Reference: Suchanek, T.H., P.J. Richerson, D.C. Nelson, C.A. Eagles-Smith, D.W. Anderson, J.J. Cech, Jr., G. Schladow, R. Zierenberg, J.F. Mount, S.C. McHatton, D.G. Slotton, L.B. Webber, A.L. Bern and B.J. Swisher 2002. Evaluating and managing a multiply-stressed ecosystem at Clear Lake, California: A holistic ecosystem approach. "Managing For Healthy Ecosystems: Case Studies", CRC/Lewis Press. pp. 1233-1265 (in press)

Evaluating And Managing A Multiply-Stressed Ecosystem At Clear Lake, California: A Holistic Ecosystem Approach

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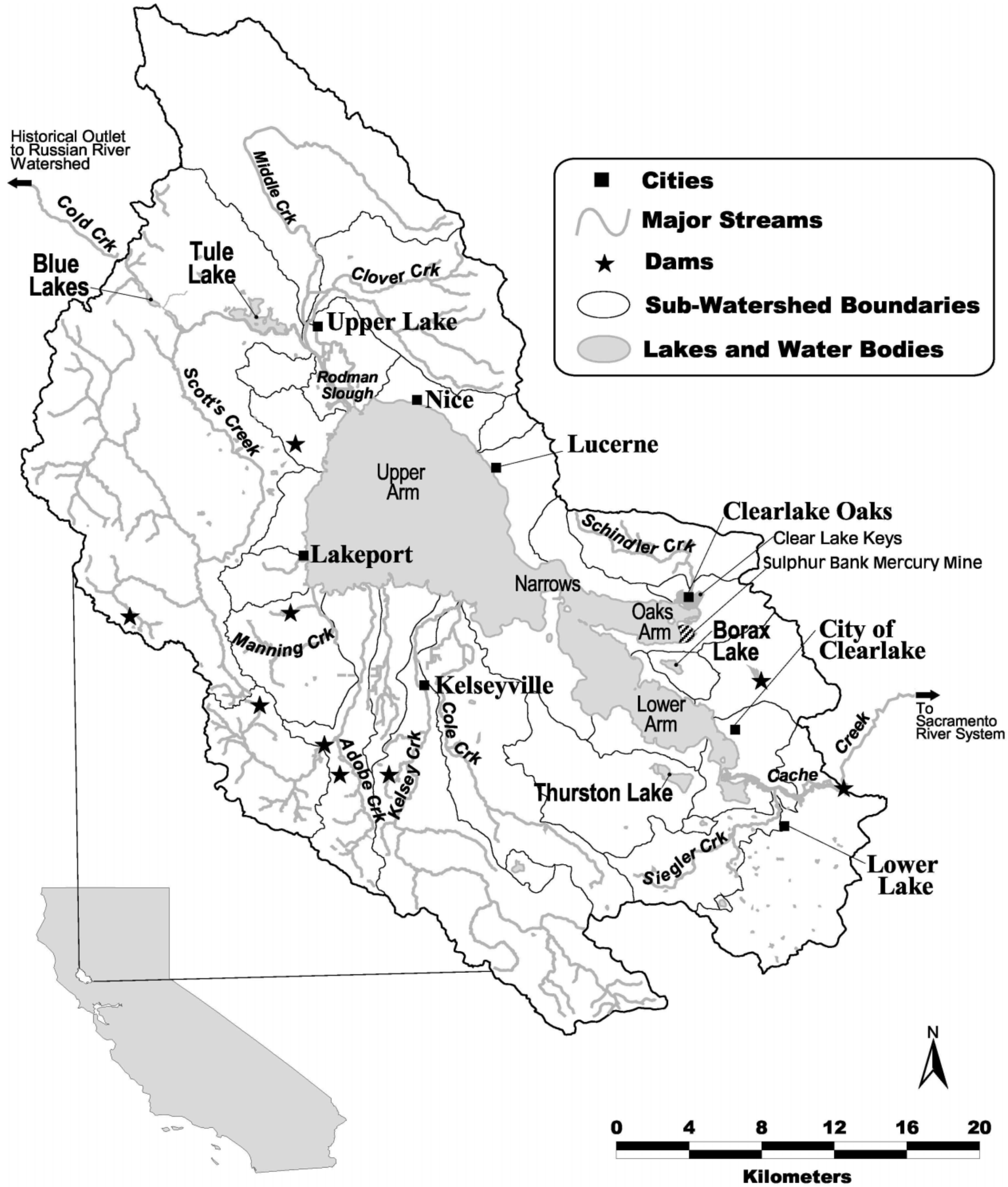
INTRODUCTION

Clear Lake (**Fig. 1**) and its watershed in Northern California constitute a serene and beautiful environment that has been used extensively by inhabitants of the surrounding basin for millennia. It has one of the oldest documented North American “early man” sites, with paleo-indian occupation of the Clear Lake basin about 10,000 years before present (ybp) at Borax Lake, immediately adjacent to Clear Lake (Heizer 1963). Native American settlement was relatively dense during European contact in the early 1800s, with about 3,000 people scattered among 30 or so villages within the basin (Baumhoff 1963). These people utilized the lake’s abundant fish as well as tens of thousands of waterfowl and runs of native fishes in adjacent streams (Simoons 1952) to supplement their staple acorn diet. Variously named “Lupiyoma”, “Hok-has-ha” or “Ka-ba-tin” by early native Americans (Mauldin 1960), “Big Waters” by some of the early European pioneers in the 1820s, “Laguna” for a short time by Spanish Californians in the 1830s, and finally “Clear Lake” in the 1840s, this lake has had a long and fascinating history. European or American trappers first started visiting the lake seasonally in 1833, but more permanent agricultural settlers did not arrive until the 1850s (Simoons 1952).

Volcanic activity in the area of the lake provided heat to drive hydrothermal systems that created rich mineral deposits. Almost immediately, settlers began to extract these minerals from the landscape. The first commercial mines were small-scale operations that exploited borax in 1864 and sulfur in 1865. Mercury mining became a significant industry with the development of the Sulphur Bank Mercury Mine in 1872. Beginning in the mid 1870s, abundant mineral springs attracted thousands of health-conscious citizens to the region (Simoons 1952).

The population of Lake County has grown from ca. 3,000 in 1860 to over 55,000 in 1999 (**Table 1**). Associated with that population growth has come dramatic land use change, altering the watershed and limnological and ecological dynamics of Clear Lake. Today the Clear Lake watershed basin includes a high proportion of forested land, oak woodlands, orchards and vineyards, other croplands and little remaining original wetlands (**Fig. 2**). Clear Lake water is used for storage of agricultural irrigation water for downstream Yolo County. The Yolo County Flood and Water Conservation District owns the rights to use the water in the lake and regulates the flow of releases from the single outlet dam to Cache Creek. The lake's rimlands and surrounding watershed also support extensive agricultural production, including pears, walnuts, grapes, and wild rice. The area supports breeding populations of several important bird



<u>Figure 121.1</u> Map of Clear lake and surrounding watershed, with locations of dams.

Table 121.1 Lake County Population Since European Settlement

Table 1. Population of Lake county
* Data from Simoons, 1952

Year	Lake county population
1850	2,210*
1870	2,900*
1890	7,100*
1900	6,017
1910	5,526
1920	5,402
1930	7,166
1940	8,069
1950	11,481
1960	13,786
1970	19,548
1980	36,366
1990	50,631
2000	55,000

associated with the lake itself, including the western grebe (*Aechmophorus occidentalis*), Clark's grebe (*Aechmophorus clarkii*), double-crested cormorant (*Phalacrocorax auritus*), great-blue heron (*Ardea herodias*), osprey (*Pandion haliaetus*) and bald eagle (*Haliaeetus leucocephalus*). In addition, this aquatic setting supports many other species of birds associated with surrounding wetlands and uplands. It supports the only commercial fishery on a lake in California and extensive sport fisheries, especially for bass and catfish. Clear Lake is used heavily for water sports (swimming, boating, water skiing, jet skiing); thus, it attracts significant recreational tourism, especially during summer months.

This aquatic ecosystem has also been subject to multiple stresses, both natural and anthropogenic. It has experienced periodic flooding and fires and has lost over 85% of its original natural wetlands habitat. Dam construction, however, in Lake County has added approximately 6,500 acres of impoundment water. The lake experienced increased nutrient loading and decreased water clarity between 1925 and 1938, likely due to the introduction of more efficient heavy earth moving equipment in the basin and the loss of original wetlands on the major tributaries (Richerson et al. 2000). By 1938, the lake had become too turbid for rooted aquatic vegetation to flourish and noxious cyanobacterial scums became a perennial problem (Lindquist and Deonier 1943, Murphy 1951). The lake also has elevated concentrations of mercury, among other contaminants; a USEPA Superfund site is located on the eastern shore of Clear Lake at the former Sulphur Bank Mercury Mine. Clear Lake was also the first site at which the deleterious effects of large concentrations of organochlorine pesticides on bird populations were

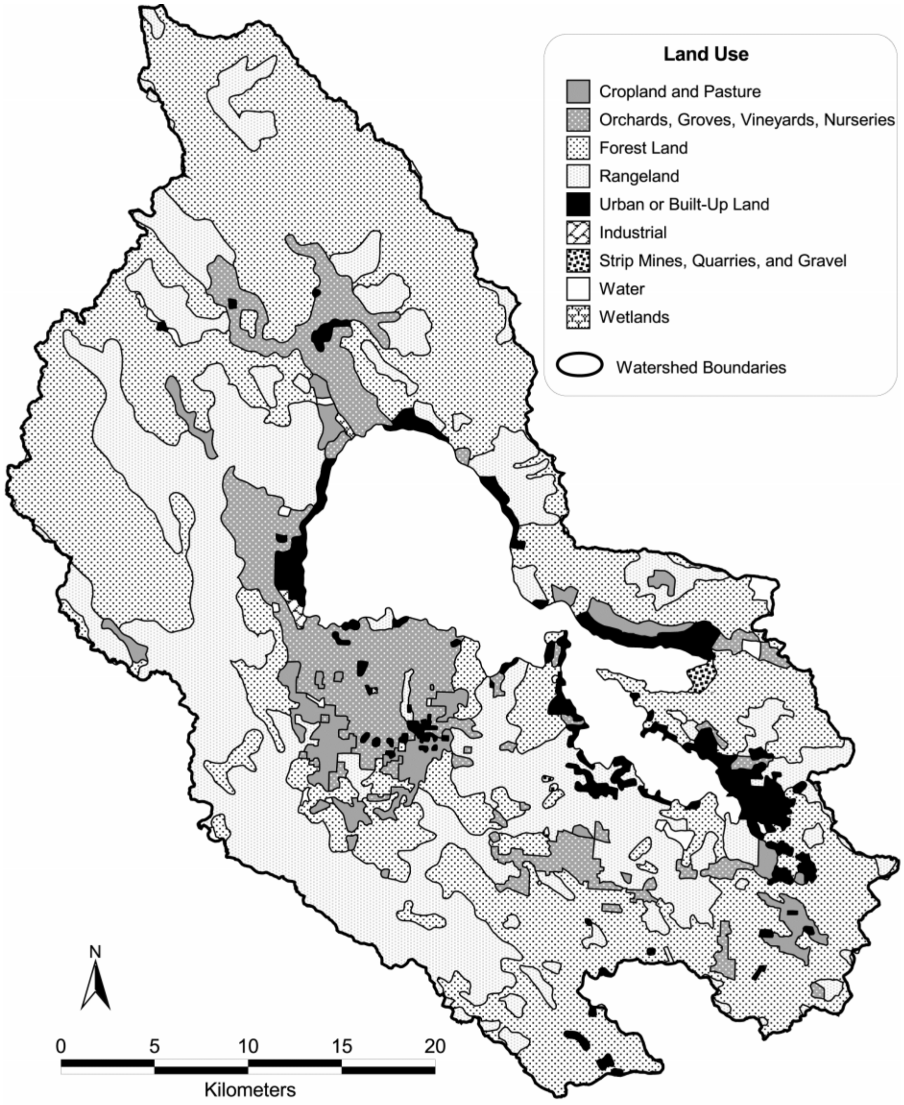


Figure 121.2 Land use within the Clear Lake watershed as of 1998.

documented (original research reported by Hunt and Bischoff 1960 and Rudd 1964, and popularized in Rachel Carson's *Silent Spring*, Carson 1962). The lake contains a fish fauna comprised of over 80% introduced species. Clear Lake has been designated by the State of California as an "impaired water body" under Section 303d of the Clean Water Act, which mandates the state to identify water bodies or stream segments that currently are not meeting, or are not expected to meet, designated beneficial uses.

Managing multiple, frequently conflicting uses of the lake and watershed is challenging; it involves ecological, economic, and political balances. Before rational management can be successful, however, managers must understand, to a useful approximation, the complex processes that drive the ecosystem's behavior. Our goal is to document the historical and modern day multiple uses and multiple stresses associated with the Clear Lake aquatic ecosystem, including the lake proper and the surrounding watershed, in an attempt to demonstrate what rational management of this and similar valuable, multiply-stressed ecosystems demands of applied science programs.

This report provides a pre-historic and historic background from which to evaluate the importance and impacts of a multitude of natural and anthropogenic stresses imposed upon Clear Lake and its watershed. Specifically, we identify major geological, climatological, ecological, political, and economic factors that influence the outcome of management and policy level decisions on the health and well-being of the entire ecosystem, especially the lake proper. Natural stressors include: geologic and tectonic events, regional and global climate change, fires, droughts and floods. Anthropogenic stressors include: (1) modifications to the landscape - including fires, logging and deforestation, dam construction, and other creek modifications; (2) contaminants – including pesticides, mining, sewage and septic overflows; (3) land use changes, including original wetland losses (and some wet habitat increases – see above), dredging, filling and creek bed alterations, water table and shoreline modifications, road building, agriculture, soil exposure and transport, livestock grazing; and (4) species introductions including intentional and accidental introductions. Finally, we illustrate how scientific research has contributed significantly to addressing multiple management objectives in this extremely complex ecosystem.

Natural Setting

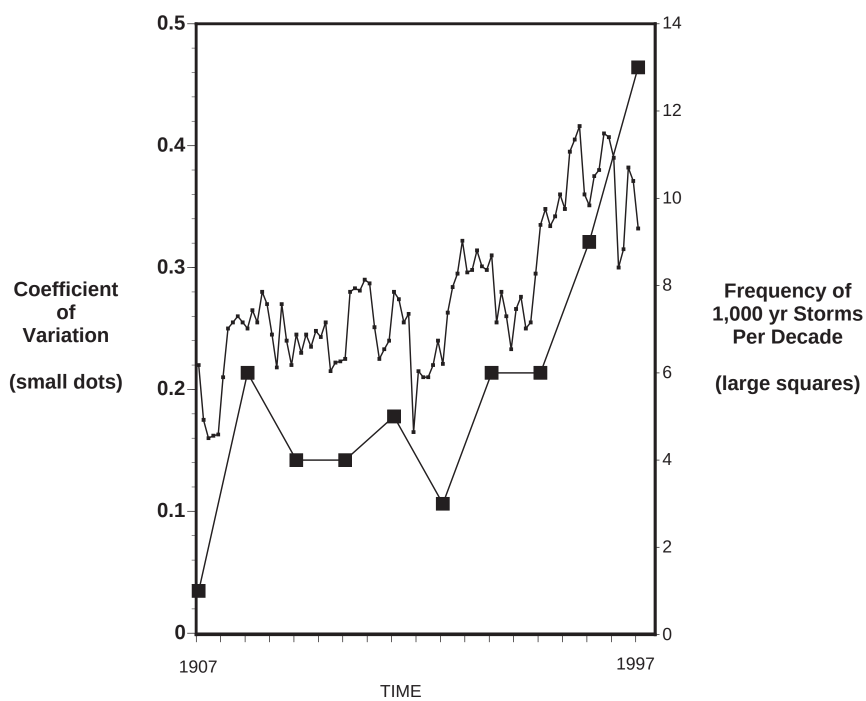
Clear Lake (**Fig. 1**) is located at 39° 00'N; 122° 45'W within Lake County in the Coast Range of California at an elevation of 402 m with surrounding ridges rising up to 1,500 m. Through evidence from a series of cores to ca. 177 m maximum sediment depth, collected by the US Geological Survey in the 1970s and 1980s, Clear Lake is believed to be the oldest lake in North America with continuous lake sediments of about 480,000 yr (Sims 1988, Sims et al. 1988). It also is possible that Clear Lake is a remnant of an ancestral lake represented by deposits of the Cache Formation, dating back to the early Pleistocene, making it 1.8 to 3.0 million years old (Casteel and Rymer 1981, Hearn et al. 1988). The Clear Lake basin represents a fault-bounded subsiding graben related to movement along the San Andreas Fault. The lake is set within an active volcanic region. Abundant geothermal springs release both fluids and gases (primarily CO_2, H_2S and methane) from the lake bottom. Clear Lake is polymictic (typically well mixed), alkaline (pH 8), shallow (average depth about 6.5m) and highly productive (eutrophic). Subsidence (caused by block faulting beneath the lake), has kept up with natural sedimentation. Thus, Clear Lake has been a relatively shallow lake since its initial formation, but at least parts of the current basin have been an open water system since the middle Pleistocene. Although early reports claim that "It derives its name from the clearness of its waters" (Menefee 1873), and it may have been clearer in the 19^{th} century than it is today, it was almost certainly a eutrophic system during the course of its entire existence (Bradbury 1988). However, many recent land use changes (described below) likely have exacerbated sediment and nutrient loading to the lake, enhancing noxious cyanobacterial (bluegreen "algae") blooms (Richerson et al. 1994). In modern times the lake supports populations of ca. 100 species of green and yellow-green algae and cyanobacteria, about 115 species of diatoms, 23 species of aquatic macrophytes, 94 species of invertebrates and 34 species of fishes, plus numerous lake-associated or lake-dependent mammals such as otter, mink, raccoon and numerous species of birds such as osprey, bald eagle and grebes (Horne 1975, Macedo 1991, Richerson et al. 1994, Meillier et al. 1997, Moyle 2002, Lake County Vector Control - unpublished).

NATURAL STRESSORS

Geologic and Tectonic Events: Two different hypotheses have been proposed for the origin of Clear Lake's drainage route. Davis (1933) proposed that Clear Lake was originally two lakes separated by an isthmus at the Narrows: one lake essentially comprising the Upper Arm (which drained westward into the Russian River system via Cold Creek), and another lake comprising the present day Oaks Arm and Lower Arm (which drained eastward via Cache Creek into California's Central Valley and the Sacramento River) (**Fig. 1**). A lava flow in the eastern drainage was believed responsible for forming a dike high enough to build up the water level in the eastern lake allowing water to overspill and cut through the narrow isthmus, thereby connecting the two lakes. The drainage flowed from the eastern lake to the Upper Arm and out Cold Creek into the Russian River system (Mauldin 1968). Later, perhaps 10,000 ybp, an earthquake likely initiated a landslide in the Cold Creek drainage which blocked the westward flow, forcing the entire lake (both halves) to drain again into the Central Valley through Cache Creek. Alternatively, Becker (1888) and Brice (1953) argue that Clear Lake occupies the lowest part of a shallow fault depression. Hodges (1966) later concurred with this hypothesis and proposed that Scotts Creek formed a fan delta and clogged the western outlet valley of Cold Creek with fluvial debris;

thus Cache Creek remained the only outlet. In either case, fish from the Central Valley colonized the Russian River system and there was some speculation that the reverse might have occurred as well (Hopkirk 1973, 1988).

Regional and Global Climate Change: California's climate has been undergoing dramatic and continuous change over the past 100 years. This change is coincident with documented global climate change over the same time period (Mann et al. 1999, Hileman 1999); yet it is uncertain how changes in regional climate are linked to more global processes. In California, the coefficient of variation in rainfall and the frequency of 100-yr. storm events has been increasing dramatically over the past century (Goodridge 1998, **Fig. 3**). In addition, the frequency of El Niño events has become unusually common in recent years (Trenberth and Hoar 1997) and this likely is linked with much of the fluctuation in regional and global climatological events at Clear Lake. Furthermore, if global warming enhances El Niño events, for which there is growing evidence (Meehl and Washington 1996), then California's climate over the next several decades may look like an amplified version of the extreme events that have taken place over the past several decades (Field et al. 1999).



<u>Figure 121.3</u>. Regional California climate changes over the past century showing dramatic increases in the coefficient of variation in rainfall and increase in the frequency of 1000-year storms (Adapted from Goodridge, J., The impact of climate change on drainage engineering in California, Report to the Alert Users Group Conference in Palm Springs, CA, 26-29 May, 1998).

Fires: The Mediterranean climate and vegetation of this region is naturally conducive to fire. The change in regional weather described above also may contribute to an increase in large fires. Lightning is a common cause of fires in this region and although we do not have documentation of fire origins, especially before European contact, we do have moderately accurate records on the extent of fires in these watersheds since the turn of the century (**Fig. 4**). It has been estimated that in more modern times (1960s to 1980s) lightning accounted for only about one third of all forest fires (West 1989).

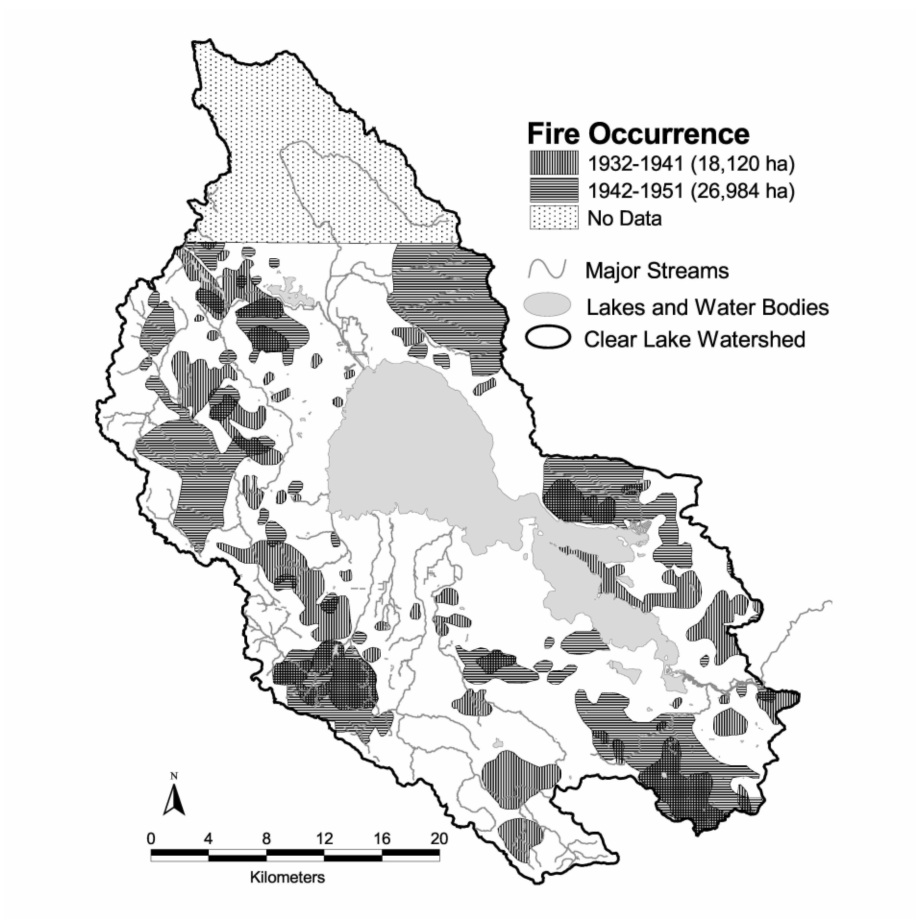
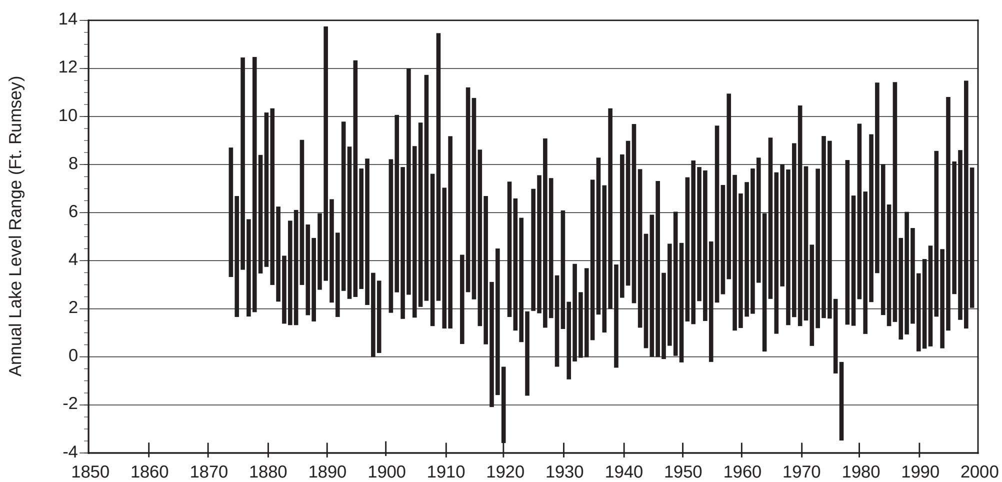


Figure 121.4. Location of fires in the Clear Lake Basin from 1932 to 1951. (Adapted from Simoons, F.J., The settlement of the Clear Lake Upland of California, Master's Thesis, University of California, Berkeley, 1952.)

Droughts and Floods: Short to medium length droughts have been documented in the historical record of California. A significant three year drought from 1975-1977 and six to seven year droughts during recent (1987-1992) and historical (1928 to 1934) periods lowered the lake level substantially (**Fig. 5**). Tree ring data from California back to the 1500s suggest decade-scale droughts (Earle 1993). More substantial 46 to 140 year long droughts (before AD ~1350) and >200 year long droughts (before AD ~1112) also have been documented in California by dating submerged tree stumps (Stine 1994). The most comprehensive understanding we have on how such droughts can impact ecological and limnological processes in and around Clear Lake comes from a 24 year Department of Water Resources water quality data set (1969 to 1992) that includes the 1975 to 1977 and 1987 to 1992 droughts. An analysis of those data by Richerson et al. (1994) shows that the drought period correlated strongly with some moderate increases in pH and Secchi disk readings (water clarity) during the longer drought in the Oaks Arm and Lower Arm of Clear Lake (but not necessarily the Upper Arm or during the shorter drought) (**Fig. 6A**). In addition, dramatic increases in water column phosphorus (especially dissolved phosphorus) and electrical conductivity have been observed in all three arms (**Fig. 6B**), especially during the longer 1985 to 1992 drought . Interestingly, during the past three years (1998 to 2000) Clear Lake has exhibited exceptional water clarity (high Secchi disk readings) during non drought conditions. Clear Lake has also experienced one of the most severe seasons of cyanobacteria (bluegreen “algae”) blooms in recorded history toward the end of these documented drought periods (**Fig. 7**), likely because of increased sediment phosphorus releases.



<u>Figure 121.5</u> Clear Lake water levels (annual minimum and maximum) relative to the Rumsey Scale.

With increasing frequency of 100 yr. storm events resulting from regional climate change (see above), there also is increased risk from natural flooding to lakeside real estate and public utilities, and additional risk of increased sedimentation, nutrient inputs, and acid mine drainage from the local Sulphur Bank Mercury Mine (see below). Figure 4 provides documented water levels (high and low water) for Clear Lake relative to a baseline depth of "0 ft Rumsey" (which is equivalent to 1318.256' 1929 NGVD) established in 1872. Flooding also has increased recently and the winter of 1997 to 1998 produced the highest recorded lake levels since the emplacement of the Cache Creek dam in 1914 (Fig. 4).

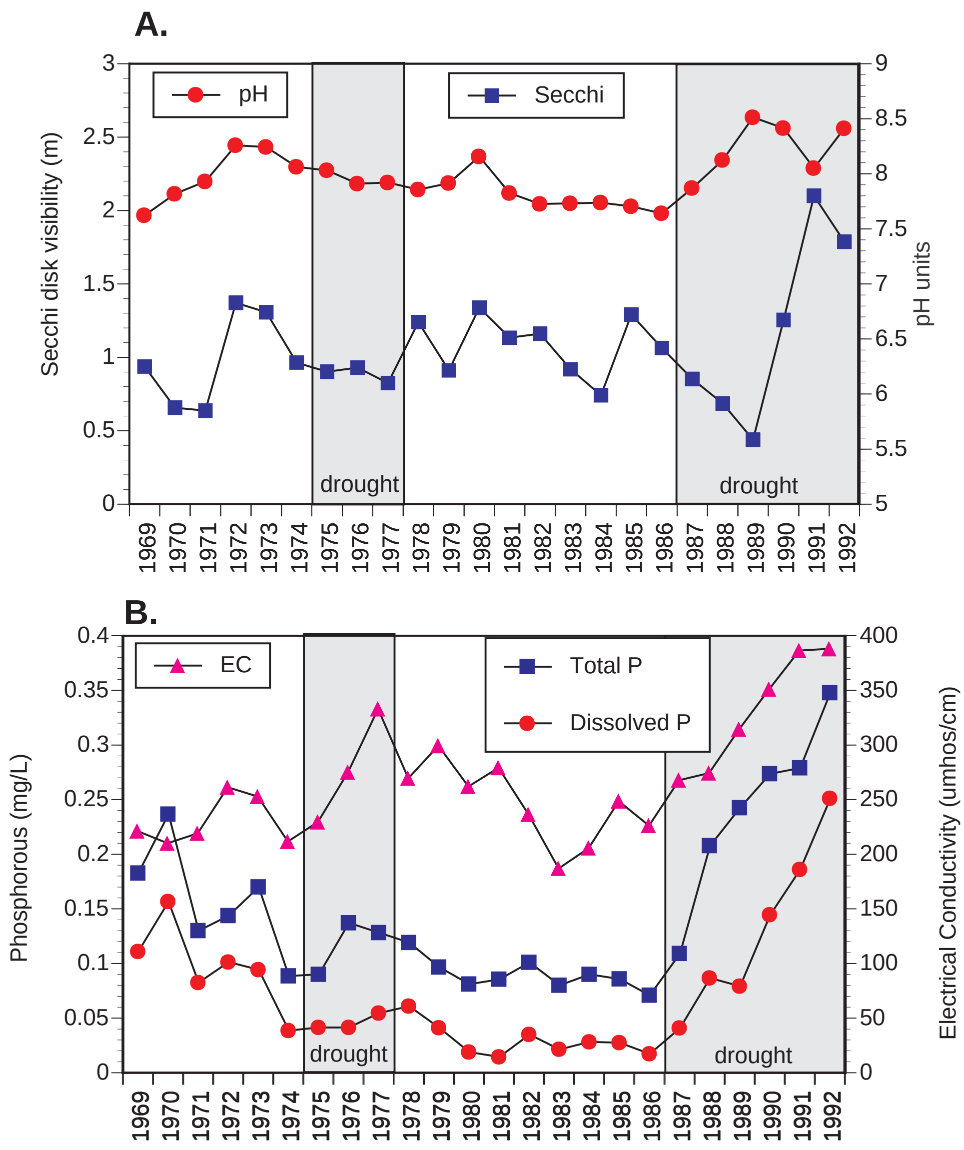


Figure 121.6 A 24-year dataset (1969-1992) of limnological conditions within the Lower Arm of Clear Lake showing dramatic changes associated with the drought from 1987 to 1992. A) Water quality as quantified by Secchi disk values and pH readings. B) Phosphorus and electrical conductivity values (Adapted from Richerson, P.J., T.H. Suchanek, and S.J. Why, The Causes and Control of Algal Blooms in Clear Lake, Clean Lakes Diagnostic/Feasibility Study for Clear Lake, CA, prepared for EPA Region IX, 1994).

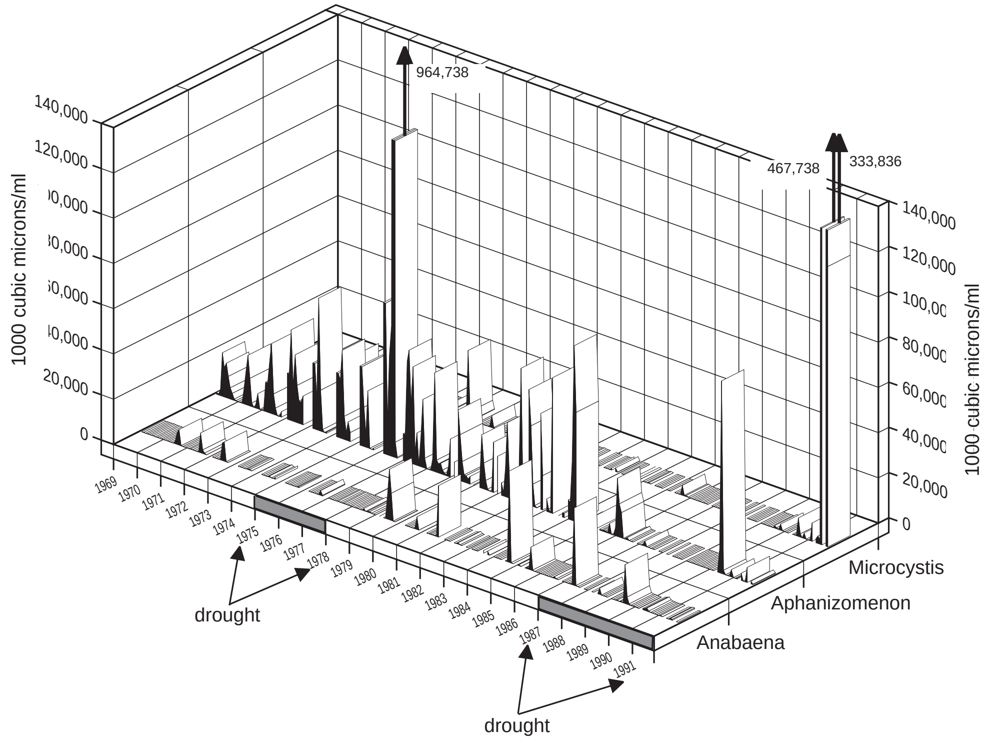


Figure 121.7 Volume of three species of scum-forming cyanobacteria (blue-green "algae") over a 24-year period (1969-1992) in the Lower Arm of Clear Lake. Note especially the abundance of Microcystis (at the end of the drought period), a particularly buoyant species that drifts into shore and accumulates in large windrows, then dies, lyses and creates noxious odors which affect shoreline aesthetics. (Adapted from Richerson, P.J., T.H. Suchanek, and S.J. why, The Causes and Control of Algal Blooms in Clear Lake, Clean Lakes Diagnostic/Feasibility Study for Clear Lake, California, prepared for USEPA Region IX, 1994.)

Anthropogenic Stressors

Modifications of the landscape

Fires Often it is difficult to discriminate between natural and anthropogenic causality for fires. Humans set fires, but also attempt to control them; yet, both processes impact natural ecosystem dynamics. It is likely that pre-Spanish fires in the Coast Range were relatively frequent (10 yrs or less) (West 1989). When Europeans first settled the basin during the mid 1800s, widespread intentional burning was common. Herdsmen intentionally burned brush on such a large scale to graze sheep, goats and cattle that California state legislation was passed in 1872 making fire-setting in wooded or forested lands illegal; yet, this had little impact on burning (Simoons 1952). These activities were many more times destructive as lumbering (see below). Early European settlers set fires primarily for three reasons: (1) to encourage grass growth for spring feed, (2) to burn needles in coniferous forests to prevent accumulations that would cause unplanned catastrophic fires, and (3) to improve deer feed. While lightning is often the cause of modern fires, anthropogenically-mediated fires are now more likely to be caused accidentally or by arson rather than as a deliberate attempt to manage the landscape using fire. The two main watersheds that provide over 50% of the inflow to Clear Lake (Scotts Creek and Middle Creek) have experienced numerous natural and anthropogenically influenced fires. An example of fires documented during the periods from 1932 to 1941 and from 1942 to 1951 (adapted from Simoons 1952), as well as more recent fires within the Scotts Creek and Middle Creek watershed, are shown in **Fig. 4** and **Table 2**. As elsewhere in California, control practices probably make fires fewer and less frequent, but more devastating when they do occur because of increased fuel accumulation. For example, the “Forks Fire” decimated over 86,000 acres just north of Clear Lake in 1996, including about 14,000 acres in the Middle Creek watershed that drains into Clear Lake.

Logging and Deforestation

Major modifications of the forested landscape by Mexican and American ranchers began as early as the 1840s. In the 1850s some of the landscape was cleared for orchards, vineyards and especially for timber harvest. The most significant timber harvest was Douglas-fir (used for mine-timbering), sugar pine, and Ponderosa pine (used mostly for lumber) and oak for fuel (Simoons 1952). Much of this wood was used

Table 121.2 Acres burned by fires in the Middle Creek watershed during the twentieth century.

DOCUMENTED FIRES WITHIN THE MIDDLE CREEK WATERSHED

YEAR	ACRES BURNED
1911	400
1912	400
1913	400
1914	400
1915	400
1916	1,364
1917	4,743
1922	2,995
1923	19,077
1928	6,394
1929	2,339
1930	105
1931	1,994
1932	419
1933	7,362
1934	1,021
1936	184
1939	3,304
1941	563
1946	1,889
1947	11,648
1951	619
1958	117
1959	593
1960	
1964	1,361
1971	1,500
1975	
1980	3,000
1981	
1991	224
1996	12,685

as fuel for the borax and mercury mining operations (see below). By 1870 no fewer than five commercial sawmills were operating on the lake; by 1905, there were eleven mills that processed over 1.5 X 10^6 board feet of lumber annually, and in 1946 more than 11 X 10^6 board feet was processed (Simoons 1952). As a result of forest removal and soil exposure, sediment transport probably increased into Clear Lake, depositing additional entrained nutrients into the system. Nevertheless, this exploitation was not severe enough to be apparent in the pollen record of Clear Lake as deduced from sediment cores (Richerson et al. 2000).

Dam Construction

The Clear Lake dam along Cache Creek was completed in 1914 for the purpose of regulating agricultural irrigation waters to downstream Yolo County, which owns the rights to Clear Lake water (discussed in Richerson et al. 1994). An earlier dam at Clear Lake's outlet (about 2.5 km upstream of the present dam) was first constructed in 1867 to increase water levels to operate a mill at that end of the lake, but was destroyed in 1868 by about 300 angry rimlander property owners who were getting flooded during periods of heavy rain. This is one of the most colorful accounts of Clear Lake history, when a vigilante group took into custody several individuals (including the sheriff, his deputies, the county judge, the superintendent of the mill works and other prominent citizens) who appeared sympathetic to the dam's owners and operators (Anonymous 1881). A pumping station was installed in this same location around 1910 to increase water flow to irrigate rice crops in downstream Capay Valley, but that station also was intentionally destroyed about 1912. Numerous other dams have been erected within the Clear Lake watershed from 1955 to 1980, primarily for irrigation or recreation purposes (see **Fig. 1** for locations). All of these dams have slowed and altered natural flow of waters from the watershed to Clear Lake and may have prevented some species of Clear Lake fishes (such as the Clear Lake splittail, *Pogonichthys ciscoides*) from migrating upstream to spawn (Moyle 2002). While there was the potential for increased flooding as the result of the construction of the Clear Lake dam, ironically lake levels have been significantly lower (**Fig. 5**) since the construction of the Cache Creek dam in 1914 . Other dams higher up in the watershed have water holding capacity that lowers flooding risks and they likely have contributed to the lowered lake levels mentioned above. They also retain sediments and nutrients that have the potential to become deposited into Clear Lake and thus help to limit eutrophication in the lake.

Other Creek Modifications

Lowering of Cache Creek: The Clear Lake outlet through Cache Creek was deepened in 1938 to accommodate more efficient agricultural irrigation, although further work was halted by a suit filed by a citizen's group.

Kelsey Creek Downcut: In 1965 the delta of Kelsey Creek was dredged to accommodate the installation of a marina. This caused destabilization of the creek bed, providing increased erosional products to be transported into Clear Lake. This increased deposition appears to be recorded in sediment cores from the region of the lake immediately offshore from Kelsey Creek and is represented as apparent increased sedimentation rate during the period starting ca. 1965 (see Suchanek et al. 1997, Richerson et al. 2000).

Contaminants

Aquatic Pesticides: Pesticide applications in Clear Lake have been used primarily to eradicate insects (the Clear Lake gnat, *Chaoborus astictopus*) and emergent macrophytes (the exotic and prolific aquatic weed *Hydrilla verticillata*).

In the 1940s the Clear Lake gnat (at larval densities of 640 larvae per square foot of lake bottom) was creating a serious aesthetic nuisance; while the adult gnats are non-biting, they would aggregate in huge clouds around the lake's rimlands (Dolphin 1959). University of California researchers had studied the gnat biology and possible control from 1916 to 1936 and in 1938 the US Congress appropriated funds to the US Department of Agriculture (USDA) for further study of the gnat and its control. The USDA and the California Department of Fish & Game began lab treatment studies in 1945 to 1946 and field trials in 1947. The Lake County Mosquito Abatement District (which became the Lake County Vector Control District in 1995) was created initially in 1948 to help deal with this problem. In order to reduce populations of the gnat, the California Department of Health Services contributed to funding three large applications of dichloro diphenyl dichloroethane (DDD), about 4×10^4 gals of 30% DDD per treatment in Clear Lake: in 1949, 1954 and 1957 (Dolphin 1959, Hunt and Bischoff 1960, Rudd 1964, Cooke 1981). DDD was added in extremely high concentrations (Clear Lake water contained ca. 0.02 ppm DDD) and resulted initially in 99% kill of the gnat larvae in sediments, although the effectiveness of this kill rate declined in future years (Hunt and Bischoff 1960). Additional treatments of DDD also were applied to 20 other small lakes and reservoirs within about 25 km of Clear Lake. Unfortunately, it also killed many other benthic invertebrates and had a devastating impact on the resident breeding populations of the western grebe (*Aechmophorus occidentalis*) (Herman et al. 1969). Five years after the initial DDD applications (in 1954), over 100 grebes were found dead in one survey season; in 1957 another 75 dead grebes were documented. No disease was identified, but in 1957 analyses of grebe fat tissues revealed extremely high concentrations of DDD (1,600 ppm). In 1958 Clear Lake fishes finally were collected and also found to have excessively high DDD concentrations (40-2,500 ppm); the largest concentrations were found in brown bullhead (*Ameiurus nebulosus*), largemouth bass (*Micropterus salmoides*) and black crappie (*Pomoxis nigromaculatus*). In addition, there was a substantial crash of the breeding grebe populations. Prior to 1949 over 1,000 nesting pairs were estimated at Clear Lake. In the period 1958 to 1959, there were fewer than 25 pairs observed, but none were nesting; and at the end of that season no fledgelings were found (Hunt and Bischoff 1960). Concentrations of DDD in plankton were about 265 fold higher than the water in which they were found, about 500 fold higher in small fishes and ca. 80,000-85,000 fold higher in predaceous birds (grebes) (Lindquist and Roth 1950, Rudd 1964). This was the first identification of the process of pesticide bioaccumulation in food webs and the phenomenon of delayed expression of toxic symptoms among biological concentrators of pesticides (Carson 1962, Rudd 1964). Interestingly, the period when the western grebe populations were declining (1950s) was the same period during which the last major mercury mining was taking place at the Sulphur Bank Mercury Mine. Yet no one has investigated the possibility that mercury also played a significant role (additively or synergistically) in the decline of the western grebe populations. We (DWA and THS) are in the process of evaluating museum specimens of western grebes collected from Clear Lake during this era to determine whether mercury levels also were elevated. The signal of residual DDD within Clear Lake sediments from this period is so prominent that it has also been used as a dating tool (Chamberlin et al. 1990, Suchanek et al. 1993, 1997).

Within a few years, DDD applications were ineffective in reducing gnat populations, likely because the insects became resistant to the pesticide (Apperson et al. 1978). As a result, a series of other insecticide compounds (including EPN, parathion, dicapthon, methyl trithion, methyl parathion, 2,4 dimethyl menzyl ester of chrysanthemumic acid, barthrin, trithion, Co-ral, DDVP, delnav, diazinon, dylox, ethion, guthion, korlan, malathion, phosphamidon, phostex and sevin) were used in laboratory tests for their efficacy in killing the Chaoborus gnat, but most were never used in Clear Lake proper (Dolphin and Peterson 1960). Because of the strong resurgence of the gnat populations, two stop-gap measures were implemented in 1959 (Dolphin and Peterson 1960). The first involved spraying a petroleum product (Richfield Larvicide) on gnat eggs located on 5,500 acres of rafts of drifting debris material along the shorelines of Clear Lake. The other stop-gap measure involved the spraying of malathion to tree and shrub resting areas of adult gnats. In 1962 three applications of methyl parathion were made to Clear Lake (at a concentration of 3.3 ppb), which effectively controlled *C. astictopus*. Methyl parathion was subsequently applied each summer from 1962 to 1975, at which point the treatments failed to control the gnat which had, once again, developed a resistance.

Hydrilla verticillata (see more documentation below under introduced species) has become an aggressively growing nuisance macrophyte since about 1994. Beginning in the summer of 1996, annual efforts to control and eliminate this weed have been undertaken primarily using two aquatic herbicides, Komeen™ (copper sulfate) which acts on the emergent vegetation and SONAR™ (fluridone) which acts on the tubers and is intended to stop production of propagules. Because copper is applied in relatively high concentrations locally, and because mercury is an ongoing contaminant in Clear Lake, it is valuable to understand the interaction of copper and mercury on aquatic biota. Only one formal study has undertaken the task of evaluating the impacts of the multiple contaminants mercury and copper on Clear Lake zooplankton (Gilmartin 1998, Gilmartin et al. 1998). These preliminary results indicate that copper and mercury act independently (i.e. additively) with respect to their effects on zooplankton behavior and reproduction.

Finally, there are many private (i.e. homeowner) uses of pesticides that are not subject to pesticide use reporting. Several over-the-counter retail pesticide products are available without a permit (defined as an operator identification number in pesticide use law) and are not regulated by California Pesticide Use Reporting requirements. These pesticides have the potential to enter Clear Lake waters, but no studies have quantified their importance, either from a loading or impacts perspective.

Terrestrial Pesticides While the human population in the Clear Lake basin has increased over the past century, so too has the conversion of the landscape to agricultural production (also see **Fig. 11** below). The widespread use of highly toxic organophosphate and organochlorine pesticides, mostly in the lake (e.g., DDD, see above) has been reduced dramatically over the past 50 years. However, intimately associated with high agricultural production, and particularly with some of the high value crops, has been an increase in the use of pesticides to increase crop yield and ensure crop quality. Since many of the orchards and vineyards surround the lake or eventually drain into the lake, it is important to evaluate whether the use of such xenobiotics may affect the ecology of the watershed. **Figure 8** illustrates trends of the ten highest use categories of pesticide application, and **Figure 9** provides trends on the application of the top 10 of the approximately 165 most heavily used pesticides in Lake County between 1990 and 1998 (California Department of Pesticide Regulation 1990 to 1999).

Nearly one million pounds annually of various petroleum and mineral oils are used primarily on pears (to delay or discourage egg laying by psylla or to smother mite eggs and in some cases codling moth eggs). On rare occasions oils are used on grapes. During the application of dormant and emergent sprays, these oils often are used simultaneously with some organophosphate pesticides (usually during

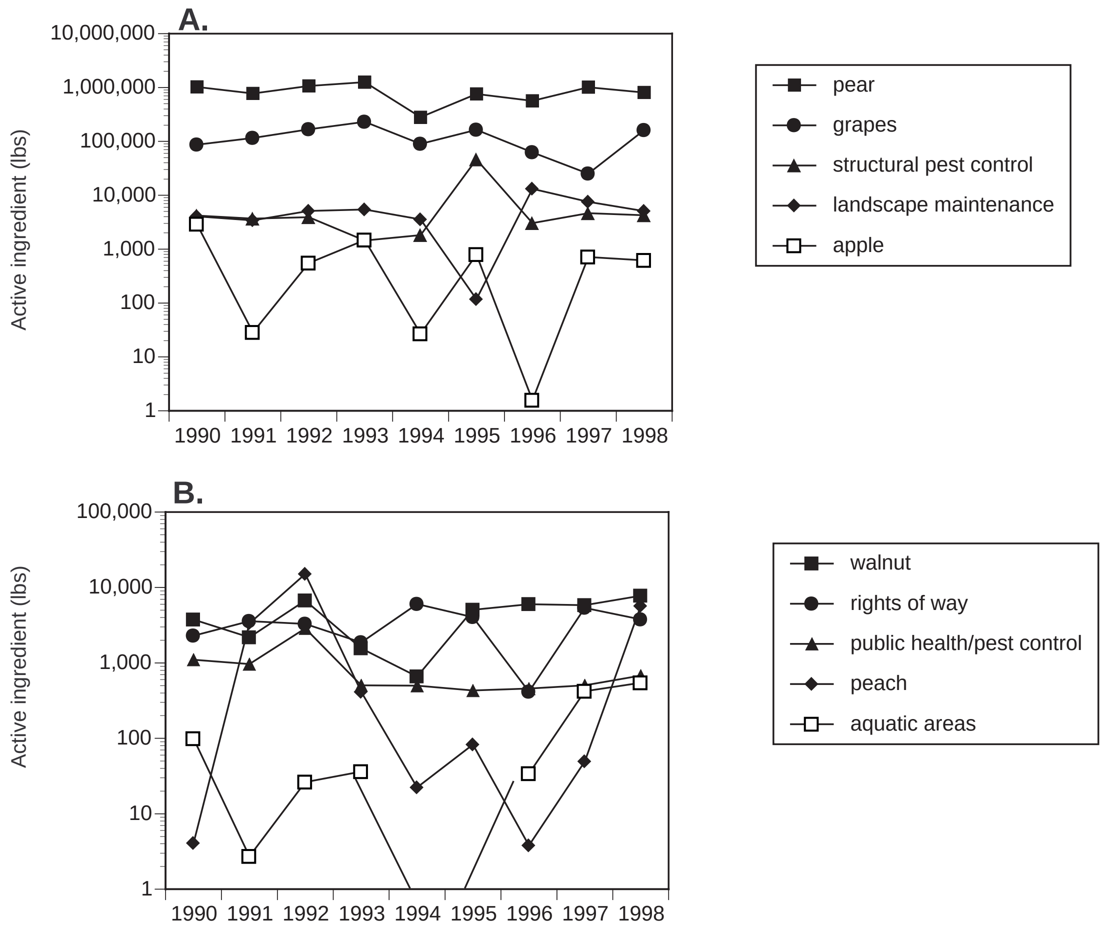
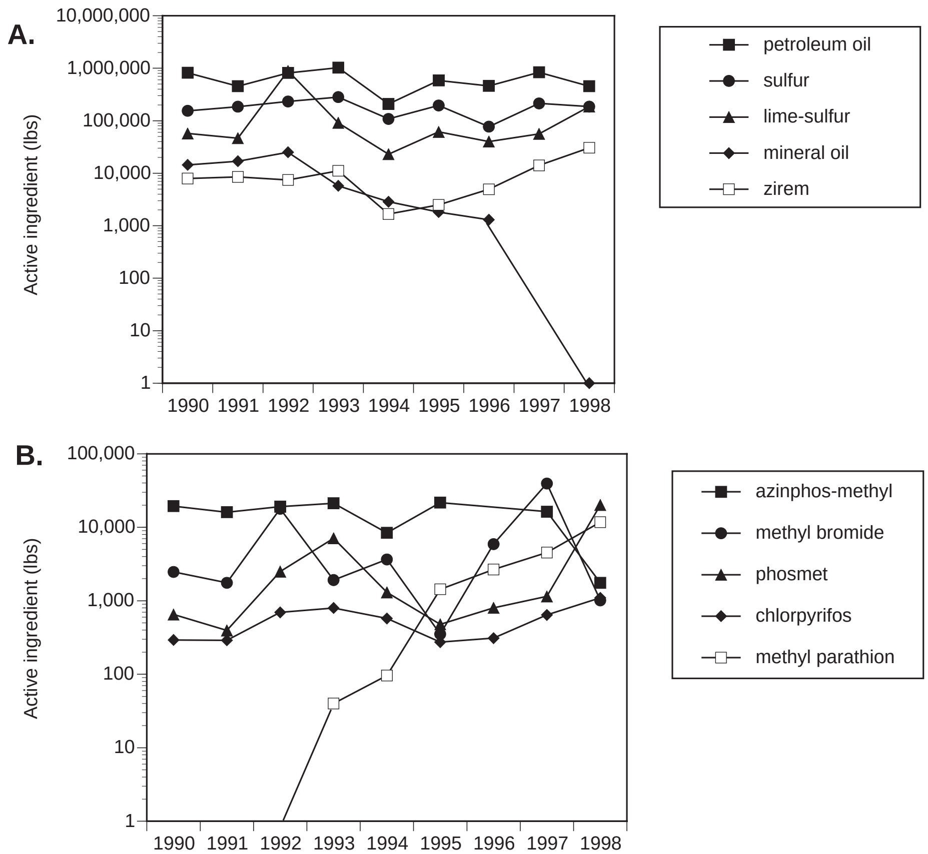


Figure 121.8 Annual cumulative pesticide applications for the top ten crops and uses in lake County from 1990 to 1998 (by weight). A) Total pesticide applications for the top five crops (by weight), B) Total pesticide applications fo rthe second five crops with the heaviest pesticide applications (by weight).

summer). Currently, alternative approaches to control codling moth involve the use of pheromone mating disrupters, especially when the density of moths is relatively low (Bentley et al. 1999, Elkins and Shorey 1998). The second most heavily used product, which is not acutely toxic to humans or wildlife at low doses, is sulfur and lime-sulfur. The primary use of these compounds has been as fungicides on vineyards for protection against powdery mildew. While not highly toxic, the high application rates have the potential to increase sulfur loading into the lake, which also may interact with sulfate-reducing bacteria in the conversion of inorganic mercury to methyl mercury. However, no studies have yet been conducted to determine the origin of sulfur compounds in Clear Lake.



<u>Figure 121.9</u> Annual pesticide applications for the ten most heavily used pesticides in lake County from 1990 to 1998 (by weight). A) Total applications for the top five pesticdes. B) Total applications for the second five most heavily applied pesticides.

Although the four most widely used pesticides each have a low environmental risk (both acute and chronic), the use of more toxic compounds is still widespread. Examples of this have been the two most heavily applied broad spectrum OPs, methyl parathion and azinphos-methyl (Guthion) (see **Fig. 9**). Methyl parathion, especially, increased dramatically from ca. 30 pounds in 1993, to nearly 12,000 pounds in 1998, mostly for use against codling moth. Guthion, on the other hand, has seen nearly constant usage from 1990 to 1998 when usage dropped significantly, mostly because codling moth began to show signs of resistance. Due to the USEPA's recent restrictions on methyl parathion residues, and a ban against its use after 1999, we expect to see a rise in Guthion rates in response, although recent restrictions on Guthion will likely keep its use low as well. Although the use of these insecticides is high, their potential ecological impact is somewhat offset by the fact that they have relatively short environmental persistence. Both compounds have terrestrial half lives from 3 to 16 days, and aquatic half lives of 1 to 6 days. This significantly reduces their risk to wildlife, unless large amounts are used near the lake as fish and aquatic invertebrates are particularly sensitive to these compounds. Nevertheless, additional research is needed to determine whether terrestrial pesticides are being transported into Clear Lake and if so, what their potential impacts to the aquatic community might be.

MTBE

Methyl tertiary butyl ether (MTBE), a synthetic chemical "oxygenate" added to gasoline to improve air quality as a part of the Clean Water Act, had been used in gasoline in limited quantities since the 1970s. It is considered a possible human carcinogen. It is highly soluble in water and does not readily degrade in the environment; most public water systems are not equipped to remove it completely from drinking water. It has a turpentine-like taste and smell and initial studies show that some people can detect it in drinking water at concentrations as low as 2.5 parts per billion (ppb). In 1992, oil companies began using it extensively and in recent years it has been detected in Clear Lake water. A 1998 University of California study indicated that there are significant risks and costs associated with water contamination due to the use of MTBE. In addition, it found that the use of gasoline containing MTBE in motor boats and crafts, in particular those with older 2-stroke engines, results in the contamination of surface water reservoirs. In January 1999, the California Department of Health Services established a secondary (taste and odor-based) Maximum Contaminant Level (MCL) allowable standard of 5 ppb, and a primary human health based MCL of 13 ppb in May 2000. In March 1999, Governor Gray Davis issued an Executive Order for California to phase out the use of MTBE by 2003, and legislation to ratify the order (Senate Bill 989) was passed during the 1999 session. In March 2000, the federal government announced it would ban the use of MTBE under the Toxic Substances Control Act.

Some water samples collected from various locations within Clear Lake have detectable levels of MTBE, but those levels were always lower than the MCL for taste and odor. Nine of 53 Lake County water samples collected from January 1984 to December 1999 showed detectable MTBE concentrations. Of those 53 samples, 23 were collected within Clear Lake proper and 8 of those 23 showed a range of MTBE concentrations of 1.1 to 4.5 ppb. These values are below the taste and odor MCL standard of 5 ppb and significantly below the human health based standard of 13 ppb, now in effect.

Mining

Clear Lake contributed significantly to mining operations within the United States. In 1864 this region was the first location to be mined for borax within the US (Bailey 1902), and a year later California's first sulfur was extracted from a surface deposit of elemental sulfur called the Sulphur Bank Mine (California Division of Mines 1950). The deeper deposits of sulfur from this site were contaminated with cinnabar (mercury sulfide) and in 1872 the site was converted to mercury mining as the Sulphur

Bank Mercury Mine. At that time California accounted for 89% of the nation's mercury production and the Sulphur Bank Mercury Mine produced about 10% of California's total mercury output (Simoons 1952). Because of elevated concentrations of mercury in fishes first documented during the 1970s (Curtis 1977), the Sulphur Bank Mercury Mine was placed onto the US Environmental Protection Agency's National Priority List as a USEPA Superfund Site in 1990 (Suchanek et al. 1993).

Mining at the Sulphur Bank Mercury Mine is believed to have contaminated the lake with both mercury and arsenic (Sims and White 1981, Chamberlin et al. 1990, Suchanek et al. 1993, 1997). Inorganic mercury concentrations in lakebed sediments are significantly elevated (over 400 ppm) close to the mine and decline exponentially with distance from the mine (Suchanek et al. 1997, 1998a, 2000b). Arsenic is only slightly elevated close to the mine, but also exhibits a recognizable background signal throughout the lake, likely as a result of outflow from numerous lakebed springs (Suchanek et al. 1993). Since 1992 detailed studies have been conducted on mercury contamination from the Sulphur Bank Mercury Mine (Suchanek et al. 1993, 1995, 1997, 1998a,b, 2000; Anderson et al. 1997; Mack et al. 1997; Slotton et al. 1997, Webber and Suchanek 1998, Wolfe and Norman 1998). Research at this site has identified acid mine drainage, which is low in pH and high in sulfate, as the most likely point source for methyl mercury contamination in Clear Lake (Suchanek et al. 1993, 1997, 2000b, Nelson et al. unpublished). Remediation of the mine is expected to begin around 2001.

Other mining operations have been widespread throughout the Clear Lake basin. **Figure 10** provides a location map for the diverse array of mining operations that have existed within this watershed over the past 150 years. With the advent of home and especially road construction in the early 1970s, Lake County needed an easily accessible source of gravel as road base. Creek beds provided this resource; thus large volumes of gravel were extracted from Scotts Creek, Middle Creek, Kelsey Creek, Adobe Creek, Forbes Creek, Cole Creek, and Burns Valley Creek (see **Fig. 10**). Gravel mining, which was common until 1987 (Zalusky 1992), changed the level of stream beds as much as 15 feet and caused destabilization and increased erosion during the next flooding season, carrying higher loads of sediments and associated nutrients into the lake. Additionally, roads now block upstream areas that once were used for spawning (e.g., hitch). Volcanic cinder cones also have been mined as a source of aggregate and decorative rock, but the environmental impacts have been relatively small compared with mining in active stream beds. Mining operations that are still active include primarily sand and gravel, cinders and decorative stone and rock.

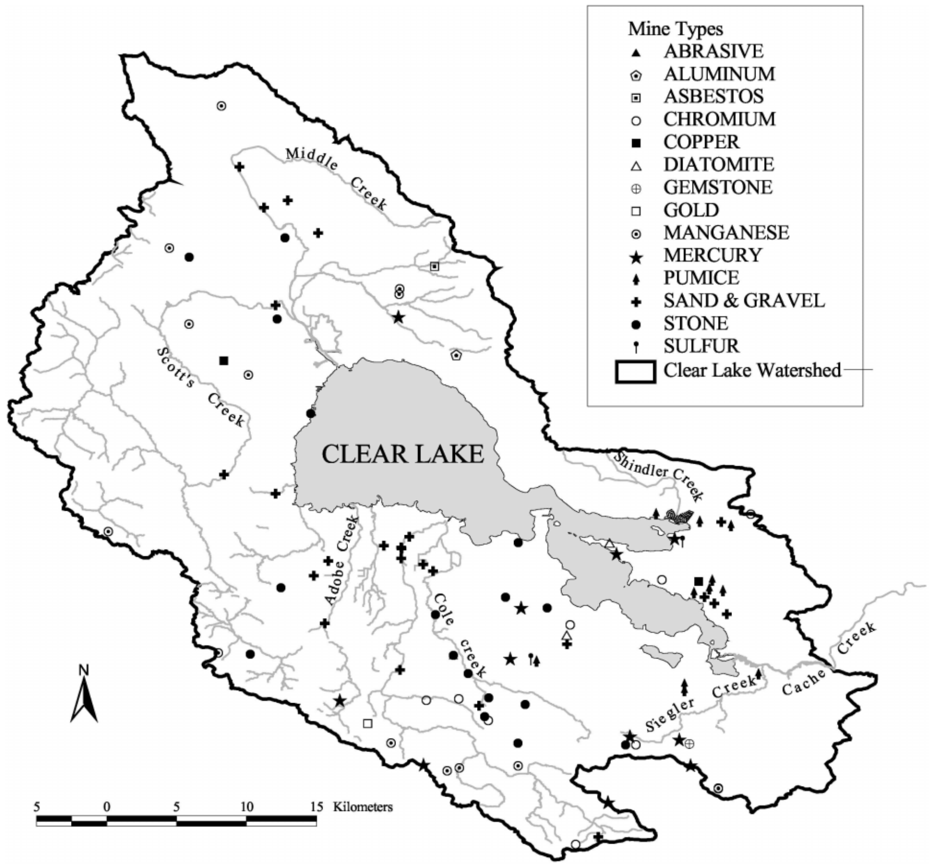


Figure 121.10 Map of mining operations within the Clear Lake watershed over the past 150 years.

Sewage and septic overflows Although there have been many sewage overflows, especially during major flooding periods, this probably does not represent a significant nutrient loading to Clear Lake (see Richerson et al. 1994 for discussion).

Land Use Changes

Wetland losses and gains Original natural wetland acreage around the rimland of Clear Lake declined by nearly 85% from around 9,000 acres in 1840 to about 1,500 acres in 1977 (**Table 3**). One of the most dramatic land use changes experienced within Clear Lake's watershed has been the process of wetland conversion to agriculture. Beginning in the 1890s a large area of natural wetlands from the Robinson Lake and Tule Lake region in the northwest side of Clear Lake was reclaimed primarily for agricultural production of string beans and lima beans (Simoons 1952). This was followed by another reclamation

Table 121.3 Wetland losses in the region surrounding Clear Lake.

Table 3: Historic wetland acreage

Year	Acres	% of original acreage
1840	9,000	100
1920	5,400	60
1952	5,300	59
1958	5,200	58
1966	3,400	38
1968	1,900	21
1977	1,500	17

project in 1927 in the Middle Creek watershed for agricultural production, and the 1959 Rodman wetland reclamation by the US Army Corps of Engineers. These projects collectively increased agricultural production, but also altered the transport of sediments and associated nutrients into Clear Lake, with the likely result that noxious cyanobacteria (bluegreen "algae") blooms significantly increased beyond previous levels (Richerson et al. 1994). Wetland reclamation is not unique to Clear Lake; it is a process that similarly was initiated in the late 1800s throughout the country and especially in the San Francisco Bay-Delta system where 79% of the marshlands have been lost in the last 200 yrs, and over 538,000 acres were converted to agricultural land (Monroe et al. 1999).

There are several categories of newly created waterbody or wetland habitats, including sewage treatment ponds, agricultural ponds, irrigated crops (such as rice), or pastures and reservoirs, which can have both positive or negative feedbacks to the Clear Lake ecosystem. For example, several tracts of original wetland habitat, such as Tule Lake, are now in rice production. These habitats are managed by flooded irrigation practices, so for much of the year they are functional wetlands and enhance populations of some invertebrates, which in turn provide food resources for some wildlife. These practices can both enhance wildlife and produce potential problems for disease vector agents such as mosquitoes. Some of the more recently created reservoirs can also be beneficial in trapping sediments with associated nutrients before they enter Clear Lake, which would also help to limit nutrient loading. However, we are not aware of any studies that have compared the functionality of original versus newly created wetlands for any of these categories.

The intrinsic ecological values, in terms of biodiversity and natural filtering capacity of wetlands, have now become more recognized, and a trend to restore/rehabilitate previously reclaimed wetlands has been popular in recent years. Presently, reclaimed former wetlands in both the San Francisco Bay-Delta system and the Clear Lake system are being considered for wetland restoration/rehabilitation. In the case of Clear Lake, the U.S. Army Corps of Engineers has completed a Reconnaissance Phase and is presently in the Feasibility Phase of a plan to restore up to 1,200 acres of wetlands in the Robinson Lake/Middle Creek region of Clear Lake (Jones and Stokes 1997, Smythe 1997, Van Nieuwenhuyse 1997).

Dredging and Filling Over the past 150 years, vast areas around the rimland of Clear Lake that previously were wetlands have been filled or converted to either private, commercial, or public use (for homes, businesses, or roads), especially in response to the population increase after about 1925. These projects also tended to deliver large volumes of sediment and nutrients to Clear Lake (Richerson et al. 1994). The residential sub-division of Clearlake Oaks (known as the “Keys”) resulted in the extensive dredging of wetlands during the 1960s, and resulted in the generation of about 6.5 miles of navigable channels. Other similar developments include Corinthian Bay and Lands End. For other smaller projects these sometimes subtle, yet continuous, changes have been the most difficult to document, for there are few records that quantify conversion of small to medium sized areas of wetlands, especially before the turn of the century.

Within the past 5 years there has been a movement by one citizens’ group to dredge Clear Lake to a depth of about 60 ft (about 18 m) or more, with the stated purpose of generally “improving water quality,” but without any documented specifics. Because the average depth of Clear Lake in most locations is 8 to 10 m, this would involve dredging another 9 m deeper. This concept is fraught with problems, not only economic, but especially ecological as well. Because relatively high concentrations of mercury and pesticides (DDD) are buried in the sediments of Clear Lake (especially within the top 60-70 cm) (Suchanek et al. 1993, 1997, Richerson et al. 2000), these materials would have a high probability of becoming remobilized into the water column and bioaccumulated into the trophic web in the course of dredging. Another problem with increasing the depth of Clear Lake to 60 ft is related to the issue of summer water column stratification. Most deep lake systems undergo temperature and oxygen stratification during the summer, whereby a temperature discontinuity (thermocline) is formed in the water column with an associated water mass at the bottom (hypolimnion) that has dramatically different physical and chemical characteristics from the surface water mass. This hypolimnion is typically cooler and is much more likely to be anoxic than surface waters. Clear Lake's present depth creates a situation in which bottom waters (near the sediment-water interface) occasionally become anoxic, but this condition does not typically last long because of wind-driven mixing. If the lake were significantly deeper, this anoxic condition would persist for long periods of time, perhaps months. This is exactly the condition under which sulfate reducing bacteria flourish. As this microbial group has been implicated in the conversion of inorganic mercury into toxic methyl mercury, a deeper lake would most likely promote a higher production of toxic methyl mercury in the bottom waters. Winter turnover of the water column would allow this methyl mercury to be remobilized and potentially bioaccumulated by organisms in the lake. Because mercury is already an issue of great concern in Clear Lake (see Contaminants above), any changes that would promote further methyl mercury production would be undesirable. Nevertheless, such proposals point to the need for ongoing studies and monitoring to understand how natural and anthropogenically mediated processes may influence the complex dynamics imposed by multiple stresses on this ecosystem.

Creek bed, water table and shoreline modifications The lower reaches of Clear Lake hitch (*Lavinia exilicauda*) spawning streams have usually dried up naturally, but due to ground water extraction, these areas dry up earlier resulting in spawning failures; additionally the loss of marshy wetland areas surrounding the lake limits the habitat available to larval hitch.

Agriculture Private fruit and nut orchards were planted early (around 1860) within the Clear Lake basin with the production of pears, plums, prunes, apples, almonds, peaches, nectarines and grapes, with commercial orchards starting in the 1880s (Simoons 1952). **Figure 11** provides estimates of acreage planted in the top five crops since the early 1900s, when reasonably accurate records were first kept. Much of the increase in wetland reclamation (see above) was driven by a desire to convert rich, easily irrigatable soils into profit-making tracts of land. The types of crops grown were driven, to a large degree, by market value. Presently wine has made a significant resurgence in the marketplace and a large movement to convert existing orchards (especially walnut orchards) into grape production is underway. Over the past 10 years, the land area committed to growing grapes has increased dramatically from about 1,400 acres in 1989 to 7,000 in 1999, with no immediate end of the surge in sight (see Fig. 11). During at least the first 1 to 2 years of the establishment of a vineyard (before any ground cover can be established), there is the potential for sheet wash erosion to transport large volumes

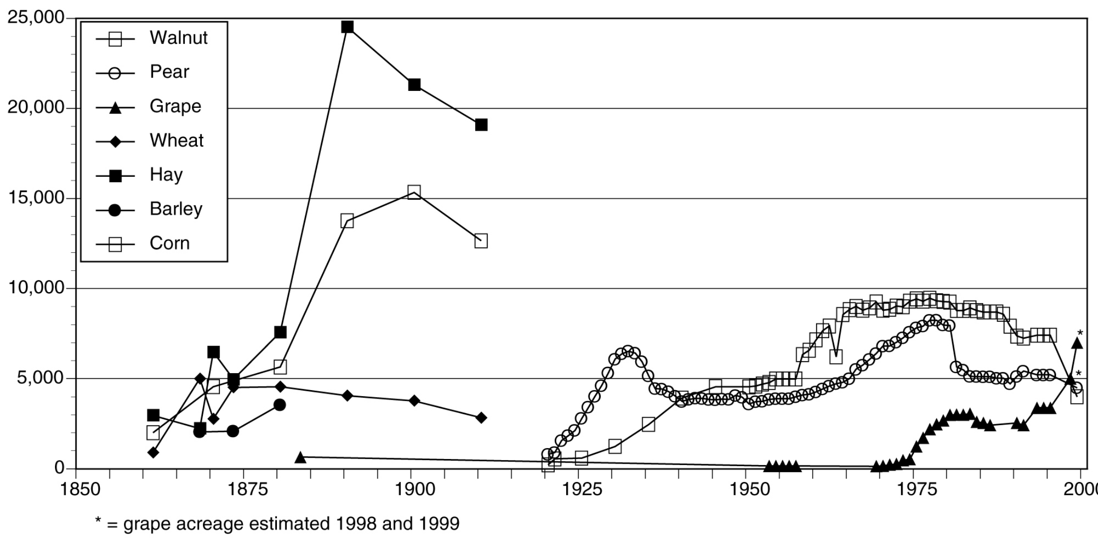


Figure 121.11 Trends in conversion of landscape to agriculture in the Clear Lake Basin. Note: no data available for hay, corn, wheat and barley after 1910; no data on walnuts and grapes before 1920; no data on grapes before 1880.

of sediment and associated nutrients into Clear Lake. This potential problem can be reduced by the early establishment of a ground cover crop that will help stabilize the soil. While this is the topic of considerable debate within the agricultural and environmental community in Lake County, to date we are unaware of any specific studies that have addressed quantitatively the impacts of vineyards or orchards on erosion within the Clear Lake basin.

Cattle and sheep grazing The first cattle (initially Longhorn and then many other breeds including Shorthorn, Hereford, Polled Hereford, Angus, and Scotch Highland) were brought to the Clear Lake in 1839 and their grazing impacts on the landscape increased thereafter (Mauldin 1968). Richerson et al. (2000) discuss some of the early farming and ranching practices. Sheep herds were abundant and peaked sharply in the late 1870s at around 50,000 head, and declined dramatically thereafter due to declining pasture quality, but increased again to nearly 40,000 head around the 1930s, and then steadily declined to today's low levels. Goats and hogs peaked around the turn of the 20th century at around 10,000 each, yet cattle numbers were more stable with about 10,000 head from 1861 through the 1980s. Even in early days, there was a problem with overgrazing, which resulted in the eventual closing of most of the local forest to cattle ranchers in 1947 (Mauldin 1968). Overgrazing causes decreased soil stability and increased erosion, and results in greater nutrient input to the lake. Recently, grazing allowed in regions of emergent vegetation, especially in low water years when cattle have access to tule beds (as happened in 1999), is also a problem because they can impact grebe nesting colonies.

Soil exposure and transport Construction of residential and commercial facilities, both along the rimlands and on the upper slopes of the Clear Lake watershed have the continual effect of transporting sediments and associated nutrients into Clear Lake during the rainy season. Nonpaved roads also contribute significant loading of erosional materials to Clear Lake. During the summer, large numbers of off-road vehicles traverse back country roads (e.g., about 20 miles along Cow Mountain), loosening soil from the roadbed. At the end of the summer season, there is often a 5-10 cm layer of fine grained soil (and associated nutrients) on the surface of the roadbed, which gets flushed into drainage pathways and the lake with the first major rainstorm.

Species introductions Due in large part to its high productivity, Clear Lake continually has supported a very rich fish fauna. The structure of the fish community has changed a great deal over approximately the last 100 years in response to numerous alien fish introductions. Prior to European settlement, there were 13 naturally occurring fish species in the lake, four of which were endemic (Hopkirk 1973). The current fish community consists of 21 species, only four (19%) of which are native to the lake (see **Table 4**). The introductions began in the late 1800s with the establishment of three species, the white catfish (*Ameiurus catus*), brown bullhead (*Ameiurus nebulosus*) and common carp (*Cyprinus carpio*) (Murphy 1951) and all three species continue to flourish in the lake.

The introduction with perhaps the greatest impact on the Clear Lake fish community in recent years was the inland silverside in 1967 (Li et al. 1976). Like the western mosquitofish (*Gambusia affinis*), the inland silverside was introduced primarily for control of the Clear Lake gnat (see above). Within one year they established themselves as one of the most abundant fish in the lake and now are the dominant planktivore of the littoral zone (Moyle 2002). This niche dominance likely acted as a catalyst for sweeping changes throughout the lake. Upon its introduction, the inland silverside reduced zooplankton populations in the nearshore regions of Clear Lake, outcompeting other planktivorous fishes in that region (Moyle 2002). Moyle also credits the introduction of the inland silverside as a major factor in the final demise of the planktivorous Clear Lake splittail (*Pogonichthyes ciscoides*), a species already in serious decline. One example of the inland silverside's effects on other fish is provided by the black

Table 121.4 Past and present fishes in Clear Lake, including dates of introduction for alien species.

Species	Family	Native/Introduced	Trophic Position (Juvenile/Adult)	Current Status	Reason for Introduction
thicktail chub (*Gila crassicauda*)	Cyprinidae	Native	omnivorous piscivore and invertivore ??@	Extinct (1941-50)	-----------
California roach (*Lavinia symmetricus*)	Cyprinidae	Native ^	benthic browser	Extinct (<1963)	-----------
Clear Lake splittail (*Pogonichthys ciscoides*)	Cyprinidae	Native	littoral planktivore/pelagic planktivore	Extinct (1972)	-----------
hitch (*Lavinia exilicauda)*	Cyprinidae	Native	littoral planktivore/pelagic planktivore	Abundant	-----------
Sacramento blackfish (*Orthodon microlepidotus*)	Cyprinidae	Native	pelagic planktivore/benthic detritivore	Abundant	-----------
Sacramento pikeminnow (*Ptychocheilus grandis*)[1]	Cyprinidae	Native ^	pelagic invertivore/ pelagic piscivore	Unknown	-----------
threespine stickleback (*Gasterosteus aculeatus*)	Gasterosteidae	Native	benthivore	Extinct (<1894)	-----------
rainbow trout (*Oncorhynchus mykiss)*	Salmonidae	Native	pelagic and benthic invertivore	Extinct (<1963)	-----------
Pacific lamprey (*Lempetra tridentata)*	Petromyzontidae	Native ^	parasite	Unknown	-----------
Sacramento sucker (*Catostomus occidentalis*)	Catostomidae	Native ^	benthic detritivore & invertivore	Unknown	-----------
Sacramento perch (*Archoplites interruptus*)	Centrarchidae	Native	littoral planktivore/benthic invertivore & piscivore	Rare	-----------
tule perch (*Hysterocarpus traski*)	Embiotochidae	Native	planktivore & invertivore	Common	-----------
prickly sculpin (*Leptocottus armatus*)	Cottidae	Native	benthic invertivore	Abundant	-----------
lake whitefish (*Coregonus clupeaformis*)	Salmonidae	Introduced (1873)*	planktivore/benthic invertivore	Unsuccessful intro.	sport fishery
common carp (*Cyprinus carpio*)	Cyprinidae	Introduced (1880)*	benthic omnivore	Abundant	accidental
brown bullhead (*Ameiurus nebulosus*)	Ictaluridae	Introduced (1880)*	benthic littoral omnivore	Abundant	sport fishery
largemouth bass (*Micropterus salmoides*)	Centrarchidae	Introduced (1888)*	top predator	Abundant	sport fishery
golden shiner (*Notemigonus crysoleucas*)	Cyprinidae	Introduced (1896)*	littoral and pelagic planktivore	Rare	forage fish
bluegill (*Lepomis macrochirus*)	Centrarchidae	Introduced (1910)*	planktivore/omnivore	Abundant	sport fishery
black crappie (*Pomoxis nigromaculatus*)	Centrarchidae	Introduced (1910)*	pelagic planktivore/omnivore	Common	sport fishery
yellow perch (*Perca flavescens*)	Percidae	Introduced (1910)*	littoral omnivore	Unsuccessful intro.	sport fishery
goldfish (*Carassius auratus*)	Cyprinidae	Introduced (1920)#	littoral herbivore & detritivore	Common	forage fish
channel catfish (*Ictalurus punctatus*)	Ictaluridae	Introduced (1920)#	omnivore--mostly inverts & fish	Common	sport fishery
white catfish (*Ameiurus catus*)	Ictaluridae	Introduced (1923)*	benthic invertivore/benthic omnivore	Abundant	sport fishery
brown trout (*Salmo trutta*)	Salmonidae	Introduced (1924)	invertivores/predators	Extinct (<1963)	sport fishery
Western mosquitofish (*Gambusia affinis*)	Poeciliidae	Introduced (1925)*	invertivore	Common	pest control
green sunfish (*Lepomis cyanellus*)	Centrarchidae	Introduced (1935)#	littoral omnivore	Common	sport fishery
fathead minnow (*Pimephales promelas*)	Cyprinidae	Introduced (1955)#	benthic omnivore	Rare ??	forage fish
white crappie (*Pomoxis annularis*)	Centrarchidae	Introduced (1955)#	pelagic omnivore	Common	sport fishery
redear sunfish (*Lepomis microlophus*)	Centrarchidae	Introduced (1965)#	molluscivore	Rare	sport fishery
inland silverside (*Menidia beryllina*)	Atherinidae	Introduced (1967)#	littoral planktivore	Abundant	pest control
threadfin shad (*Dorosoma petenense*)	Clupeidae	Introduced (1985)	epi-pelagic planktivore	Abundant??	forage fish

[1] formerly known as squawfish
* = from Murphy, 1951
\# = from Li and Moyle, 1979
^ = found in watershed streams
@ = Moyle, 2002

crappie (*Pomoxis nigromaculatus*) and white crappie (*Pomoxis annularis*). After the introduction of the inland silverside, the mean standard length of young crappie (also planktivores) decreased and that of adult crappie increased from pre-introduction levels (Li et al. 1976). This suggests that the inland silverside may have competed with young crappie and that adult crappie were likely preying on silversides. The silversides also have become the primary forage fish for other predatory species and undoubtedly have helped the already booming sport fishing industry in Clear Lake.

Other introductions that have had dramatic impacts on the structure of the aquatic community are the myriad sportfishes such as several species of catfish (e.g. *Ameiurus catus*, *Ictalurus punctatus*), the largemouth bass (*Micropterus salmoides*) and other centrarchids. Moyle (2002) notes that the success of the white catfish (*Ameiurus catus*) was associated with a decline of the native cyprinids. He additionally credits the elimination of the pikeminnow (*Ptychocheilus grandis*, previously called squawfish) and the extinction of the thicktail chub (*Gila crassicauda*) to the presence of the largemouth bass and other exotic predators.

The most recent fish introduction is that of the threadfin shad (*Dorosoma petenense*) in 1985 (Anderson et al. 1986). The impacts of the shad introduction have not been thoroughly quantified; however, it is generally assumed that they compete heavily with the silversides for food, leading to greatly fluctuating zooplankton populations. It also has been observed that the shad themselves go through very large population fluctuations as evidenced by numerous die-offs that have occurred since their introduction. These generally occur in winter (as occurred during the winters of 1990 to 1991 and 1998 to 1999 when tens of thousands of threadfin shad died and floated to shore), and likely is due to their poor tolerance of cold water, because they have great difficulty feeding below 9°C (Griffith 1978). The introduction of the threadfin shad resulted in a significant decline in *Daphnia* populations that serve as the primary food source for young-of-year largemouth bass. Thus, a cascade effect that reduced the numbers of largemouth bass was correlated with the introduction of shad. Furthermore, when the shad population crashed in 1990, the largemouth bass population made a significant rebound, which most likely was due to the resurgence in the number of *Daphnia* found in the lake (Colwell et al. 1997). One study suggests that *Daphnia* consume primarily planktonic diatoms, but typically leave the less palatable bluegreen algae (Elser et al. 1990). Additionally, Colwell et al. (1997) have shown a strong positive correlation between threadfin shad abundance and that of various piscivorous birds such as Clark's grebes (*Aechmophorus clarkii*) and western grebes (*Aechmophorus occidentalis*), double-crested cormorants (*Phalacrocorax auritus*), and California gulls (*Larus californicus*). This may be due to the fact that the shad prefer well lighted surface waters, making them easy prey for the birds. After the 1990 population crash, the populations of the aforementioned birds returned to pre-introduction levels. This combination of top-down and bottom-up strong interactions suggests that if this species ever establishes permanently high densities its introduction may result in dramatic changes throughout the ecosystem, perhaps greater than the changes caused by any previous introduction.

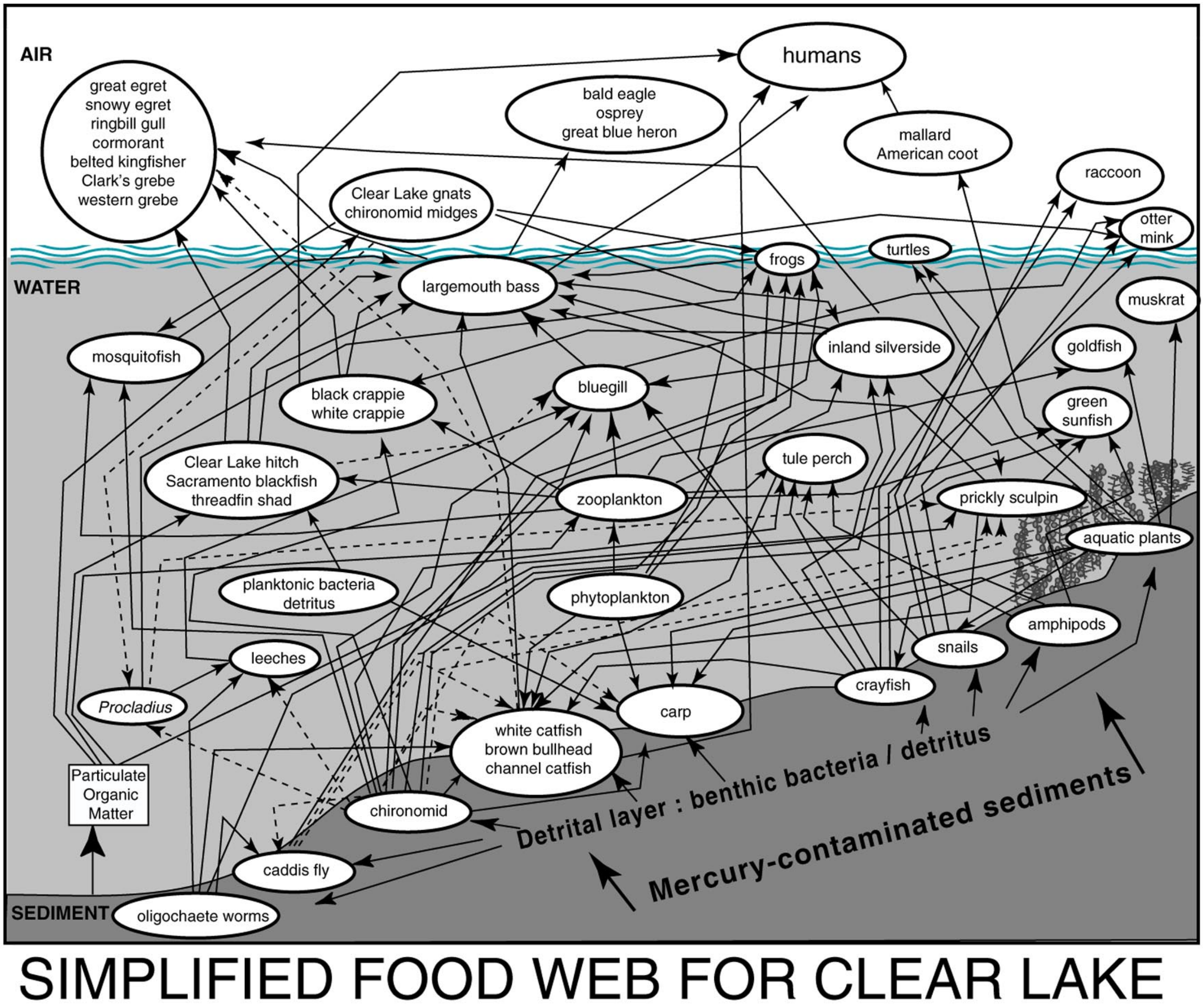
Over the past decade there typically have been three to four commercial fishing licenses on Clear Lake, mostly focused on the Sacramento blackfish (*Orthodon microlepidotus*) and common carp (*Cyprinus carpio*), which typically are sold live to Asian markets in the San Francisco Bay region. In the 1960s and 1970s, there were years when over 317,000 kg of carp were taken from the lake and sold mostly to processing plants for catfood. A single haul of carp in about 1990, toward the end of the six year drought, yielded about 45,400 kg; yet in recent years carp and blackfish have been in relatively low abundance (M. Meadows, personal communication 2000).

Today there still exist numerous threats to the survival of many Clear Lake fishes. For example, threats to hitch (*Lavinia exilicauda*) are loss of spawning habitat and loss of nursery areas. And, the establishment of the threadfin shad (*Dorosoma petenense*) tended to greatly reduce populations of the zooplankton *Daphnia*, a principal food of hitch.

Hydrilla (*Hydrilla verticillata*), indigenous to SE Asia (Langeland 1996), is a noxious non-native submerged aquatic weed that is spreading rapidly throughout the United States. It was first discovered in Florida in the 1960s and for the first time in Clear Lake in August 1994 (O'Connell and Dechoretz 1997, Dechoretz 1998). Where it occurs, it causes substantial economic hardships, interferes with various water uses, displaces native aquatic plant communities, and adversely affects freshwater habitats (Langeland 1996). In 1994, about 175 to 200 surface acres in Clear Lake experienced infestation. This area increased to 648 acres by 1998 (Dechoretz 1998), and in 1999 the affected area expanded to 845 acres[1] (M. Lockhart, personal communication 2000). This weed is adapted to grow at low light levels, competes effectively for sunlight and has a rapid growth rate (up to one inch per day). It has four different modes of reproduction and has the potential to spread with enormous speed to clog enclosed and open waterways, including water bodies as large as Clear Lake (Langeland 1996).

Ecosystem Complexity

The aquatic ecosystem of Clear Lake and its supporting basin and watershed are extremely productive and complex. The trophic structure of the lake's biota is both complicated and dynamic. **Figure 12** represents a simplified version of an elaborate, multi-tiered trophic network for some of the more common species in Clear Lake. Richerson et al. (1994: Table 3.3) also provide documentation of a preliminary food web for Clear Lake, including known predator-prey relationships. Many of the factors identified above are dynamic, affecting the ecological relationships between species, and present significant challenges to resolving system-wide ecological problems. While considerable research has been conducted on the Clear Lake aquatic ecosystem, there exists a large degree of uncertainty about our knowledge of the impacts from the multiple stresses outlined above.



<u>Figure 121.12</u> Simplified food web for Clear Lake.

Multiple Management Objectives

The discussion above highlights many multiple stresses that affect the aquatic ecosystem of Clear Lake proper and the surrounding watershed and basin. These impacts affect not only the natural ecology of the system, but interact with human dimensions as well, including aesthetic and economic. The Clear Lake basin is an aesthetically beautiful setting and, as it has for over a century, attracts many thousands of tourists each year. Tourist visitation revenues for Lake County were estimated at $162 million in

1992 and increased on average about 7.9% per year to $237.5 million in 1998 (Dean Runyan Associates 1999). It is estimated that 7 to 10 million dollars of tourist revenue is lost annually due to the influence of poor water quality associated with cyanobacterial blooms alone (Goldstein and Tolsdorf 1994). Given the complexities of managing a productive and multi-use watershed, many conflicts exist. For example, what is the best solution for maintaining the lake level? Downstream farmers in Yolo County would like to accumulate as much water as possible in Clear Lake during periods of winter precipitation for future use the following summer; yet, the higher the lake levels rise, the greater risk of flooding to citizens living along the rimlands, as occurred when the first Clear Lake dam was erected in 1867 (see above). Another example relates to the use of pesticides and fertilizers for agricultural crops. Farmers typically use pesticides and fertilizers to maximize production; yet, the health of the aquatic ecosystem (especially its resources for sport and commercial fisheries) may be negatively affected by these practices. Some Lake County residents strive to enact regulations or change land use patterns to reduce the free floating cyanobacterial blooms and the noxious odors associated with their stranding on shore. During years when the blooms are minimal, water clarity is improved, but shallow-rooted aquatic macrophytes proliferate and clog boat propellers. Yet macrophytes are desirable as refuges and habitats for increased biodiversity and often act as nursery grounds for young fishes. Trade-offs will always exist, but it is the responsibility of science to provide informed decision-making options (and their inherent consequences) before exploiting multiple-use resources found within Clear Lake and its watershed.

Lake County has been one of the most progressive counties in the state in developing a Coordinated Resource Management and Planning (CRMP) process (Follansbee 1996). Simply put, using a consensus model, the CRMP process brings together citizen interest groups and representatives from local, state, and federal agencies to develop integrated approaches to complex resource management issues. The first use of the CRMP process in 1949 to address grazing for an allotment in Oregon was documented by Anderson and Baum (1988). Over 200 such CRMPs are in existence within California and several have been started within Lake County. One of the first Clear Lake CRMPs dealt with the problems associated with the cyanobacterial blooms. A committee initially established as the “Algae Abatement Committee” in 1984 (and now operating under a broader mandate as the “Clear Lake Advisory Subcommittee – CLAS”) has met regularly (typically monthly) since its inception to address problems and potential solutions to eutrophication and other issues related to water use and quality within Clear Lake and its surrounding watershed. It has since evolved into an entity that addresses county-wide resource issues in an integrated manner while attempting to maintain and enhance the ecosystems and economy of Lake

County (Follansbee 1996). This group has been folded into a more structured Lake County Coordinating Resource Management Committee (RMC), which began in 1989, and now includes representatives from county level resource agencies, agricultural interests, Native Americans, fishing and hunting groups, environmental special interest groups, realtors, Chambers of Commerce, and the University of California. The structure of the RMC includes four subcommittees: Clear Lake Advisory (noted above), Biological Resources, Land and Water Resources, and Database and Information Outreach. These subcommittees seek out information from each of the representative participants and draw heavily upon past and ongoing scientific research that is conducted on Clear Lake and its surrounding watershed. In general, the RMC seeks to improve coordination of planning, research, and land and resource management by obtaining input from all interested parties, sharing information, collecting data, conducting research, and developing policies and regulations that will maximize benefits for the citizenry of the county (Follansbee 1996). In addition to the Clear Lake (Upper Cache Creek) Watershed CRMP, there are several other local and regional CRMPs that interact closely to resolve environmental issues. These include: High Valley and Schindler Creek CRMP, Lake Pillsbury Watershed CRMP, Middle Creek CRMP, and the Scott's Creek CRMP.

Recommendations from the RMC (above), which receives input from the various CRMPs, are passed to the county Board of Supervisors who then vote on whether to adopt or modify them. One example of a process initiated and mediated by the Clear Lake CRMP has been an investigation of "The Causes and Control of Algal Blooms in Clear Lake" (see Richerson et al. 1994). UC Davis scientists conducted a study (funded by the USEPA Clean Lakes Program) to evaluate possible remediation options to reduce bluegreen algal blooms in Clear Lake. A series of recommendations from this study were provided to the RMC and voted on by the Board of Supervisors. As a result, Lake County has been engaged in several remediation strategies to reduce nutrient inputs to Clear Lake. Two examples include: (1) stabilization of creek bed channels (disrupted by gravel mining) by replanting willows and cottonwoods, and (2) initiation of a process to restore and rehabilitate up to 1200 acres of wetlands in the northwest region of Clear Lake (formerly Robinson Lake) that were converted to agricultural production over the past 100 yrs (discussed above). The CRMP process is holistic and appears to be working well, yet is always dependent upon accurate scientific data for proper strategic planning.

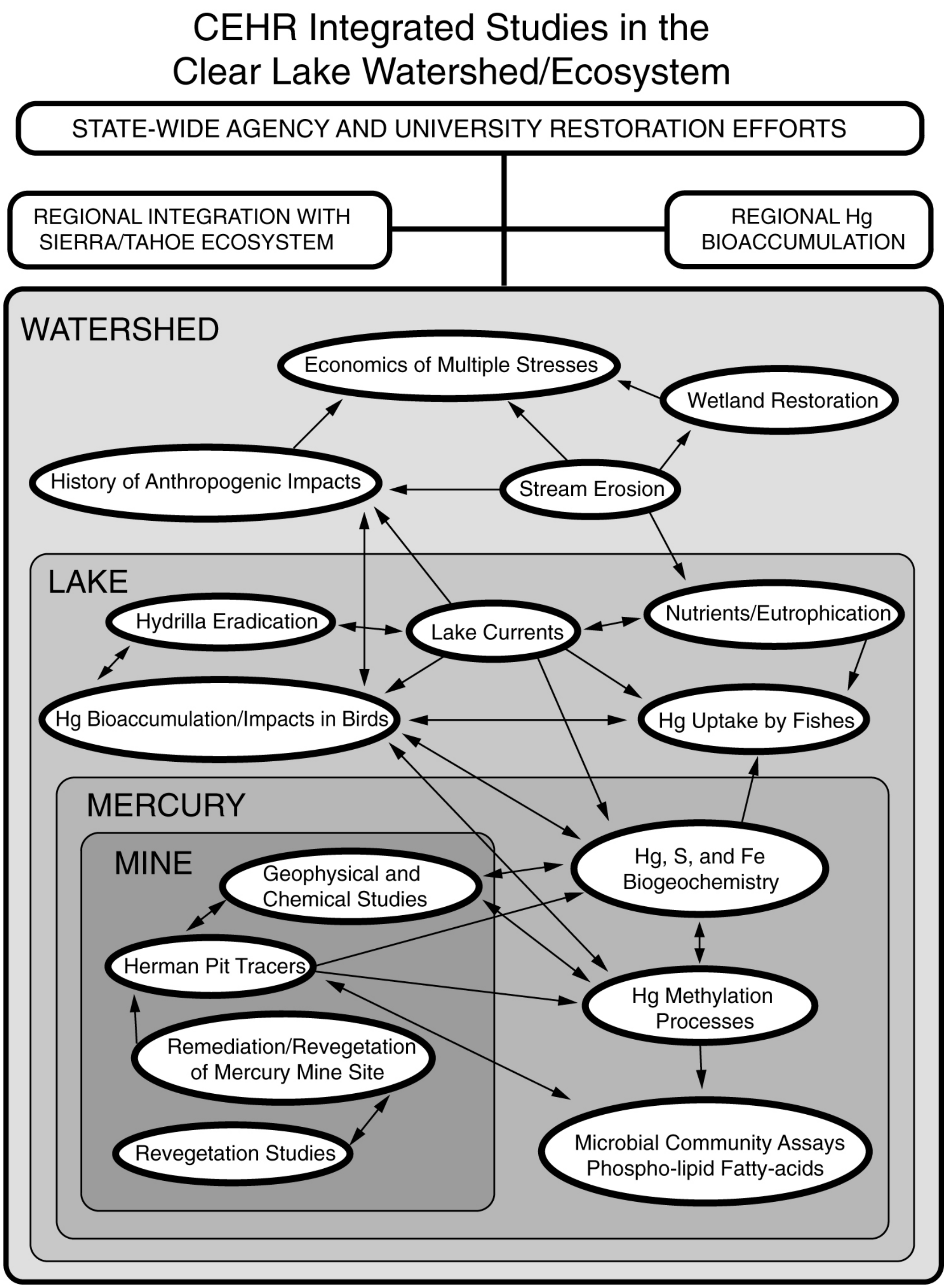
Research

Some of the earliest environmental and ecological research at Clear Lake was a series of observations dealing with fish biology that were initiated shortly after Europeans arrived in the basin (Stone 1874), and a more broadly based biological survey of the lake in the 1920s (Coleman 1930). Unfortunately we have found no documented history of the ecology of the lake before 1870, which would have provided a true aboriginal baseline, especially regarding the level of eutrophication in Clear Lake. The most productive periods of scientific research in Clear Lake have been associated with: (1) application of DDD to control the Clear Lake gnat (e.g. Lindquist and Deonier 1943, Dolphin 1959, Hunt and Bischoff 1960); (2) early water quality investigations (e.g. - Goldman and Wetzel 1963, Lallatin 1966, Kaiser Engineers 1968); (3) cyanobacterial bloom research undertaken by the Clear Lake Algal Research Unit (CLARU) during the period from 1969 to 1972 (e.g., Horne et al. 1971, 1972, Horne and Goldman 1972, 1974; Wrigley and Horne 1974; Horne and Commins 1987; and see Richerson et al. 1994 for a more complete list); (4) a multi-disciplinary investigation of the tectonic, stratigraphic and paleoclimatic history of the Clear Lake basin, especially as evidenced by deep (168 m depth) sediment cores collected in the 1970s and early 1980s (e.g., Sims et al. 1981, 1988; Sims and White 1981; Sims 1988, West 1989); (5) studies on mercury and arsenic contamination from the Sulphur Bank Mercury Mine that are still ongoing (e.g., Columbia Geosciences 1988, Chamberlin et al. 1990, Suchanek et al. 1993, 1995, 1997, 1998a, b, 2000a, 2000b); (6) an ongoing monitoring program by the Lake County Vector Control District that encompasses water quality, plankton, benthic invertebrates and fishes; and (7) a series of ongoing integrated studies by UC Davis researchers since the early 1990s on the impacts of multiple stresses on the Clear Lake aquatic ecosystem.

The earliest studies (e.g., water quality work, Clear Lake gnat research, cyanobacterial bloom studies), especially in the 1940s and 1950s, were typically “special purpose” programs designed to address specific problems. There was little integration and little continuity; the science was relatively unsophisticated, even though the scientific teams were utilizing the most modern standards of the day. Initially, DDD treatments of the lake were effective in cutting back the populations of the Clear Lake gnat, but (as indicated above) some deleterious side effects did occur. Later observations, however, suggested failure of the large pesticide applications and fish predator introductions to reduce and eliminate populations of the Clear Lake gnat, and indicated secondary consequences of population crashes of the western grebe, presumably from DDD contamination. However, western grebes have rebounded in recent years and in the year 2000 exhibited the largest population size ever recorded at Clear Lake (about 210,000 individuals). The 1970s spawned an era of more consistent data collection efforts, with the California Department of Water Resources (DWR) launching a water quality monitoring program begun in 1969 and continuing to the present day. These data collection efforts provided continuity, but still lacked directed investigation or integration with lake-wide environmental issues. As addressed above, results of Goldstein and Tolsdorf's (1994) study suggested that compromised water quality in Clear Lake likely is diminishing tourism by $7-10M per year. The economic impact suggests that there has been far too little investment in acquiring management-relevant data. Unfortunately, Lake County's responsibilities to support these efforts far outstrips its financial resources to do so.

The US Environmental Protection Agency (USEPA) has supported much of the recent work (since 1990) that has been conducted at Clear Lake, both on hyper-eutrophication and associated cyanobacterial blooms (USEPA Clean Lakes Program, about $100,000) and studies on multiple stresses affecting Clear Lake and its watershed (USEPA Office of Research and Development – UC Davis Center for Ecological Health Research, about $100,000/yr from 1992 to 2001). The USEPA also has funded studies on the impacts of mercury from the Sulphur Bank Mercury Mine on the lake's aquatic ecosystem (USEPA Superfund Program, about $500,000/yr from 1994 to 1998). As a cumulative effort since 1990, funding has supported about 5 Masters theses and 7 PhD dissertations (the result of about 42 graduate student study-years) to date.

The USEPA-funded Center for Ecological Health Research (CEHR) at UC Davis, operating at the watershed scale, is utilizing Clear Lake as one of three model ecosystems (the other two are the Sierra Nevada Ecosystem, including Lake Tahoe, and the Sacramento River Watershed) in which to evaluate the impacts of multiple stresses on ecosystem health. Another USEPA watershed project (funded by the NCERQA program) involves policy and management issues associated with assessing water management options. The CEHR program at Clear Lake involves numerous sub-projects that are focused on many inter-related questions associated with the dynamics of this system subjected to diverse natural and anthropogenic stresses and how these relate to more regionally based water quality issues. The intimate relationship between the various disciplines and projects being undertaken by this program is diagramed in **Fig 13**. Virtually every project has its own set of ongoing investigations (with a rich publication record too extensive to list here), but is well coordinated and integrated with the other



<u>Figure 121.13</u> Relationship between Clear Lake research projects within the EPA-funded Center for Ecological Health Research.

projects. The CEHR work is inter-disciplinary, reviewed semi-annually through scoping and evaluation meetings with a CEHR national Scientific Advisory Committee, and is in the process of producing a synthetic publication summarizing nearly 10 years of research on this ecosystem.

To date we have made significant progress in understanding the complex dynamics of natural and anthropogenic stressors on the Clear Lake aquatic ecosystem from first principles. For example, the ecological assessment of the impacts of the Sulphur Bank Mercury Mine on Clear Lake was nearing completion in 1995 when we discovered a significant amount of acid mine drainage (AMD) from the mine site entering Clear Lake through underground seepage, not just as surface runoff. This shifted the entire emphasis of the investigations from the lakebed sediments (which previously were believed to be the point source for the lake's mercury contamination) to ongoing investigations of AMD. This discovery was made possible only through an active and ongoing monitoring program (Suchanek et al. 2000b). It is possible that our current understanding of the dynamics and influence of sediment and nutrient loading on Clear Lake's productivity also may be incomplete. No "silver bullets" have been found to resolve the complexities of the many natural and anthropogenic stresses imposed on Clear Lake and its surrounding watershed, nor are they likely to be. However, as our work demonstrates, although uncertainties about ecosystem processes remain, we continue to improve our abilities to predict the effects of anthropogenic impacts and manage this productive resource. With unpredictable changes associated with global and regional climate change, new species introductions (purposeful or accidental) and other, as yet unidentified, stressors, this system will need continued and sophisticated adaptive management. In such a complex ecosystem as Clear Lake, research can (1) make steady progress in understanding the complexities of the system, (2) guard against indefensible plans such as the deep dredging of Clear Lake, and (3) offer recommendations for future actions based in the spirit of adaptive management.

If society wants to manage complex ecosystems like Clear Lake at a state-of-the-art level, it must be prepared to make substantial investments in monitoring, research, and modeling on an ongoing basis. Because these investments involve contributions to understanding ecosystems at a fairly fundamental level that will be applicable to many other similarly stressed systems, a substantial federal contribution is warranted. However, a healthy and meaningful program requires more state and local investment than has been forthcoming thus far. A strong commitment from federal, state and local funding agencies will be needed to provide a reliable technical basis for science-based decision-making and management.

Lake Tahoe, with its much higher profile nationally, has a relatively well funded research and monitoring program. However, even this program is weakly institutionalized, has periodic funding crises, and has a funding base that is none too generous considering the scope of its problems. Multiply-stressed ecosystems require a sustained and rather costly investment of scientific and technical resources. Recent requests by the National Science Foundation for a major increase in environmental science funding are a step in the right direction, but the more applied and management-oriented part of the investment portfolio still will be neglected unless other agencies step forward.

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