind the bar. The bar was again breached artificially by farmers on 31 October.



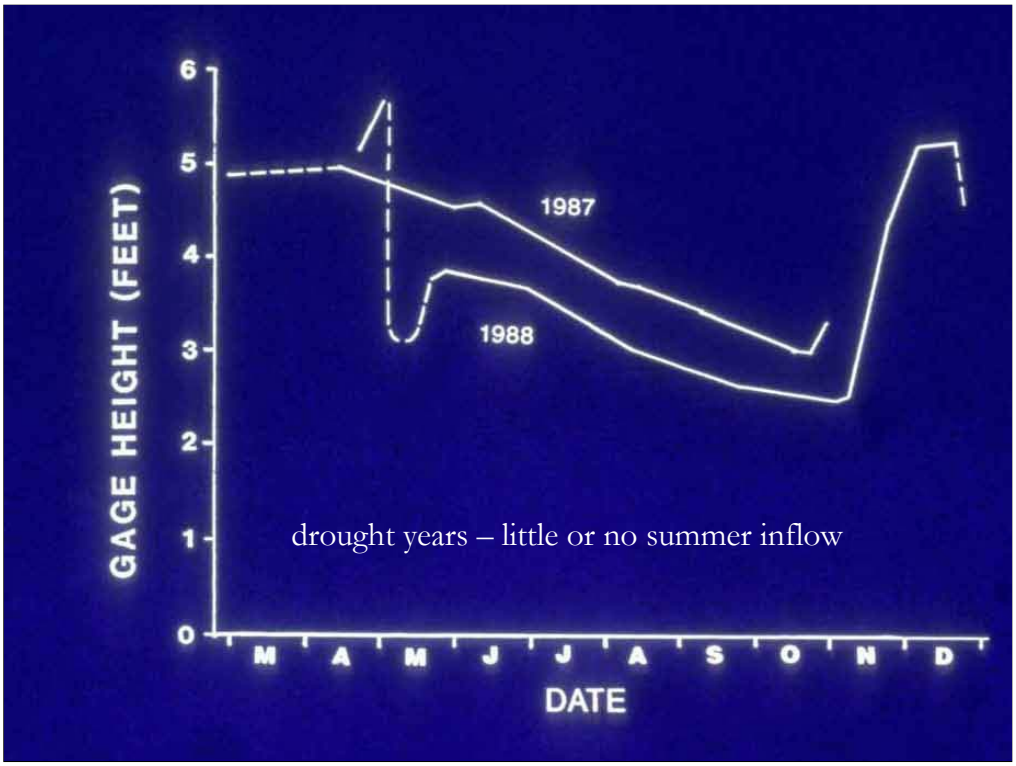
Because of low inflows after sandbar formation, the lagoon maintained a slowly decreasing saltwater lens that blocked mixing through September.



The lower embayment at Pescadero was tidally mixed and cool through early summer. It then rapidly heated on the bottom in the stratified salinity conditions after bar formation. Invertebrate abundance dropped and steelhead grew poorly during the transition period. Destratification by late September resulted in a mixed and relatively cool lagoon.

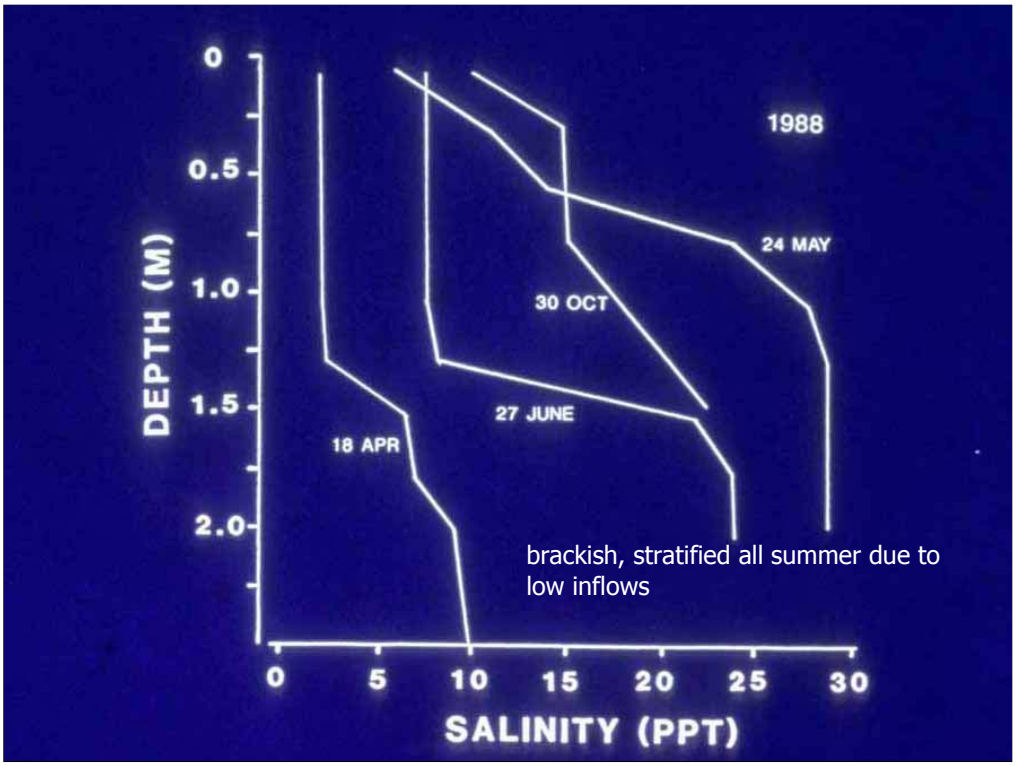


Bottom dissolved oxygen levels fluctuated widely during the day after sandbar formation, but were generally poor at the bottom, sharply reducing invertebrates and affecting steelhead growth.

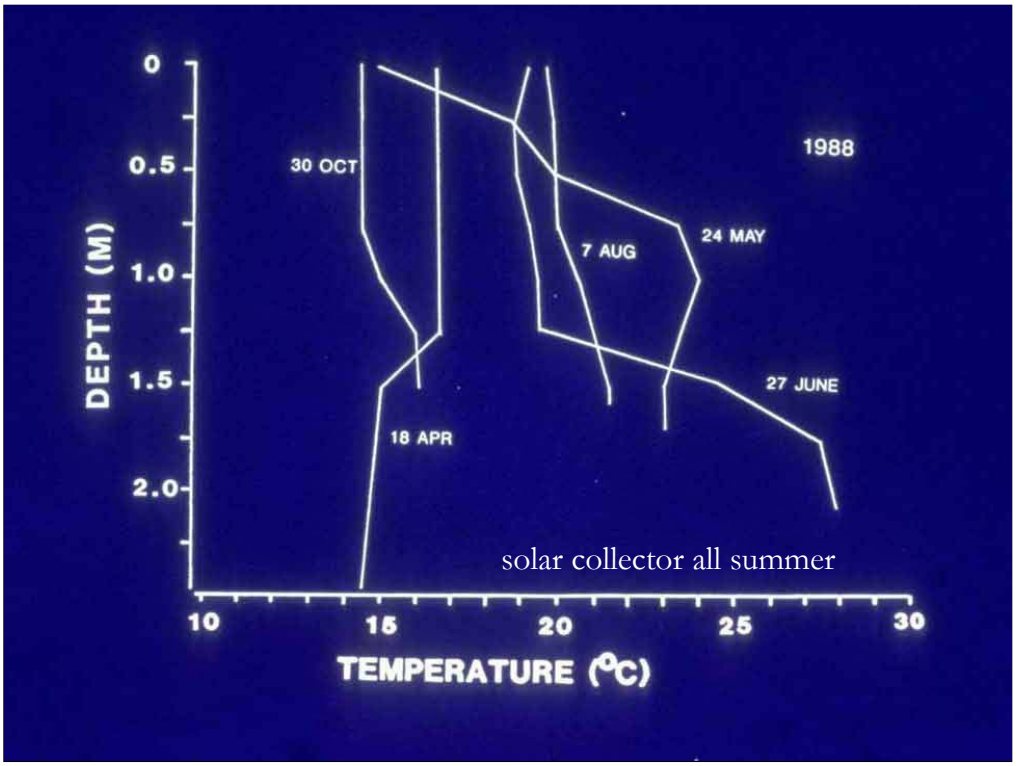


In 1987, 1988 and 1989 the sandbars formed early because mild and few winter storms did not erode the beach substantially.

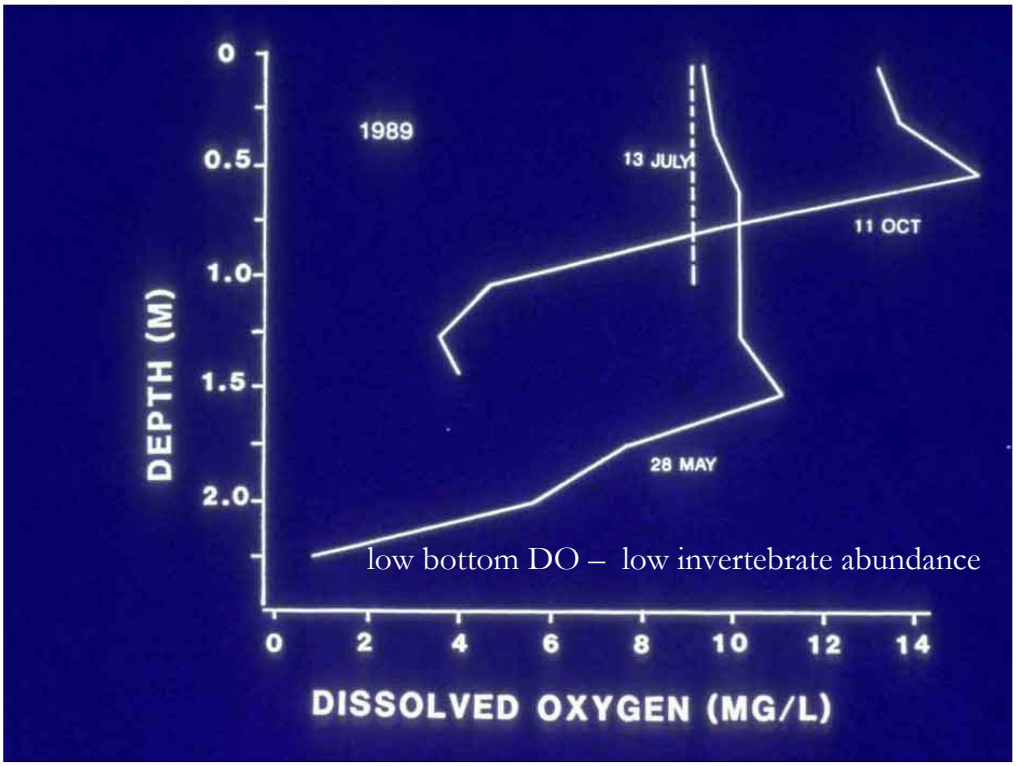
Very low inflows resulted in lower and progressively declining lagoon water levels over the summer.



Because of a lack of inflows the lagoon remained brackish and stratified all summer.



The saltwater layers were warm throughout the summer, invertebrates were relatively scarce, and almost no steelhead survived the summer.

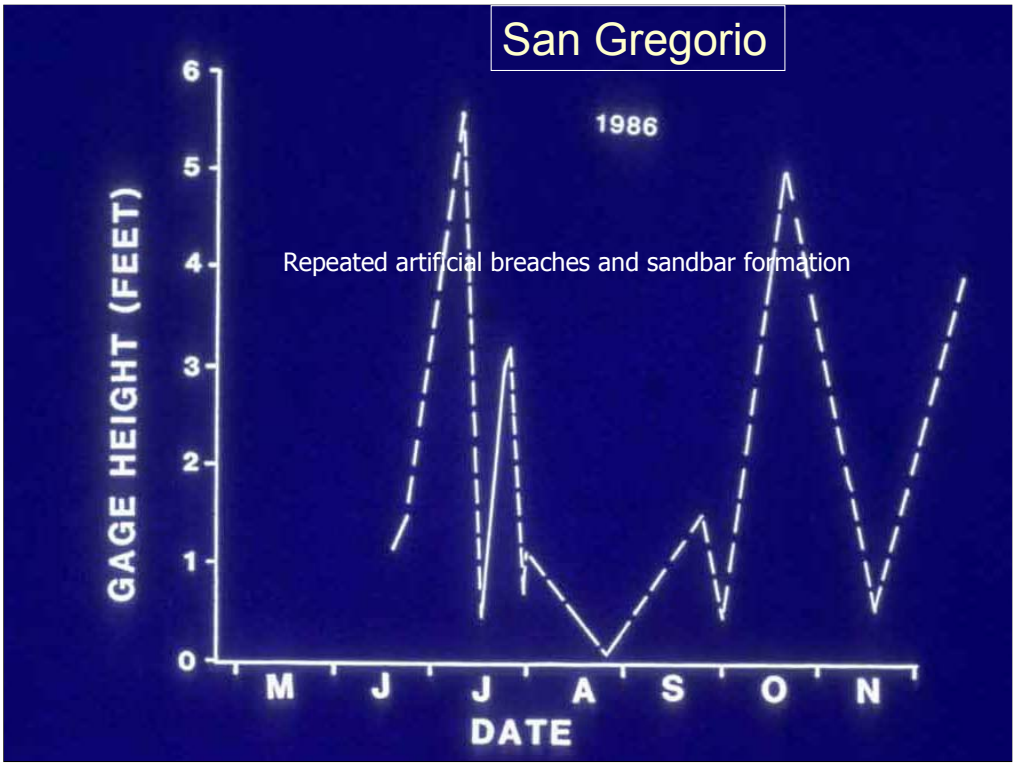


Dissolved oxygen levels were low on the bottom throughout the summer, greatly reducing invertebrate abundance and food available for steelhead.

- Bar formation increases lagoon area & depth
- Summer primary production can be high
- Inflows convert lagoon towards destratified fresh water
- Transition periods & insufficient inflows result in stratified, warm, lagoon
- Stratification can result in poor invertebrate abundance and poor steelhead survival and growth

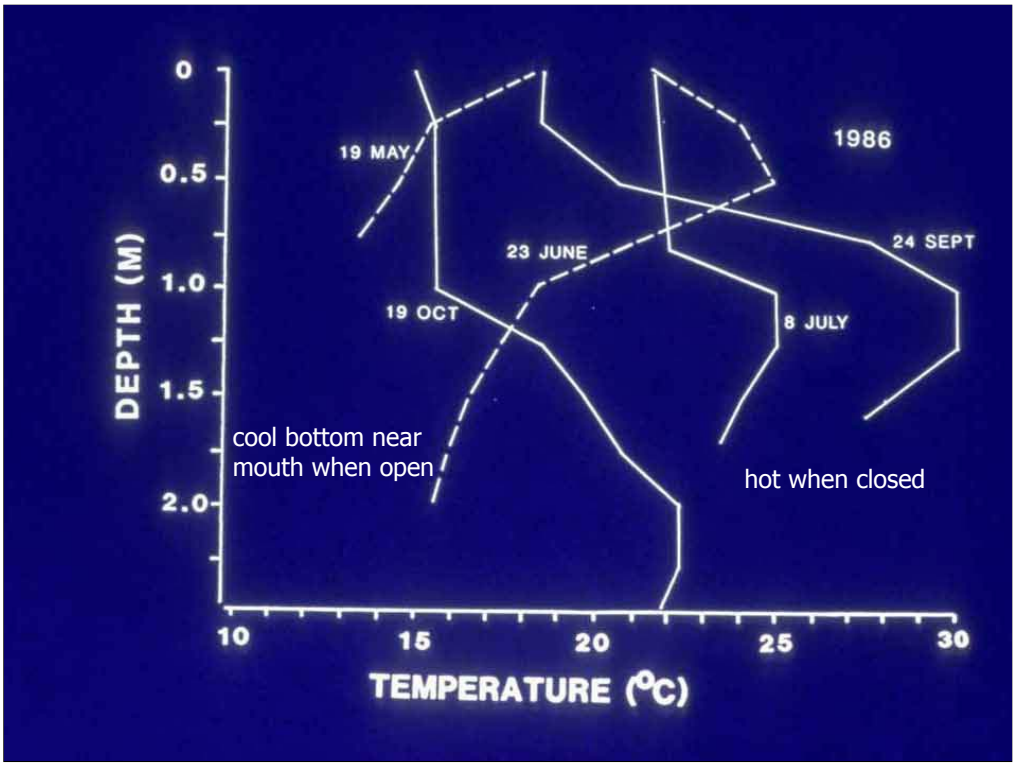
Summer production can be high in the closed lagoon if inflows are sufficient to quickly convert the system to a mixed freshwater lagoon.

Prolonged transitions or persistent brackish, stratified conditions result in fewer invertebrates and slow steelhead growth and/or very low survival.



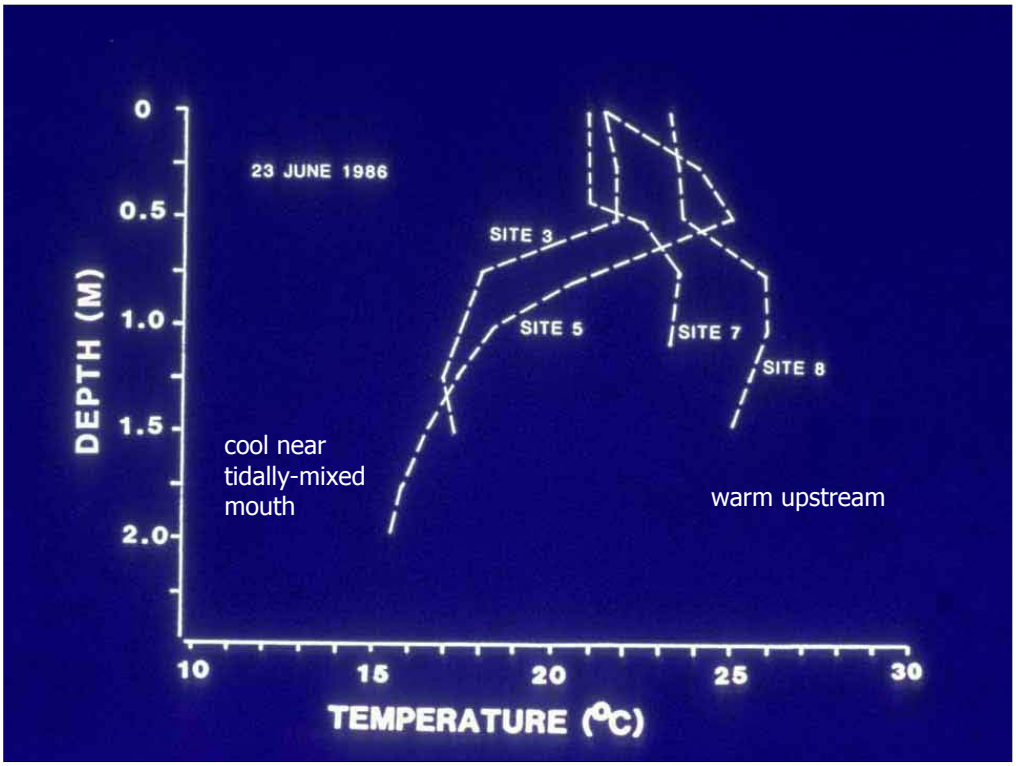
San Gregorio shows the same general pattern of high production with closed, freshwater conditions. However, it is subject to frequent artificial sandbar breachings in summer.

In 1986 the sandbar at San Gregorio was repeatedly breached over the summer to provide access to the beach by State Park visitors. Breaching was done by State Parks and by beach visitors. Breaching was also apparently done by farmers who diverted water from the upstream portion of the lagoon, since they feared that their diversion would pump saltwater (even though the surface water in upstream areas was fresh).



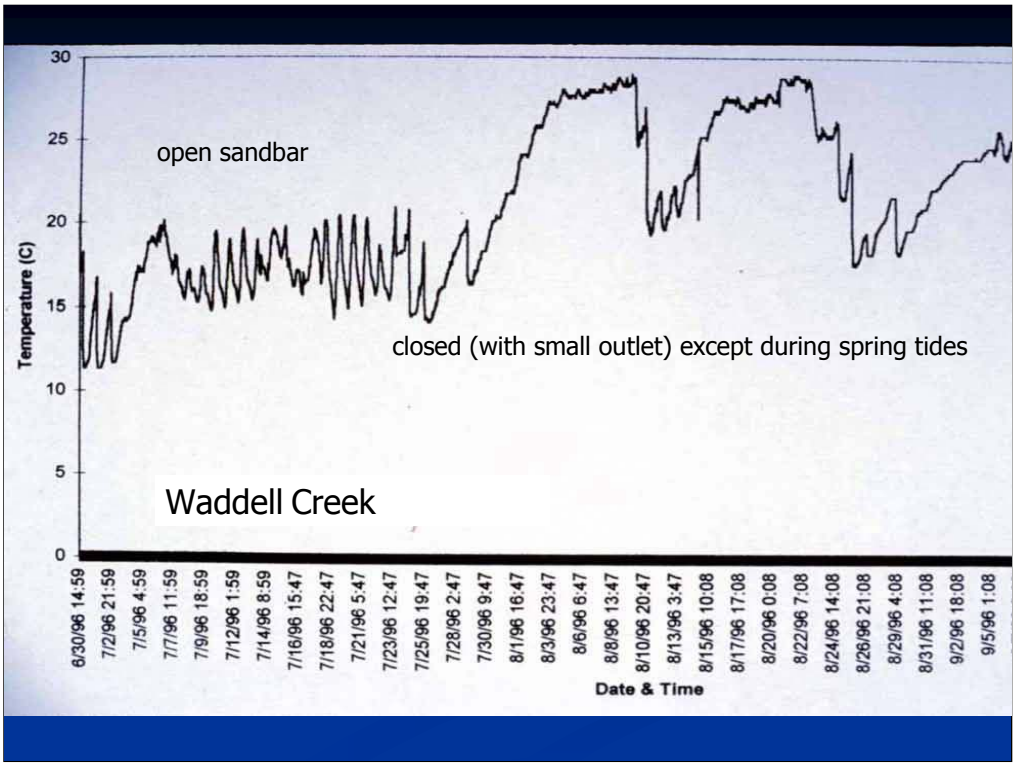
When San Gregorio lagoon was open (dashed lines, 19 May & 23 June) the lower part of the water column profile in the area near the sandbar was cooled by tidal action.

After each sandbar closure (solid lines, 8 July & 24 September) the bottom saltwater layer rapidly heated up and often suffered dissolved oxygen problems due to the lack of mixing.



Although the lagoon was cool and mixed by tidal action when the sandbar was open, this effect expended upstream for only a small part of the lagoon (through sites 3 and 5—at and downstream of Highway 1).

At upstream sites the lagoon rose and fell and sloshed up- and downstream with tidal action, but there was no mixing with cooling ocean tides. The lower, salty portion of the water column heated up quickly. Steelhead primarily used only a small downstream portion of the lagoon for rearing.

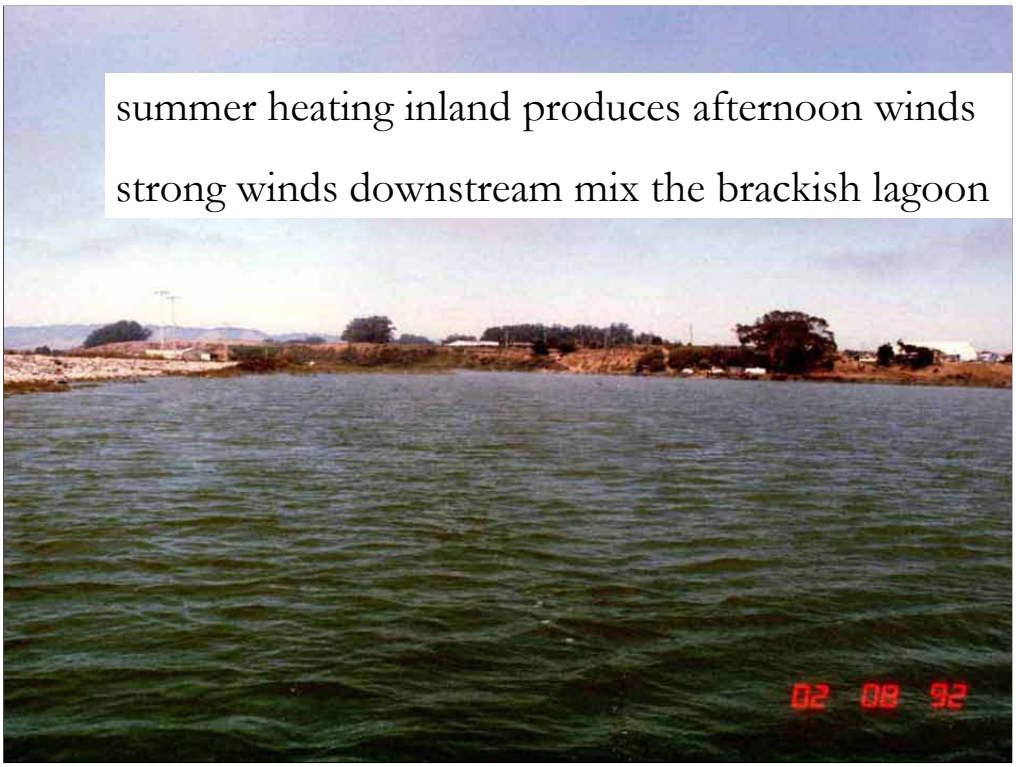


The sandbar at Waddell Creek has only partially closed in summer since about 1995 (compared to full closure in the 1980's). Periodic full closures are usually overtopped or artificially breached by beach visitors.

After the mouth pinched off to a small outlet in 1996, the saltwater layer near the bottom rapidly heated up to 28+ degrees. The bottom was briefly cooled (and depressed oxygen levels were raised) every 2 weeks during the higher tides of the spring tide periods.

The Pajaro River (Santa Cruz/Monterey county line) tends to remain open with a progressively smaller opening all summer, apparently due to insufficient sand to close the mouth—the partially open mouth gradually moves south along the coast.

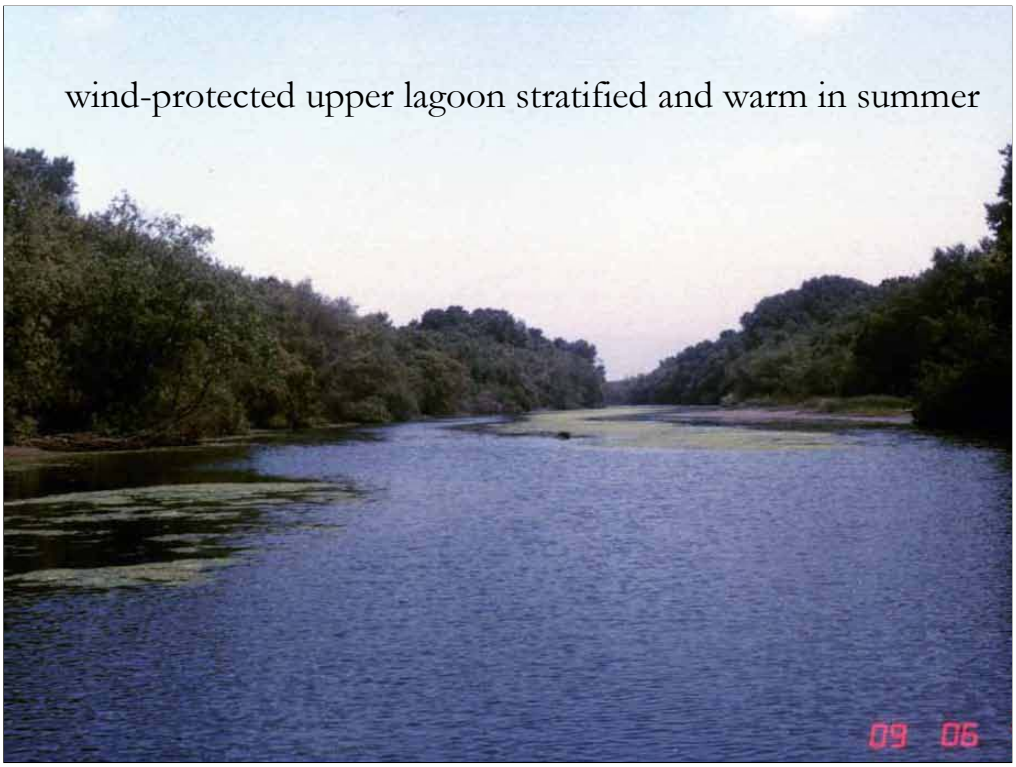
The first mild storms in fall (late September-November) tend to pull some sand off the beach, and the additional available sand usually results in sandbar closure in fall. The mouth is usually artificially breached as lagoon levels get high enough to cause flooding in fall or if a large storm is anticipated.



The downstream portion of the large Pajaro lagoon has high winds that are capable of mixing the brackish water of a closed or partially closed lagoon. Despite the brackish conditions the mixed lagoon can be relatively cool (with abundant cooling at night).

Also, despite eutrophic conditions due to abundant agricultural return flows, the mixed lagoon usually has good dissolved oxygen levels.

Conditions are suitable for steelhead rearing, but apparently little or no rearing occurs because spawning areas are quite far upstream, mostly upstream of stream sections that are dry by early summer.



Even when the windy downstream areas of the Pajaro lagoon are well mixed, the narrow, tree-lined and protected upstream 2/3 of the lagoon is strongly stratified for salinity, warm in the bottom layer, and suffers from periodic to persistent dissolved oxygen problems. Fish abundance (primarily euryhaline species) is highest in the mixed, downstream portion of the lagoon.

The Salinas River mouth is oriented to the north and catches abundant longshore drift. The mouth closes easily and early in all but the wettest years. It remained closed through the entire 1987-1991 drought.

A culvert to the Old Salinas River channel (north side, near the hill in the picture to the left) drains off modest lagoon inflows. The lagoon is artificially opened during or immediately prior to high lagoon levels from major storms

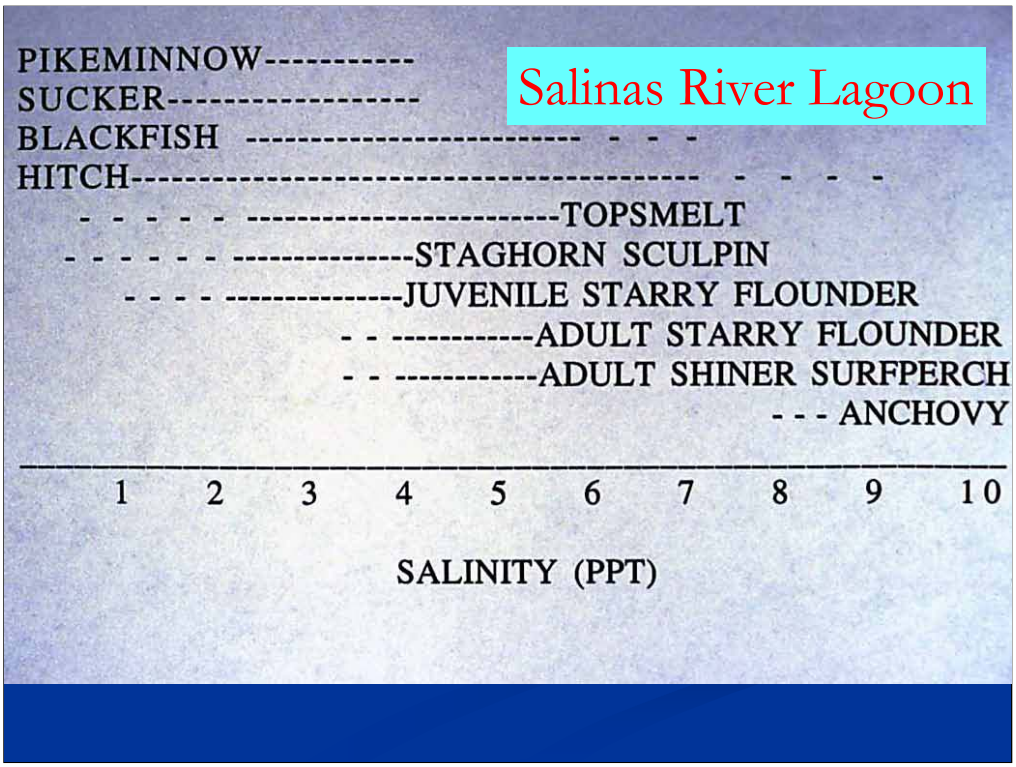
As at the Pajaro River, strong afternoon winds mix this brackish lagoon, resulting in a lack of salinity stratification, relatively cool water and usually high dissolved oxygen levels, despite highly eutrophic conditions (due to agricultural return flows as the major inflows in summer).Upstream of Highway 1, the narrow, tree-lined and wind-sheltered channel is stratified for salinity, temperature and dissolved oxygen.

Also, as at the Pajaro River, conditions in summer would be suitable for rearing steelhead, but spawning areas are far upstream (more than 40 miles for the Salinas); no steelhead rearing apparently occurs.

- Open systems can be productive (and cool) in tidally mixed area near mouth
- Wind can mix some wide, shallow, closed brackish systems
- Upstream of tidal mixing or wind, brackish lagoons are stratified, warm and hypoxic

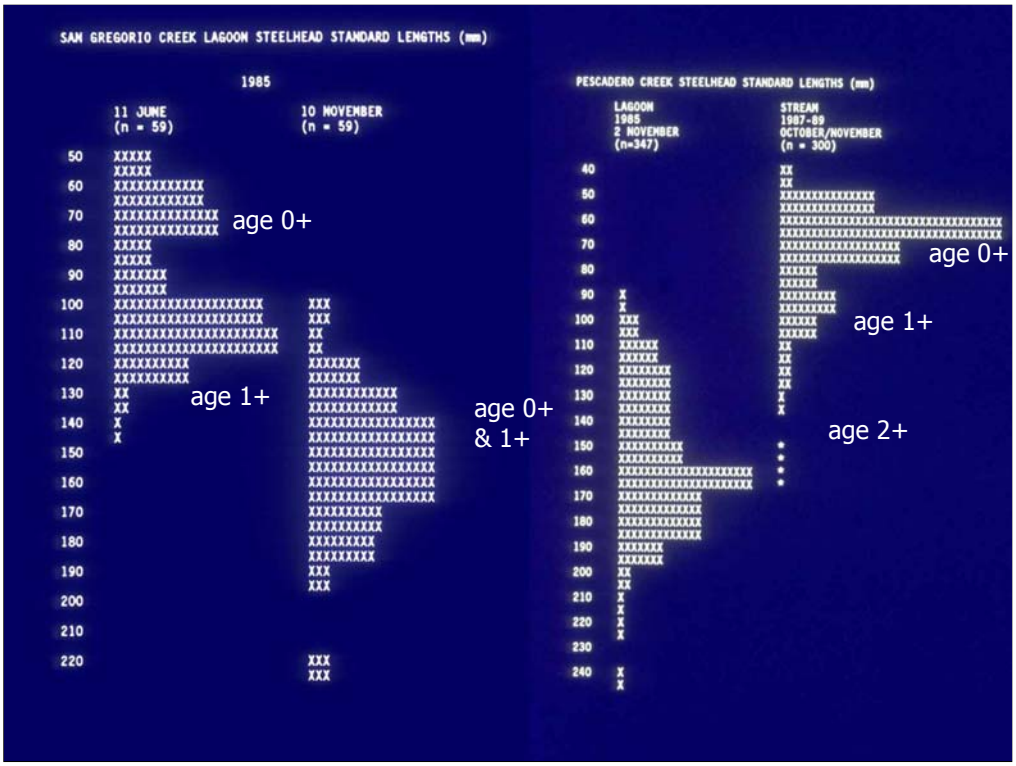
The tidally mixed or wind mixed area of an open lagoon may be a relatively small compared to conditions in a closed, freshwater lagoon.

Whether an open or closed system is better depends upon the extent of the tidal mixing effect and on whether there is sufficient freshwater inflow to destratify most of closed system.



Because of the destratification of the lower Salinas River lagoon, there is often a progressive decrease in salinity upstream, but without any vertical difference at a site.

This provided ideal conditions to test salinity tolerances, and demonstrated that native “freshwater” fish like pikeminnow, blackfish, hitch and suckers can use brackish lagoons at salinities up to 10-20% of full sea water. It also demonstrated that freshening of lagoons from freshwater inflow would progressively eliminate many saltwater fish; few species (topsmelt, staghorn sculpin and juvenile starry flounder) would survive below about 10% seawater.

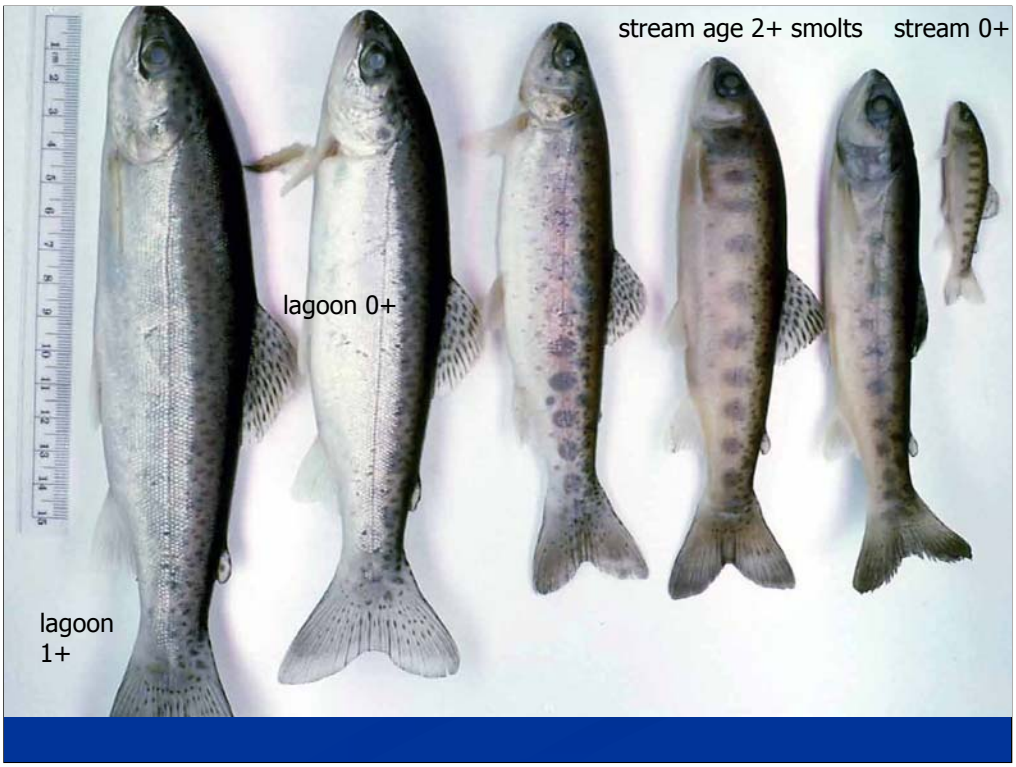


Under well-mixed conditions in the lagoons steelhead growth is excellent. Young-of-year (YOY) and yearling steelhead show a bimodal size distribution in early summer (Left graph, for San Gregorio in 1985), but both age groups grow fast and the YOY catch up by the end of the summer, producing a unimodal size distribution by fall (November 1985 for both San Gregorio and Pescadero lagoons).

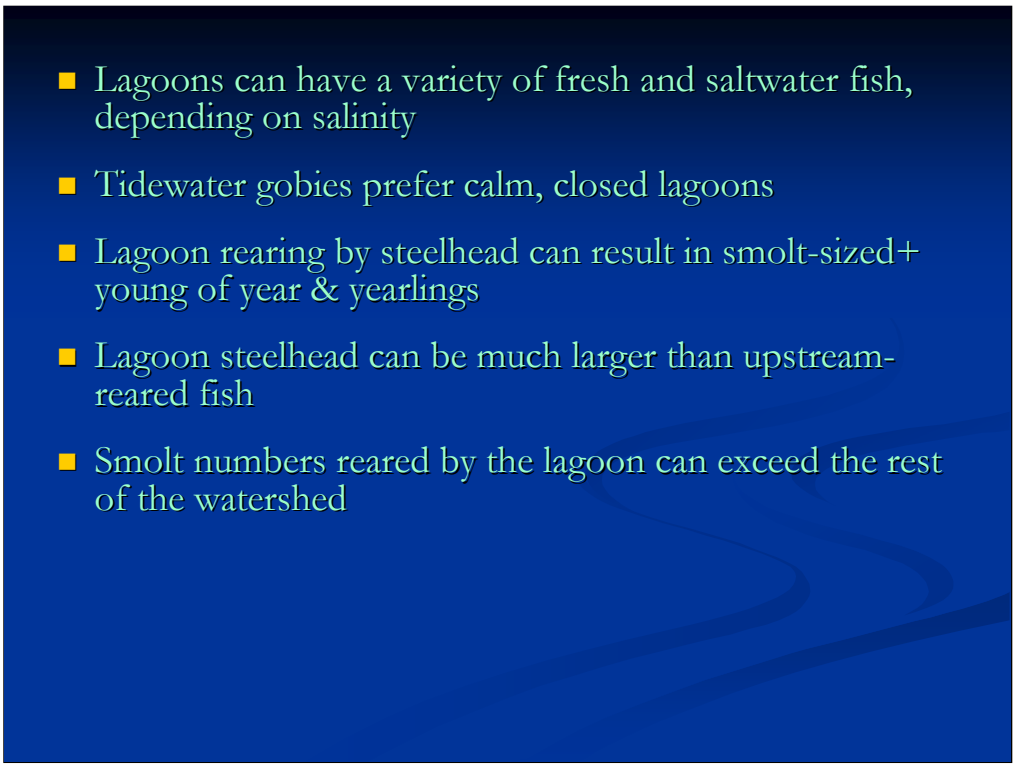
In many lagoons (San Gregorio, Scott) substantial numbers of yearling fish apparently move to the lagoon to rear their second year.

Sizes are extremely large compared to the fish reared in upstream habitats (right graph), where most yearlings are smaller than YOY reared in the lagoon.

Density of steelhead in the lagoon can also affect sizes, so in small lagoons with large numbers of fish (Waddell Creek in the 1980's) fish sizes can be smaller than at Pescadero and San Gregorio lagoons, but still much larger than those reared in upstream habitats.



Steelhead from Pescadero Creek (in 1985) showing average sized yearling and large YOY reared in the lagoon; smolts reared 2 full summers and a spring in upstream habitat; and typical YOY reared in upstream habitat.

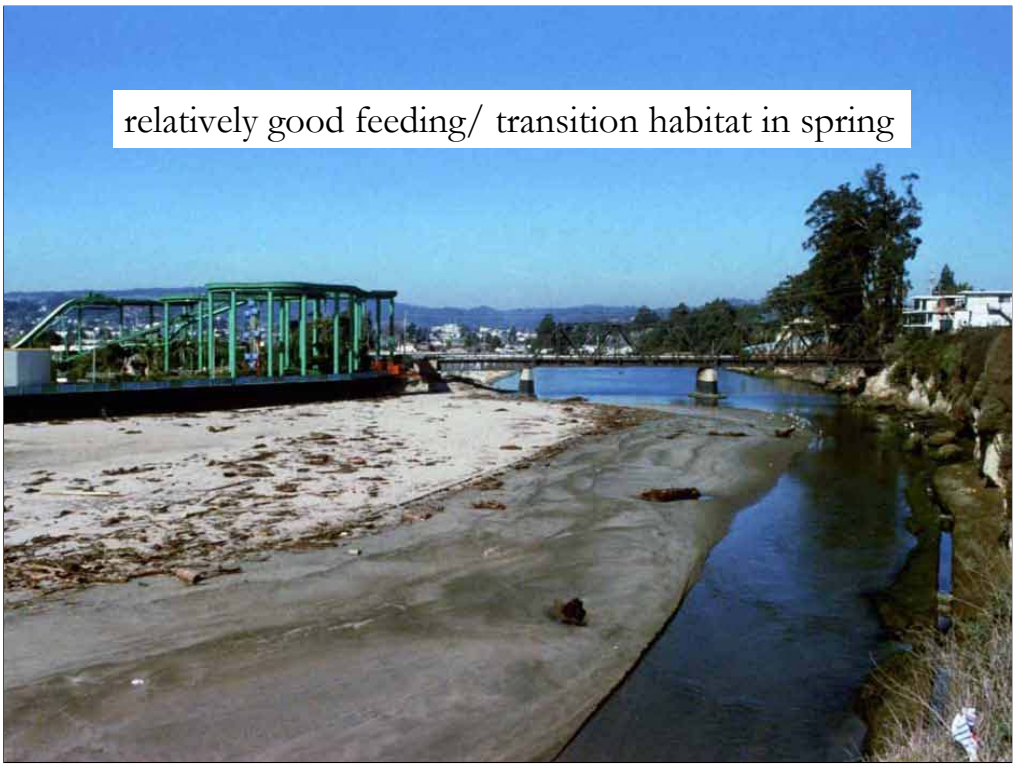


In small lagoons the common marine fish that may be present are tolerant of freshwater conditions (Staghorn sculpin, starry flounder, topsmelt). In larger lagoons with deep water, additional marine species may be present in open lagoons or be present until eliminated by freshening conditions in closed lagoons.

Tidewater gobies have different habitat requirements than steelhead and need calm conditions (rather than tidal) in summer, so a sandbar is necessary for abundant gobies. They also need flood refuges in winter and refuges against droughts, which might dry small lagoons.

Steelhead can be relatively large and abundant compared to upstream habitats. Because of their large size lagoon-reared steelhead have much higher ocean survival and may contribute disproportionately to the adult run (Smith 1990; Bond 2006). At Waddell Creek examination of 202 adult steelhead from 1991-1994, found that about 40% were reared in the lagoon, and this was during a period when lagoon conditions were not optimal because of drought and/or diversions.

The San Lorenzo River has an urban lagoon that is subject to summer sandbar breaching because of flooding of the beach and seepage through the levees.



In spring the open estuary has sufficient residual depth at low tide (1+ m) (due to scour at the channel bend, against the cliff and at the trestle abutments) so that it provides good feeding habitat for upper watershed smolts migrating through. The residual depth also traps salt water from high tides in late spring and provides a layered brackish habitat that alllows smolts to adjust to sea water before entering the ocean. These springtime conditions are important in increasing ocean survival and adult return rates for upper watershed smolts.

During summer the sandbar periodically forms, extending the crowded beach across the stream mouth. The closed lagoon was considered a nuisance, because of the risk of a breach through a crowded beach and because of frequent swimming in the warm, calm lagoon.

In the 1980's the bar was frequently breached by the city of Santa Cruz (as often as alternate Fridays), switching the lagoon between closed and stratified and open; the lagoon was never allowed to freshen (and mix) before it was breached again.

The city no longer breaches the sandbar, but it still frequently breached in summer by surfers, local residents and beach visitors. Its full potential for steelhead rearing as a closed, freshwater mixed lagoon is never realized.

In contrast, at Soquel Lagoon the sandbar is installed by Memorial Day, if it doesn't form on it's own by then. A water control structure allows smolt outmigration immediately after closure and also can be modified to speed conversion of the lagoon to fresh water.

The relatively shallow summer lagoon (about 1 m) serves as a recreational resource (with paddle boats) and rears 1-6000 smolt-sized steelhead annually.

However, when the sandbar is blown out in winter and spring there is little residual depth. Smolts from the upper watershed have little chance to feed or adjust to salt water before entering the ocean.

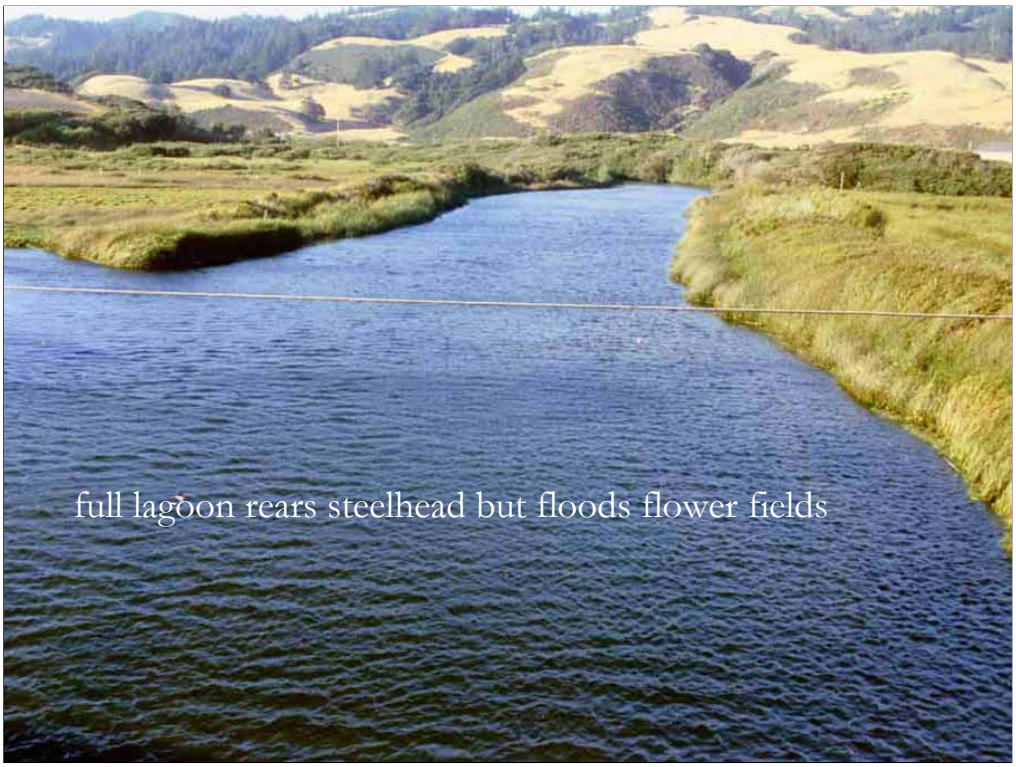
The lagoon also has no winter refuge for tidewater gobies, so they occur only sporadically as colonists from Corcoran Lagoon immediately to the North.

Scott Creek lagoon has been shown to rear substantial numbers of large steelhead in summers when the sandbar remains in place.

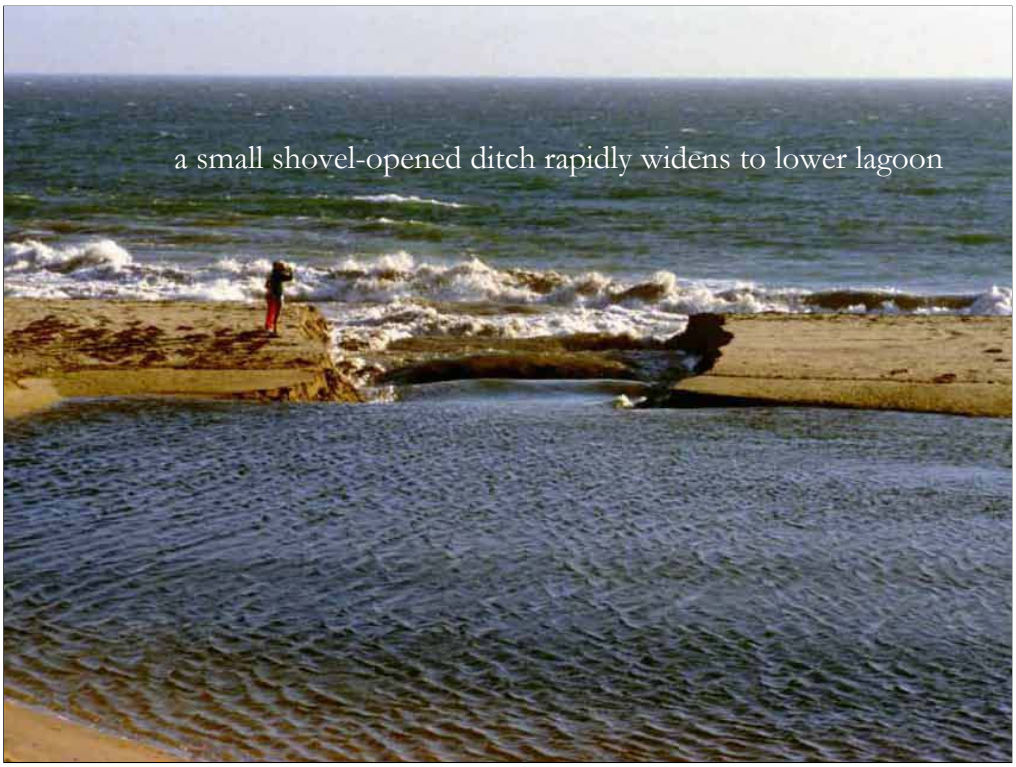
However, because the channel was straightened during the construction of the present Highway 1 bridge, there is little residual depth in winter, spring or even in summer if the sandbar is open.

Smolts from the upper watershed are usually unable to feed or adjust to saltwater in spring before entering the ocean. Their ocean survival is reduced and the contribution of upper watershed smolts to the adult run is substantially reduced (making summer rearing relatively even more important).

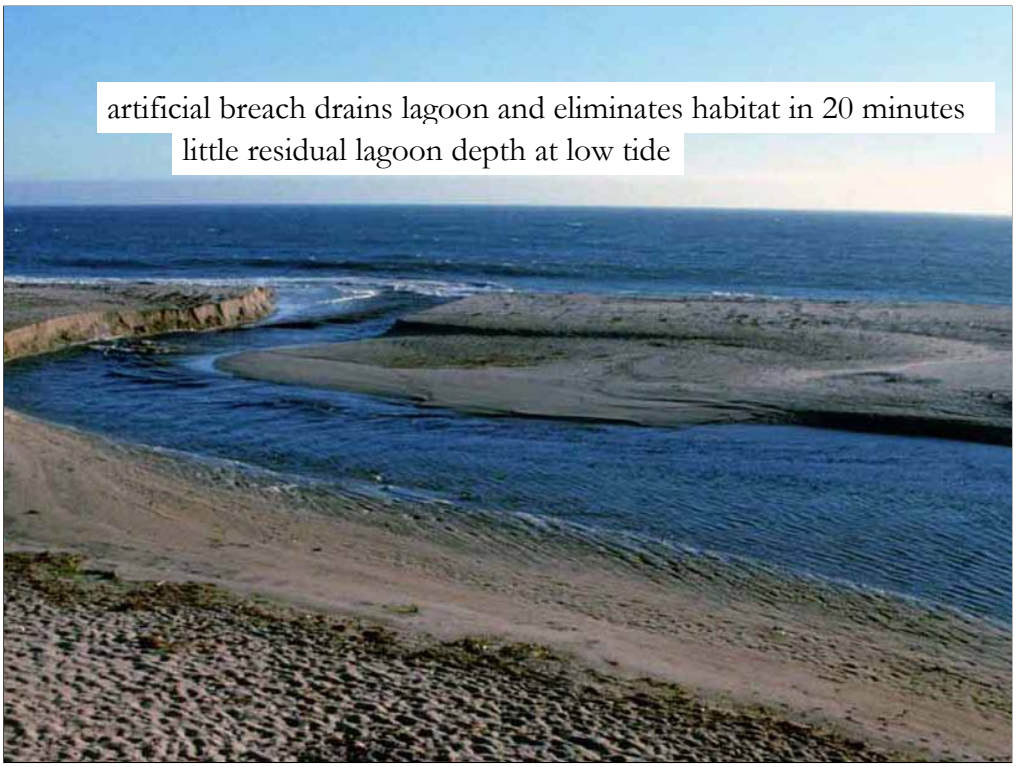
The original channel had a sharp bend to the west (left) at the head of the original lagoon and also a sharp bend against the western cliff before entering the ocean. Those bends would have produced deep scour holes (like at the Little Sur River) of residual depth. They would have provided the valuable feeding and saltwater transition habitat that is now lacking.



Summer rearing at Scott Creek has frequently been impacted by artificial breaching of the sandbar. In 1986 the lagoon was high and was rearing a large number of fast-growing steelhead. However, the high lagoon flooded a corner of a low-laying agricultural field upstream.



The lagoon was artificially breached by several minutes of shoveling open a narrow channel. After 5 minutes the opening had widened to 12 feet.

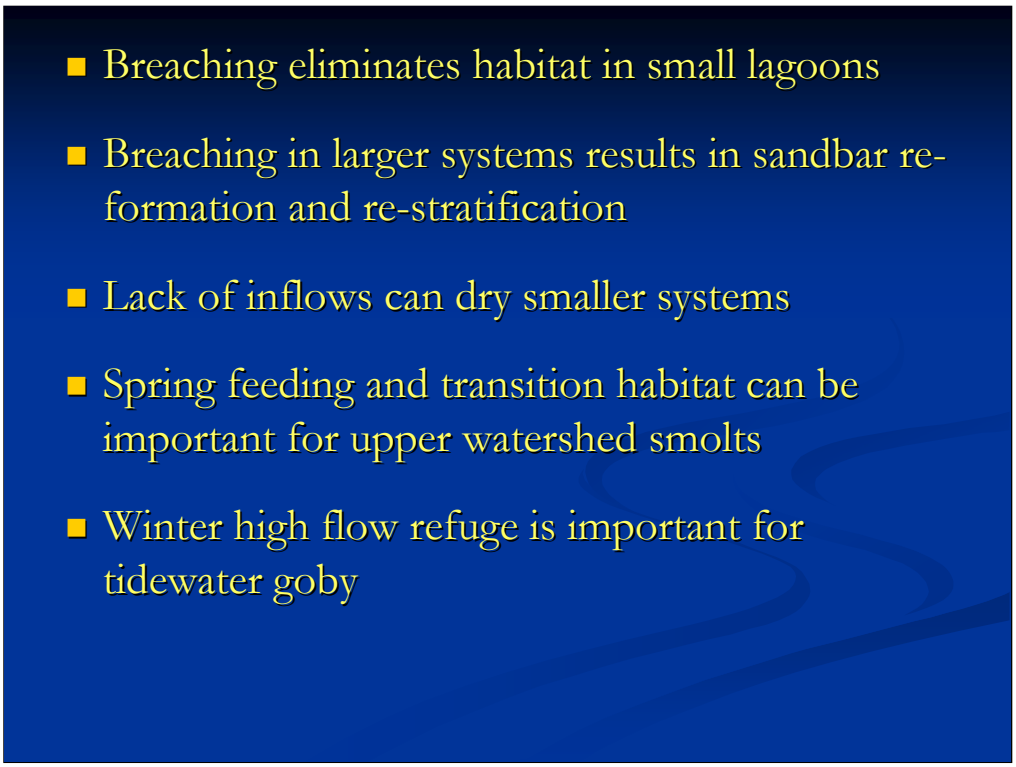


The entire lagoon was drained (and its steelhead lost) in 20 minutes. Artificial breaches still regularly occur when the lagoon curves to the west (“north”) because wind and kite surfers have trouble accessing the beach when the lagoon is closed and high. When the mouth curves to the east (“south”) access is not a problem and illegal breaches occur less frequently.

After a breach there is little residual depth in the lagoon and few steelhead are able to rear. The lack of residual depth in the open lagoon also means that feeding habitat and saltwater transition habitat is scarce or absent for smolts from the upper watershed in spring.

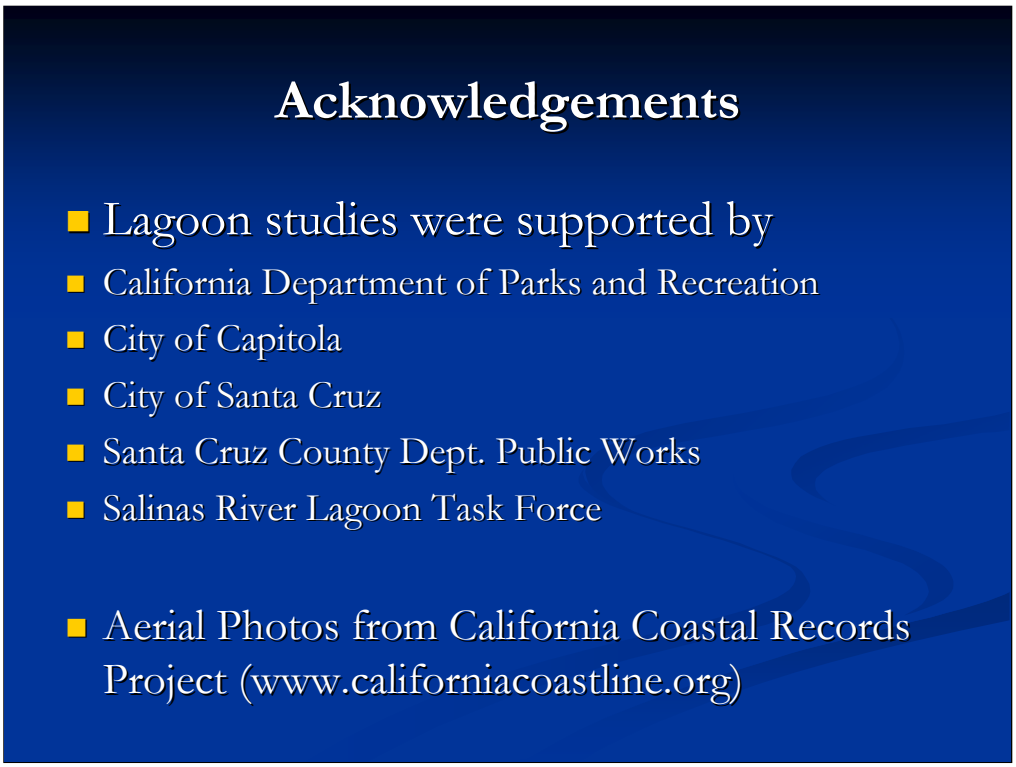
During droughts (or even average years if diversions are high enough) closed lagoons may nearly or completely dry up. This was a problem at Scott Creek throughout the 1987-1991 drought.

It has also been an ongoing problem at Laguna Creek several miles “south”, where city of Santa Cruz and agricultural diversions frequently produce a nearly dry lagoon. The drying of lagoons is a threat to tidewater goby, as well as to steelhead.



In small shallow systems almost all of the habitat in the lagoon comes from impounding freshwater inflows (or tidal overwash) behind the sandbar. Breaching eliminates that habitat. Lack of inflows can dry the lagoon.

In large (and deeper) systems breaching puts the system through repeated breach/re-formation cycles with stratified warm water.



California Department of Parks and Recreation has supported my studies of San Gregorio, Pomponio, Pescadero, Waddell, Baldwin and Lombardi lagoons. They permitted my tidewater goby and habitat investigations at Arroyo Frijoles, Gazos, Wilder, Moores, Aptos and Pajaro lagoons.

The city of Capitola supported studies of Soquel Creek lagoon.

The city of Santa Cruz supported studies of San Lorenzo River lagoon.

Santa Cruz Department of Public Works supported studies of Pajaro River lagoon.

The Salinas River Task Force supported studies of Salinas River lagoon.

Additional lagoon studies have been done at Scott, Corcoran, Moran and Dairy Gulch lagoons.