Section 5

Mono Basin Waterfowl
Habitat and Population Monitoring
2010-2011

Mono Lake Waterfowl Restoration Project
Compliance Checklist
2010

Hydrology	**Section 2**
Mono Lake Elevation	☑
Walker Creek Flows	☑
Parker Creek Flows	☑
Lee Vining Creek Flows	☑
Rush Creek Flows	☑
Mono Basin Exports	☑
Limnology	**Appendix 1**
Meteorology	☑
Physicochemical Variables	☑
Primary Producers	☑
Secondary Producers	☑
Ornithology	**Appendix 2**
Population Surveys	☑
Aerial Photos	☑
Time Activity Budget	**Required at Stabilization**

Brian White

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APPENDIX 1

Limnology

2010 ANNUAL REPORT

MIXING AND PLANKTON DYNAMICS IN MONO LAKE, CALIFORNIA

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EXECUTIVE SUMMARY

Limnological monitoring of Mono Lake was conducted during 2010 as part of a long-term monitoring program begun in 1982. Chapter 1 describes the seasonal plankton dynamics observed from 1979 through 2009, a period which encompassed a wide range of varying hydrologic and annual vertical mixing regimes including three periods of persistent chemical stratification or meromixis (1983–1988, 1995–2003, 2005–2007). In brief, long-term monitoring has shown that Mono Lake is highly productive compared to other temperate salt lakes, that this productivity is nitrogen-limited, and that year-to-year variation in the plankton dynamics has largely been determined by the complex interplay between varying climate and hydrologic regimes and the resultant seasonal patterns of thermal and chemical stratification which modify internal recycling of nitrogen. The importance of internal nutrient cycling to productivity is highlighted in the years immediately following the onset of persistent chemical stratification (meromixis) when upward fluxes of ammonium are attenuated and during the breakdown of meromixis when ammonium supply is increased.

Local climatic variation and these year-to-year variations in the mixing and nutrient environments have largely prevented accurate assessment of the effects of changing salinity over the range observed during the period of regular limnological monitoring (1982-present). However, the last six years confirm that there has been a significant increase in the size of the 1st generation of adult *Artemia* and a more rapid autumn decline in *Artemia* accompanying the general decrease in salinity from 1982 to present.

Laboratory, field, and analytical methods are described in Chapter 2 and the results of the 2010 limnological monitoring program including a number of integrative measures encompassing the long-term record (1982–2010) are presented in Chapter 3.

The multi-year trend beginning in 2004 of above average primary productivity and large spring generations of *Artemia* followed by a smaller than average late summer population of *Artemia* and rapid autumn decline continued in 2010. While the 2010 abundance (~40,000 m^{-2}) of 1st generation adult *Artemia* was higher than all the years of record from 1981 to 2003, it was slightly less than the most recent six years, 2004–2009. This was most likely due to unusually cool spring water temperatures.

Recruitment of ovoviviparously-produced nauplii into the summer adult population was very low and August abundance was the lowest on record. Late season adult abundance remained among the lowest recorded through December. The combination of these factors resulted in the lowest annual cyst production (2.2 million m^{-2}; only 52% of the long term mean) of the entire period 1982 to present.

The estimated 2010 primary production was 1,474 g C m^{-2}, well above the long-term (1982–2010) mean of 688 g C m^{-2}. Annual average *Artemia* biomass in 2010, an index of secondary production, was 5.1 g m^{-2}, only 58% of the long-term mean of 8.8 g m^{-2}.

Annually-filtered (365-day running mean) mixed-layer chlorophyll *a* concentration and adult *Artemia* abundance provide two measures of long-term ecological trends. They both highlight the role of year-to-year changes in the annual mixing regime (meromixis/monomixis). While inter-year and seasonal variation is large, there is a long-term trend of increasing chlorophyll *a* with a linear least squares regression explaining 36% of the overall variation mean annual chlorophyll. The response of *Artemia* to variations in mixing is muted compared to chlorophyll and while there has been a shift to earlier in the year, there is no significant long term trend in mean annual *Artemia* abundance.

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LIMNOLOGICAL MONITORING COMPLIANCE

This report fulfills the Mono Lake limnological monitoring requirements set forth in compliance with State Water Resources Control Board Order Nos. 98-05 and 98-07. The limnological monitoring program consists of four components: meteorological, physical/chemical, phytoplankton, and brine shimp population data. Meteorological data are collected continuously at a station on Paoha Island, while the other three components are assessed on monthly surveys (except January). A summary of previous monitoring is included in Chapter 1, the methodology employed is detailed in Chapter 2, and results and discussion of the monitoring conducted during 2010 and long-term integrative measures presented in Chapter 3. The relevant pages of text, and the table and figure numbers for the specific elements of each of the four required components are given below.

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CHAPTER 1
INTRODUCTION

Background

Saline lakes are widely recognized as productive aquatic habitats, which in addition to harboring distinctive assemblages of species, often support large populations of migratory birds. Saline lake ecosystems throughout the world are threatened by decreasing size and increasing salinity due to diversions of freshwater inflows for irrigation and other human uses (Williams 1993, 2002); notable examples in the Great Basin of North America include Mono Lake (Patten et al. 1987), Walker Lake (Cooper and Koch 1984), and Pyramid Lake (Galat et al. 1981). At Mono Lake, California, diversions of freshwater streams out of the basin beginning in 1941 led to a 14 m decline in surface elevation and an approximate doubling of the lake's salinity.

In 1994, following two decades of scientific research, litigation, and environmental controversy, the State Water Resources Control Board (SWRCB) of California issued a decision to amend Los Angeles' water rights to "establish fishery protection flows in streams tributary to Mono Lake and to protect public trust resources at Mono Lake and in the Mono Lake Basin" (Decision 1631). The decision restricts water diversions until the surface elevation of the lake reaches 1,948 m (6391 ft) and requires long-term limnological monitoring of the plankton dynamics.

Long-term monitoring of the plankton and their physical, chemical, and biological environment is essential to understanding the effects of changing lake levels. Measurements of the vertical distribution of temperature, oxygen, conductivity, and nutrients are requisite for interpreting how variations in these variables affect the plankton populations. Consistent methodologies have been employed during the 30-yr period, 1979–2009, and have yielded a standardized data set from which to analyze seasonal and year-to-year changes in the plankton. The limnological monitoring program at Mono Lake includes the interpretation of a wide array of limnological data collected during monthly surveys conducted during February through December.

Seasonal Mixing Regime and Plankton Dynamics

Limnological monitoring at Mono Lake can be divided into several periods corresponding to two different annual circulation patterns, meromixis and monomixis, and the transition between them.

Monomictic and declining lake levels, 1964–82

The limnology of Mono Lake, including seasonal plankton dynamics, was first documented in the mid 1960s (Mason 1967). During this period Mono Lake was characterized by declining lake levels, increasing salinity, and a monomictic thermal regime. No further limnological research was conducted until summer 1976 when a broad survey of the entire Mono Basin ecosystem was conducted (Winkler 1977). Subsequent studies (Lenz 1984; Melack 1983, 1985) beginning in 1979, further described the seasonal dynamics of the plankton. During the period 1979–81, Lenz (1984) documented a progressive increase in the ratio of peak summer to spring abundances of adult brine shrimp. The smaller spring generations resulted in greater food availability and much higher ovoviviparous production by the first generations, leading to larger second generations. Therefore, changes in the size of the spring hatch can result in large changes in the ratio of the size of the two generations.

In 1982, an intensive limnological monitoring program funded by LADWP was established to monitor changes in the physical, chemical, and biological environments in Mono Lake. This monitoring program has continued to the present. Detailed descriptions of the results of the monitoring program are contained in a series of reports to LADWP (Dana *et al.* 1986, 1992; Jellison *et al.* 1988, 1989, 1990, 1991, 1994, 1995a, 1996a, 1997, 1998a, 1999, 2001, 2002, 2003; Jellison and Melack 2000; Jellison 2004, 2005, 2006) and are summarized below.

Meromixis, 1983–87

In 1983, a large influx of freshwater into Mono Lake resulted in a condition of persistent chemical stratification (meromixis). A decrease in surface salinities resulted in a chemical gradient of ca. 15 g total dissolved solids l^{-1} between the mixolimnion (the mixed layer) and monimolimnion (layer below persistent chemocline). In subsequent years evaporative concentration of the surface water led to a decrease in this gradient and in November 1988 meromixis was terminated.

Following the onset of meromixis, ammonium and phytoplankton were markedly affected. Ammonium concentrations in the mixolimnion were reduced to near zero during spring 1983 and remained below 5 µM until late summer 1988. Accompanying this decrease in mixolimnetic ammonium concentrations was a dramatic decrease in the algal bloom associated with periods when the *Artemia* are less abundant (November through April). At the same time, ammonification of organic material and release from the anoxic sediments resulted in a gradual buildup of ammonium in the monimolimnion over the six years of meromixis to 600 to 700 µM. Under previous monomictic conditions, summer ammonium accumulation beneath the thermocline was 80–100 µM, and was mixed into the upper water column during the autumn overturn.

Artemia dynamics were also affected by the onset of meromixis. The size of the first generation of adult *Artemia* in 1984 (~31,000 m^{-2}) was nearly ten times as large as observed in 1981 and 1982, while peak summer abundances of adults were much lower. Following this change, the two generations of *Artemia* were relatively constant during the meromictic period from 1984 to 1987. The size of the spring generation of adult *Artemia* only varied from 23,000 to 31,000 m^{-2} while the second generation of adult *Artemia* varied from 33,000 to 54,000 m^{-2}. The relative sizes of the first and second generation are inversely correlated. This is at least partially mediated by food availability as a large first generation results in decreased algal levels for second generation nauplii and vice versa. During 1984 to 1987, recruitment into the first generation adult class was a nearly constant but small percentage (about 1 to 3%) of the cysts calculated to be available (Dana *et al*. 1990). Also, fecundity showed a significant correlation with ambient algal concentrations (r^2, 0.61).

In addition to annual reports submitted to Los Angeles and referenced herein, a number of published manuscripts document the limnological conditions and algal photosynthetic activity during the onset, persistence, and breakdown of meromixis, 1982–90 (Jellison *et al.* 1992; Jellison and Melack 1993a, 1993b; Jellison *et al.* 1993; Miller *et al.* 1993).

Response to the breakdown of meromixis, 1988–89

Although complete mixing did not occur until November 1988, the successive deepening of the mixed layer during the period 1986–88 led to significant changes in the plankton dynamics. By spring 1988, the mixed layer included the upper 22 m of the lake and included 60% of the area and 83% of the lake's volume. In addition to restoring an annual mixing regime to much of the lake, the deepening of the mixed layer increased the nutrient supply to the mixolimnion by entraining water with very high ammonium concentrations (Jellison *et al.* 1989). Mixolimnetic ammonium concentrations were fairly high during the spring (8–10 μM), and March algal populations were much denser than in 1987 (53 vs. 15 μg chl *a* l^{-1}).

The peak abundance of spring adult *Artemia* in 1988 was twice as high as any previous year from 1979 to 1987. This increase could have been due to enhanced hatching and/or survival of nauplii. The pool of cysts available for hatching was potentially larger in 1988 since cyst production in 1987 was larger than in the four previous years (Dana *et al.* 1990) and significant lowering of the chemocline in the autumn and winter of 1987 allowed oxygenated water to reach cysts in sediments which had been anoxic since 1983. Cysts can remain dormant and viable in anoxic water for an undetermined number of years. Naupliar survival may also have been enhanced since chlorophyll *a* levels in the spring of 1988 were higher than the previous four years. This hypothesis is corroborated by the results of the 1988 development experiments (Jellison *et al.* 1989). Naupliar survival was higher in the ambient food treatment relative to the low food treatment.

Mono Lake returned to its previous condition of annual autumnal mixing from top to bottom with the complete breakdown of meromixis in November 1988. The mixing of previously isolated monimolimnetic water with surface water affected biotic components of the ecosystem. Ammonium, which had accumulated to high levels (> 600 μM) in the monimolimnion during meromixis, was dispersed throughout the water column raising surface concentrations above previously observed values (>50 μM). Oxygen was diluted by mixing with the anoxic water and consumed by the biological and chemical oxygen demand previously created in the monimolimnion. Dissolved oxygen concentration immediately fell to zero. *Artemia* populations experienced an immediate and total die-off following deoxygenation. Mono Lake remained anoxic for a few months following the breakdown of meromixis in November 1988. By mid-February 1989, dissolved oxygen concentrations had increased (2–3 mg l^{-1}) but were still below those observed in previous years (4–6 mg l^{-1}). The complete recovery of dissolved oxygen concentrations occurred in March when levels reached those seen in other years.

Elevated ammonium concentrations following the breakdown of meromixis led to high chlorophyll *a* levels in spring 1989. Epilimnetic concentrations in March and April were the highest observed (40–90 µg chl *a* l^{-1}). Subsequent decline to low midsummer concentrations (<0.5–2 µg chl *a* l^{-1}) due to brine shrimp grazing did not occur until late June. In previous meromictic years this decline occurred up to six weeks earlier. Two effects of meromixis on the algal populations, decreased winter-spring concentrations and a shift in the timing of summer clearing are clearly seen over the period 1982–89.

The 1989 *Artemia* population exhibited a small first generation of adults followed by a summer population over one order of magnitude larger. A similar pattern was observed from 1980–83. In contrast, the pattern observed during meromictic years was a larger first generation followed by a summer population of the same order of magnitude. The timing of hatching of *Artemia* cysts was affected by the recovery of oxygen. The initiation of hatching occurred slightly later in the spring and coincided with the return of oxygenated conditions. First generation numbers in 1989 were initially high in March (~30,000 individuals m^{-2}) and within the range seen from 1984–88, but decreased by late spring to ~4,000 individuals m^{-2}. High mortality may have been due to low temperatures, since March lake temperatures (2–6°C) were lower than the suspected lethal limit (ca. 5–6°C) for *Artemia* (Jellison *et al.* 1989). Increased mortality may also have been associated with elevated concentrations of toxic compounds (H_2S, NH_4+, As) resulting from the breakdown of meromixis.

High spring chlorophyll levels in combination with the low first generation abundance resulted in a high level of fecundity that led to a large second generation of shrimp. Spring chlorophyll *a* concentrations were high (30–44 µg chl *a* l^{-1}) due to the elevated ammonium levels (27–44 µM) and are typical of pre-meromictic levels. This abundant food source (as indicated by chlorophyll *a*) led to large *Artemia* brood sizes and high ovigerity during the period of ovoviviparous reproduction and resulted in the large observed summer abundance of *Artemia* (peak summer abundance, ~93,000 individuals m^{-2}). Negative feedback effects were apparent when the large summer population of *Artemia* grazed the phytoplankton to very low levels (<0.5–2 µg chl *a* l^{-1}). The low algal densities led to decreased reproductive output in the shrimp population. Summer brood size, female length, and ovigerity were all the lowest observed in the period 1983–89.

Small peak abundance of first generation adults were observed in 1980–83, and 1989. However, the large (2–3 times the mean) second generations were only observed in 1981, 1982, and 1989. During these years, reduced spring inflows resulted in less than usual density stratification and higher than usual vertical fluxes of nutrients thus providing for algal growth and food for the developing *Artemia* population.

Monomictic conditions with relatively stable lake levels, 1990–94

Mono Lake was monomictic from 1990 to 1994 (Jellison *et al.* 1991, Dana *et al.* 1992, Jellison *et al.* 1994, Jellison *et al.* 1995b) and lake levels (6374.6 to 6375.8 ft asl) were similar to those in the late 1970s. Although the termination of meromixis in November 1988 led to monomictic conditions in 1989, the large pulse of monimolimnetic ammonium into the mixed layer led to elevated ammonium concentrations in the euphotic zone throughout 1989, and the plankton dynamics were markedly different than 1990–94. In 1990–94, ammonium concentrations in the euphotic zone decreased to levels observed prior to meromixis in 1982. Ammonium was low, 0–2 µM, from March through April and then increased to 8–15 µM in July. Ammonium concentrations declined slightly in late summer and then increased following autumn turnover. This pattern of ammonium concentrations in the euphotic zone and the hypolimnetic ammonium concentrations were similar to those observed in 1982. The similarities among the years 1990–94 indicate the residual effects of the large hypolimnetic ammonium pulse accompanying the breakdown of meromixis in 1988 were gone. This supports the conclusion by Jellison *et al.* (1990) that the seasonal pattern of ammonium concentration was returning to that observed before the onset of meromixis.

Spring and summer peak abundances of adult *Artemia* were fairly constant throughout 1990 to 1994. Adult summer population peaks in 1990, 1991, and 1992 were all ~35,000 m^{-2} despite the large disparity of second generation naupliar peaks (~280,000, ~68,000, and ~43,000 m^{-2} in 1990, 1991, and 1992, respectively) and a difference in first generation peak adult abundance (~18,000, ~26,000, and ~21,000 m^{-2} in 1990, 1991, and 1992, respectively). Thus, food availability or other environmental factors are more important to determining summer abundance than recruitment of second generation nauplii. In 1993, when freshwater inflows were higher than usual and thus density stratification enhanced, the summer generation was slightly smaller (~27,000 m^{-2}). Summer abundance of adults increased slightly (~29,000 m^{-2}) in 1994 when runoff was lower and lake levels were declining.

Meromictic conditions with rising (1995-1999) and falling (1999-2002) lake levels

1995

The winter (1994/95) period of holomixis injected nutrients which had previously accumulated in the hypolimnion into the upper water column prior to the onset of thermal and chemical stratification in 1995 (Jellison *et al*. 1996a). During 1995, above normal runoff in the Mono Basin coupled with the absence of significant water diversions out of the basin led to rapidly rising lake levels. The large freshwater inflows resulted in a 3.4 ft rise in surface elevation and the onset of meromixis, a condition of persistent chemical stratification with less saline water overlying denser more saline water. Due to holomixis during late 1994 and early 1995, the plankton dynamics during the first half of 1995 were similar to those observed during the past four years (1991–94). Therefore 1995 represents a transition from monomictic to meromictic conditions. In general, 1995 March mixed-layer ammonium and chlorophyll *a* concentrations were similar to 1993. The peak abundance of summer adult *Artemia* (~24,000 m^{-2}) was slightly lower to that observed in 1993 (~27,000 m^{-2}) and 1994 (~29,000 m^{-2}). The effects of increased water column stability due to chemical stratification only became evident later in the year. As the year continued, a shallower mixed layer, lower mixed-layer ammonium and chlorophyll *a* concentrations, slightly smaller *Artemia,* and smaller brood sizes compared to 1994 were all observed. The full effects of the onset of meromixis in 1995 were not evident until 1996.

1996

Chemical stratification persisted and strengthened throughout 1996 (Jellison *et al*. 1997). Mixolimnetic (upper water column) salinity ranged from 78 to 81 g kg^{-1} while monimolimnetic (lower water column) were 89–90 g kg^{-1}. The maximum vertical density stratification of 14.6 kg m^{-3} observed in 1996 was larger than any year since 1986. During 1996, the annual maximum in Secchi depth, a measure of transparency, was among the highest observed during the past 18 years and the annual minimum was higher than during all previous years except 1984 and 1985 during a previous period of meromixis. While ammonium concentrations were <5 µM in the mixolimnion throughout the year, monimolimnetic concentrations continued to increase. The spring epilimnetic chlorophyll *a* concentrations (5–23 µg chl *a* l^{-1}) were similar to those observed in previous meromictic years, but were much lower than the concentrations observed in March 1995 before the onset of the current episode of meromixis. During previous monomictic years, 1989–94, the spring maximum epilimnetic chlorophyll *a* concentrations ranged between 87–165 µg chl *a* l^{-1}.

A single mid-July peak in adults characterized *Artemia* population dynamics in 1996 with little evidence of recruitment of second generation *Artemia* into the adult population during late summer. The peak abundance of first generation adults was observed on 17 July (~35,000 m^{-2}), approximately a month later than in previous years. The percent ovigery during June 1996 (42%) was lower than that observed in 1995 (62%), and much lower than that observed 1989–94 (83–98%). During the previous meromictic years (1984–88) the female population was also slow to attain high levels of ovigery due to lower algal levels. The maximum of the mean female length on sampling dates through the summer, 10.7 mm, was shorter than those observed during 1993, 1994, and 1995 (11.7, 12.1, and 11.3 mm, respectively). In 1996, brood size ranged from 29 to 39 eggs $brood^{-1}$ during July through November. The summer and autumn brood sizes were smaller than those observed during 1993–95 (40 to 88 eggs $brood^{-1}$), with the exception of September 1995 (34 eggs $brood^{-1}$) when the brood size was of a similar size to September 1996 (33 eggs $brood^{-1}$).

1997

Chemical stratification continued to increase in 1997 as the surface elevation rose an additional 1.6 ft during the year. The midsummer difference in density between 2 and 28 m attributable to chemical stratification increased from 10.4 kg m^{-3} in 1996 to 12.3 kg m^{-3} in 1997. The lack of holomixis during the previous two winters resulted in depleted nutrient levels in the mixolimnion and reduced abundance of phytoplankton. In 1997, the spring (February–April) epilimnetic chlorophyll *a* concentrations at 2 m (2–3 µg chl *a* l^{-1}) were lower than those observed during 1996 (5–8 µg chl *a* l^{-1}), and other meromictic years 1984–89 (1.6–57 µg chl *a* l^{-1}), and much lower than those observed during the spring months in the last period of monomixis, 1989–95 (15–153 µg chl *a* l^{-1}). Concomitant increases in transparency and the depth of the euphotic zone were also observed. As in 1996, a single mid-July peak in adults characterized the *Artemia* population dynamics in 1997 with little evidence of recruitment of second generation *Artemia* into adults. The peak midsummer adult abundance (~27,000 m^{-2}) was slightly lower than 1996 but similar to 1995 (~24,000 m^{-2}). The mean length of adult females was 0.2–0.3 mm shorter than the lengths observed in 1996 and the brood sizes lower, 26–33 eggs $brood^{-1}$ in 1997 compared to 29 to 53 eggs $brood^{-1}$ in 1996.

1998

In 1998 the surface elevation of the lake rose 2.2 ft. The continuing dilution of saline mixolimnetic water and absence of winter holomixis led to increased chemical stratification. The peak summer difference in density between 2 and 28 m attributable to chemical stratification increased from 12.3 kg m^{-3} in 1997 to 14.9 kg m^{-3} in August 1998. The 1998 peak density difference due to chemical stratification was higher than that seen in any previous year, including 1983–84. The lack of holomixis during the previous three winters resulted in depleted nutrient levels in the mixolimnion and reduced abundance of phytoplankton. Chlorophyll *a* concentrations at 2 m generally decreased from 14.3 µg chl *a* l^{-1} in February to 0.3 µg chl *a* l^{-1} in June, when the seasonal chlorophyll *a* concentration minimum was reached. After that it increased to 1–2 µg chl *a* l^{-1} during July–October and to ~8 µg chl *a* l^{-1} in early December. In general, the seasonal pattern of mixolimnetic chlorophyll *a* concentration was similar to that observed during the two previous meromictic years, 1996 and 1997, in which the spring and autumn algal blooms are much reduced compared to monomictic years.

As in 1996 and 1997, a single mid-July peak in adults characterized the Artemia population dynamics in 1998 with little evidence of recruitment of second generation *Artemia* into adults. The peak abundance of adults observed on 10 August (~34,000 m^{-2}) was slightly higher than that observed in 1997 (~27,000 m^{-2}) and, while similar to the timing in 1997, approximately two weeks to a month later than in most previous years. The mean female length ranged from 9.6 to 10.3 mm in 1998 and was slightly shorter than observed in 1996 (10.1–10.7 mm) and 1997 (9.9–10.4 mm). Mean brood sizes in 1998 were 22–50 eggs $brood^{-1}$. The maximum brood size (50 eggs $brood^{-1}$) was within the range of maximums observed in 1995–97 (62, 53, and 33 eggs $brood^{-1}$, respectively), but was significantly smaller than has been observed in any other previous year 1987–94 (81–156 eggs $brood^{-1}$).

1999

Meromixis continued but weakened slightly in 1999 as the net change in surface elevation over the course of the year was -0.1 ft. The midsummer difference in density between 2 and 28 m attributable to chemical stratification declined from 14.9 kg m^{-3} in 1998 to 12.2 kg m^{-3}. The lack of holomixis during the past four winters resulted in depleted inorganic nitrogen concentrations in the mixolimnion and reduced abundance of phytoplankton. In 1999, the spring (February–April) epilimnetic chlorophyll *a* concentrations at 2 m (10–16 µg chl *a* l^{-1}) were similar to those observed in 1998 but slightly higher than the two previous years of meromixis, 1997 (2–3 µg chl *a* l^{-1}) and 1996 (5–8 µg chl *a* l^{-1}). However, they are considerably lower than those observed during the spring months of the last period of monomixis, 1989–95 (15–153 µg chl *a* l^{-1}). As in all of the three immediately preceding years of meromixis, 1996–98, the *Artemia* population dynamics in 1999 were characterized by a single late-summer peak in adults with little evidence of recruitment of second generation *Artemia* into adults. The peak midsummer adult abundance (~38,000 m^{-2}) was slightly higher than 1996 (~35,000 m^{-2}), 1997 (~27,000 m^{-2}), and 1998 (~34,000 $m^{-}2$). The mean length of adult females was slightly longer (10.0–10.7 mm) than 1998 (9.6–10.3 mm) and similar to 1996 (10.1–10.7

mm) and 1997 (9.9–10.4 mm), while the range of mean brood sizes (27–48 eggs brood^{-1}) was similar (22–50 eggs brood^{-1}; 1996–98).

2000

In 2000, persistent chemical stratification (meromixis) continued but weakened due to evaporative concentration of the upper mixed layer accompanying a net 0.7 ft annual decline in surface elevation and slight freshening of water beneath the chemocline. The midsummer difference in density between 2 and 28 m attributable to chemical stratification declined from 12.2 kg m^{-3} in 1999 to 10.5 kg m^{-3} in 2000. Most likely of greater significance to the overall plankton dynamics is the marked midwinter deepening (ca. 2 m) of the chemocline. Not only were significant amounts of ammonium-rich monimolimnetic water entrained, but less of the lake is now effectively meromictic; only 38% of the lake's area and 16% of the volume were beneath the chemocline.

Algal biomass, as characterized by the concentration of chlorophyll *a*, was higher in 2000 compared to 1999 and varied in the mixolimnion from a midsummer low of 1.4 µg chl *a* l^{-1} to the December high of 54.2 µg chl *a* l^{-1}. The December value is the highest observed during the entire 21 years of study. Although adult *Artemia* abundance (peak of ~22,000 m^{-2}) was anomalously low (50% of the long-term mean), *Artemia* biomass and total annual cyst production were only slightly below the long-term mean, 12 and 16%, respectively. Thus, while meromixis persisted in 2000, the combined effects of declining lake levels, the reduced proportion of the lake beneath the chemocline, and increased upward fluxes of ammonium due to the large buildup of monimolimnetic ammonium offset, to some degree, the effect of the absence of winter holomixis.

2001

Persistent chemical stratification (meromixis) continued but weakened in 2001 due to evaporative concentration of the upper mixed layer accompanying a net 0.8 ft decline in surface elevation and slight freshening of water beneath the chemocline. Colder than average mixolimnetic temperatures (1.5–2.2ºC) observed in February 2001 enhanced deep mixing. The midsummer difference in density between 2 and 28 m attributable to chemical stratification has declined from 10.5 kg m^{-3} in 2000 to 8.9 kg m^{-3} in 2001. Most likely of greater significance to the overall plankton dynamics was the marked midwinter deepening (ca. 2 m) of the chemocline. Not only were significant amounts of ammonium-rich monimolimnetic water entrained, but less of the lake was effectively meromictic. At the end of 2001, only 33% of the lake's area and 12% of the volume were beneath the chemocline. Ammonium concentrations in the monimolimnion continued their 6-year increase with concentrations at 28 and 35 m generally 900–1200 µM.

Algal biomass, as characterized by chlorophyll *a* concentration, was similar to that observed during 2000 except that the autumn bloom was somewhat later as adult *Artemia* were more abundant in September and October compared to 2000.

As in 2000, the 2001 *Artemia* population was characterized by fairly rapid development of the 1st generation, a pulse of ovoviviparous reproduction in June, peak of adult abundance in July at ~38,000 m^{-2}, followed by a decline to very low numbers by November. In 2000, the autumn decline was very rapid and resulted in the lowest seasonal mean abundance of any year studied. In 2001 the autumn decline was less rapid and resulted in a seasonal mean abundance identical to the long-term mean of ~20,000 m^{-2}. The 2001 mean annual *Artemia* biomass was 8.8 g m^{-2} or 9 % below the long-term mean of 9.7 g m^{-2} and slightly higher than calculated in 2000 (8.2 g m^{-2}).

In Mono Lake, oviparous (cyst) reproduction is always much higher than ovoviviparous (live-bearing) reproduction. Although adult *Artemia* were more abundant in 2001 compared to 2000, total annual cyst production was lower, 3.02×10^6 m^{-2} compared to 4.03×10^6 m^{-2} in 2000. While this is 37% below the long-term mean of 4.77×10^6 m^{-2}, it is not expected to have a significant impact on 2002 abundance as food availability is a much stronger determinant of the spring generation of *Artemia.*

2002

Meromixis continued but weakened due to evaporative concentration of the upper mixed layer accompanying a net 0.8 ft decline in surface elevation and slight freshening of water beneath the chemocline. The peak difference in density between 2 and 28 m attributable to chemical stratification declined from 10.5 kg m^{-3} in 2000 to 8.9 kg m^{-3} in 2001 to 5.5 kg m^{-3} in 2002. More importantly the chemical stratification between 2 and 32 m decreased to ~1 kg m^{-3} and the chemocline was eroded downward several meters to ~30 m. Not only were significant amounts of ammonium-rich monimolimnetic water entrained, but only 14% by area and 3% by volume of the lake is below the chemocline.

Algal biomass, as characterized by chlorophyll *a* concentration, was high during both spring (60-78 μg chl *a* l^{-1}, February and March) and autumn (60-80 μg chl *a* l^{-1}, November). Annual estimates of lakewide primary production were 723 g C m^{-2} y^{-1} and continued the consistent upward trend from the lowest value of 149 g C m^{-2} y^{-1} in 1997.

As in 2000 and 2001, the *Artemia* population was characterized by fairly rapid development of the 1st generation, a pulse of ovoviviparous reproduction in June, adult abundance peak in August at ~26,000 m^{-2}, followed by a decline to very low numbers by November. In 2002, the mean annual *Artemia* biomass was 4.9 g m^{-2} almost 50% below the long-term mean of 9.7 g m^{-2}. Recent analysis of seasonal *Artemia* dynamics indicates small changes in algal biomass immediately following maturation of the 1st generation, dramatically affects recruitment into the summer generation. In 2002, a larger spring hatch and spring adult generation lowered algal biomass and led to decreased recruitment into the summer adult population. This inter-generational compensatory interaction is a dominant feature of the seasonal and annual variation of adult abundance observed in the long-term monitoring (1982-present).

Total annual cyst production (2.5×10^6 m^{-2}), along with abundance of ovigerous females, was less than in the previous three years ($3.0\text{-}4.2 \times 10^6$ m^{-2}), though the size of ovigerous females was larger than in these years. Annual cyst production was the same as in 1997, and was 53% below the long term mean of 4.77×10^6 m^{-2}.

Response to the breakdown of an 8-yr period of meromixis (2003–2004)

2003

The persistent chemical stratification (meromixis) initiated in 1995 nearly broke down early in the year (February-March) prior to the onset of seasonal thermal stratification. This resulted in an upward pulse of nutrients (ammonia) into the upper mixed layer early in the year. Following a small rise in surface elevation and slight freshening of the mixed layer due to snowmelt runoff, decreased inflow and evaporative concentration led to an inverse chemical gradient with slightly more saline mixolimnetic water overlying the monimolimnion (region beneath the chemocline). Thus, autumn cooling led to holomixis (complete mixing of the lake) in mid-November and the end of an 8-yr period of meromixis (1995-2003).

Algal biomass, as characterized by chlorophyll *a* concentration, was high throughout the winter and spring (50-96 µg chl *a* l^{-1}, January through May) and autumn (50-62 µg chl *a* l^{-1}, October through November). While *Artemia* grazing and nutrient limitation normally result in low summer algal biomass (~1µg chl *a* l^{-1}), values in summer 2003 never fell below 3 µg chl *a* l^{-1} despite near average *Artemia* abundance. Thus, primary production was unusually high. The 2003 estimated annual primary production was 1,645 g C m^{-2} y^{-1}, more than twice that observed in 2002 (763 g C m^{-2} y^{-1}), and the highest of any year from 1982-2003.

In 2003, the *Artemia* population was characterized by early development of a moderate 1st generation (18 June, 24,600 m^{-2}) followed by recruitment balancing mortality through the summer (13 August, 27,300 m^{-2}). Mean annual *Artemia* biomass increased 53% from 4.9 g m^{-2} in 2002 to 7.5 g m^{-2} in 2003, although it was still slightly below the long-term (1983-2003) average of 9.2 g m^{-2}. Recruitment of ovoviviparous (live-bearing) reproduction into the 2nd generation was low and accounts for below average mean annual biomass. Recent analysis of seasonal *Artemia* dynamics indicates small changes in algal biomass immediately following maturation of the 1st generation dramatically affects recruitment into the summer generation. A detailed cohort analysis of 2003 stage-specific *Artemia* data is being conducted. Total annual cyst production also increased over 2002 and was 4.2 x 10^6 m^{-2}, close to the long-term (1983-2003) mean of 4.5 x 10^6 m^{-2}.

2004

The breakdown of an 8-yr period of meromixis in November 2003 mixed nutrient-rich bottom waters throughout the water column. Thus, 2004 began with high ammonia concentrations (10–29 µM) throughout the water column, and a large algal bloom (105 µg chl *a* $liter^{-1}$) had developed by the February survey. While the upper mixed-layer ammonia concentrations decreased to <1 µM by mid-March, algal biomass remained high (89–95 µg chl *a* $liter^{-1}$). Dissolved oxygen concentrations in the lake had recovered following low values observed in November 2003 associated with the breakdown of meromixis and hatching of over-wintering *Artemia* cysts began in February as indicated by the presence of abundant (47,324 m^{-2}) 1st instar nauplii on 24 February. Record high (68,746 m^{-2}) naupliar abundance was observed on the 19 March survey. A large hatch, abundant food, and warmer than average water temperatures led to the largest and earliest 1st generation of adult *Artemia* in Mono Lake observed during the 26-yr period of record (1979-2004). This large 1st generation of adults depleted algal biomass and suppressed fecundity and recruitment into subsequent generations resulting in an early decline in adult abundance.

Artemia grazing maintained low phytoplankton abundance throughout the summer and annual primary production was lower (864 g C m^{-2}) than the record levels (1645 g C m^{-2}) observed in 2003 as meromixis weakened and broke down. However, the mean annual *Artemia* biomass increased 46% from 7.5 g m^{-2} in 2003 to 11.0 g m^{-2} in 2004 and was 18% above the long-term (1983-2004) average of 9.4 g m^{-2}. Total annual cyst production decreased to 2.6 x 10^6 m^{-2} from the 4.2 x 10^6 m^{-2} observed in 2003. While this was among the lowest estimates of annual cyst production, there is little correlation between cyst production and the subsequent year's population of *Artemia*.

Third episode of meromixis (2005-2007)

2005

On the March 2005 survey, nutrient levels were similar to those observed in 2004, with ammonia concentrations <1 µM in the near-surface mixed layer and 30–40 µM in the hypolimnion. However, the spring algal bloom was somewhat smaller in 2005, with chlorophyll concentrations at 2 and 8 m depth of 57–59 µg chl *a* $liter^{-1}$ compared to 91–105 µg chl *a* $liter^{-1}$ in 2004. The March survey indicated the spring *Artemia* hatch was well underway with abundance across 12 stations ranging from 18,000 to 57,000 m^{-2} with a lakewide mean of 31,800 m^{-2}. While not as large as 2004 (75,500 m^{-2}), abundant food and above average water temperatures in 2005 led to the third largest 1st generation of adults (45,400 m^{-2}) observed during the entire 27-yr period (1979-2005). Although ovoviviparous reproduction was 25 % above the long-term mean, the large 1st generation of adults depleted food availability and reduced recruitment into the second generation resulting in a rapid late summer decline in adults.

Annual primary production was 1,111 g C m^{-2} or twice the long-term mean of 573 g C m^{-2}. Average *Artemia* biomass, a measure of secondary production, was 11.8 g m^{-2}, 25 % above the long-term mean. Total annual cyst production was 3.8 million m^{-2} or 15 % below the long-term mean of 4.4 million m^{-2}. However, secondary productivity is not limited by cyst production and there is little correlation between annual cyst production and the subsequent year's population of *Artemia*.

Snowmelt runoff into the epilimnion of Mono Lake causes seasonal salinity stratification which typically breaks down in November following late summer evaporative concentration, epilimnetic cooling, and declining lake levels. In early 2005, above average snowmelt runoff led to a 1.8 ft seasonal rise in surface elevation. While late summer evaporative concentration and cooling of the upper mixed-layer decreased vertical stratification and almost initiated holomixis, freshwater inputs late in 2005 increased salinity stratification just enough to prevent winter holomixis and initiated a third period of meromixis.

2006

Deep (23-24 m) mixing occurred in January-February 2006 resulting in significant upward fluxes of ammonia and the effects of the initiation of meromixis on the 2006 spring plankton dynamics were minimal. On the 13 February 2006 survey, hatching of over-wintering cysts had already begun and increased further during March. Unusually warm conditions in early May and possibly decreased salinity resulted in the 3rd largest 1st generation of adult *Artemia* for the entire 28-yr period of record (1979-2006). A pulse of ovoviviparous reproduction by the 1st generation adults led to a large second generation in early July. There was little further recruitment into the adult population in late summer and the *Artemia* population declined rapidly and by mid-October was virtually gone. While the virtual absence of adult *Artemia* in mid-October has only been observed in one other year (2002), low (<5,000 m^{-2}) mid-October abundances were also observed in 1986, 2000, 2003, and 2004.

Integrative measures of primary and secondary productivity in 2006 were within the ranges observed in previous years. In 2006, annual primary production was 1,075 g C m^{-2} or 84 % higher than the long-term mean of 584 g C m^{-2} but much less than the highest estimated productivity of 1,645 g C m^{-2} in 2003. Average *Artemia* biomass in 2006, a measure of secondary production, was 6.8 g m^{-2} or 26 % below the long-term mean. Total annual cyst production was 4.8 million m^{-2} or 10 % higher than the long-term mean of 4.4 million m^{-2}.

A second year of above average snowmelt runoff resulted in a net annual rise in surface elevation of 2.2 ft, increased salinity stratification, and strengthening and continuation of the 3rd episode of meromixis. The lake was more strongly stratified through the winter of 2006-2007 compared to the previous winter.

2007

On the 15 February 2007 survey, hatching of over-wintering cysts had already begun and increased through April. Growth and survivorship to adults was high resulting in the 5th highest abundance of 1st generation adults in the 27-yr record (1981–2007). While a pulse of ovoviviparous reproduction by 1st generation adults occurred in late May and early June, recruitment of these young into the adult population was low and there was no midsummer July increase in adults. The abundance of adults declined through July and by September was the smallest adult population observed at this time of year for the entire period of records. As observed in 2002 and 2006, adult abundance was very low by mid-October. While the virtual absence of adult *Artemia* in mid-October is unusual, low (<5,000 m^{-2}) mid-October abundances were also observed in 1986, 2000, 2003, and 2004.

The estimated 2007 primary production was the highest on record (1,766 g C m^{-2}) but similar to that observed in 2003 (1,645 g C m^{-2}) when the second episode of meromixis was breaking down. Annual average *Artemia* biomass in 2007, a measure of secondary production, was 7.0 g m^{-2} or 23 % below the long-term mean of 9.1 g m^{-2}. Total annual cyst production in 2007 (3.4 million m^{-2}) was also 23 % below the long-term mean of 4.4 million m^{-2}.

Recent monomictic period (2008-)

2008

During 2008, limited hatching of over-wintering cysts had already begun by the 21 February survey, and increased during both March and April. While the abundance of 1st generation adults was lower than observed in 2004–2007, it was still higher than most years of record. A large pulse of ovoviviparous reproduction by 1st generation adults occurred in late May and early June, but recruitment of these young into the adult population was low and there was no midsummer July increase in adults. The abundance of adults declined through July and by September was the 2nd smallest adult population observed and were virtually absent (<200 m^{-2}) in mid-October. Adult abundance was also near zero in October 2002, 2006, and 2007. While the virtual absence of adult *Artemia* in mid-October is unusual, low (<5,000 m^{-2}) mid-October abundances were also observed in 1986, 2000, 2003, and 2004. This pattern continues the recent trend of larger first generations followed by little late summer recruitment and rapid autumn declines.

The estimated 2008 primary production was 1,189 g C m^{-2}. This was significantly lower than observed in 2007 during the breakdown of 2-yr episode of meromixis, but well above the long-term (1982–2008) mean of 659 g C m^{-2}. Annual average *Artemia* biomass in 2008, an index of secondary production, was 5.8 g m^{-2} or 36% below the long-term mean of 9.0 g m^{-2}. Total annual cyst production in 2008 (3.1 million m^{-2}) was 29 % below the long-term mean of 4.3 million m^{-2}.

2009

During 2009, hatching of over-wintering cysts was already well underway by the 21 February survey and increased significantly during March. The abundance of 1st generation adults (~72,000 m^{-2}) was the second highest on record (1981–2009). Low phytoplankton abundance accompanying abundant *Artemia* resulted in both below average summer ovoviviparous reproduction (58 %) and total annual cyst production (69 %). Low ovoviviparous production and subsequent recruitment into the late summer adult population led to an early decline, and *Artemia* were virtually absent by the mid-November survey. This pattern of a large first (early summer) generation followed by a rapid decline and autumn die-off constitutes a long-term trend of an overall shift of the temporal occurrence of *Artemia* to earlier in the year.

Annual average *Artemia* biomass in 2009, an index of secondary production, was 8.8 g m^{-2}, close to the long-term mean of 9.0 g m^{-2}. Total annual cyst production in 2009 (2.9 million m^{-2}) was 31 % below the long-term mean of 4.3 million m^{-2}.

Long-term integrative measures: annual primary productivity, mean annual *Artemia* biomass and egg production

The availability of dissolved inorganic nitrogen or phosphorus has been shown to limit primary production in a wide array of aquatic ecosystems. Soluble reactive phosphorus concentrations are very high (>400 µM) in Mono Lake and thus will not limit growth. However, inorganic nitrogen varies seasonally, and is often low and potentially limiting to algal growth. A positive response by Mono Lake phytoplankton in ammonium enrichments performed during different periods from 1982 to 1986 indicates inorganic nitrogen limits the standing biomass of algae (Jellison 1992, Jellison and Melack 2001). In Mono Lake, the two major sources of inorganic nitrogen are brine shrimp excretion and vertical mixing of ammonium-rich monimolimnetic water.

Algal photosynthetic activity was measured from 1982 to 1992 (Jellison and Melack, 1988, 1993a; Jellison *et al.* 1994) and clearly showed the importance of variation in vertical mixing of nutrients to annual primary production. Algal biomass during the spring and autumn decreased following the onset of meromixis and annual photosynthetic production was reduced (269–462 g C m^{-2} yr^{-1}; 1984 to 1986) compared to non-meromictic conditions (499–641 g C m^{-2} yr^{-1}; 1989 and 1990) (Jellison and Melack 1993a). Also, a gradual increase in photosynthetic production occurred even before meromixis was terminated because increased vertical fluxes of ammonium accompanied deeper mixing with ammonium-rich monimolimnetic water. Annual production was greatest in 1988 (1,064 g C m^{-2} yr^{-1}) and 2003 (1,645 g C m^{-2} y^{-1}) when the weakening of chemical stratification and eventual breakdown of meromixis in November resulted in large fluxes of ammonium into the euphotic zone.

Estimates of annual primary production integrate annual and seasonal changes in photosynthetic rates, algal biomass, temperature, and insolation. Although measurements of photosynthetic rates were discontinued after 1992 (restarted in 2002) most of the variation in photosynthetic rates can be explained by regressions on environmental covariates (i.e. temperature, nutrient, and light regimes) (Jellison and Melack 1993a, Jellison *et al.* 1994). Therefore, estimates of annual primary production using previously derived regressions and current measurements of algal biomass, temperature, and insolation were made during 1993-2001. These estimates of annual primary production indicate a period of declining productivity (1994–1997) associated with the onset of meromixis and increasing chemical stratification, followed by continually increasing estimates of annual primary production through the breakdown of meromixis in 2003 when the second highest estimated annual primary production occurred (1,645 g C m^{-2} y^{-1}). Estimated annual productivity declined somewhat in 2004–06 ranging from 864 to 1,111 g C m^{-2} y^{-1} and then increased to1,766 g C m^{-2} y^{-1} as the 2-yr episode of meromxis broke down.

The mean annual biomass of *Artemia* was estimated from instar-specific abundance and length-weight relationships for the period 1983–99 and by direct weighing from 2000 to the present. The mean annual biomass has varied from 5.3 to 17.6 g m^{-2} with a 23-yr (1983-2006) mean of 9.3 g m^{-2}. The highest estimated mean annual biomass (17.6 g m^{-2}) occurred in 1989 just after the breakdown of meromixis during a period of elevated phytoplankton nutrients (ammonium) and phytoplankton. The lowest annual estimate was in 1997 following two years of meromixis and increasing density stratification. Mean annual biomass was somewhat below the long-term mean during the first 3 years of the 1980s episode of meromixis and then above the mean the next 3 years as meromixis weakened and ended. The years with the lowest annual biomass of *Artemia* were 1997 (5.3 g m^{-2}) and 2002 (4.9 g m^{-2}), both during the extended period of meromixis, 1995–2003). However, mean annual *Artemia* biomass increased in

2003 as meromixis weakened to 7.5 g m^{-2}, and further to 11.0 g m^{-2} in 2004 following the breakdown of meromixis in late 2003. Mean annual *Artemia* biomass during 2005–09 varied from 5.8 to 8.8 g m^{-2}.

Peer-reviewed scientific publications

In addition to the long-term limnological monitoring, the City of Los Angeles has partially or wholly funded a number of laboratory experiments, analyses, and analytical modeling studies resulting in a large number of peer-reviewed research publications by University of California, Santa Barbara (UCSB) researchers. In addition to research on mixing dynamics, nutrient cycling, and primary and secondary productivity, data collected as part of the long-term limnological monitoring has also contributed to analyses of other aspects Mono Lake's ecology including bacteria, viruses, and avian populations.

Dana, G. L. and P.H. Lenz. 1986. Effects of increasing salinity on an *Artemia* population from Mono Lake, California. Oecologia 68:428-436.

Dana, G.L., C. Foley, G. Starrett, W. Perry and J.M. Melack. 1988. In situ hatching of *Artemia monica* cysts in hypersaline Mono Lake, Pages 183-190. In: J.M. Melack, ed., Saline Lakes. Developments in Hydrobiology. Dr. W. Junk Publ., The Hague (also appeared in Hydrobiologia 158: 183-190.)

Dana, G. L., R. Jellison, and J. M. Melack. 1990. *Artemia monica* egg production and recruitment in Mono Lake, California, USA. Hydrobiologia 197:233-243.

Dana, G. L., R. Jellison, J. M. Melack, and G. Starrett. 1993. Relationships between *Artemia monica* life history characteristics and salinity. Hydrobiologia 263:129-143.

Dana, G. L., R. Jellison, and J. M. Melack. 1995. Effects of different natural regimes of temperature and food on survival, growth, and development of Artemia. J. Plankton Res. 17:2115-2128.

Jellison, R. 1987. Study and modeling of plankton dynamics in Mono Lake, California. Report to Community and Organization Research Institute, Santa Barbara.

Jellison, R., G. L. Dana, and J. M. Melack. 1992. Ecosystem responses to changes in freshwater inflow to Mono Lake, California, p. 107–118. In C. A. Hall, Jr., V. Doyle-Jones, and B. Widawski [eds.] The history of water: Eastern Sierra Nevada, Owens Valley, White-Inyo Mountains. White Mountain Research Station Symposium 4. Univ. of Calif., Los Angeles.

Jellison, R., J. Romero, and J. M. Melack. 1998a. The onset of meromixis during restoration of Mono Lake, California: Unintended consequences of reducing water diversions. Limnol. Oceanogr. 43:706-711.

Jellison, R. and J. M. Melack. 1988. Photosynthetic activity of phytoplankton and its relation to environmental factors in hypersaline Mono Lake, California. Hydrobiologia 158:69-88.

Jellison, R., and J. M. Melack. 1993. Algal photosynthetic activity and its response to meromixis in hypersaline Mono Lake, California. Limnol. Oceanogr. 38:818–837.

Jellison, R., and J. M. Melack. 1993. Meromixis in hypersaline Mono Lake, California I. Vertical mixing and density stratification during the onset, persistence, and breakdown of meromixis. Limnol. Oceanogr. 38:1008–1019.

Jellison, R. and J. M. Melack. 2001. Nitrogen limitation and particulate elemental ratios of seston in hypersaline Mono lake, California, USA. Hydrobiol. 466:1-12.

Jellison, R., L. G. Miller, J. M. Melack, and G. L. Dana. 1993. Meromixis in hypersaline Mono Lake, California II. Nitrogen fluxes. Limnol. Oceanogr. 38:1020–1039.

Jellison, R., G. L. Dana, and J. M. Melack. 1995. Zooplankton cohort analysis using systems identification techniques. J. Plankton Res. 17:2093–2115.

Jellison, R., R. Anderson, J. M. Melack, and D. Heil. 1996. Organic matter accumulation in Mono Lake sediments during the past 170 years. Limnol. Oceanogr. 41:1539–1544.

Melack, J.M. and R. Jellison. 1998. Limnological conditions in Mono Lake: Contrasting monomixis and meromixis in the 1990s. Hydrobiologia 384:21-39.

Miller, L. G., R. Jellison, R. S. Oremland, and C. W. Culbertson. 1993. Meromixis in hypersaline Mono Lake, California III. Breakdown of stratification and biogeochemical response to overturn. Limnol. Oceanogr. 38:1040–1051.

Romero, J.R., J.C. Patterson, and J. M. Melack. 1996. Simulation of the effect of methane bubble plumes on vertical mixing in Mono Lake. Aquat. Sci. 58:210–223.

Romero, J.R. and J.M. Melack. 1996. Sensitivity of vertical mixing to variations in runoff. Limnol. Oceanogr. 41:955–965.

Romero, J. R., R. Jellison, J. M. Melack. 1998. Stratification, vertical mixing, and upward ammonium flux in hypersaline Mono Lake, California. Archiv fur Hydrobiol. 142: 283-315.

Joye, S.B., Connell, T. L. Miller, L. G. Oremland, R. S. Jellison, R. 1999. Oxidation of ammonia and methane in an alkaline, saline lake. Limnol. Oceanogr. **44**:178-188.

Jellison, R., S. MacIntyre, and F. Millero. 1999. The density characteristics of Mono Lake brine. Int. J. Salt Lake Res. **8:** 41-53.

MacIntyre, S., K. Flynn, R. Jellison, J. Romero. 1999. Boundary mixing and nutrient fluxes in Mono Lake, California. Limnol. Oceanogr. **44**: 512-529.

Jellison, R. and J. M. Melack. 2001. Nitrogen limitation and sestonic elemental ratios in hypersaline Mono Lake, California. Hydrobiologia **466:**1-12.

Jellison, R., H. Adams, and J. M. Melack. 2001. Re-appearance of rotifers in hypersaline Mono Lake, California, during a period of rising lake levels and decreasing salinity. Hydrobiologia **466:**39-43.

MacIntyre, S. and R. Jellison. 2001. Nutrient Fluxes from Upwelling and High Turbulence at the Top of the Pycnocline in Mono Lake, CA. Hydrobiologia **466:**13-29.

Jiang, S., G. F. Steward, R. Jellison, W. Chu, and S. Choi. 2004. Abundance, Distribution, and Diversity of Viruses in Alkaline, Hypersaline Mono Lake, California. Microbial Ecology **47**:9-17.

Steward, G. F., J. P. Zehr., R. Jellison., J. P. Montoya, and J.T. Hollibaugh. 2004. Vertical Distribution of Nitrogen-Fixing Phylotypes in a Meromictic, Hypersaline Lake. Microbial Ecology **47**:30-40.

Hollibaugh, J.T., S. Carini, H. Gurleyuk, R. Jellison, S. B. Joye, G. LeCleir, L. Vasquex, and D. Wallschlager. 2005. Arsenic speciation in Mono lake, California: Response to seasonal stratification and anoxia. Geochimica et Cosmochimica Acta **69:**1925-1937.

Brum, J. R., G. F. Steward, S. C. Jiang, and R. Jellison. 2005. Spatial and temporal variability of prokaryotes, viruses, and viral infections of prokaryotes in an alkaline, hypersaline lake. Aquatic Microbial Ecology **41**:247-260.

Wrege, P. H., W. D. Shuford, D. W. Winkler, and R. Jellison. 2006. Annual variation in numbers of breeding California Gulls at Mono Lake, California: the importance of natal philopatry and local and regional conditions. Condor **108**:82-96.

Jorgensen, N. O. G., P. Engel, R. Jellison, and J. T. Hollibaugh. 2008. Contribution of bacterial cell wall components to DOM in alkaline, hypersaline Mono Lake, California. Geomicrobiology Journal **25**:38-55.

Bruce, L. C., R. Jellison, J. Imberger, and J. M Melack. 2008. Effect of benthic boundary layer transport on the productivity of Mono Lake, California. Saline Systems 4:11.

MacIntye, S., J. F. Clark, R. Jellison, and J. P. Fram. 2009. Turbulent mixing induced by nonlinear internal waves in Mono Lake, California. Limnol. Oceanogr: **54:**2255-2272.

CHAPTER 2

METHODS

Meteorology

Continuous meteorological data are collected at the Paoha Island station located on the southern tip of Paoha Island. The station is approximately 30 m from the shoreline of the lake with the base located at 1948 m asl, several meters above the current surface elevation of the lake. Sensor readings are made every second and stored as either ten minute or hourly values. A Campbell Scientific CR1000 datalogger records up to 6 months of measurements. Data are downloaded to a storage module which is collected monthly during the regular sampling trips to the lake.

Wind speed and direction (RM Young wind monitor) are measured at a height of 3 m above the surface of the island and are averaged over a 10-minute interval. The maximum wind speed during the ten-minute interval is also recorded. The 10-minute wind vector magnitude, wind vector direction, and the standard deviation of the wind vector direction are computed from the measurements of wind speed and wind direction and stored. Hourly measurements of photosynthetically available radiation (PAR, 400 to 700 nm, Li-Cor 192-S), total rainfall (Campbell Scientific TE525MM-L tipping bucket), and ten minute averages of relative humidity (Vaisalia HMP35C) and air temperature (Vaisalia HMP35C and Campbell Scientific Temp 107) are also made and stored. The detection limit for the tipping bucket gage is 1 mm of water. As the tipping bucket is not heated, the instrument is less accurate during periods of freezing due to sublimation of ice and snow.

The Cain Ranch meteorological station is located approximately 7 km southwest of the lake at an elevation of 2088 m. Throughout the 1980s, LADWP measured wind and temperature at this station. Currently UCSB maintains and records hourly averages of incoming shortwave (280 to 2800 nm; Eppley pyranometer), longwave radiation (3000 to 50000 nm; Eppley pyrgeometer) and PAR (400 to 700 nm; Li-Cor 192-S) at this site.

Sampling Regime

The limnological monitoring program for Mono Lake specifies monthly surveys from February through December. Surveys are conducted over one or two days depending on the weather conditions, the number of depths at which productivity is being estimated, and meteorological station maintenance requirements. When conducted over two days, every effort is made to collect the lakewide survey and the station 6 profiles including productivity data on consecutive days.

Field Procedures

In situ profiles

Water temperature and conductivity were measured at nine buoyed, pelagic stations (2, 3, 4, 5, 6, 7, 8, 10 and 12) (Fig. 1) with a high-precision conductivity-temperature-depth profiler (CTD)(Idronaut, Model 316Plus). The CTD is lowered at a rate of ~0.2 m s^{-1} and sampled at 200 ms intervals or approximately every 4 cm. Pressure readings were converted to depth using the density of Mono Lake water at the in situ temperature and salinity. Conductivity readings at in situ temperatures (C_t) were standardized to 25°C (C_{25}) using

$$C_{25} = \frac{C_t}{1 + 0.02124(t - 25) + 9.16 \times 10^{-5}(t - 25)^2}$$

where t is the in situ temperature. Resulting conductivity profiles were visually examined for spiking and smoothed with a 7-pt box car moving average.

To describe the general seasonal pattern of density stratification, the contributions of thermal and chemical stratification to overall density stratification were calculated based on conductivity and temperature differences between 2 and 28 m at station 6 and the following density equation:

$$\begin{aligned}\rho(t, C_{25}) = {} & 1.0034 + 1.335 \times 10^{-5} t - 6.20 \times 10^{-6} t^2 + 4.897 \times 10^{-4} C_{25} \\ & + 4.23 \times 10^{-6} C_{25}^2 - 1.35 \times 10^{-6} t C_{25}\end{aligned}.$$

The relationship between total dissolved solids and conductivity for Mono Lake water was given by:

$$TDS\left(g\ kg^{-1}\right) = 3.386 + 0.564 \times C_{25} + 0.00427 \times C_{25}^2.$$

To obtain TDS in grams per liter, the above expression was multiplied by the density at 25°C for a given standardized conductivity given by:

$$\rho_{25}(C) = 0.99986 + 5.2345 \times 10^{-4} C + 4.23 \times 10^{-6} C^2$$

A complete description of the derivation of these relationships is given in Chapter 4 of the 1995 Annual Report.

Dissolved oxygen was measured at one centrally located station (Station 6). Dissolved oxygen concentration was measured with a Yellow Springs Instruments temperature-oxygen meter (YSI, model 58) and probe (YSI, model 5739). The oxygen electrode is calibrated at least once each year against Miller titrations of Mono Lake water (Walker *et al.* 1970).

Water samples

Chlorophyll and nutrient samples were collected from seven to eight depths at one centrally located station (Station 6). In addition, 9-m integrated samples for chlorophyll *a* determination and nutrient analyses were collected with a 2.5 cm diameter tube at seven stations (Station 1, 2, 5, 6, 7, 8, and 11) (Fig. 1). Samples for nutrient analyses were filtered immediately upon collection through Gelman A/E glass-fiber filters, and kept chilled and dark until returned to the lab. Water samples used for the analysis of chlorophyll *a* were filtered through a 120-µm sieve to remove all stages of *Artemia*, and kept chilled and dark until filtered in the laboratory.

Artemia samples

The *Artemia* population was sampled by one net tow from each of twelve, buoyed stations (Fig. 1). Samples were taken with a plankton net (1 m x 0.30 m diameter, 120 μm Nitex mesh) towed vertically through the water column. Samples were preserved with 5% formalin in lake water. Two additional samples were collected at Stations 1, 6, and 8, to analyze for presence of rotifers, and to archive a representative of the population. When adults were present, an additional net tow is taken from Stations 1, 2, 5, 6, 7, 8 and 11 to collect adult females for brood size and length analysis.

Laboratory Procedures

Water samples

Samples are returned to the laboratory within several hours of collection and immediately processed for ammonium and chlorophyll determinations. Ammonium concentrations were measured immediately, while chlorophyll samples were filtered onto 47 mm Whatman GF/F filters and kept frozen until the pigments were analyzed within two weeks of collection.

Chlorophyll *a* was extracted and homogenized in 90% acetone at room temperature in the dark. Following clarification by centrifugation, absorption was measured at 750 and 663 nm on a spectrophotometer (Abbott Corporation, model SV1100D Spectrophotometer). The sample was then acidified in the cuvette, and absorption was again determined at the same wavelengths to correct for phaeopigments. Absorptions were converted to phaeophytin-corrected chlorophyll *a* concentrations with the formulae of Golterman (1969). During periods of low phytoplankton concentrations (<5 μg chl *a* l^{-1}), the fluorescence of extracted pigments was measured on a fluorometer (Turner Designs, model TD-700) which was calibrated using a fluorometer solid standard and an acetone blank.

Ammonium concentrations were measured using the indophenol blue method (Strickland and Parsons 1972). In addition to regular standards, internal standards were analyzed because the molar extinction coefficient is less in Mono Lake water than in distilled water. Oxygen gas was bubbled into Mono Lake water and used for standards and sample dilutions. Oxygenating saline water may help reduce matrix effects that can occur in the spectrophotometer (S. Joye, pers. comm.) When calculating concentration, the proportion of ammonium in the Mono Lake dilution water in diluted (deep) samples was subtracted from the total concentration.

Artemia samples

Artemia abundances were counted under a stereo microscope (6x or 12x power). Depending on the density of shrimp, counts were made of the entire sample or of subsamples made with a Folsom plankton splitter. Samples were split so that a count of >100 animals was obtained. Shrimp were classified into adults (instars > 12), juveniles (instars 8–11), and nauplii (instar 1–7) according to Heath's classification (Heath 1924). Adults were sexed and the adult females were divided into ovigerous and non-ovigerous. Ovigerous females included egg-bearing females and females with oocytes. Adult ovigerous females were further classified according to their reproductive mode, ovoviviparous or oviparous. A small percentage of ovigerous females were unclassifiable if eggs were in an early developmental stage. Nauplii at seven stations (Stations 1, 2, 5, 6, 7, 8, and 11) were further classified as to instars 1–7.

Live females collected for brood size and length analysis were kept cool and in low densities during transport to the laboratory. Immediately on return to the laboratory, females are randomly selected, isolated in individual vials, and preserved. Brood size was determined by counting the number of eggs in the ovisac including those dropped in the vial, and egg type and shape were noted. Female length was measured from the tip of the head to the end of the caudal furca (setae not included).

Long-term integrative measures of productivity

Primary Production

Photosynthetically available radiation (PAR, 400-700 nm) was recorded continuously at Cain Ranch, seven kilometers southwest of the lake, from 1982 to 1994 and on Paoha Island in the center of the lake beginning in 1991 with a cosine-corrected quantum sensor. Attenuation of PAR within the water column was measured at 0.5-m intervals with a submersible quantum sensor. Temperature was measured with a conductivity-temperature-depth profiler (Idronaut, Model 316Plus) (see Methods, Chapter 2). Phytoplankton samples were filtered onto glass fiber filters and extracted in acetone (see above).

Photosynthetic activity was measured using the radiocarbon method. Carbon uptake rates were measured in laboratory incubations within five hours of sample collection. Samples were kept near lake temperatures and in the dark during transport. Samples were incubated in a "photosynthetron", a temperature-controlled incubator in which twenty-four 20-ml samples are exposed to a range of light intensities from 0 to 1500 $\mu E\ m^{-2}\ s^{-1}$. After a 4-h incubation, samples were filtered through a Whatman GF/F filter at a pressure not exceeding 125 mm of Hg and rinsed three times with filtered Mono Lake water. Filters were then soaked for 12 h in 1 ml of 2.0 N HCl, after which 10 ml of scintillation cocktail were added and activity measured on a liquid scintillation counter. Chlorophyll-normalized light-limited (α^B) and saturated (P_m^B) parameters were determined via non-linear least-squared fitting to a hyperbolic tangent equation: $P^B = P_m{}^B \tanh\left(\frac{\alpha^B I}{P_m{}^B}\right)$ where I is the light intensity and P^B is the measured chlorophyll-specific uptake of carbon.

Estimates of daily integral production were made using a numerical interpolative model (Jellison and Melack 1993a). Inputs to the model include the estimated photosynthetic parameters, insolation, the vertical attenuation of photosynthetically available irradiance and vertical water column structure as measured by temperature at 1 m intervals and chlorophyll a from samples collected at 4–6 m intervals. Chlorophyll-specific uptake rates based on temperature were multiplied by ambient chlorophyll a concentrations interpolated to 1-m intervals. The photosynthetically available light field was calculated from hourly-integrated values at Paoha meteorological station, measured water column attenuation, and a calculated albedo. The albedo was calculated based on hourly solar declinations. All parameters, except insolation that was recorded continuously, were linearly interpolated between sampling dates. Daily integral production was calculated by summing hourly rates over the upper 18 m.

Artemia biomass and reproduction

Average daily biomass and annual cyst and naupliar production provide integrative measures of the *Artemia* population allowing comparison among years. Prior to 2000, *Artemia* biomass was estimated from stage specific abundance and adult length data, and weight-length relationship determined in the laboratory simulating in situ conditions of food and temperature (see Jellison and Melack 2000 for details). Beginning in 2000, biomass was determined directly by drying and weighing of *Artemia* collected in vertical net tows.

The resulting biomass estimates are approximate because actual instar-specific weights may vary within the range observed in the laboratory experiments. However, classifying the field samples into one of the three categories will be more accurate than using a single instar-specific weight-length relationship. Because length measurements of adult females are routinely made, they were used to further refine the biomass estimates. The adult female weight was estimated from the mean length on a sample date and one of the three weight-length regressions determined in the laboratory development experiments. As the lengths of adult males are not routinely determined, the average ratio of male to female lengths determined from individual measurements on 15 dates from 1996 and 1999 was used to estimate the average male length of other dates.

Naupliar and cyst production was calculated using a temperature-dependent brood interval, ovigery, ovoviviparity versus oviparity, fecundity, and adult female abundance data from seven stations on each sampling date.

Long-term trends in annual algal biomass and adult Artemia abundance

The seasonality in algal biomass and adult *Artemia* abundance can be removed by calculating yearly moving averages. Because the intervals between sampling dates varied among years, daily values are derived by linearly interpolating between sample dates prior to calculating a 365-day moving average. Thus, each point represents a moving average of 365 days centered on each sample. This seasonally-filtered data can be used to detect long-term trends in algal biomass and adult *Artemia.*

CHAPTER 3
RESULTS AND DISCUSSION

Overview

The lake has exhibited a "typical" monomictic regime with an extended midwinter period of holomixis since the breakdown of a short episode of meromixis, 2005–07. The multi-year trend beginning in 2004 of above average primary productivity and large spring generations of *Artemia* followed by a smaller than average late summer population of *Artemia* and rapid autumn decline continued in 2010. While the abundance of 1st generation of adult *Artemia* was higher than all the years of record from 1981 to 2003, it was smaller than the most recent six years, 2004–2009. This was most likely due to unusually cool spring water temperatures. Late summer abundance was the lowest on record.

The inverse correlation between the sizes of the spring and summer *Artemia* generations has been observed during many years. Large spring generations of adult *Artemia* reduce phytoplankton to concentrations which become severely limiting to the growth and survival of ovoviviparously produced nauplii of the spring generation. Thus, recruitment into the summer population is reduced and the autumn abundance is greatly reduced. This larval recruitment bottleneck, most apparent in recent years, is the key to understanding and interpreting much of the observed spatial and temporal variation in *Artemia* population dynamics.

Here, we describe the limnological conditions observed during 2010 and calculate several long-term integrative measures of ecosystem productivity.

Meteorological Data

The Mono Lake limnological monitoring program includes collection of a full suite of meteorological data at a station located on the southern tip of Paoha Island and radiation (shortwave, longwave, and photosynthetically available radiation) at Cain Ranch located approximately 7 km southwest of the lake since 1990.

In May 2010, our monthly maintenance check of the Paoha Island station revealed the anemometer was damaged immediately after our April survey. A replacement was installed the following survey but there is no wind data available from this station from April 7 through June 24. Data from alternative meteorological sites which are available for this period include a Lee Vining site maintained by the Mono Lake Committee and a site on the northeast shore maintained by the Great Basin Pollution Control District.

Wind Speed and Direction

Mean daily wind speed varied from 0.2 to 11.5 m s^{-1} over the year, with an overall annual mean of 3.1 m s^{-1} (Fig. 2). This annual mean is slightly lower than observed in 2009 (3.4 m s^{-1}) but falls within the range observed during the period 2001–09 (3.0 – 3.5 m s^{-1}). The daily maximum 10-min averaged wind speeds recorded on Paoha Island averaged 4.0 times mean daily wind speeds. The maximum recorded 10-min reading

(28.1 m s^{-1}, 63 mph) occurred on the afternoon of December 19 (Fig. 2). The mean monthly wind speed varied from 2.3 to 4.0 m s^{-1} (coefficient of variation, 17 %). This was similar to 2009 when the mean monthly wind speed varied from 2.2 to 4.0 m s^{-1}. As observed in the past, winds were predominately from the south (mean, 190 deg).

Air Temperature

Mean daily air temperatures ranged from a minimum of –8.2°C on 30 December to a maximum of 22.8°C on 15 July (Fig. 3). Air temperatures ranged from 5.1°C to 32.5°C during the summer (June through August) with a mean daily range of 9.4°C to 22.8°C and from –11.8°C to 12.9°C during the winter (December through February) with a mean daily range of -8.2°C to 9.2°C.

May 2010 mean air temperatures were unusually low. The monthly mean air temperature was only 8.0°C compared to 12.6°C, 9.7°C, and 13.9°C in 2007, 2008 and 2009, respectively. This resulted in cooler water temperatures and significant impacts on the development of the *Artemia* population (see below)

Incident Photosynthetically Available Radiation (PAR)

Photosynthetically available radiation (400-700 nm) exhibits a regular sinusoidal curve dictated by the temperate latitude (38°N) of Mono Lake. Maximum daily values typically range from about ~19 Einsteins m^{-2} day^{-1} at the winter solstice to ~64 Einsteins m^{-2} day^{-1} in mid-June (Fig. 4). Daily values that diverge from the curve indicate overcast or stormy days. During 2010, the annual mean was 39.4 Einsteins m^{-2} day^{-1}, with daily values ranging from 1.4 Einsteins m^{-2} day^{-1} on 19 December to 64.9 Einsteins m^{-2} day^{-1} on 27 May. The 2010 annual mean was within the range (35.0–39.9 Einsteins m^{-2} day^{-1}) observed during 2002–09.

Relative Humidity and Precipitation

Mean daily relative humidity values followed the general pattern of high values (mostly 70-90 %) in January, decreasing to lows (mostly 30-50 %) in April through September and then gradually to above 60 % through December (Fig. 5). The 2010 annual mean was 55.7 % slightly higher than the 2009 value (52.6 %) but within the range observed during 2003–2007 (54.0–57.9 %).

The 2010 annual precipitation measured at Paoha Island was 223.4 mm (8.8 inches). Two large precipitation events occurred late in the year. The first event on 4 October delivered 27.2 mm and the second on 19 December delivered 34.2 mm (Fig. 6). Total precipitation was higher than in 2001, 2002, 2003, 2004, 2009 (87.9 mm, 69.1 mm, 101.1 mm, 102.7 mm, 120.6 mm respectively) but lower than in 2005 and 2006 (230.9 mm and 242.5 mm). Annual precipitation data for 2007 and 2008 are not available from Paoha Island. Precipitation measured in Lee Vining (elevation 6800 ft, lat: 37º 57' 0" N, long: 119º07' 30" W) during 2007 and 2008 was 148.8 mm and 329 mm, respectively, but precipitation generally declines by half across the lake (LADWP unpub., Vorster 1985) and the Lee Vining data are not directly comparable.

Surface Elevation

The surface elevation of Mono Lake was 6381.4 ft on 1 January 2010. Surface elevation rose to a maximum of 6382.3 ft in August. The gradual seasonal decline in the second half of the year to 6381.9 ft on 1 January 2011 resulted in a net annual increase of 0.5 ft in surface elevation (Fig. 7).

Temperature

The annual pattern of thermal stratification in Mono Lake results from seasonal variations in climatic factors (e.g. air temperature, solar radiation, wind speed, humidity) and their interaction with density stratification arising from the timing and magnitude of freshwater inputs. The annual pattern observed during 1990–94 is typical of large temperate lakes except that in hypersaline Mono Lake the absence of ice cover and temperature-density properties result in a single extended period of winter holomixis. In Mono Lake, the annual winter period of holomixis typically extends from late November to early February after which seasonal thermal and salinity stratification are initiated due to warming air temperatures, increased insolation, and increased inflows. This pattern has been altered by three recent episodes of meromixis (1983–88, 1995–03, 2005–07) during which vertical salinity gradients accompanying increased freshwater inflows prevented winter holomixis (Fig. 7). During 2008 through 2010 winter holomixis and monomictic conditions prevailed.

January represents a period of low biological activity due to cold water temperatures, low light levels, and the absence of *Artemia*. January surveys are only conducted when unusual circumstances warrant it and weather permitting. Monthly surveys are initiated each year in February. Due to inclement weather and ramp access problems the initial survey in 2010 was pushed back until early March.

The first survey of the year was conducted on 5 March 2010 (Table 1, Fig. 8). A slight amount of warming was present in the upper 5 m with water temperatures ranging from 3.6 °C at 5 m depth to 4.0 °C at 1 m depth. Below 5 m the water column was well-mixed with temperature gradually decreasing from 3.4 °C at 6 m to 2.4 °C at 17 - 28 m depth. Temperature increased slightly in the hypolimnion ranging from 2.5 -2.6 °C between 29 and 38 m depth.

During spring and early summer, multiple weak thermoclines and complex profiles were present due to the interactions among seasonal warming, freshwater inflows, and meteorological events. Due to below average spring air temperatures, the lake warmed slowly. On 13 May 2010 the water temperature at 2 m was 9.3 °C compared to 19.0 °C on 18 May 2009. A strong (>1 °C) persistent thermocline was not present until mid-June when a sharp temperature gradient was present at 8–9 m depth. Epilimnetic water temperatures on the 17 June survey were 15.5–16.1 °C. Temperature decreased sharply from 15.6 °C at 8 m depth to 10.5 °C at 10 m depth. Below this depth, temperature declined more slowly in the hypolimnion to 4.4 °C near the bottom at 35–38 m.

Annual maximum water temperatures were observed during the August survey when temperatures in the well-defined epilimnion (≤9 m) were 21.2–22.5 °C. August hypolimnetic water temperatures increased to 5.4 °C at 34 m indicating some deep vertical mixing.

During late summer the epilimnion gradually cooled, the persistent thermocline deepened, and the hypolimnion warmed slowly. By 14 October 2010 the top of the thermocline was at 14–15 m depth. Holomixis (i.e. "autumn turnover") occurred prior to the 30 November 2010 survey at which time the water column was nearly isothermal with water temperatures only varying between 6.4 and 6.5 °C between 4 m and 38 m. The upper 3 m were slightly warmer ranging from 6.6 to 6.8 °C.

Holomixis continued through December as indicated by a nearly isothermal water column (5.6–5.9 °C).

While the seasonal pattern and magnitude of water temperatures observed during 2010 were typical of those observed in previous years during monomictic conditions, a cold spring resulted in slower lake warming especially during May when the first generation of *Artemia* are usually reaching sexual maturity.

Conductivity and Salinity

The third recent episode of meromixis initiated in 2005 ended in late 2007 and a monomictic regime of annual stratification has persisted through the present. Despite winter holomixis, a slight degree of vertical salinity stratification due to freshwater inputs and rising lake levels was present on the 5 March 2010 survey. Conductivities in the upper 14 m ranged from 81.8 to 82.1 mS cm^{-1} while they were 82.5–82.6 beneath 16 m depth (Table 2, Fig. 9). Conductivity at 2 m depth decreased to a minimum of 74.2 mS cm^{-1} 17 August 2010 following snowmelt runoff and then increased through the rest of the year as the thermocline deepened and the surface elevation declined. During the 16 December 2010 survey, conductivity was 82.3 mS cm^{-1} at 1 m depth and increased slightly to 82.6 mS cm^{-1} near the bottom (38 m). This conductivity range corresponds to a salinity of 78.7–79.1 g kg^{-1}.

Salinity, expressed as total dissolved solids, can be calculated from conductivity measurements corrected to a reference temperature (25 °C, see Methods). Because total dissolved solids are conservative at the current salinities in Mono Lake, salinity fluctuates with volume due to changes in the balance between freshwater inputs (streams and precipitation) and evaporative losses. The observed range of conductivities from an epilimnetic midsummer minimum of 74.2 mS cm^{-1} to the annual maximum of 82.6 mS cm^{-1} observed in March, November and December correspond to salinities of 68.7 and 79.1 g kg^{-1}, respectively. Given the density of Mono Lake water at 25°C this is equivalent to 73 and 84 g l^{-1}, respectively.

Density Stratification: Thermal and Chemical

The large seasonal variation in freshwater inflows associated with the eastern Sierra and year-to-year climatic variation have led to complex patterns of seasonal density stratification over the last 30 years. Much of the year-to-year variation in the plankton dynamics observed at Mono Lake can be attributed to marked differences in chemical stratification resulting from variation in freshwater inflows and its affect on nutrient cycling. Excess density varied from 57.7 to 72.4 kg m^{-3} over the course of the year (Table 3).

Seasonal density stratification reflects contributions from both thermal and salinity stratification (Table 4, Fig 10). Peak stratification during monomictic periods usually occurs during July due to the combined effect of spring runoff and warm epilimnetic temperatures. In 2010, peak stratification occurred in July and August. During this period the difference in salinity between 2 and 32 m contributed 8.9–9.1 kg m^{-3} to vertical density stratification, almost double the 4.5 kg m^{-3} due to temperature stratification. The overall density stratification in July and August was as high as observed during many meromictic years.

Transparency and Light Attenuation

In Mono Lake, variation in transparency is predominately due to changes in algal biomass. Standing algal biomass reflects the balance between all growth and loss processes. Thus, variation in transparency as measured by Secchi depth often reflects the detailed development of the *Artemia* population as much as any changes in nutrient availability and primary productivity.

In 2010, lakewide transparencies during spring as measured by Secchi depth were among the lowest observed ranging from 0.79±0.01 in early March to 0.64±0.02 m in mid May (Fig. 11, Table 5). In only two other years (1982 and 2003) was mid-May transparency so low. As *Artemia* grazing reduced midsummer phytoplankton, mean lakewide transparency increased to 1.9±0.1 m, 6.3±0.1 and 5.1±0.1 m in June, July and August, respectively. These values are lower than observed in 2009, 5.9±0.2 m, 6.6±0.3 and 5.5±0.2 m comparatively and are among the lowest observed. The only other years in which midsummer transparencies were less occurred in 2003 and 2008. While both 2003 and 2008 followed periods of meromixis, low midsummer transparencies were not observed following the breakdown of meromixis in 1988. Secchi depths decreased to 0.8–0.9 m during October–December as *Artemia* abundance declined to near zero and a large autumn phytoplankton bloom occurred.

Secchi depth is an integrative measure of light attenuation within the water column. Because light absorption is exponential with depth, long-term variation in Secchi depth is most appropriately viewed on a logarithmic scale. While the annual pattern of Secchi depths during 2010 was similar to other years, values were clearly among the lowest observed since 1979 (Fig. 12).

The attenuation of PAR within the water column varies seasonally, primarily as a function of changes in algal biomass. In 2010, the depth of the euphotic zone, operationally defined as the depth at which only 1 % of the surface insolation is present, increased from ~4 m during March and April to ~12 m during July and August , and then decreased to 4.5–6.5 m late in the year (October–December) (Fig. 13).

Dissolved Oxygen

Dissolved oxygen concentrations are primarily a function of salinity, temperature, and the balance between photosynthesis and overall community respiration. In the euphotic zone of Mono Lake, dissolved oxygen concentrations are typically highest during the spring algal bloom. As the water temperature and *Artemia* population increase through the spring, dissolved oxygen concentrations decrease. Beneath the euphotic zone, bacterial and chemical processes deplete the oxygen once the lake stratifies. During meromictic periods, the monimolimnion (the region beneath the persistent chemocline) remains anoxic throughout the year.

In 2010, dissolved oxygen concentrations in the upper mixed layer (< 10 m) ranged from 2.6 to 7.4 mg l^{-1} (Table 6, Fig. 14) with the highest concentrations occurring in the upper 5 m during March through May. The lowest epilimnetic values occurred during the July survey when dissolved oxygen was <3.0 mg l^{-1} in the upper 6 m of the water column. Epilimnetic values were also low in November as anoxic hypolimnetic waters were actively mixing into the surface. The hypolimnion was suboxic during the initial sampling on 5 March and became anoxic (<0.5 mg l^{-1}) by 13 May below the mid-depth thermocline through October. Epilimnetic values were also low in November as anoxic hypolimnetic waters appeared to be actively mixing into the surface. December values ranged from 4.6 mg l^{-1} at 1 m to 1.5 mg l^{-1} at 37 m indicating that while the water column had indeed mixed it had become weakly restratified.

Nutrients (ammonia/ammonium)

Nitrogen is the primary limiting macronutrient in Mono Lake as phosphate is super-abundant (350-450 µM) throughout the year (Jellison *et al.* 1994). External inputs of nitrogen are low relative to recycling fluxes within the lake (Jellison and Melack 1993a, b). Ammonium concentrations in the euphotic zone reflect the dynamic balance between excretion by shrimp, uptake by algae, upward vertical fluxes through thermo- and chemocline(s), release from sediments, ammonium volatilization, and small external inputs. Because a large portion of particulate nitrogen, in the form of algal debris and *Artemia* fecal pellets, sink to the bottom and are remineralized to ammonium in the hypolimnion (or monimolimnion during meromixis), vertical mixing controls much of the annual internal recycling of nitrogen.

After a winter period of holomixis, early March ammonium concentrations showed signs of stratification throughout the water column ranging from 0.4 at 2 m to 9.1 µM at 35 m (Table 7, Fig. 15). Lakewide epilimnetic ammonium concentrations remained low throughout the year with only slight increases in June and July (lakewide mean, 1.2 and 2.8 µM, respectively) due to Artemia excretion and a small spike in November at 4.1 µM (Table 8, Fig. 16) at or near autumn overturn. Epilimnetic ammonium concentrations tended to be higher at the western stations compared to the eastern ones through most of the year though only significantly higher at all western stations in November. The typical pattern of higher concentrations at the western stations in late summer accompanying higher Artemia abundance was not observed 2010. Higher concentrations accompanying the spatially variable peak abundance of *Artemia* is observed during both meromictic and monomictic conditions, but is generally larger during monomictic periods. The causal connection to grazing is highlighted by the variation in the prominence of this feature across the lake which shows an inverse correlation with adult *Artemia* abundance. 2010 was an atypical year as Artemia matured slowly at the cold water temperatures present during May and experienced an early decline (Figure 20).

Hypolimnetic ammonium concentrations increased throughout the stratified period in 2010 from ~9 µM in March to ~92 µM (35 m) in mid-October (Table 7). Autumn "turnover" occurred prior to the 30 November survey when ammonium concentrations throughout the water column ranged from 3.7 µM to 4.5 µM. By 16 December, ammonium concentrations were reduced to 0.7 to 2.8 µM between 2 and 28 m but increased slightly to 9.4 µM at 35 m depth indicating a weakly stratified water column.

Phytoplankton (algal biomass and fluorescence)

The phytoplankton community, as characterized by chlorophyll *a* concentration, shows pronounced seasonal variation. As observed in all years from 1982 to the present, spring and autumn-winter phytoplankton blooms were separated by a period of low phytoplankton biomass during summer due to *Artemia* grazing.

On 5 March 2010 chlorophyll concentrations at Station 6 were high throughout the water column ranging from 63 to 78 µg chl l^{-1} (Table 9, Fig. 17). Chlorophyll *a* in the upper 9-m integrated samples at 7 lakewide stations ranged from 71 to 77 µg chl l^{-1} with a mean of 73.8 ± 0.8 µg chl l^{-1} (Table 10, Fig. 18). Concentrations at Station 6 remained high during April and May ranging from 58 to 73 and 64 to 78 µg chl l^{-1}, respectively. By June algal biomass in the upper 9 m, as measured by chlorophyll *a* concentration, was reduced to 8.9–18.2 µg chl l^{-1}, much lower than observed in June 2009 (20.4–54.0) and 2008 (14.5–26.5 µg chl l^{-1}) but much higher than in 2007 (1.2–2.5 µg chl l^{-1}). Lower algal biomass observed in 2007 is due to reduced vertical mixing and internal recycling of nutrients accompanying the onset of meromixis.

Epilimnetic chlorophyll (upper 9 m) concentrations remained low (≤4.9 µg chl l^{-1}) during July and August and only started to increase in September as the mixed-layer deepened and the *Artemia* population declined. By October, epilimnetic chlorophyll had increased to 23–31 µg liter^{-1} with a lakewide mean of 28.3 µg liter^{-1}. High algal biomass was present during both the November and December surveys (67 µg chl l^{-1} and 79 µg chl l^{-1}, respectively) as ammonium availability increased during holomixis and *Artemia* abundance was low. A peak chlorophyll concentration of 82 µg chl l^{-1} was observed at 12 m depth on 16 December 2010.

As observed in all years, chlorophyll *a* concentration in deep samples (24 and 28 m depth) were high throughout the year ranging from 58 to 82 µg chl l^{-1} during March through August, decreasing slightly to 61–69 µg chl l^{-1} in September and November before increasing in December to 72–80 µg chl l^{-1}.

The large seasonal variation in epilimnetic (upper 9-m integrated) chlorophyll obscures the significant but less marked spatial differences observed during the course of the year. Phytoplankton, as indicated by chlorophyll *a*, are generally less abundant in the eastern portion of the lake compared to western stations early in the year and more abundant during summer. This pattern is inversely related to *Artemia* abundance. In 2010, chlorophyll concentrations were generally lower at the eastern stations during March, April, and May (Fig. 18). However, concentrations were quite similar across the lake during the remainder of the year.

***Artemia* Population Dynamics**

Zooplankton populations in temperate lakes are highly variable across spatial and temporal scales. The Mono Lake monitoring program collects samples from 12 stations distributed across the lake and the relative standard errors of lakewide estimates are typically 10-20 %. However, on any given sample date the standard error of a lakewide estimate may be smaller or larger depending on the observed spatial variability. In extreme cases, local convergences of water masses may concentrate shrimp to well above the overall mean. For these reasons, a single level of significant figures in presenting data (e.g. rounding to 10s, 100s, 1000s or even 10,000s) is inappropriate and we include the standard error of each lakewide estimate using the "±" notation. The reader is cautioned to always consider the standard errors when making inferences from the data.

Hatching of over-wintering cysts and maturation of the 1st generation

Hatching of over-wintering cysts is initiated by warming water temperatures and oxic conditions. The peak of hatching usually occurs during March but significant hatching may also occur during February. A small amount of hatching may even occur during January in shallow nearshore regions during periods of above normal air temperatures. The 5 March survey indicated the spring hatch of over-wintering cysts was well underway. Lakewide mean abundance of naupliar instars was 27,998±5,706 m^{-2} (Table 11a-b) with nearly all 97 % in the 1st instar developmental stage (Table 12). A small number of instars 2 and 3 were present but no juveniles or adults were detected.

Artemia lakewide abundance reached 64,558±25,095 m^{-2} by the 9 April 2010 survey as the spring hatch continued (Table 11a, b). The population was dominated by instars 1, 2 and 3 (25.2 %, 53.3 % and 19.4 %, respectively) (Table 12). Naupliar abundance continued to increase in May 2010 with abundances ranging from 7,445 to 244,668 m^{-2} across the 12 stations and an overall lakewide mean of 67,005 ±17,991 m^{-2} (Table 11a,b). On 13 May, naupliar instars still constituted 91.6 % of the total population with juveniles and adults being 6.4 % and 2 %, respectively. Naupliar abundance dropped significantly to 9,188±1,301 m^{-2} by 18 June.

Adult *Artemia* constituted only 2 % of the total population on 13 May 2010 when they numbered 1,462±628. No fecund females were present during the 13 May survey. Mean lakewide adult abundance increased to 39,933±4,261 m^{-2} in June and peaked in July at 46,237±6,019 m^{-2}. Adult abundance then declined rapidly to11,714±1,681 m^{-2} in August and further to 4,732±1,137 m^{-2} by 13 September). By 14 October adults numbered on 773±79 m^{-2} and were virtually absent in November (92±41 m^{-2}) and December (55±14 m^{-2}) (Table 12, Fig. 19).

Typically, hatching of over-wintering cysts is greater in the eastern sectors of the lake. No statistical difference was detected between sectors in early March but by 24 March nauplii abundance at the eastern station (Stations 7-12) was roughly 4 times higher than that observed at the western stations (Stations 1-6). On 9 April abundance was 11.1 times higher in the East. Naupliar abundance remained higher at the eastern stations through June. This changed in July when naupliar abundance in the western sector was low but almost double that observed in the east (Table 11a).

The 2010 abundance of 1st generation adults (14 July) was above average in the 30-yr record (1981–2010) (Fig. 20). However, recruitment of ovoviviparously-produced nauplii into the summer adult population was very low and August abundance was the lowest on record (Fig. 20). Late season adult abundance remained among the lowest recorded through December.

Ovoviviparous reproduction and the second generation

Ovoviviparous reproduction depends on ambient food levels and age of the individual. *Artemia* produce multiple broods and ovoviviparous reproduction in the lake occurs, if at all, almost exclusively with the first brood, rarely occurring in an individual's second and subsequent broods.

On 13 May 1,375±623 adult females comprised 1.9% of the total population, although none were ovigerous (Table 11a, b, c, 13a, b, c, Fig. 21). Ovigery increased to 14.5 % of 20,456±2,512 individuals on 18 June with 12.2 % reproducing ovoviviparously (naupliar eggs as opposed to encapsulated cysts) and the remaining 87.8 % producing cysts. Ovigery increased to 40.0 % of 22,093±2,491 females on 14 July; peaked on 17 August at 94.0% of 5,785±894, decreased on 13 September to 92.7 % of 1,846±503 and to 73.5 % of 221±39 in October. In November only 3 fecund females were collected in all of 12 net tows. Cyst production ranged between 87.8 % and 97.7% from mid-June through mid-October (Table 13a, b, c). The low numbers of later naupliar instars during August–September (Table 12) and the absence of a second peak in adult abundance indicate that relatively few ovoviviparously produced individuals in July and August were recruited into the adult population.

Fecundity (eggs per brood) is a function of food availability and adult female size. Lakewide mean fecundity ranged from 24 to 33 eggs $brood^{-1}$ during June to August, (Table 14). Lakewide mean individual fecundity increased in September and October (73 and 59 eggs $brood^{-1}$, respectively) as food became abundant but total reproduction was virtually absent by mid-November as adult number were very low. The mean length of adult females varied from 9.8 to 11.2 mm (Table 14) during the year. These sizes are similar to previous years.

<u>Artemia</u> Population Statistics, 1979–2010

Year to year variation in climate, hydrological conditions, vertical stratification, food availability, and salinity have led to large inter-year differences in *Artemia* population dynamics. During years when the first generation was small due to reduced hatching, high mortality, or delayed development, (1981, 1982, and 1989) the second generation peak of adults was 2–3 times the long term average (Table 15, Fig. 22). Early season (May-June) peak abundances were also significantly higher (1.5–2 times the mean) in 1987 and 1988 as the 1980s episode of meromixis weakened and nutrients that had accumulated beneath the chemocline were transported upward. The highest early summer abundances were observed in 2004 following breakdown of the 1995-2003 episode of meromixis (Fig. 20). In many years the seasonal peaks of adult abundance were similar (30–40,000 m^{-2}) although the 1st generation has become significantly larger in recent years beginning in 2004 and continuing through 2010. The seasonal (1 May to November 30) mean of adult abundance has varied less within a range of 11,000–37,000 m^{-2}. The overall mean seasonal abundance of adult *Artemia* from 1979 to 2010 was 19,638 m^{-2}. During this 30-yr record, mean seasonal abundance was lowest in 2000 (~10,500 m^{-2}) and 2002 (~11,600 m^{-2}) and highest in 1982 (~36,600 m^{-2}), 1989 (~36,400 m^{-2}), and 2004 (~32,000 m^{-2}). This year, mean seasonal abundance was 14,921 m^{-2}, somewhat below the long-term (32-yr) mean of 19,638 m^{-2}.

During most years, the seasonal distribution of adult abundance is roughly normal or lognormal. However, in several years the seasonal abundance was not described well by either of these distributions. Therefore, the abundance-weighted centroid of temporal occurrence was calculated to compare overall seasonal shifts in the timing of adult abundance. The center of the temporal distribution of adults varied from day 180 (28 June) to 252 (9 September) in the 32-yr record from 1979 to 2010 (Table 15, Fig. 23). During five years when there was a small spring hatch (1980–83, and 1989) the overall temporal distribution of adults was much later (24 August – 9 September) and during 2004 the exceptionally large and early 1st generation shifted the seasonal temporal distribution much earlier to 28 June. The trend of a large 1st generation followed by a small and rapidly declining late summer population has been observed in each of the seven most recent years (2004–2010)(Fig. 20, Table 15). In 2010, the center of the temporal distribution was day 191.

Over the long-term record there has been a general shift in seasonal adult abundance to earlier in the year. Although there has been significant year-to-year variation among years due to the onset, persistence, and breakdown of three episodes of meromixis during the period 1979 to 2008, a linear regression explains 55 % of the variation in the temporal abundance of adults. The centroid of adult abundance has shifted an average of 1.6 d yr^{-1} over the 32-yr period of variable but generally decreasing salinity. The larger size of the 1st generation and subsequent earlier autumn decline is advantageous to breeding gulls (Wrege et al. 2006) and disadvantageous to migrating grebes (Jellison & Jehl unpublished).

Long term integrative measures of productivity

Planktonic primary production

Photosynthetic rates were determined by laboratory radiocarbon uptake measurements from 1982-1992 (Jellison and Melack 1988, 1993b) and combined with an interpolative model of chlorophyll, temperature, and in situ photosynthetically-available light (PAR) to estimate annual productivity. While radiocarbon uptake measurements were not conducted from 1993-2001, a significant fraction of the chlorophyll-specific variance in maximum (P_m^B) and light-limited uptake rates (α^B) is explained by temperature (Jellison and Melack 1988, 1993b) and estimates of primary production in subsequent years were made employing measurements of light, chlorophyll, temperature and estimates of P_m^B and $\alpha^{B.}$ As 1989 and 1990 had elevated ammonium concentrations due to the breakdown of meromixis, regressions were performed on just 1991 and 1992 for use in subsequent years. The exponential equation:

$$P_m^B = 0.237 \times 1.183^T \qquad n=42,\ r^2=0.86$$

where T is temperature (°C) explained 86 % of the overall variation. As found in previous analyses (Jellison and Melack 1993b), there was a strong correlation between light-limited and light-saturated rates. A linear regression on light-saturated rates explained 82 % of the variation in light-limited rates:

$$\alpha^B = 2.69 + (1.47 \times P_m^B) \qquad n=42,\ r^2=0.82$$

Both light-limited and light-saturated carbon uptake rates reported here are within the range reported in other studies (Jellison and Melack 1993b).

In 1995, rising lake levels and greater salinity stratification reduced the vertical flux of nutrients and may have affected the photosynthetic rates, but previous regression analyses (Jellison and Melack 1993b) using an extensive data set collected during periods of different nutrient supply regimes indicated little of the observed variance in photosynthetic rates can be explained by simple estimates of nutrient supply. The differences in annual phytoplankton production throughout the period, 1982–1992, resulted primarily from changes in the amount of standing biomass; year to year changes in photosynthetic parameters during the years they were measured (1983–92) were not correlated with annual production. Thus, we suggested the above regressions might explain most of the variance in photosynthetic rates and provide a reasonable alternative to frequent, costly field and laboratory measurements using radioactive tracers.

In 2001, new "photosynthetrons" (see Methods, Chapter 2) were constructed and direct measurements of carbon uptake were resumed to determine photosynthetic parameters. The new "photosynthetrons" provide more light levels and better control and measurement of the incubator's light and temperature. Thus, more accurate measurements of P_m^B and α^B are possible and carbon uptake experiments are now routinely conducted with a sample from the upper mixed layer (2 m). These measurements enable annual productivity changes associated with varying nutrient regimes or changing phytoplankton composition to be estimated more accurately than during 1993 to 2001 when P_m^B and α^B were estimated from previously derived regressions.

During 2010, ten carbon uptake experiments were conducted with natural phytoplankton assemblages from the upper mixed-layer (2 m depth) (Table 16). Chlorophyll-specific maximum carbon uptakes (P_m^B) rates and light-limited rates (α^B) were determined for each sample by fitting a hyperbolic tangent curve to the data using least-squares nonlinear estimation (Fig. 24). Chlorophyll-specific maximum carbon uptakes (P_m^B) rates for samples collected at 2 m depth ranged from 1.0–1.4 g C g Chl a^{-1} h^{-1} early and late in the year to 12.9 g C g Chl a^{-1} h^{-1} on 14 July (Table 16), while light-limited rates (α^B) for these samples ranged from 8.5 to 31.5 g C g Chl a^{-1} $Einst^{-1}$ m^2

Using the interpolative model to integrate the photosynthetic parameters with in situ temperature, chlorophyll, and light resulted in an annual productivity estimate of 1,474 g C m^{-2} during 2010 (Table 17, Figs. 24-26). The estimated daily production values are within the bounds of those calculated for previous years, 2002–2008 (Fig. 27).The estimated annual production in 2009 is not reported here as suspect data and calculations are under review.

Estimated annual primary production in 2010 was about twice the long-term mean (1982–2008) of 688 g C m^{-2} (Table 17, Fig. 28). Estimates from previous years ranged from 149 g C m^{-2} in 1997 to 1645 g C m^{-2} in 2003. In 1988, a 5-yr episode of meromixis was breaking down and nutrients which had accumulated beneath the thermocline were mixed into the euphotic zone leading to higher algal biomass and estimated annual production of 1,064 g C m^{-2}. During 2003, an 8-yr period of chemical stratification broke down and significant amounts of ammonium were entrained into the mixed layer. Estimates of planktonic photosynthesis at Mono Lake are generally higher than other hypersaline lakes in the Great Basin: Great Salt Lake (southern basin), 145 g C m^{-2} yr^{-1} (Stephens and Gillespie 1976); Soap Lake, 391 g C m^{-2} yr^{-1} (Walker 1975); and Big Soda, 500 g C m^{-2} yr^{-1} (350 g C m^{-2} yr^{-1} phototrophic production) (Cloern *et al.* 1983).

Artemia biomass and egg production

Artemia biomass was estimated from instar-specific population data and previously derived weight-length relationships for the period 1982–99. Variation in weight-length relationships among sampling dates was assessed from 1996–99 and found to lead to errors of up to 20 % in the annual estimates. Thus, in 2000 we implemented direct drying and weighing of vertical net tow samples collected explicitly for biomass determinations.

In 2010, *Artemia* biomass was 0.07 g dry weight m^{-2} on 5 March and increased to the yearly peak of 22.4 g dry weight m^{-2} on 14 July. The 2010 mean annual *Artemia* biomass was 5.1 g m^{-2}, significantly below the long-term (1983–2010) mean of 8.8 g m^{-2} (Table 17, Fig. 29)

The highest estimated mean annual *Artemia* biomass (17.6 g m^{-2}) occurred in 1989 just after the breakdown of meromixis during a period of elevated nutrients (ammonium) and phytoplankton. Mean annual biomass was somewhat below the long-term mean during the first 3 years of the 1980s episode of meromixis and then above the mean during the next 3 years as meromixis weakened and ended. Except for lower values in 1997 and in 2002, *Artemia* biomass has remained relatively constant since 1993 and was only slightly higher during 1990–92. The higher value in 2004 is associated with the largest spring generation observed. Since 2005 the mean annual *Artemia* biomass has varied from 5.1 to 8.8 g m^{-2}.

In Mono Lake, oviparous (cyst) reproduction is always much higher than ovoviviparous (live-bearing) reproduction (Fig. 30, Table 17). In 2010, total annual naupliar production (0.10×10^6 m^{-2}) was less than half the long term (1983–2010) mean of 0.24×10^6 m^{-2}. Low ovoviviparous reproduction resulted from delayed maturation of the 1st generation and low midsummer food. Total annual cyst production in 2010 was 2.2×10^6 m^{-2}, about half the long term mean of 4.2×10^6 m^{-2}.

Long-term trends in inter-year variation in algal biomass and adult Artemia abundance

The long-term record of plankton dynamics in Mono Lake show marked seasonal and inter-year variation (Figs. 31-32). In particular, standing algal biomass has been reduced during the first years of the three multi-year episodes of meromixis and then elevated during and immediately after the breakdown of meromixis. This inter-year variation caused by changes in mixing regime precludes the possibility of determining the effects of variation in salinity from any small subset of years. Here, we examine the long term trends in algal biomass in the upper water column (< 10 m) and adult *Artemia* biomass from 1982 through 2010.

The seasonal trends can be removed by calculating yearly moving averages. Because the intervals between sampling dates varied among years, daily values were derived by linearly interpolating between sample dates prior to calculating a 365-day moving average. Thus, each point represents a moving average of 365 days centered about a given day. The seasonally-filtered chlorophyll *a* concentrations (Fig. 31, heavy line) show the marked impact of the three episodes of meromixis, 1983–88, 1995–03, 2005–07). The seasonally-filtered mean chlorophyll ranged from a minimum of 2.8 µg $liter^{-1}$ following the onset of meromixis in 1984 to 51.4 µg $liter^{-1}$ in late 2003 and 52.5 µg $liter^{-1}$ in 2008 as the second and third episodes of meromixis ended. This represents an 18-fold difference.

There is a trend of increasing epilimnetic algal biomass over the long-term record (1983–2010). A least squares linear regression of the annual means of the daily interpolated chlorophyll values on year explains 36% of the observed variation ($p<0.001$) (Fig. 32). The upward trend (i.e. slope) is 1.04 (±0.26) µg $liter^{-1}$ yr^{-1}.

The seasonally-filtered adult *Artemia* abundance shows much less inter-year variation (Fig. 33) with mean abundance ranging from 6,200 m^{-2} in 2000 to 24,000 m^{-2} in 1982 or about a 4-fold difference. There is no statistically significant long-term trend in this seasonally-filtered measure of *Artemia* abundance. However, a significant shift in *Artemia* abundance to earlier in the year has occurred over the last couple decades.

REFERENCES

Clark, J. F. and G. B. Hudson. 2001. Quantifying the flux of hydrothermal fluids into Mono Lake by use of helium isotopes. Limnol. Oceanogr. **46:** 189-196.

Cloern, J. E., B. E. Cole, and R. S. Oremland. 1983. Autotrophic processes in meromictic Big Soda Lake, Nevada. Limnol. Oceanogr. **28:** 1049–1061.

Cooper, J. J.and D. L. Koch 1984. Limnology of a desertic terminal lake, Walker Lake, Nevada, U.S.A. Hydrobiologia **118:** 275-292.

Dana, G. L. 1981. Comparative population ecology of the brine shrimp *Artemia.* Master thesis. San Francisco State Univ.

Dana, G. L. and P.H. Lenz. 1986. Effects of increasing salinity on an *Artemia* population from Mono Lake, California. Oecologia **68:**428-436.

Dana, G. L., R. Jellison, and J. M. Melack. 1990. *Artemia monica* egg production and recruitment in Mono Lake, California, USA. Hydrobiologia **197:**233-243.

Dana, G. L., R. Jellison, and J. M. Melack. 1995. Effects of different natural regimes of temperature and food on survival, growth, and development of *Artemia*. J. Plankton Res. **17:**2115-2128.

Dana, G. L., R. Jellison, and J. M. Melack. 1986. Abundance and life history variations of an *Artemia* population in a changing environment (Mono Lake, California). Final Report to LADWP.

Dana, G. L., R. Jellison, J. M. Melack, and G. Starrett. 1993. Relationships between *Artemia monica* life history characteristics and salinity. Hydrobiologia **263:**129-143.

Dana, G. L., R. Jellison, J. Romero, and J. M. Melack. 1992. Mixing and plankton dynamics in Mono Lake, California. 1991 Annual Report to LADWP.

Galat, D. L., E. L. Lider, S. Vigg, and S. R. Robertson. 1981. Limnology of a large, deep, North American terminal lake, Pyramid Lake, Nevada, U.S.A. Hydrobiologia **82:** 281-317.

Golterman, H. L. 1969. [ed.] Methods for chemical analysis of fresh waters. International Biological Program Handbook. No. 8. Blackwell Scientific Publications, Oxford. 166p.

Heath, H. 1924. The external development of certain phyllopods. J. Morphol. **38:**453–83.

Imberger, J. and J.C. Patterson. 1981. A dynamic reservoir simulation model-DYRESM, p. 310-361. *In* H.B. Fischer [ed.], Transport models for inland and coastal waters. Academic.

Jellison, R, S. K. Roll, and J. M. Melack. 2001. Mixing and plankton dynamics in Mono Lake, California. 2000 Annual report to the Los Angeles Department of Water and Power. 100 p.

Jellison, R, S. K. Roll, and J. M. Melack. 2002. Mixing and plankton dynamics in Mono Lake, California. 2001 Annual report to the Los Angeles Department of Water and Power. 99 p.

Jellison, R, S. K. Roll, and J. M. Melack. 2003. Mixing and plankton dynamics in Mono Lake, California. 2002 Annual report to the Los Angeles Department of Water and Power. 117 p.

Jellison, R. 1987. Study and modeling of plankton dynamics in Mono Lake, California. Report to Community and Organization Research Institute, Santa Barbara.

Jellison, R. 1992. Limnology of hypersaline Mono Lake, California during the onset, persistence, and breakdown of meromixis. Ph. D. dissertation. University of California, Santa Barbara. 247 pp.

Jellison, R. 2004. Mixing and plankton dynamics in Mono Lake, California. 2003 Annual report to the Los Angeles Department of Water and Power. 108 p.

Jellison, R. 2005. Mixing and plankton dynamics in Mono Lake, California. 2004 Annual report to the Los Angeles Department of Water and Power. 95 p.

Jellison, R. 2006. Mixing and plankton dynamics in Mono Lake, California. 2005 Annual report to the Los Angeles Department of Water and Power. 103 p.

Jellison, R. and J. M. Melack. 1988. Photosynthetic activity of phytoplankton and its relation to environmental factors in hypersaline Mono Lake, California. Hydrobiologia **158:**69-88.

Jellison, R. and J. M. Melack. 2000. Mixing and plankton dynamics in Mono Lake, California. 1999 Final Report to LADWP. 114p.

Jellison, R. and J. M. Melack. 2001. Nitrogen limitation and particulate elemental ratios of seston in hypersaline Mono lake, California, USA. Hydrobiol. **466**:1-12.

Jellison, R., and J. M. Melack. 1993a. Algal photosynthetic activity and its response to meromixis in hypersaline Mono Lake, California. Limnol. Oceanogr. **38:**818–837.

Jellison, R., and J. M. Melack. 1993b. Meromixis in hypersaline Mono Lake, California I. Vertical mixing and density stratification during the onset, persistence, and breakdown of meromixis. Limnol. Oceanogr. **38:**1008–1019.

Jellison, R., G. L. Dana, and J. M. Melack. 1988. Phytoplankton and brine shrimp dynamics in Mono Lake, California. 1987 Final Report to LADWP.

Jellison, R., G. L. Dana, and J. M. Melack. 1989. Phytoplankton and brine shrimp dynamics in Mono Lake, California. 1988 Final Report to LADWP.

Jellison, R., G. L. Dana, and J. M. Melack. 1990. Phytoplankton and brine shrimp dynamics in Mono Lake, California. 1989 Report to LADWP.

Jellison, R., G. L. Dana, and J. M. Melack. 1992. Ecosystem responses to changes in freshwater inflow to Mono Lake, California, p. 107–118. In C. A. Hall, Jr., V. Doyle-Jones, and B. Widawski [eds.] The history of water: Eastern Sierra

Nevada, Owens Valley, White-Inyo Mountains. White Mountain Research Station Symposium 4. Univ. of Calif., Los Angeles.

Jellison, R., G. L. Dana, and J. M. Melack. 1995b. Zooplankton cohort analysis using systems identification techniques. J. Plankton Res. **17:**2093–2115.

Jellison, R., G. L. Dana, Romero, J., and J. M. Melack. 1991. Phytoplankton and brine shrimp dynamics in Mono Lake, California. 1990 Report to LADWP.

Jellison, R., J. M. Melack, and D. Heil. 1999. Mixing and plankton dynamics in Mono Lake, California. 1998 Final Report to LADWP. 144 p.

Jellison, R., J. Romero, and J. M. Melack. 1998b. The onset of meromixis during restoration of Mono Lake, California: unintended consequences of reducing water diversions. Limnol. Oceanogr. **43:**706–711.

Jellison, R., J. Romero, J. M. Melack, and D. Heil. 1994. Mixing and plankton dynamics in Mono Lake, California. 1992 Annual report to the Los Angeles Department of Water and Power. 184p.

Jellison, R., J. Romero, J. M. Melack, and D. Heil. 1996a. Mixing and plankton dynamics in Mono Lake, California. 1995 Annual report to the Los Angeles Department of Water and Power. 163p.

Jellison, R., J. Romero, J. M. Melack, and D. Heil. 1997. Mixing and plankton dynamics in Mono Lake, California. 1996 Annual report to the Los Angeles Department of Water and Power. 186p.

Jellison, R., J. Romero, J. M. Melack, D. Heil, and G. L. Dana. 1995a. Mixing and plankton dynamics in Mono Lake, California. 1993–94 Annual report to the Los Angeles Department of Water and Power. 248p.

Jellison, R., L. G. Miller, J. M. Melack, and G. L. Dana. 1993. Meromixis in hypersaline Mono Lake, California II. Nitrogen fluxes. Limnol. Oceanogr. **38:**1020–1039.

Jellison, R., R. Anderson, J. M. Melack, and D. Heil. 1996b. Organic matter accumulation in Mono Lake sediments during the past 170 years. Limnol. Oceanogr. **41:**1539–1544.

Jellison, R., Romero, J., J. M. Melack, and D. Heil. 1998a. Mixing and plankton dynamics in Mono Lake, California. 1997 Final Report to LADWP. 147 p.

Lenz, P. H. 1984. Life-history analysis of an *Artemia* population In a changing environment. J. Plankton Res. 6: 967-983.

MacIntyre, S., K. Flynn, R. Jellison, and J. Romero. 1999. Boundary mixing and nutrient fluxes in Mono Lake, California. Limnol. Oceanogr. **44:** 512-529.

MacInytre, S. and R. Jellison. 2001. Nutrient fluxes from upwelling and enhanced turbulence at the top of the pycnocline in Mono Lake, California. Hydrobiologia **466:** 13-29.

Mason, D. T. 1967. Limnology of Mono Lake, California. Univ. Calif. Publ. Zool. 83:1-110.

Melack, J. M. 1985. The ecology of Mono Lake. National Geographic Society Research Reports. 1979 Projects. pp. 461–470.

Melack, J. M. 1983. Large, deep salt lakes: a comparative limnological analysis. Hydrobiologia 105: 223-230.

Melack, J. M., R. Jellison. 1998. Limnological conditions in Mono Lake: Contrasting monomixis and meromixis in the 1990s. Hydrobiologia **384:** 21-39.

Miller, L. G., R. Jellison, R. S. Oremland, and C. W. Culbertson. 1993. Meromixis in hypersaline Mono Lake, California III. Breakdown of stratification and biogeochemical response to overturn. Limnol. Oceanogr. **38:**1040–1051.

Patten, D. T., F. P. Conte, W. E. Cooper, J. Dracup, S. Dreiss, K. Harper, G. L. Hunt, P. Kilham, H. E. Klieforth, J. M. Melack, and S. A. Temple. 1987. The Mono Basin ecosystem: Effects of changing lake level. National Academy Press, Washington, D.C. 272 p.

Romero, J. R., R. Jellison, J. M. Melack. 1998. Stratification, vertical mixing, and upward ammonium flux in hypersaline Mono Lake, California. Archiv fur Hydrobiologia **142:** 283-315.

Romero, J.R. and J.M. Melack. 1996. Sensitivity of vertical mixing to variations in runoff. Limnol. Oceanogr. **41:**955–965.

Romero, J.R., J.C. Patterson, and J. M. Melack. 1996. Simulation of the effect of methane bubble plumes on vertical mixing in Mono Lake. Aquat. Sci. **58:**210–223.

Stephens, D. W., and D. M. Gillespie. 1976. Phytoplankton production in the Great Salt Lake, Utah, and a laboratory study of algal response to enrichment. Limnol. Oceanogr. **21:** 74-87.

Strickland, J. D. and T. R. Parsons. 1972. A practical handbook of seawater analysis. Bull. Fish. Res. Bd. Can. 167p.

Vorster, P. 1985. A Water Balance Forecast Model for Mono Lake, California. Forest Service/USDA Region 5. Monograph No. 10. 350 pp.

Walker, K. F. 1975. The seasonal phytoplankton cycles for two saline lakes in central Washington. Limnol. Oceanogr. **20:** 40-53.

Walker, K. F., W. D. Williams, and U. T. Hammer. 1970. The Miller method for oxygen determination applied to saline lakes. Limnol. Oceanogr. **15:**814-815.

Williams, W. D. 1993. Conservation of salt lakes. Hydrobiologia **267:** 291-306.

Williams, W. D. 2002. Environmental threats to salt lakes and the likely status of inland saline ecosystems in 2025. Environ. Cons. **29**(2):154–167.

Winkler, D.W. 1977. [ed.] An ecological study of Mono Lake, California. Institute of Ecology Publication No. 12. University of California, Davis, California.

Wrege, P.H., D. W. Shuford, D. W. Winkler, and R. Jellison. 2006. Annual variation in numbers of breeding California Gulls at Mono Lake, California: The importance of natal philopatry and local and regional conditions. Condor **108**(1):82-96

Table 1. Temperature (ºC) at Station 6, March – December, 2010.

Depth (m)	3/5*	3/24	4/9	5/13	6/17	7/14	8/17	9/13	10/14	11/30	12/16
1	4.0	6.5	6.8	9.3	15.8	21.3	22.5	17.8	15.2	6.8	5.6
2	3.7	6.1	6.4	9.3	15.5	22.2	22.4	17.7	15.2	6.7	5.7
3	3.6	5.8	5.6	9.1	15.8	22.1	22.3	17.6	15.3	6.6	5.7
4	3.6	5.9	5.2	9.0	16.1	22.0	22.2	17.5	15.4	6.5	5.7
5	3.6	6.0	5.1	8.9	16.1	21.7	22.0	17.5	15.6	6.5	5.8
6	3.4	5.7	5.1	8.9	16.1	21.4	21.6	17.5	15.3	6.5	5.8
7	3.4	5.3	5.0	8.8	16.1	20.8	21.5	17.6	15.3	6.5	5.7
8	3.3	4.7	5.0	8.7	15.6	19.7	21.5	17.2	15.2	6.5	5.7
9	3.0	4.0	4.9	8.7	12.2	17.9	21.2	17.1	15.2	6.5	5.7
10	3.0	3.7	4.8	8.5	10.5	13.0	19.3	16.9	15.1	6.5	5.7
11	3.0	3.4	4.7	8.3	10.3	10.8	16.3	16.9	15.1	6.5	5.7
12	3.1	3.2	4.5	8.0	9.5	9.6	11.9	16.6	15.1	6.5	5.7
13	3.1	3.0	4.3	7.3	9.1	9.0	9.9	16.3	15.0	6.5	5.7
14	2.9	2.8	4.2	7.0	8.9	8.7	9.0	13.3	14.5	6.5	5.8
15	2.6	2.7	4.2	6.3	8.7	8.4	8.6	9.7	13.3	6.5	5.8
16	2.5	2.6	4.0	5.8	8.3	7.9	8.3	8.3	10.6	6.5	5.8
17	2.4	2.6	3.9	5.6	8.0	7.3	8.0	7.8	8.6	6.5	5.8
18	2.4	2.5	3.9	5.0	7.8	6.7	7.5	7.3	7.7	6.5	5.9
19	2.4	2.5	3.8	4.9	7.2	6.6	7.1	7.1	7.4	6.5	5.9
20	2.4	2.4	3.4	4.7	6.5	6.4	6.8	6.9	7.2	6.5	5.9
21	2.4	2.4	3.3	4.6	6.0	6.1	6.6	6.6	7.0	6.5	5.9
22	2.4	2.4	3.2	4.5	5.9	5.8	6.4	6.4	6.7	6.5	5.9
23	2.4	2.4	3.1	4.4	5.7	5.7	6.2	6.3	6.5	6.5	5.9
24	2.4	2.4	3.1	4.2	5.5	5.6	6.1	6.2	6.4	6.5	5.9
25	2.4	2.5	3.0	4.1	5.4	5.5	5.9	6.1	6.2	6.5	5.9
26	2.4	2.5	2.9	4.0	5.1	5.4	5.8	6.0	6.1	6.5	5.9
27	2.4	2.5	2.9	4.0	5.1	5.3	5.8	5.9	6.0	6.5	5.9
28	2.4	2.5	2.9	3.9	5.0	5.2	5.8	5.8	5.9	6.5	5.9
29	2.5	2.5	2.8	3.8	5.0	5.1	5.7	5.8	5.9	6.5	5.9
30	2.5	2.5	2.8	3.8	4.8	5.1	5.5	5.7	5.8	6.5	5.9
31	2.5	2.5	2.7	3.8	4.7	5.1	5.5	5.7	5.8	6.5	5.9
32	2.5	2.5	2.7	3.7	4.6	5.0	5.5	5.6	5.7	6.5	5.9
33	2.5	2.5	2.7	3.6	4.5	4.9	5.4	5.6	5.7	6.5	5.9
34	2.5	2.5	2.6	3.6	4.5	4.8	5.4	5.5	5.7	6.5	5.9
35	2.6	2.6	2.6	3.5	4.4	4.7	-	5.5	5.6	6.4	5.9
36	2.6	2.6	2.6	3.5	4.4	4.7	-	5.5	5.6	6.4	5.9
37	2.6	2.6	2.6	3.5	4.4	4.6	-	5.4	5.5	6.4	5.9
38	2.6	2.6	-	3.5	4.4	4.6	-	5.4	5.5	6.4	5.9

*First survey usually conducted in February was delayed until March 5 due to weather and lake access

Table 2. Conductivity (mS cm^{-1} at 25ºC) at Station 6, March – December, 2010.

Depth (m)	3/5*	3/24	4/9	5/13	6/17	7/14	8/17	9/13	10/14	11/30	12/16
1	81.8	81.4	81.8	81.9	81.4	76.0	74.0	82.2	81.7	82.4	82.3
2	81.9	81.7	81.8	82.0	81.6	74.4	74.2	82.3	82.1	82.4	82.4
3	81.9	81.9	81.7	82.0	82.0	74.6	74.4	82.4	82.2	82.5	82.4
4	81.9	82.0	82.1	82.0	82.0	74.8	74.5	82.4	82.2	82.5	82.4
5	81.8	81.8	82.1	82.0	82.0	75.3	75.0	82.4	82.3	82.5	82.4
6	81.9	81.9	82.1	82.0	82.0	75.8	75.5	82.5	82.4	82.5	82.4
7	81.9	81.7	82.0	82.0	82.0	76.8	75.7	82.5	82.5	82.5	82.4
8	81.9	81.6	82.0	82.0	81.6	78.8	75.9	82.5	82.5	82.5	82.5
9	81.9	81.6	82.1	82.0	81.4	81.7	77.1	82.6	82.6	82.5	82.5
10	82.1	81.9	82.0	82.0	82.2	81.6	81.2	82.6	82.6	82.5	82.5
11	82.0	82.0	82.1	82.0	81.5	82.3	81.1	82.6	82.6	82.5	82.5
12	82.1	82.0	82.0	81.8	81.8	82.2	82.4	82.6	82.6	82.5	82.5
13	82.1	82.2	82.1	81.7	82.1	82.3	82.8	82.6	82.6	82.5	82.5
14	81.9	82.3	82.1	81.5	82.0	82.3	82.5	81.9	82.1	82.5	82.5
15	82.2	82.4	82.1	81.8	82.0	82.1	82.2	81.7	82.1	82.5	82.5
16	82.4	82.4	82.1	81.9	81.8	82.2	82.3	82.1	81.8	82.5	82.5
17	82.5	82.5	82.2	81.8	82.2	82.1	82.1	82.2	81.8	82.5	82.5
18	82.5	82.5	82.2	82.0	82.0	82.3	82.1	82.1	82.1	82.5	82.5
19	82.5	82.4	82.1	82.1	81.2	82.2	82.4	82.2	82.3	82.5	82.5
20	82.5	82.5	82.1	82.1	81.5	82.1	82.2	82.2	82.3	82.5	82.6
21	82.5	82.5	82.3	82.1	82.2	82.1	82.3	82.2	82.2	82.5	82.5
22	82.5	82.5	82.3	82.2	82.1	82.2	82.3	82.2	82.3	82.6	82.5
23	82.5	82.5	82.3	82.1	82.1	82.2	82.2	82.3	82.3	82.6	82.6
24	82.6	82.5	82.4	82.0	82.1	82.3	82.2	82.2	82.3	82.6	82.6
25	82.5	82.5	82.4	82.2	82.0	82.2	82.3	82.2	82.3	82.6	82.6
26	82.6	82.5	82.4	82.2	82.2	82.2	82.3	82.2	82.2	82.6	82.6
27	82.6	82.5	82.4	82.2	82.2	82.2	82.2	82.2	82.2	82.6	82.6
28	82.6	82.5	82.4	82.3	82.3	82.2	82.2	82.2	82.2	82.6	82.6
29	82.6	82.6	82.4	82.3	82.2	82.3	82.2	82.2	82.2	82.6	82.6
30	82.6	82.6	82.4	82.2	82.1	82.3	82.2	82.2	82.2	82.6	82.6
31	82.6	82.6	82.5	82.3	82.2	82.2	82.2	82.2	82.2	82.6	82.6
32	82.6	82.6	82.5	82.3	82.2	82.3	82.2	82.2	82.2	82.6	82.6
33	82.6	82.6	82.5	82.2	82.2	82.2	82.2	82.2	82.3	82.5	82.6
34	82.6	82.6	82.5	82.3	82.2	82.2		82.3	82.2	82.6	82.6
35	82.6	82.6	82.5	82.3	82.3	82.2		82.3	82.2	82.6	82.6
36	82.6	82.6	82.5	82.3	82.3	82.3		82.2	82.2	82.6	82.6
37	82.6	82.6	82.5	82.3	82.3	82.2		82.2	82.2	82.6	82.6
38	82.6	82.6		82.3	82.2	82.3		82.2	82.2	82.6	82.6

*First survey usually conducted in February was delayed until March 5 due to weather and lake access

Table 3. Excess density (kg m^{-3}) at Station 6, March – December, 2010.

Depth (m)	3/5*	3/24	4/9	5/13	6/17	7/14	8/17	9/13	10/14	11/30	12/16
1	71.3	70.4	70.8	70.4	68.2	60.4	57.7	68.5	68.7	71.6	71.6
2	71.4	70.9	70.9	70.6	68.6	58.3	57.9	68.7	69.1	71.5	71.8
3	71.4	71.1	70.9	70.6	68.9	58.6	58.3	68.8	69.3	71.7	71.8
4	71.4	71.2	71.4	70.7	68.8	58.8	58.4	68.9	69.3	71.6	71.7
5	71.3	71.0	71.4	70.7	68.8	59.4	59.0	68.9	69.3	71.7	71.8
6	71.4	71.1	71.4	70.7	68.9	60.1	59.7	69.0	69.6	71.7	71.8
7	71.5	70.9	71.4	70.7	68.9	61.4	59.9	68.9	69.6	71.7	71.8
8	71.5	70.9	71.4	70.7	68.5	64.1	60.2	69.1	69.7	71.7	71.8
9	71.5	71.1	71.5	70.7	69.2	67.9	61.8	69.2	69.8	71.7	71.8
10	71.8	71.4	71.4	70.7	70.5	69.2	67.2	69.3	69.8	71.7	71.8
11	71.6	71.5	71.5	70.8	69.8	70.5	68.5	69.3	69.8	71.7	71.8
12	71.7	71.6	71.4	70.6	70.3	70.7	70.8	69.4	69.8	71.7	71.8
13	71.7	71.9	71.6	70.6	70.8	71.0	71.5	69.5	69.8	71.7	71.8
14	71.6	72.0	71.6	70.5	70.6	71.0	71.3	69.5	69.4	71.7	71.8
15	71.9	72.1	71.6	70.9	70.7	70.8	71.0	70.1	69.7	71.7	71.8
16	72.2	72.2	71.7	71.1	70.5	71.0	71.1	70.9	70.0	71.7	71.8
17	72.3	72.2	71.7	71.0	71.0	71.1	71.1	71.0	70.5	71.7	71.8
18	72.3	72.3	71.8	71.4	70.8	71.4	71.2	71.1	71.0	71.7	71.8
19	72.4	72.2	71.7	71.5	70.0	71.3	71.5	71.2	71.3	71.7	71.8
20	72.4	72.3	71.7	71.5	70.6	71.3	71.3	71.3	71.3	71.7	71.9
21	72.4	72.3	72.0	71.6	71.5	71.3	71.5	71.3	71.3	71.7	71.8
22	72.4	72.3	72.0	71.6	71.3	71.5	71.5	71.4	71.4	71.8	71.8
23	72.4	72.3	72.0	71.6	71.4	71.5	71.4	71.4	71.4	71.8	71.9
24	72.4	72.3	72.1	71.5	71.4	71.6	71.4	71.4	71.5	71.7	71.9
25	72.4	72.3	72.1	71.7	71.3	71.5	71.5	71.4	71.5	71.8	71.9
26	72.4	72.4	72.1	71.8	71.6	71.6	71.5	71.5	71.4	71.8	71.9
27	72.4	72.4	72.1	71.8	71.6	71.5	71.5	71.5	71.4	71.8	71.9
28	72.4	72.4	72.2	71.8	71.7	71.6	71.5	71.5	71.5	71.8	71.9
29	72.4	72.4	72.2	71.8	71.6	71.7	71.5	71.5	71.5	71.8	71.9
30	72.4	72.4	72.1	71.8	71.5	71.6	71.6	71.5	71.5	71.8	71.9
31	72.4	72.4	72.2	71.9	71.6	71.6	71.6	71.5	71.5	71.8	71.9
32	72.4	72.4	72.3	71.9	71.7	71.7	71.6	71.5	71.5	71.8	71.9
33	72.4	72.4	72.3	71.8	71.7	71.6	71.6	71.5	71.5	71.7	71.9
34	72.5	72.4	72.3	71.9	71.7	71.6		71.6	71.5	71.8	71.9
35	72.4	72.4	72.3	71.9	71.8	71.6		71.6	71.5	71.8	71.9
36	72.4	72.5	72.3	71.9	71.7	71.7		71.6	71.5	71.8	71.9
37	72.4	72.4	72.3	71.9	71.8	71.7		71.6	71.5	71.8	71.9
38	72.4	72.4		71.9	71.7	71.7		71.6	71.6	71.8	71.9

*First survey usually conducted in February was delayed until March 5 due to weather and lake access.

Table 4. Temperature, conductivity, and density stratification (kg m^{-3}) at Station 6, March – December, 2010.

Date	Temperature		Conductivity		Density Difference due to		
	2 m	32 m	2 m	32 m	Temperature	Conductivity	Both
3/5	3.7	2.5	81.9	82.6	0.15	0.87	1.02
3/24	6.1	2.5	81.7	82.6	0.54	1.02	1.56
4/9	6.4	2.7	81.8	82.5	0.57	0.83	1.41
5/13	9.3	3.7	82.0	82.3	0.99	0.29	1.28
6/17	15.5	4.6	81.6	82.2	2.43	0.69	3.13
7/14	22.2	5.0	74.4	82.3	4.51	8.88	13.38
8/17	22.4	5.4	74.2	82.2	4.49	9.13	13.62
9/13	17.7	5.6	82.3	82.2	2.93	-0.15	2.78
10/14	15.2	5.7	82.1	82.2	2.17	0.18	2.35
11/30	6.7	6.5	82.4	82.6	0.04	0.19	0.23
12/16	5.7	5.9	82.4	82.6	-0.05	0.18	0.14

Table 5. Secchi Depths (m), March – December 2010.

	Dates										
Station	3/5	3/24	4/9	5/13	6/18	7/14	8/17	9/13	10/14	11/30	12/16
Western Sector											
1	0.80	0.80	0.70	0.55	1.50	7.70	6.20	2.50	0.90	0.85	0.80
2	0.80	0.80	0.70	0.62	1.60	6.80	5.10	2.00	0.80	0.85	0.80
3	0.75	0.80	0.70	0.70	1.40	6.10	5.10	1.75	0.90	0.85	0.80
4	0.80	0.80	0.80	0.60	1.80	6.00	4.60	2.00	0.80	0.85	0.80
5	0.80	0.80	0.80	0.50	2.00	5.90	5.10	1.25	0.80	0.85	0.80
6	0.80	0.80	0.80	0.70	1.80	6.30	5.00	1.75	1.00	0.90	0.75
Avg.	0.79	0.80	0.75	0.61	1.68	6.47	5.18	1.88	0.87	0.86	0.79
S.E.	0.01	0.00	0.02	0.03	0.09	0.28	0.22	0.17	0.03	0.01	0.01
n	6	6	6	6	6	6	6	6	6	6	6
Eastern Sector											
7	0.80	0.80	0.80	0.70	1.40	6.10	4.90	1.25	0.90	0.85	0.85
8	0.80	0.80	0.73	0.80	2.50	6.30	5.00	1.80	0.80	0.85	0.85
9	0.75	0.80	0.70	0.65	2.30	6.40	4.95	2.00	0.80	0.90	0.90
10	0.80	0.85	0.75	0.65	2.20	6.10	5.00	1.40	0.85	0.85	0.80
11	0.80	0.90	0.60	0.65	2.20	6.40	5.60	1.40	0.85	0.85	0.70
12	0.80	0.80	0.80	0.60	2.00	5.90	5.10	1.50	0.90	0.85	0.80
Avg.	0.79	0.83	0.73	0.68	2.10	6.20	5.09	1.56	0.85	0.86	0.82
S.E.	0.01	0.02	0.03	0.03	0.15	0.08	0.11	0.12	0.02	0.01	0.03
n	6	6	6	6	6	6	6	6	6	6	6
Total Lakewide											
Avg.	0.79	0.81	0.74	0.64	1.89	6.33	5.14	1.72	0.86	0.86	0.80
S.E.	0.01	0.01	0.02	0.02	0.11	0.14	0.12	0.11	0.02	0.01	0.01
n	12	12	12	12	12	12	12	12	12	12	12

Table 6: Dissolved Oxygen (mg l^{-1}) at Station 6, March – December, 2010.

Depth (m)	3/5	4/9	5/13	6/17	7/14	8/17	9/13	10/14	11/30*	12/16
1	6.9	6.8	6.3	4.9	2.9	4.2	4.9	5.5	3.2	4.6
2	6.8	7.0	6.5	5.0	2.6	4.1	5.0	5.4	3.3	4.5
3	7.4	6.8	6.2	4.8	2.6	4.1	5.0	5.5	3.3	4.2
4	7.4	6.3	6.3	4.8	2.7	4.1	5.0	5.6	3.1	4.1
5	7.0	5.4	6.3	4.8	2.7	4.2	5.0	5.6	2.9	4.0
6	6.8	5.4	6.2	4.8	2.8	4.2	4.6	5.1	3.1	4.0
7	6.7	5.4	6.2	4.7	3.0	4.2	4.5	4.7	3.1	3.9
8	6.5	5.2	6.3	5.9	3.6	4.2	4.7	4.5	2.8	3.9
9	6.5	5.1	6.2	6.0	4.5	4.8	4.9	4.5	2.8	3.9
10	6.6	5.1	6.2	5.0	6.8	7.3	4.8	4.4	3.0	3.9
11	6.4	4.9	5.9	3.6	6.1	8.2	4.6	4.4	-	3.8
12	6.1	4.8	5.8	3.5	2.3	7.0	4.1	4.3	-	3.8
13	6.0	4.6	5.0	3.3	1.3	3.0	3.0	4.0	-	3.7
14	5.4	4.3	4.5	2.9	0.6	<0.5	2.1	0.9	-	3.7
15	4.7	4.2	4.2	2.8	<0.5	<0.5	<0.5	<0.5	-	3.6
16	4.0	4.2	3.8	2.3	-	<0.5	<0.5	<0.5	-	3.6
17	3.8	4.2	3.3	1.4	-	-	-	-	-	3.5
18	3.6	4.0	3.1	0.6	-	-	-	-	-	3.5
19	3.6	3.7	2.6	<0.5	-	-	-	-	-	3.3
20	3.5	3.1	2.4	<0.5	-	-	-	-	-	3.3
21	3.6	2.7	2.0	-	-	-	-	-	-	3.3
22	3.6	2.6	2.0	-	-	-	-	-	-	3.3
23	3.6	2.5	1.8	-	-	-	-	-	-	3.2
24	3.7	2.4	1.6	-	-	-	-	-	-	3.2
25	3.7	2.1	1.3	-	-	-	-	-	-	3.2
26	3.8	2.1	1.1	-	-	-	-	-	-	3.2
27	3.5	2.0	0.8	-	-	-	-	-	-	3.1
28	3.5	1.9	0.8	-	-	-	-	-	-	3.0
29	3.2	1.8	0.5	-	-	-	-	-	-	3.0
30	3.2	1.8	0.5	-	-	-	-	-	-	2.8
31	3.1	1.6	<0.5	-	-	-	-	-	-	2.3
32	3.1	1.6	<0.5	-	-	-	-	-	-	1.8
33	2.8	1.2	<0.5	-	-	-	-	-	-	1.6
34	2.7	1.2	-	-	-	-	-	-	-	1.6
35	2.6	1.3	-	-	-	-	-	-	-	1.5
36	2.5	1.3	-	-	-	-	-	-	-	1.5
37	2.2	1.1	-	-	-	-	-	-	-	1.4

*Probe failed in field during profile

Table 7. Ammonium (µM) at Station 6, March – December, 2010.

Depth (m)	3/5	4/9	5/13	6/17	7/14	8/17	9/13	10/14	11/30	12/16
1	-	-	-	-	-	-	-	-	-	-
2	0.4	0.4	0.4	0.6	3.2	0.4	0.7	0.7	3.5	0.7
3	-	-	-	-	-	-	-	-	-	-
4	-	-	-	-	-	-	-	-	-	-
5	-	-	-	-	-	-	-	-	-	-
6	-	-	-	-	-	-	-	-	-	-
7	-	-	-	-	-	-	-	-	-	-
8	1.8	0.4	0.6	0.8	0.6	0.6	0.7	0.8	4.1	1.2
9	-	-	-	-	-	-	-	-	-	-
10	-	-	-	-	-	-	-	-	-	-
11	-	-	-	-	-	-	-	-	-	-
12	1.5	0.2	0.5	1.3	0.6	0.5	1.8	1.0	4.2	1.2
13	-	-	-	-	-	-	-	-	-	-
14	-	-	-	-	-	-	-	-	-	-
15	-	-	-	-	-	-	-	-	-	-
16	1.5	5.4	0.6	0.6	2.0	12.9	9.3	16.5	4.2	2.0
17	-	-	-	-	-	-	-	-	-	-
18	-	-	-	-	-	-	-	-	-	-
19	-	-	-	-	-	-	-	-	-	-
20	3.2	0.3	0.7	6.4	24.6	33.1	41.0	48.1	4.3	1.8
21	-	-	-	-	-	-	-	-	-	-
22	-	-	-	-	-	-	-	-	-	-
23	-	-	-	-	-	-	-	-	-	-
24	4.5	0.2	4.6	17.4	32.8	44.5	61.3	81.2	4.3	2.8
25	-	-	-	-	-	-	-	-	-	-
26	-	-	-	-	-	-	-	-	-	-
27	-	-	-	-	-	-	-	-	-	-
28	4.6	11.2	9.2	5.9	29.4	49.7	67.5	79.3	4.5	2.8
29	-	-	-	-	-	-	-	-	-	-
30	-	-	-	-	-	-	-	-	-	-
31	-	-	-	-	-	-	-	-	-	-
32	-	-	-	-	-	-	-	-	-	-
33	-	-	-	-	-	-	-	-	-	-
34	-	-	-	-	-	-	-	-	-	-
35	9.1	14.9	17.9	15.9	44.8	63.9	77.6	92.3	3.7	9.4

Table 8. Ammonium (µM) at 7 stations in upper 9 m of water column, March – December, 2010.

Station	3/5	3/24	4/9	5/13	6/18	7/14	8/17	9/13	10/14	11/30	12/16
1	2.3	0.8	0.5	0.8	1.0	5.3	1.1	2.1	0.6	6.6	1.6
2	2.1	0.6	0.4	0.7	1.8	2.8	0.5	0.7	0.7	6.4	2.0
5	1.3	0.6	0.5	0.8	1.2	2.1	0.7	0.9	0.7	4.5	1.2
6	0.6	0.2	0.4	0.7	1.4	2.5	0.6	0.9	0.7	4.4	2.5
7	1.1	0.4	0.4	0.5	1.1	1.9	0.9	2.1	0.7	2.9	1.7
8	1.2	0.6	0.7	0.7	1.1	1.9	0.8	1.6	0.7	2.4	1.1
11	1.0	0.9	0.5	0.7	0.6	3.0	2.2	0.8	0.6	1.7	1.1
Mean	1.36	0.56	0.51	0.68	1.17	2.79	0.95	1.30	0.67	4.13	1.60
SE	0.23	0.10	0.04	0.04	0.14	0.46	0.22	0.24	0.01	0.72	0.20

Table 9. Chlorophyll *a* (μg l^{-1}) at Station 6, March – December, 2010.

Depth (m)	3/5	4/9	5/13	6/17	7/14	8/17	9/13	10/14	11/30	12/16
1	-	-	-	-	-	-	-	-	-	-
2	64.7	66.0	68.2	8.5	1.9	2.4	9.2	27.6	66.5	74.1
3	-	-	-	-	-	-	-	-	-	-
4	-	-	-	-	-	-	-	-	-	-
5	-	-	-	-	-	-	-	-	-	-
6	-	-	-	-	-	-	-	-	-	-
7	-	-	-	-	-	-	-	-	-	-
8	70.0	64.2	63.5	9.9	3.9	2.2	20.8	35.3	65.1	82.1
9	-	-	-	-	-	-	-	-	-	-
10	-	-	-	-	-	-	-	-	-	-
11	-	-	-	-	-	-	-	-	-	-
12	69.7	71.8	72.3	59.0	24.9	18.9	19.4	32.1	67.7	82.4
13	-	-	-	-	-	-	-	-	-	-
14	-	-	-	-	-	-	-	-	-	-
15	-	-	-	-	-	-	-	-	-	-
16	78.2	71.4	78.1	57.9	64.2	71.8	80.3	48.9	68.3	73.0
17	-	-	-	-	-	-	-	-	-	-
18	-	-	-	-	-	-	-	-	-	-
19	-	-	-	-	-	-	-	-	-	-
20	63.4	73.4	76.9	69.3	80.1	70.1	68.6	66.2	66.3	78.0
21	-	-	-	-	-	-	-	-	-	-
22	-	-	-	-	-	-	-	-	-	-
23	-	-	-	-	-	-	-	-	-	-
24	68.2	68.2	67.0	74.3	82.4	62.8	61.4	61.3	61.5	80.0
25	-	-	-	-	-	-	-	-	-	-
26	-	-	-	-	-	-	-	-	-	-
27	-	-	-	-	-	-	-	-	-	-
28	68.6	58.3	71.4	74.4	75.7	63.2	62.5	60.6	68.7	72.1

Table 10. Chlorophyll *a* ($\mu g\ l^{-1}$) at 7 stations in upper 9 m of water column, March – December 2010.

Station	3/5	3/24	4/9	5/13	6/18	7/14	8/17	9/13	10/14	11/30	12/16
1	74.4	70.0	67.3	68.8	14.8	1.4	3.7	11.1	29.4	66.0	76.4
2	70.6	67.1	69.2	67.6	18.2	2.5	4.8	12.6	31.3	68.1	74.6
5	76.7	71.6	71.8	72.2	17.9	2.4	4.5	18.0	30.6	61.9	81.0
6	72.9	68.1	74.9	65.5	9.5	2.9	4.2	11.5	26.1	64.9	84.9
7	76.2	59.5	61.8	62.1	9.1	3.0	2.5	14.3	27.7	71.6	80.4
8	73.0	71.5	69.6	55.4	12.9	3.2	3.7	15.4	29.9	73.2	78.8
11	73.0	56.9	52.8	57.8	8.9	2.3	1.8	13.9	23.1	64.2	77.5
Mean	73.8	66.4	66.8	64.2	13.0	2.5	3.6	13.8	28.3	67.1	79.1
SE	0.8	2.2	2.8	2.3	1.5	0.2	0.4	0.9	1.1	1.5	1.3

Table 11a. *Artemia* lake and sector means, 2010.

	Instars 1-7	8-11	adult male	adult fem ?	adult fem e	adult fem c	adult fem n	adult fem tot	adult total	total
Lakewide Mean:										
3/5	27,998	0	0	0	0	0	0	0	0	27,998
3/24	34,775	0	0	0	0	0	0	0	0	34,775
4/9	64,588	0	0	0	0	0	0	0	0	64,588
5/13	67,005	4,655	87	0	1,375	0	0	1,375	1,462	73,122
6/18	9,188	2,441	19,477	2,307	17,492	577	80	20,456	39,933	51,563
7/14	3,957	469	24,145	1,167	13,266	7,311	349	22,093	46,237	50,664
8/17	2,760	0	5,929	423	345	4,873	144	5,785	11,714	14,474
9/13	2,161	67	2,886	70	134	1,593	49	1,846	4,732	6,960
10/14	723	49	552	18	59	141	3	221	773	1,544
11/30	223	7	50	0	37	2	3	42	92	322
12/16	280	3	30	0	25	0	0	25	55	339
Western Sector Mean:										
3/5	26,459	0	0	0	0	0	0	0	0	26,459
3/24	13,615	0	0	0	0	0	0	0	0	13,615
4/9	10,704	0	0	0	0	0	0	0	0	10,704
5/13	33,192	1,636	13	0	228	0	0	228	241	35,070
6/18	7,834	1,797	18,860	2,710	15,077	537	134	18,457	37,317	46,948
7/14	5,017	671	29,564	1,207	16,767	7,378	429	25,781	55,345	61,033
8/17	2,803	0	7,726	577	416	5,781	215	6,989	14,715	17,518
9/13	2,998	74	3,478	60	154	1,781	23	2,019	5,496	8,568
10/14	748	54	490	13	44	114	7	178	667	1,469
11/30	17	0	0	0	0	0	3	3	3	20
12/16	134	7	20	0	30	0	0	30	50	191
Eastern Sector Mean:										
3/5	29,537	0	0	0	0	0	0	0	0	29,537
3/24	55,936	0	0	0	0	0	0	0	0	55,936
4/9	118,471	0	0	0	0	0	0	0	0	118,471
5/13	100,818	7,673	161	0	2,522	0	0	2,522	2,683	111,174
6/18	10,543	3,085	20,094	1,905	19,906	617	27	22,455	42,549	56,177
7/14	2,897	268	18,726	1,127	9,765	7,243	268	18,404	37,129	40,295
8/17	2,716	0	4131	268	275	3,964	74	4,581	8,712	11,429
9/13	1,325	60	2294	80	114	1,405	74	1,673	3,967	5,352
10/14	698	44	614	23	74	168	0	265	879	1,620
11/30	429	13	101	0	74	3	3	80	181	624
12/16	426	0	40	0	20	0	0	20	60	486

(?): undifferentiated egg mass (e): empty ovisac (c): cysts (n): nauplii

Table 11b. Standard errors of *Artemia* sector means (Table 11a), 2010.

	Instars 1-7	8-11	adult male	adult fem ?	adult fem e	adult fem c	adult fem n	adult fem tot	adult total	total
SE of Lakewide Mean:										
3/5	5,706	0	0	0	0	0	0	0	0	5,706
3/24	9,526	0	0	0	0	0	0	0	0	9,526
4/9	25,095	0	0	0	0	0	0	0	0	25,095
5/13	17,991	2,249	57	0	623	0	0	623	628	20,757
6/18	1,301	408	1,827	311	2,235	124	37	2,512	4,261	5,320
7/14	825	202	3,739	139	2,245	554	74	2,491	6,019	6,873
8/17	407	0	851	98	88	762	45	894	1,681	1,703
9/13	376	11	657	16	53	443	20	503	1,137	1,402
10/14	74	13	58	5	16	25	2	39	79	144
11/30	91	4	24	0	16	2	2	17	41	133
12/16	70	3	7	0	11	0	0	11	14	74
SE of Western Sector Mean:										
3/5	8,061	0	0	0	0	0	0	0	0	8,061
3/24	4,745	0	0	0	0	0	0	0	0	4,745
4/9	4,045	0	0	0	0	0	0	0	0	4,045
5/13	10,700	621	13	0	212	0	0	212	210	11,477
6/18	665	222	2,894	437	3,052	245	65	3,651	6,523	6,696
7/14	1,500	391	6,969	255	4,057	858	107	4,554	11,083	12,723
8/17	621	0	1,236	150	162	1,351	77	1,540	2,685	2,604
9/13	499	19	1,254	25	99	856	13	968	2,199	2,564
10/14	122	22	104	7	14	28	4	38	138	247
11/30	13	0	0	0	0	0	3	3	3	16
12/16	33	7	10	0	19	0	0	19	24	46
SE of Eastern Sector Mean:										
3/5	8,793	0	0	0	0	0	0	0	0	8,793
3/24	14,060	0	0	0	0	0	0	0	0	14,060
4/9	39,916	0	0	0	0	0	0	0	0	39,916
5/13	29,195	4,268	110	0	1,066	0	0	1,066	1,047	34,423
6/18	2,505	720	2,481	412	3,215	87	27	3,581	5,881	8,438
7/14	545	99	1,098	138	905	783	99	1,059	1,839	1,728
8/17	586	0	607	99	75	630	30	753	1,275	1,508
9/13	305	14	435	21	49	344	37	405	786	1,023
10/14	94	16	52	6	28	41	0	68	66	167
11/30	140	7	40	0	25	3	3	26	65	202
12/16	109	0	7	0	10	0	0	10	16	116

(?): undifferentiated egg mass (e): empty ovisac (c): cysts (n): nauplii

Table 11c. Percentage in different classes for *Artemia* sector means (Table 11a), 2010.

	Instars 1-7	8-11	adult male	adult fem ?	adult fem e	adult fem c	adult fem n	adult fem tot	adult total	total
Lakewide (%):										
3/5	100.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100
3/24	100.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100
4/9	100.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100
5/13	91.6	6.4	0.1	0.0	100.0	0.0	0.0	1.9	2.0	100
6/18	17.8	4.7	37.8	77.8	85.5	19.5	2.7	39.7	77.4	100
7/14	7.8	0.9	47.7	13.2	60.0	82.8	4.0	43.6	91.3	100
8/17	19.1	0.0	41.0	7.8	6.0	89.6	2.7	40.0	80.9	100
9/13	31.1	1.0	41.5	4.1	7.3	93.0	2.8	26.5	68.0	100
10/14	46.8	3.1	35.7	11.3	26.5	86.6	2.1	14.3	50.1	100
11/30	69.3	2.1	15.6	0.0	88.0	33.3	66.7	13.0	28.6	100
12/16	82.7	1.0	8.9	0.0	100.0	0.0	0.0	7.4	16.3	100
Western Sector (%):										
3/5	100.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100
3/24	100.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100
4/9	100.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100
5/13	94.6	4.7	0.0	0.0	100.0	0.0	0.0	0.7	0.7	100
6/18	16.7	3.8	40.2	80.2	81.7	15.9	4.0	39.3	79.5	100
7/14	8.2	1.1	48.4	13.4	65.0	81.8	4.8	42.2	90.7	100
8/17	16.0	0.0	44.1	8.8	6.0	88.0	3.3	39.9	84.0	100
9/13	35.0	0.9	40.6	3.2	7.6	95.5	1.3	23.6	64.1	100
10/14	50.9	3.7	33.3	10.0	24.5	85.0	5.0	12.1	45.4	100
11/30	83.3	0.0	0.0	0.0	0.0	0.0	100.0	16.7	16.7	100
12/16	70.2	3.5	10.5	0.0	100.0	0.0	0.0	15.8	26.3	100
Eastern Sector (%):										
3/5	100.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100
3/24	100.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100
4/9	100.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100
5/13	90.7	6.9	0.1	0.0	100.0	0.0	0.0	2.3	2.4	100
6/18	18.8	5.5	35.8	74.7	88.6	24.2	1.1	40.0	75.7	100
7/14	7.2	0.7	46.5	13.0	53.1	83.9	3.1	45.7	92.1	100
8/17	23.8	0.0	36.2	6.2	6.0	92.1	1.7	40.1	76.2	100
9/13	24.7	1.1	42.9	5.2	6.8	90.1	4.7	31.3	74.1	100
10/14	43.1	2.7	37.9	12.3	27.8	87.7	0.0	16.4	54.2	100
11/30	68.8	2.2	16.1	0.0	91.7	50.0	50.0	12.9	29.0	100
12/16	87.6	0.0	8.3	0.0	100.0	0.0	0.0	4.1	12.4	100

(?): undifferentiated egg mass (e): empty ovisac(c): cysts (n): nauplii
“Fem ?”, “fem n”, and “fem c”, given as percentage of ovigerous females.
“Fem e” given as percentage of adult females.
“Instars 1-7”, “Instars 8-11”, “adult male”, “adult fem tot”, “adult total” given as percentage of total shrimp.

Table 12. Lakewide *Artemia* instar analysis, 2010.

	Instars									
	1	2	3	4	5	6	7	8-11	adults	total
Mean:										
3/5	33,757	972	92	0	0	0	0	0	0	34,820
3/24	18,310	12,417	719	11	0	0	0	0	0	31,457
4/9	7,014	14,849	5,404	512	57	0	0	0	0	27,836
5/13	16,746	10,135	9,922	11,653	11,957	10,698	6,214	6,462	1,667	85,456
6/18	2,139	1,288	805	1,978	943	851	644	1,817	37,666	48,129
7/14	3,081	1,288	46	184	92	0	23	621	51,348	56,683
8/17	667	1,690	310	57	0	0	0	0	10,911	13,636
9/13	190	664	437	354	124	69	23	52	2,932	4,843
10/14	66	118	132	184	80	55	32	34	742	1,443
11/30	37	26	17	14	14	3	3	6	66	187
12/16	98	26	6	6	23	6	3	6	46	218
Standard error of the mean:										
3/5	8,510	247	48	0	0	0	0	0	0	8,737
3/24	6,774	4,953	338	11	0	0	0	0	0	11,947
4/9	2,524	6,302	2,122	161	46	0	0	0	0	10,627
5/13	10,294	3,696	2,042	3,853	4,034	4,452	3,196	3,792	1,038	35,075
6/18	515	476	279	464	303	411	122	235	5,971	7,751
7/14	1,058	222	46	184	92	0	23	334	10,065	11,469
8/17	116	436	112	23	0	0	0	0	1,707	1,783
9/13	27	209	169	92	19	9	11	11	496	688
10/14	15	22	20	35	30	13	16	16	129	228
11/30	18	23	14	8	11	3	3	6	56	135
12/16	31	10	4	6	8	4	3	6	20	46
Percentage in different age classes:										
3/5	96.9	2.8	0.3	0.0	0.0	0.0	0.0	0.0	0.0	100
3/24	58.2	39.5	2.3	0.0	0.0	0.0	0.0	0.0	0.0	100
4/9	25.2	53.3	19.4	1.8	0.2	0.0	0.0	0.0	0.0	100
5/13	19.6	11.9	11.6	13.6	14.0	12.5	7.3	7.6	2.0	100
6/18	4.4	2.7	1.7	4.1	2.0	1.8	1.3	3.8	78.3	100
7/14	5.4	2.3	0.1	0.3	0.2	0.0	0.0	1.1	90.6	100
8/17	4.9	12.4	2.3	0.4	0.0	0.0	0.0	0.0	80.0	100
9/13	3.9	13.7	9.0	7.3	2.6	1.4	0.5	1.1	60.5	100
10/14	4.6	8.2	9.2	12.7	5.6	3.8	2.2	2.4	51.4	100
11/30	20.0	13.8	9.2	7.7	7.7	1.5	1.5	3.1	35.4	100
12/16	44.7	11.8	2.6	2.6	10.5	2.6	1.3	2.6	21.1	100

All data in this table are from stations 1, 2, 5, 6, 7, 8, and 11 only.

Table 13a. *Artemia* reproductive summary, lake and sector means, 2010.

	Adult Females					
	Total	Ovigery	e	?	c	n
Lakewide Mean:						
3/5	0	0	0	0	0	0
3/24	0	0	0	0	0	0
4/9	0	0	0	0	0	0
5/13	1,375	0	1,375	0	0	0
6/18	20,456	2,965	17,492	2,307	577	80
7/14	22,093	8,826	13,266	1,167	7,311	349
8/17	5,785	5,439	345	423	4,873	144
9/13	1,846	1,712	134	70	1,593	49
10/14	221	163	59	18	141	3
11/30	42	5	37	0	2	3
12/16	25	0	25	0	0	0
Western Sector Mean:						
3/5	0	0	0	0	0	0
3/24	0	0	0	0	0	0
4/9	0	0	0	0	0	0
5/13	228	0	228	0	0	0
6/18	18,457	3,380	15,077	2,710	537	134
7/14	25,781	9,014	16,767	1,207	7,378	429
8/17	6,989	6,573	416	577	5,781	215
9/13	2,019	1,865	154	60	1,781	23
10/14	178	134	44	13	114	7
11/30	3	3	0	0	0	3
12/16	30	0	30	0	0	0
Eastern Sector Mean:						
3/5	0	0	0	0	0	0
3/24	0	0	0	0	0	0
4/9	0	0	0	0	0	0
5/13	2,522	0	2,522	0	0	0
6/18	22,455	2,549	19,906	1,905	617	27
7/14	18,404	8,639	9,765	1,127	7,244	268
8/17	4,581	4,306	275	268	3,964	74
9/13	1,673	1,559	114	80	1,405	74
10/14	265	191	74	23	168	0
11/30	80	7	74	0	3	3
12/16	20	0	20	0	0	0

(?): undifferentiated egg mass (e): empty ovisac (c): cysts (n): nauplii

Table 13b. Standard errors of *Artemia* reproductive summary (Table 13a), 2010.

	Adult Females					
	Total	Ovigery	e	?	c	n
Standard Error of Lakewide Mean:						
3/5	0	0	0	0	0	0
3/24	0	0	0	0	0	0
4/9	0	0	0	0	0	0
5/13	623	0	623	0	0	0
6/18	2,512	387	2,235	311	124	37
7/14	2,491	607	2,245	139	554	74
8/17	894	857	88	98	762	45
9/13	503	454	53	16	443	20
10/14	39	25	16	5	25	2
11/30	17	3	16	0	2	2
12/16	11	0	11	0	0	0
Standard Error of Western Sector Mean:						
3/5	0	0	0	0	0	0
3/24	0	0	0	0	0	0
4/9	0	0	0	0	0	0
5/13	212	0	212	0	0	0
6/18	3,651	648	3,052	437	245	65
7/14	4,554	929	4,057	255	858	107
8/17	1,540	1,487	162	150	1,351	77
9/13	968	871	99	25	856	13
10/14	38	28	14	7	28	4
11/30	3	3	0	0	0	3
12/16	19	0	19	0	0	0
Standard Error of Eastern Sector Mean:						
3/5	0	0	0	0	0	0
3/24	0	0	0	0	0	0
4/9	0	0	0	0	0	0
5/13	1,066	0	1,066	0	0	0
6/18	3,581	412	3,216	412	87	27
7/14	1,059	862	905	138	783	99
8/17	753	711	75	99	630	30
9/13	405	374	49	21	344	37
10/14	68	41	28	6	41	0
11/30	26	4	25	0	3	3
12/16	10	0	10	0	0	0

(?): undifferentiated egg mass (e): empty ovisac (c): cysts (n): nauplii

Table 13c. *Artemia* percentages in different reproductive categories (Table 13a), 2010.

	Adult Females					
	Total	Ovigery	e	?	c	n
Lakewide Mean (%):						
3/5	–	–	–	–	–	–
3/24	–	–	–	–	–	–
4/9	–	–	–	–	–	–
5/13	100.0	0.0	100.0	–	–	–
6/18	100.0	14.5	85.5	77.8	87.8	12.2
7/14	100.0	40.0	60.0	13.2	95.4	4.6
8/17	100.0	94.0	6.0	7.8	97.1	2.9
9/13	100.0	92.7	7.3	4.1	97.0	3.0
10/14	100.0	73.5	26.5	11.3	97.7	2.3
11/30	100.0	12.0	88.0	0.0	33.3	66.7
12/16	100.0	0.0	100.0	–	–	–
Western Sector Mean (%):						
3/5	–	–	–	–	–	–
3/24	–	–	–	–	–	–
4/9	–	–	–	–	–	–
5/13	100.0	0.0	100.0	–	–	–
6/18	100.0	18.3	81.7	80.2	80.0	20.0
7/14	100.0	35.0	65.0	13.4	94.5	5.5
8/17	100.0	94.1	6.0	8.8	96.4	3.6
9/13	100.0	92.4	7.6	3.2	98.7	1.3
10/14	100.0	75.5	24.5	10.0	94.4	5.6
11/30	100.0	100.0	0.0	0.0	0.0	100.0
12/16	100.0	0.0	100.0	–	–	–
Eastern Sector Mean (%):						
3/5	–	–	–	–	–	–
3/24	–	–	–	–	–	–
4/9	–	–	–	–	–	–
5/13	100.0	0.0	100.0	–	–	–
6/18	100.0	11.4	88.7	74.7	95.8	4.2
7/14	100.0	46.9	53.1	13.0	96.4	3.6
8/17	100.0	94.0	6.0	6.2	98.2	1.8
9/13	100.0	93.2	6.8	5.2	95.0	5.0
10/14	100.0	72.2	27.8	12.3	100.0	0.0
11/30	100.0	8.3	91.7	0.0	50.0	50.0
12/16	100.0	0.0	100.0	–	–	–

(?): undifferentiated egg mass (e): empty ovisac (c): cysts (n): nauplii

Total, ovigery, and e given as percentages of total number of females.

? given as percentage of ovigerous females.

Cyst and naup given as percentages of individuals with differentiated egg masses.

Table 14. *Artemia* fecundity summary, 2010.

	#eggs/brood				female length		
	mean	SE	%cyst	%intended	mean	SE	n
Lakewide Mean:							
6/18	33.3	1.6	0.9	0.3	10.1	0.2	7
7/14	24.0	1.1	1.0	0.5	9.8	0.1	7
8/17	32.3	1.5	1.0	0.5	9.8	0.1	7
9/13	73.4	3.6	0.9	0.3	11.2	0.1	7
10/14	59.2	5.2	0.9	0.4	10.9	0.2	7
Western Sector Mean:							
6/18	34.4	2.8	0.9	0.3	10.2	0.3	4
7/14	24.7	1.2	1.0	0.6	10.0	0.1	4
8/17	31.9	2.7	1.0	0.5	9.7	0.1	4
9/13	73.8	4.2	1.0	0.4	11.2	0.2	4
10/14	61.6	9.4	1.0	0.4	10.8	0.3	4
Eastern Sector Mean:							
6/18	31.7	0.9	0.9	0.4	10.0	0.1	3
7/14	23.0	2.1	1.0	0.5	9.7	0.1	3
8/17	32.9	0.4	1.0	0.6	9.8	0.3	3
9/13	72.9	7.5	0.9	0.3	11.1	0.2	3
10/14	56.0	2.0	0.8	0.3	10.9	0.4	3

‘n’ in last column refers to number of stations averaged.
Ten females were collected and measured from each station.

Table 15. Summary Statistics of Adult *Artemia* Abundance from 1 May through 30 November, 1979–2010.

Year	**Mean**	**Median**	**Peak**	**Centroid**[*]
1979	14,118	12,286	31,700	216
1980	14,643	10,202	40,420	236
1981	32,010	21,103	101,670	238
1982	36,643	31,457	105,245	252
1983	17,812	16,314	39,917	247
1984	17,001	19,261	40,204	212
1985	18,514	20,231	33,089	218
1986	14,667	17,305	32,977	190
1987	23,952	22,621	54,278	226
1988	27,639	25,505	71,630	207
1989	36,359	28,962	92,491	249
1990	20,005	16,775	34,930	230
1991	18,129	19,319	34,565	226
1992	19,019	19,595	34,648	215
1993	15,025	16,684	26,906	217
1994	16,602	18,816	29,408	212
1995	15,584	17,215	24,402	210
1996	17,734	17,842	34,616	216
1997	14,389	16,372	27,312	204
1998	19,429	21,235	33,968	226
1999	20,221	21,547	38,439	225
2000	10,550	9,080	22,384	210
2001	20,031	20,037	38,035	209
2002	11,569	9,955	25,533	200
2003	13,778	12,313	29,142	203
2004	32,044	36,909	75,466	180
2005	17,888	15,824	45,419	192
2006	21,518	20,316	55,748	186
2007	18,826	17,652	41,751	186
2008	11,823	12,524	27,606	189
2009	25,970	17,919	72,086	181
2010	14,921	7,447	46,237	191
Mean	**19,638**	**18,457**	**45,032**	**213**
Min	10,550	7,447	22,384	180
Max	36,643	36,909	105,245	252

*Centroid calculated as the abundance-weighted mean day of occurrence.

Table 16. Photosynthetic parameters during 2010.

Date	**Depth** (m)	**Temperature** (C)	**α^B** ($g\ C\ g\ Chl\ a^{-1}\ h^{-1}$)	**P_m^B** ($g\ C\ g\ Chl\ a^{-1}\ Einst^{-1}\ m^2$)
3/5	2	3.8	14.0	1.0
4/9	2	6.4	17.7	1.3
5/13	2	9.2	18.7	1.5
6/17	2	16.2	24.9	3.1
7/14	2	21.5	31.5	12.9
8/17	2	21.5	15.9	3.3
9/13	2	17.5	21.8	3.5
10/14	2	14	8.5	1.1
11/30	2	6	21.9	1.3
12/16	2	5.3	24.1	1.4

P_m^B: Chlorophyll-specific maximum carbon uptakes rates ($g\ C\ g\ Chl\ a^{-1}\ h^{-1}$)

α^B: Chlorophyll-specific light-limited uptake rates ($g\ C\ g\ Chl\ a^{-1}\ Einst^{-1}\ m^2$)

Table 17. Long term Integrative Measures of Productivity: Annual Primary Production, *Artemia* biomass and egg production (see Chapter 2 for methods), 1982–2010.

Year	**Planktonic Primary Production*** (g C m^{-2} y^{-1})	***Artemia*** **Biomass** (g dry weight m^{-2})	***Artemia*** **Naupliar Production** (10^6 m^{-2})	***Artemia*** **Cyst Production** (10^6 m^{-2})
1982	1,107	-	-	-
1983	523	9.3	0.15	4.8
1984	269	7.8	0.08	3.7
1985	399	7.8	0.22	4.6
1986	462	7.7	0.44	3.0
1987	371	12.5	0.23	6.4
1988	1,064	15.2	0.21	4.7
1989	499	17.6	0.11	6.7
1990	641	11.0	1.02	6.1
1991	418	9.7	0.69	5.5
1992	435	10.2	0.26	5.8
1993	602	8.9	0.35	6.3
1994	446	8.7	0.16	5.6
1995	227	8.4	0.40	4.9
1996	221	8.2	0.05	3.6
1997	149	5.3	0.01	2.5
1998	228	8.0	0.01	2.8
1999	297	8.9	0.03	4.2
2000	484	8.2	0.08	4.0
2001	532	8.8	0.10	3.0
2002	763	4.9	0.10	2.5
2003	1,645	7.5	0.60	4.2
2004	864	11.0	0.04	2.6
2005	1,111	8.8	0.31	3.8
2006	1,075	6.8	0.32	4.8
2007	1,766	7.0	0.29	3.4
2008	1,189	5.7	0.34	3.1
2009	—	8.8	0.15	2.9
2010	1,474	5.1	0.10	2.2
Mean	**713**	**8.8**	**0.24**	**4.2**

*Carbon uptake measurements not conducted during 1982, 1993-2001. Estimates in these years are based on temperature, chlorophyll, light, and regressions of photosynthetic rates (P_m^B) and (α^B) versus temperature (see methods). 2009 estimate under review.

FIGURE CAPTIONS

Fig. 1. UCSB sampling stations at Mono Lake. Solid circles represent permanently moored buoys.

Fig. 2. Wind speed; daily mean and 10-min. maximum, 2010.

Fig. 3. Daily air temperature; mean, maximum, and minimum, 2010.

Fig. 4. Daily photosynthetically available radiation, 2010.

Fig. 5. Mean daily relative humidity, 2010.

Fig. 6. Daily precipitation, 2010.

Fig. 7. Mono Lake surface elevation (ft asl), 1979–2010, USGS datum.

Fig. 8. Temperature (°C) at station 6, 2010.

Fig. 9. Conductivity (mS cm^{-1} corrected to 25°C) at station 6, 2010.

Fig. 10. Density difference (kg m^{-3}) between 2 and 32 m at station 6 due to temperature and chemical stratification from 1991–2010.

Fig. 11. Transparency as measured by mean lakewide Secchi depth (m), 1994–2010. Error bars show standard errors of the lakewide estimate based on 12-20 stations.

Fig. 12. Mean lakewide Secchi depth (log$_{10}$ m) 1979–2010.

Fig. 13. Light attenuation (% of surface) at station 6, 2010.

Fig. 14. Dissolved oxygen (mg O_2 l^{-1}) at station 6, 2010. Dots denote the dates and depths of samples.

Fig. 15. Ammonium (µM) at station 6, 2010. Dots denote the dates and depths of samples.

Fig. 16. Ammonium (µM) in upper 9 m of the water column at 7 stations, 2010.

Fig. 17. Chlorophyll *a* (µg chl *a* l^{-1}) at station 6, 2010. Dots denote the dates and depths of samples.

Fig. 18. Chlorophyll *a* (µg chl *a* l^{-1}) in upper 9 m of the water column at 7 stations, 2010.

Fig. 19. Lakewide *Artemia* abundance during 2010: nauplii (instars 1-7), juveniles (instars 8-11), and adults (instars 12+).

Fig. 20. Lakewide estimates of adult *Artemia* based on 3-20 stations, 1982–2010 (see Methods). The mean relative error of the lakewide estimates is 20-25%.

Fig. 21. Reproductive characteristics of *Artemia* during 2010: lakewide mean abundance of total females and ovigerous females (top), percent of females ovoviviparous and ovigerous (middle), and brood size (bottom). Vertical lines are the standard error of the estimate.

Fig. 22. Summary statistics of the seasonal (1 May through 30 November) lakewide abundance of adult *Artemia*, 1979–2010. Values are based on interpolated daily abundances.

Fig. 23. Temporal center of abundance-weighted centroid of the seasonal (1 May through 30 November) distribution of adult *Artemia*, 1979–2010. Centroid is based on interpolated daily abundances of adult *Artemia*.

Fig. 24. Chlorophyll-specific uptake rates during March, August, and December 2010 for samples collected from the surface mixed layer and the deep chlorophyll maximum.

Fig. 25. Chlorophyll-specific light saturated carbon uptake rate (g C g Chl^{-1} h^{1}), algal biomass (mg m^{-3}), and daily primary production (g C m^{-2}), 2010.

Fig. 26. Comparison of 2002–2010 photosynthetic rates and algal biomass. A) Chlorophyll-specific specific light saturated carbon uptake rate (g C g Chl^{-1} h^{1}) B) Mixed-layer (2 m depth) chlorophyll *a* concentrations µg Chl l^{-1}.

Fig. 27. Comparison of 2002–2010 daily primary production (g C m^{-2} y^{-1}) calculated with a numerical interpolative model of chlorophyll, temperature, insolation, attenuation, and photosynthetic parameters.

Fig. 28. Annual phytoplankton production estimates (g C m^{-2}), 1982–2010. Photosynthetic parameters used in the 2009 estimate are under review and will like be revised.

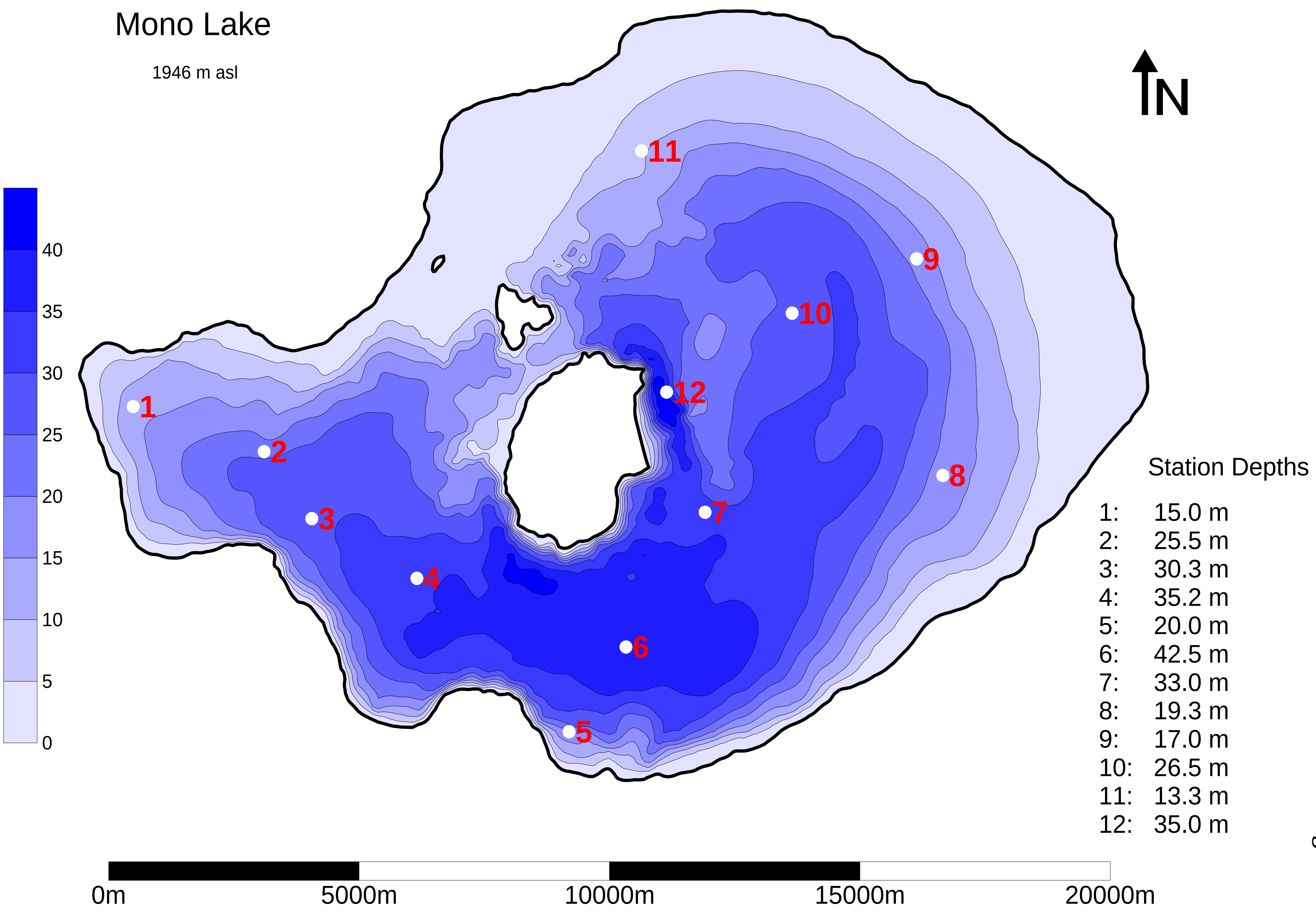
Fig. 29. Mean annual *Artemia* biomass, 1983–10. Data for the period 1982–99 estimated from instar-specific population data and previously derived weight-length relationships. In 2000–2010, *Artemia* biomass was measured directly by determining dry weights of plankton tows.

Fig. 30. Annual *Artemia* reproduction, ovoviviparous (live-bearing) and oviparous (cyst-bearing), 1983–2010.

Fig. 31. Lakewide mean of mixolimnetic (<10 m) chlorophyll *a*, 1982–2010. Heavy line shows seasonally filtered data formed by linearly interpolating between sampling dates to daily values and then calculating a 365-day running mean.

Fig. 32. Long-term trend of increasing mean annual mixolimnetic (<10 m) chlorophyll *a*, 1983–2010. Annual values are means of 365 daily values derived by linearly interpolating between sampling dates.

Fig. 33. Lakewide mean of adult *Artemia* abundance, 1982–2010. Heavy line shows seasonally filtered data formed by linearly interpolating between sampling dates to daily values and then calculating a 365-day running mean.



Station Depths

1: 15.0 m
2: 25.5 m
3: 30.3 m
4: 35.2 m
5: 20.0 m
6: 42.5 m
7: 33.0 m
8: 19.3 m
9: 17.0 m
10: 26.5 m
11: 13.3 m
12: 35.0 m

Figure 1

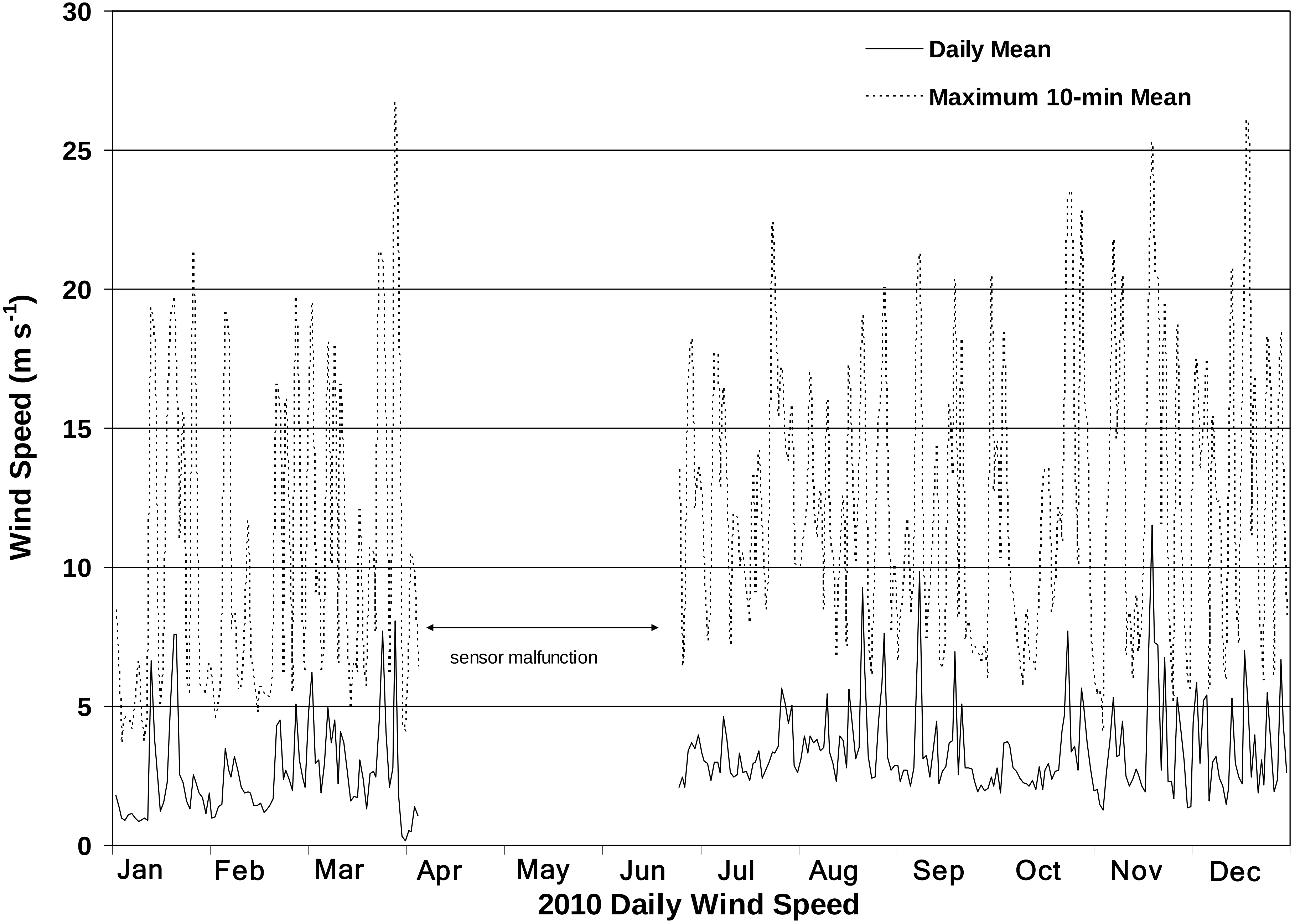
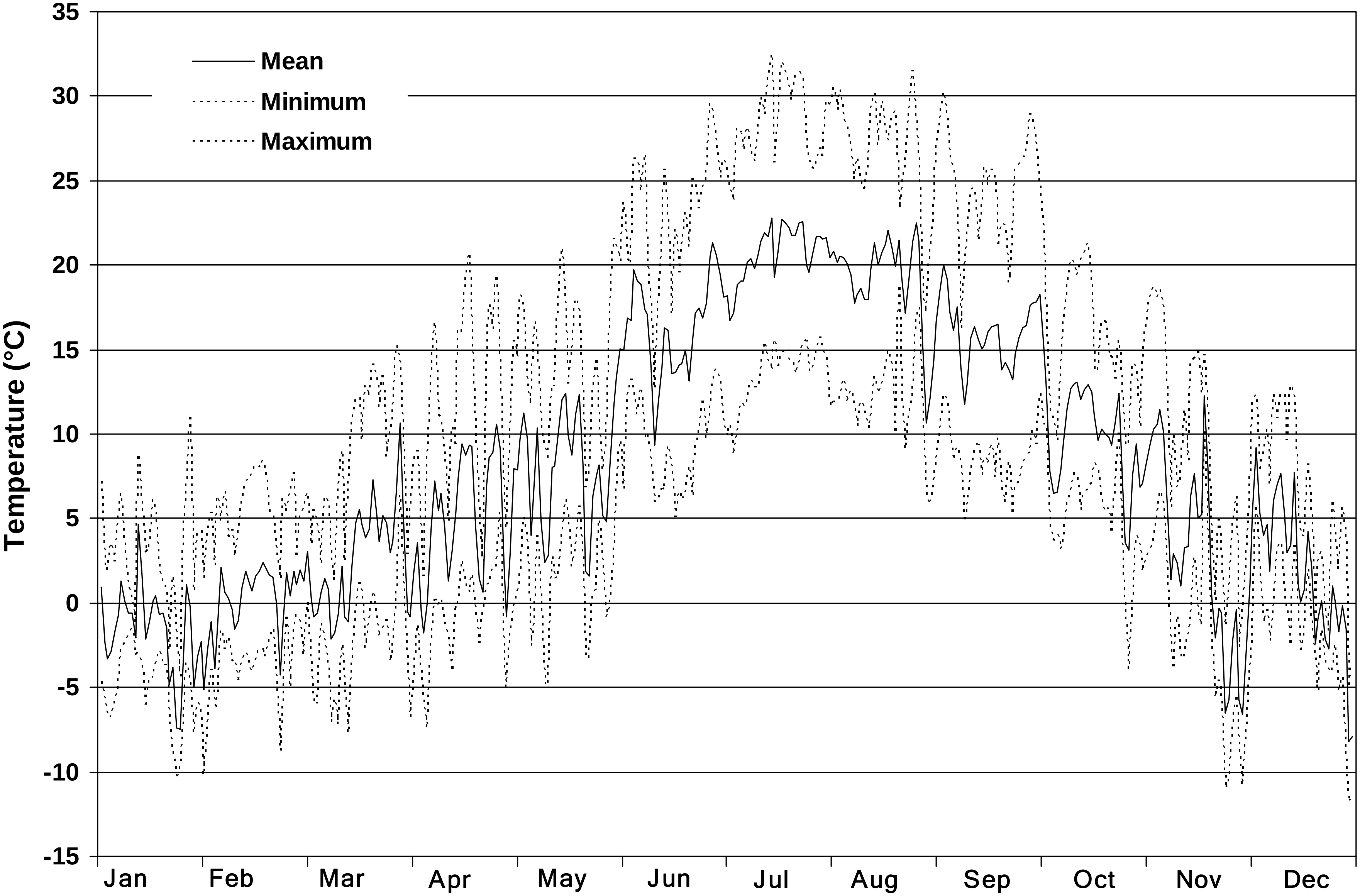

Daily Mean
Maximum 10-min Mean
sensor malfunction
Wind Speed (m s-1)
30
25
20
15
10
5
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
2010 Daily Wind Speed

Figure 2



2010 Daily Air Temperature

Figure 3

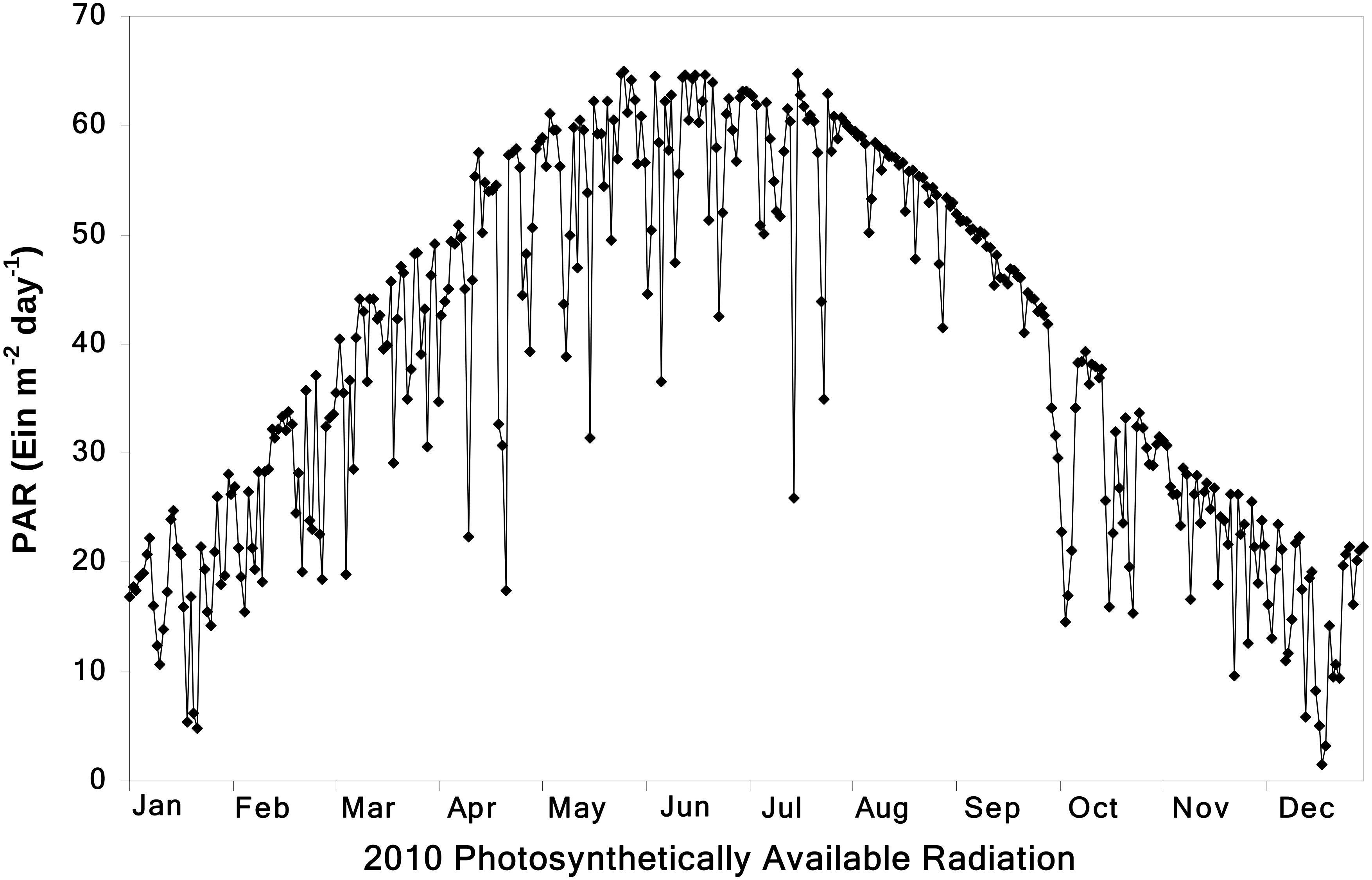

PAR (Ein m^{-2} day^{-1})
70
60
50
40
30
20
10
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
2010 Photosynthetically Available Radiation

Figure 4

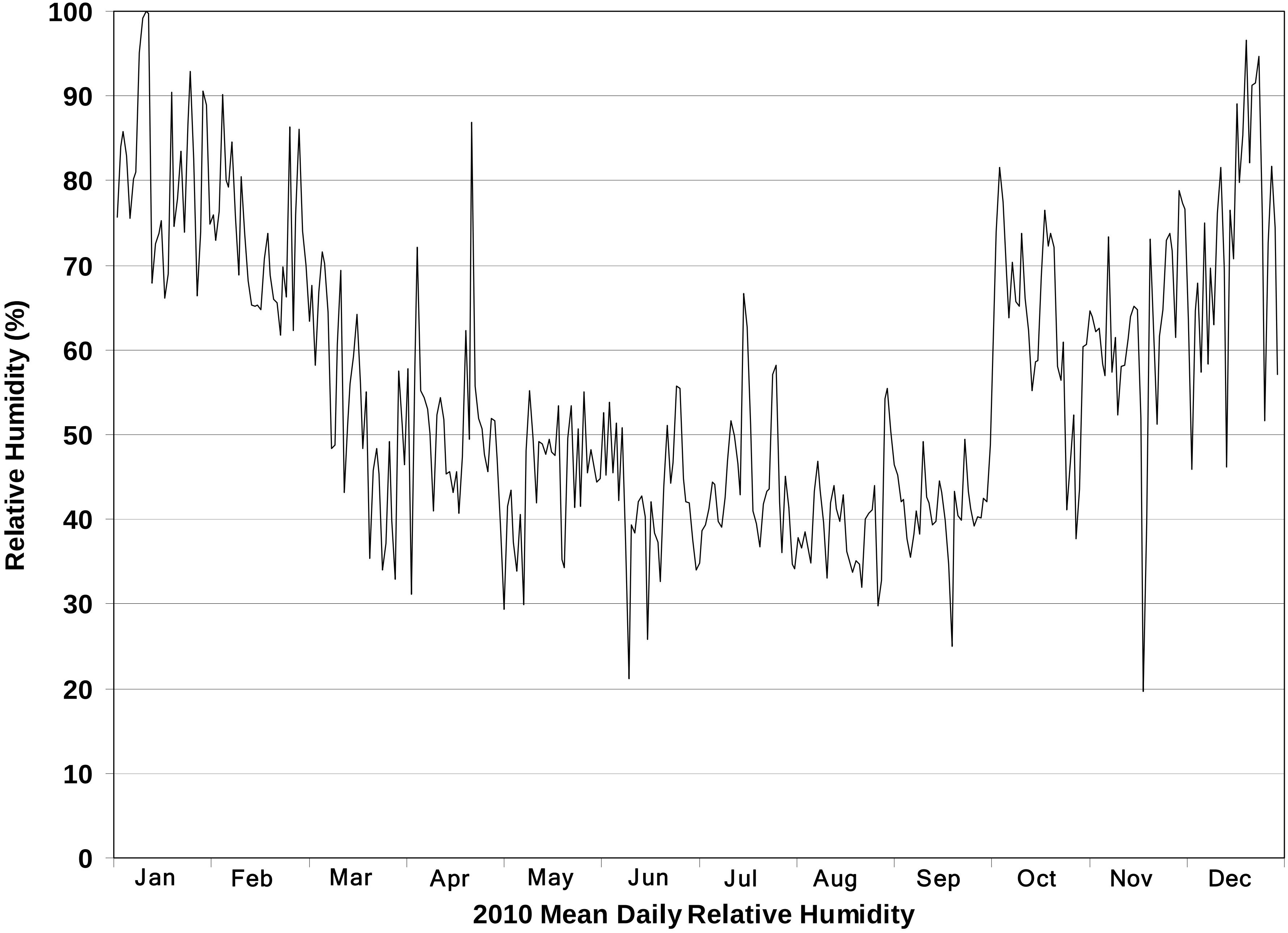

Relative Humidity (%)
100
90
80
70
60
50
40
30
20
10
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
2010 Mean Daily Relative Humidity

Figure 5

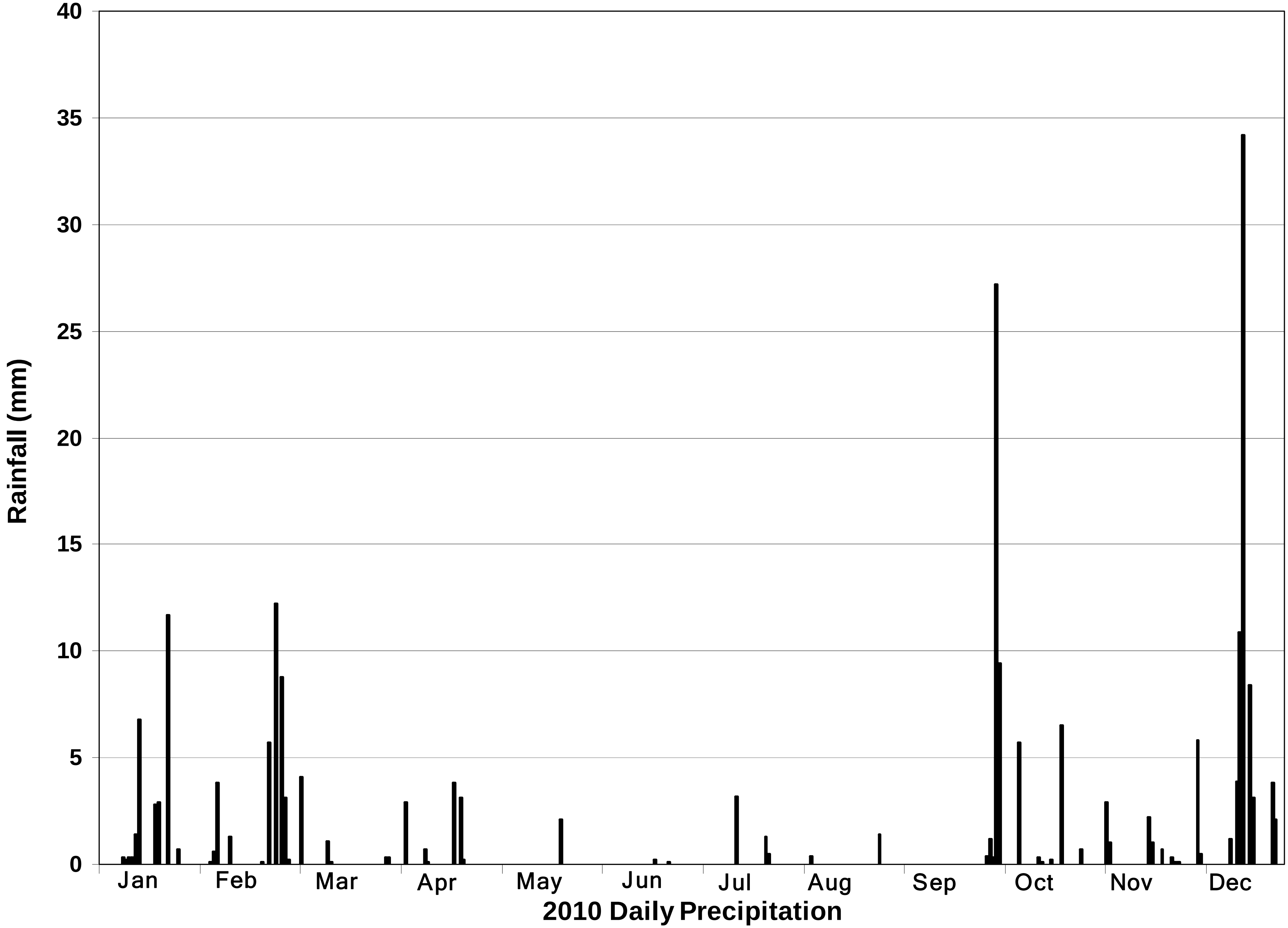
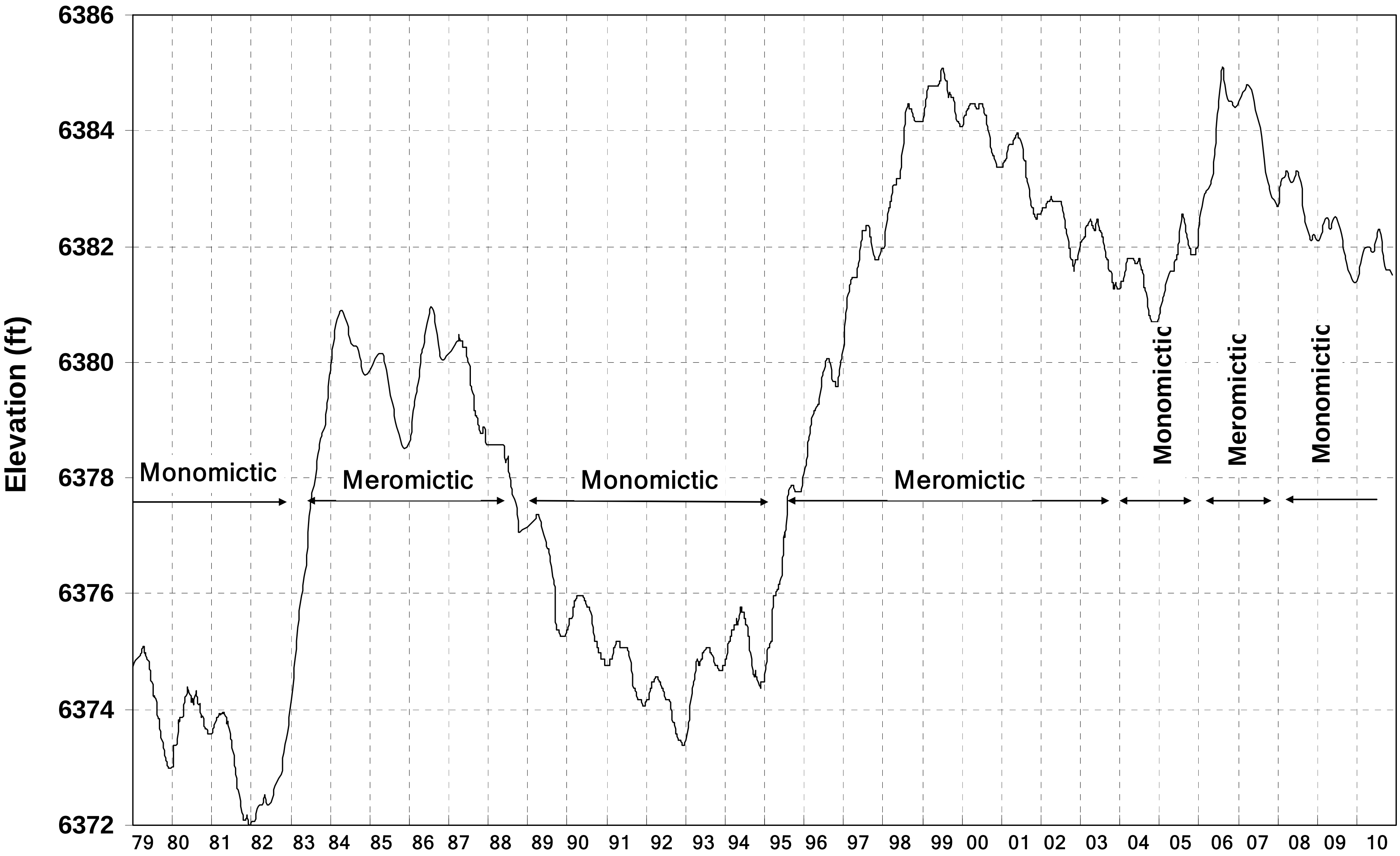
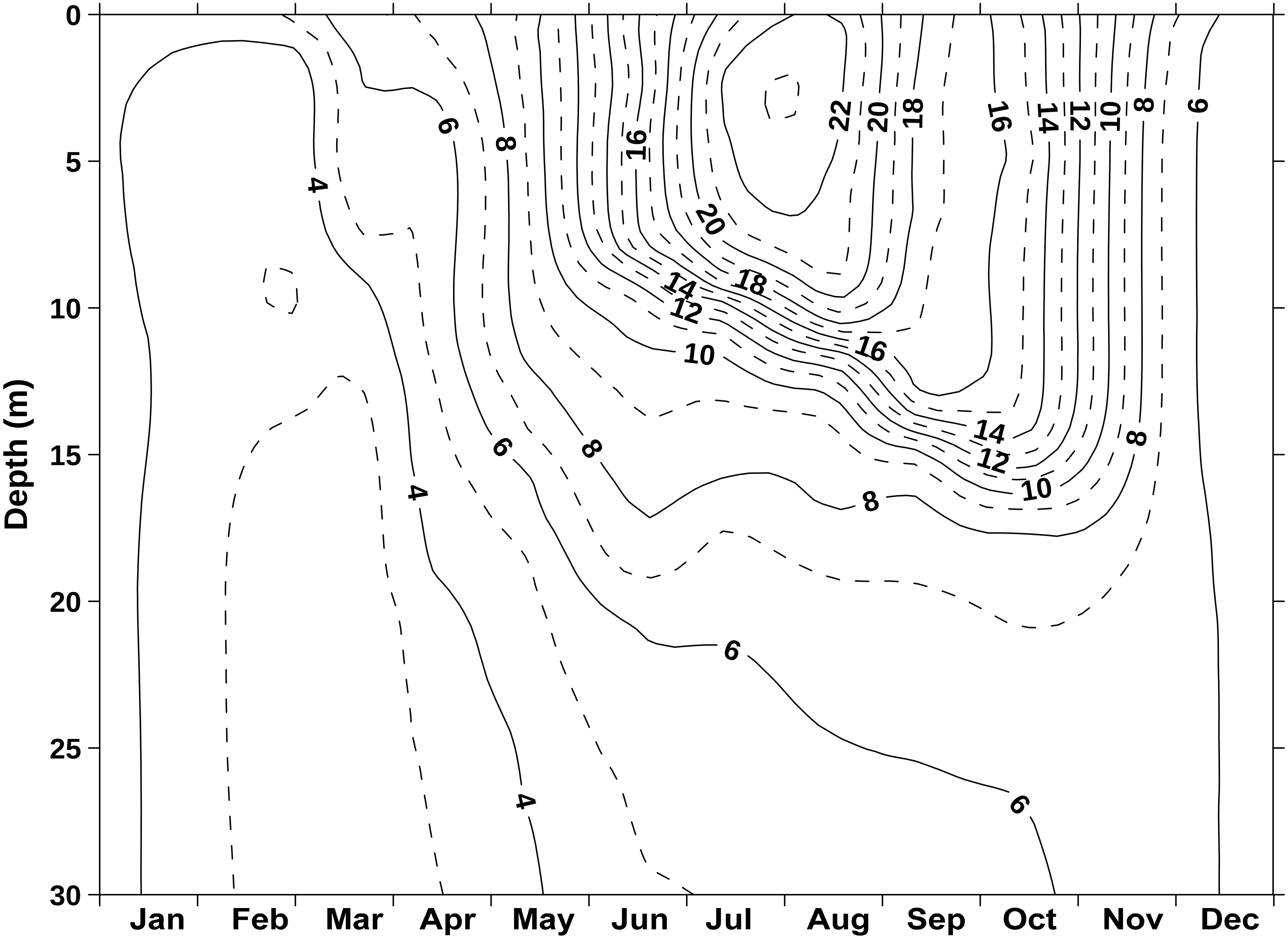

Rainfall (mm)
40
35
30
25
20
15
10
5
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
2010 Daily Precipitation

Figure 6



Mono Lake Surface Elevation (1979 - 2010)

Figure 7



Temperature (°C) at Station 6, 2010

Figure 8

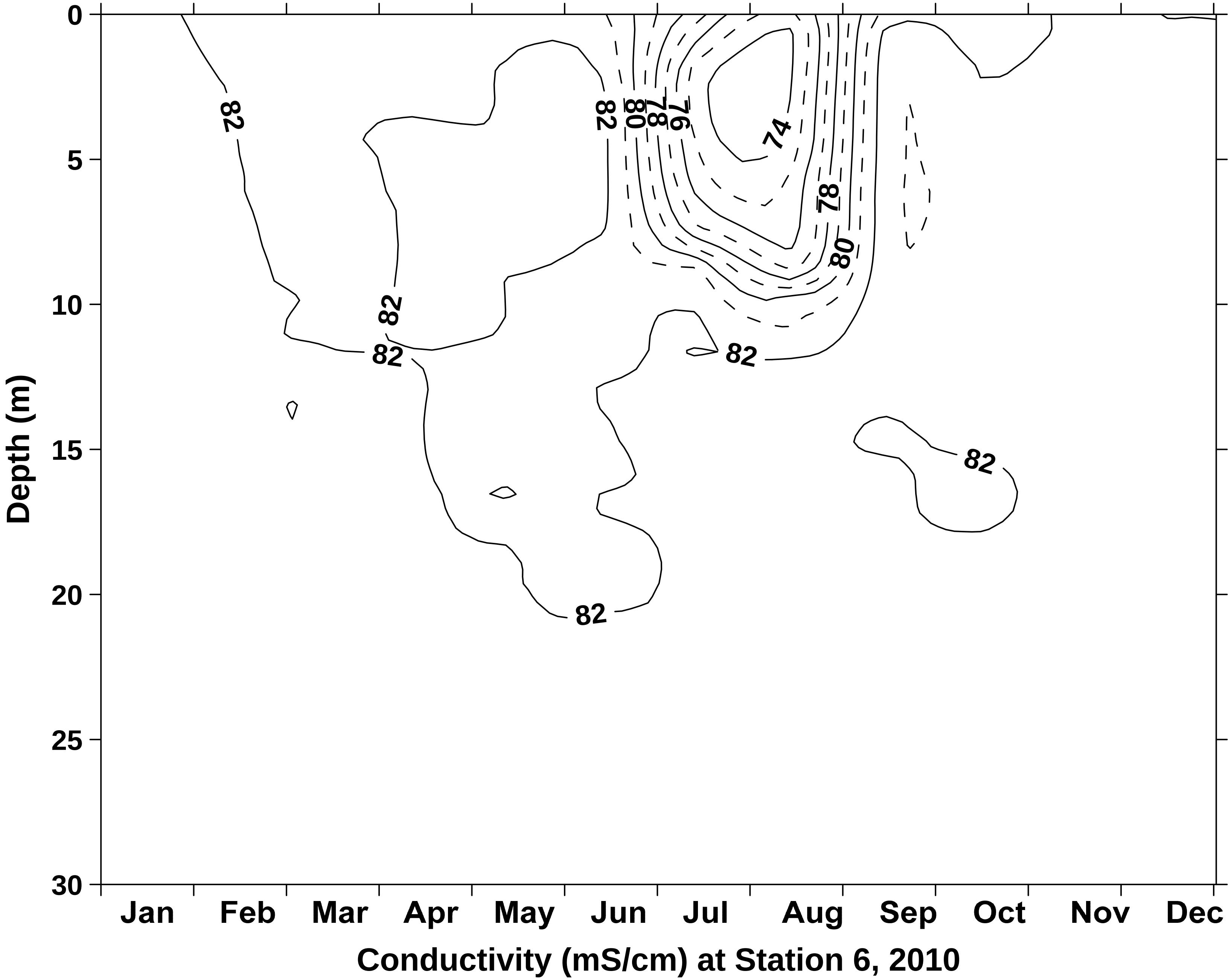
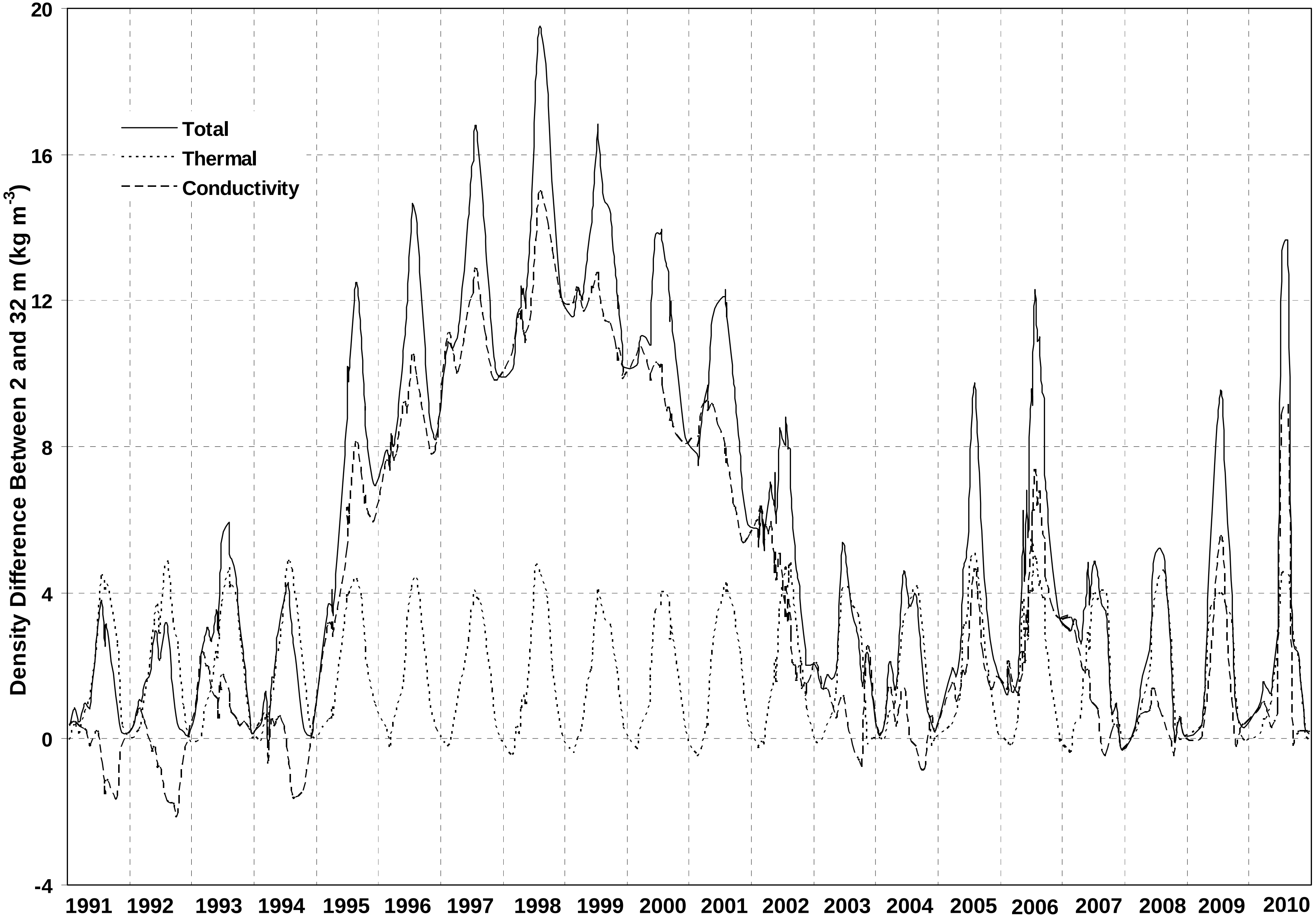
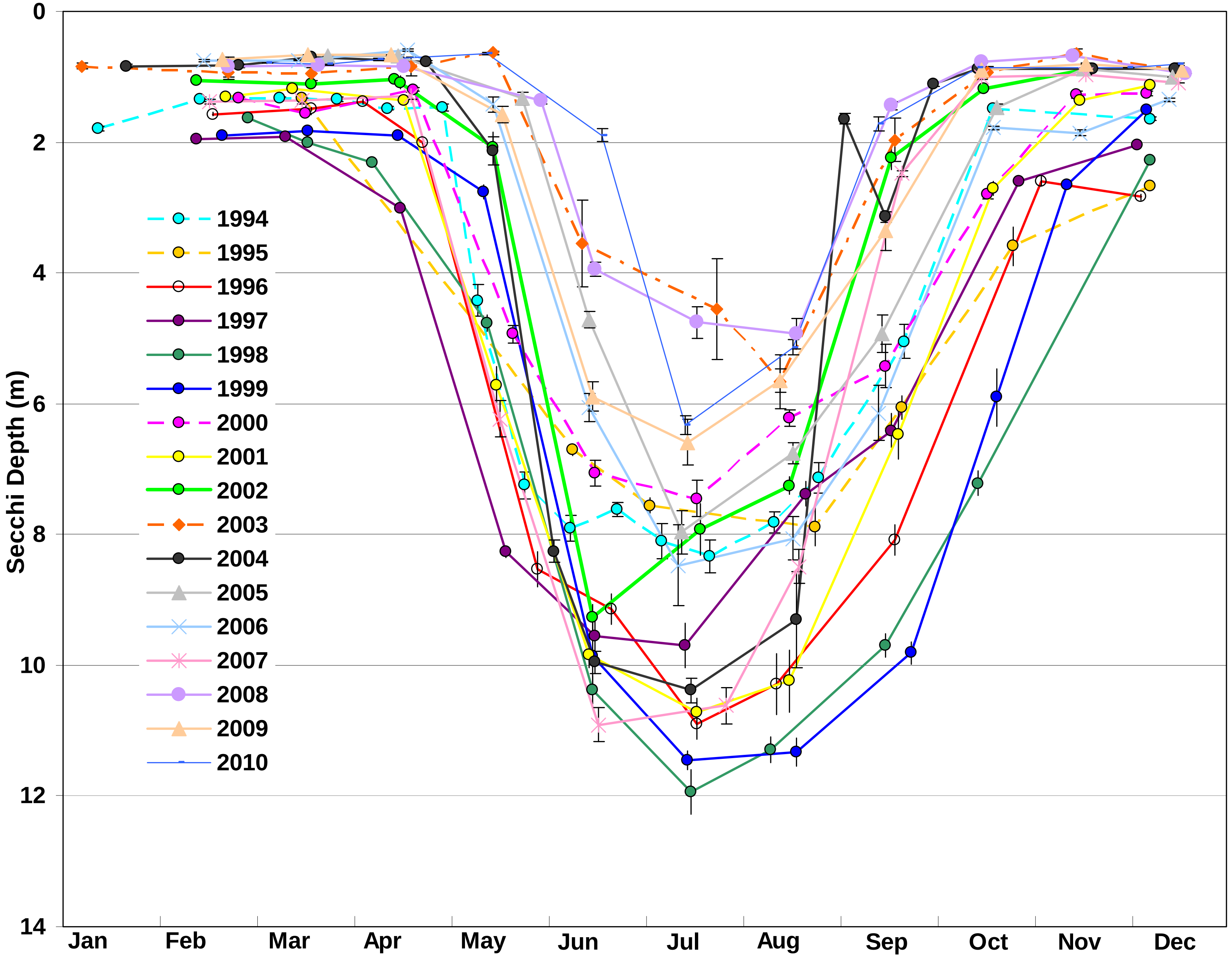

0
5
10
15
20
25
30
Depth (m)
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
82
82
82
82
82
80
78
76
74
78
80
82
82
82
Conductivity (mS/cm) at Station 6, 2010

Figure 9



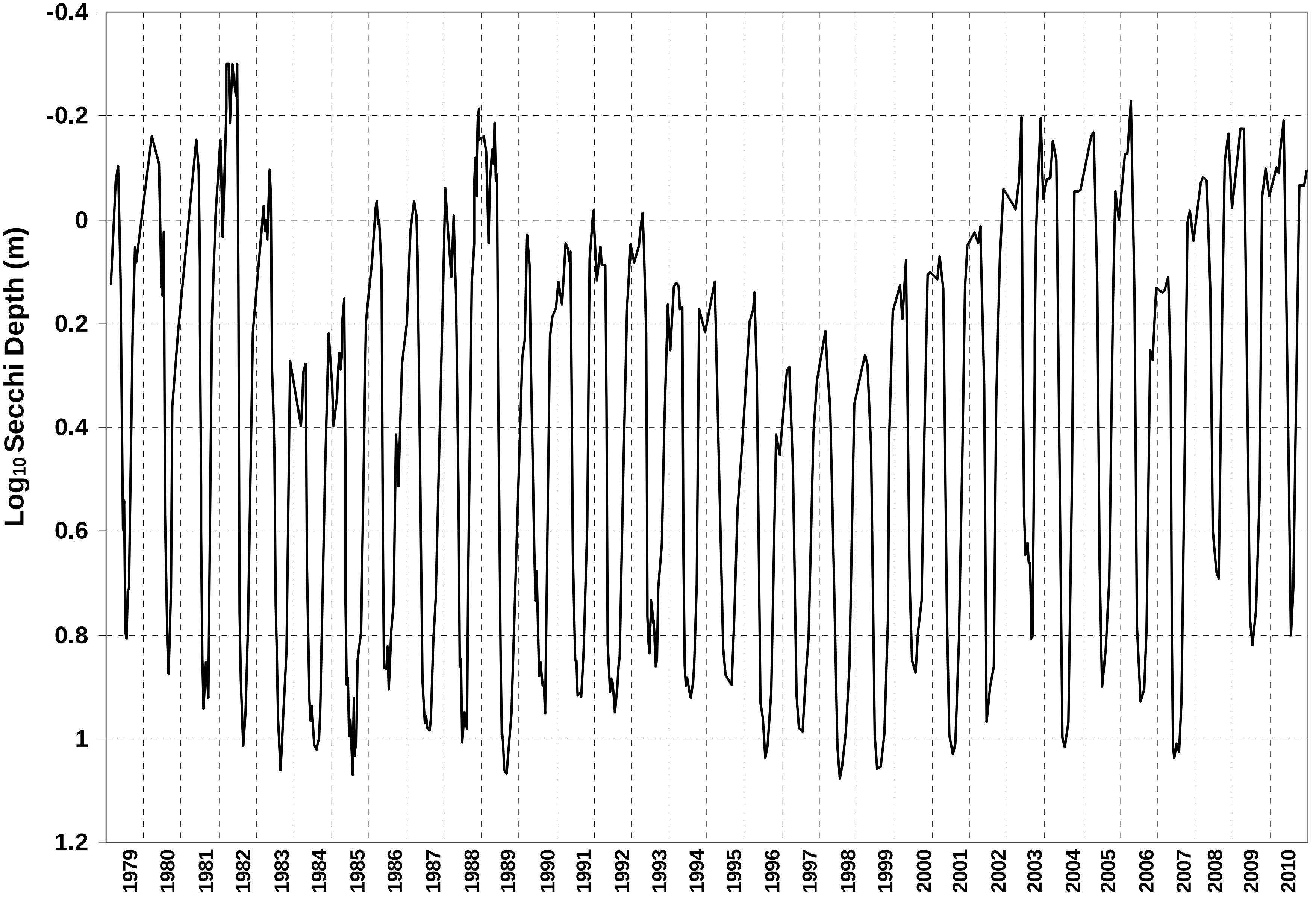
Density Stratification (2-32 m)

Figure 10



Mono Lake Transparency

Figure 11



Water Transparency in Mono Lake

Figure 12

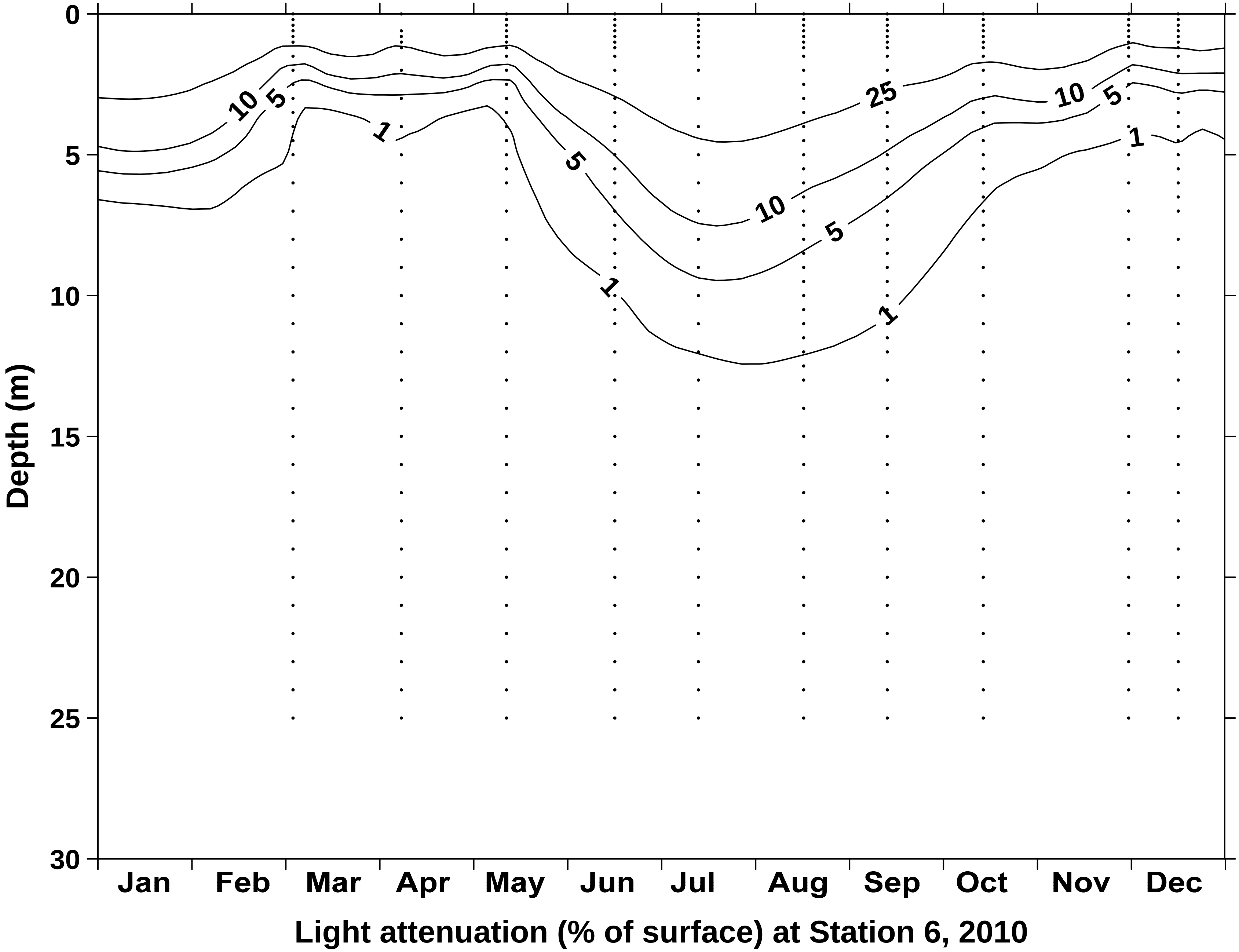
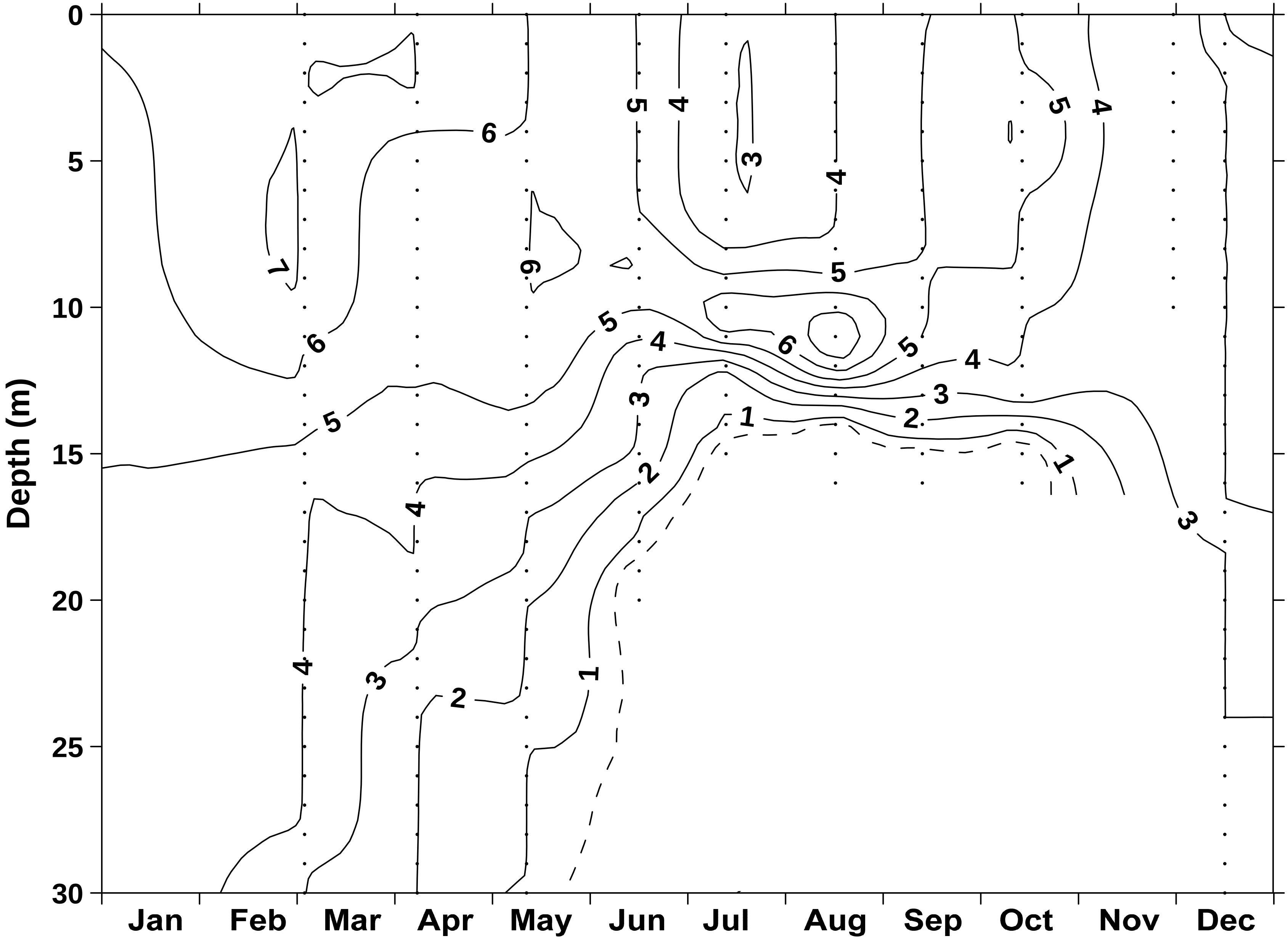

Depth (m)
0
5
10
15
20
25
30
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
25
10
5
1
10
5
1
1
5
10
5
1
25
10
5
1
Light attenuation (% of surface) at Station 6, 2010

Figure 13



Dissolved oxygen (mg/l) at Station 6, 2010

Figure 14

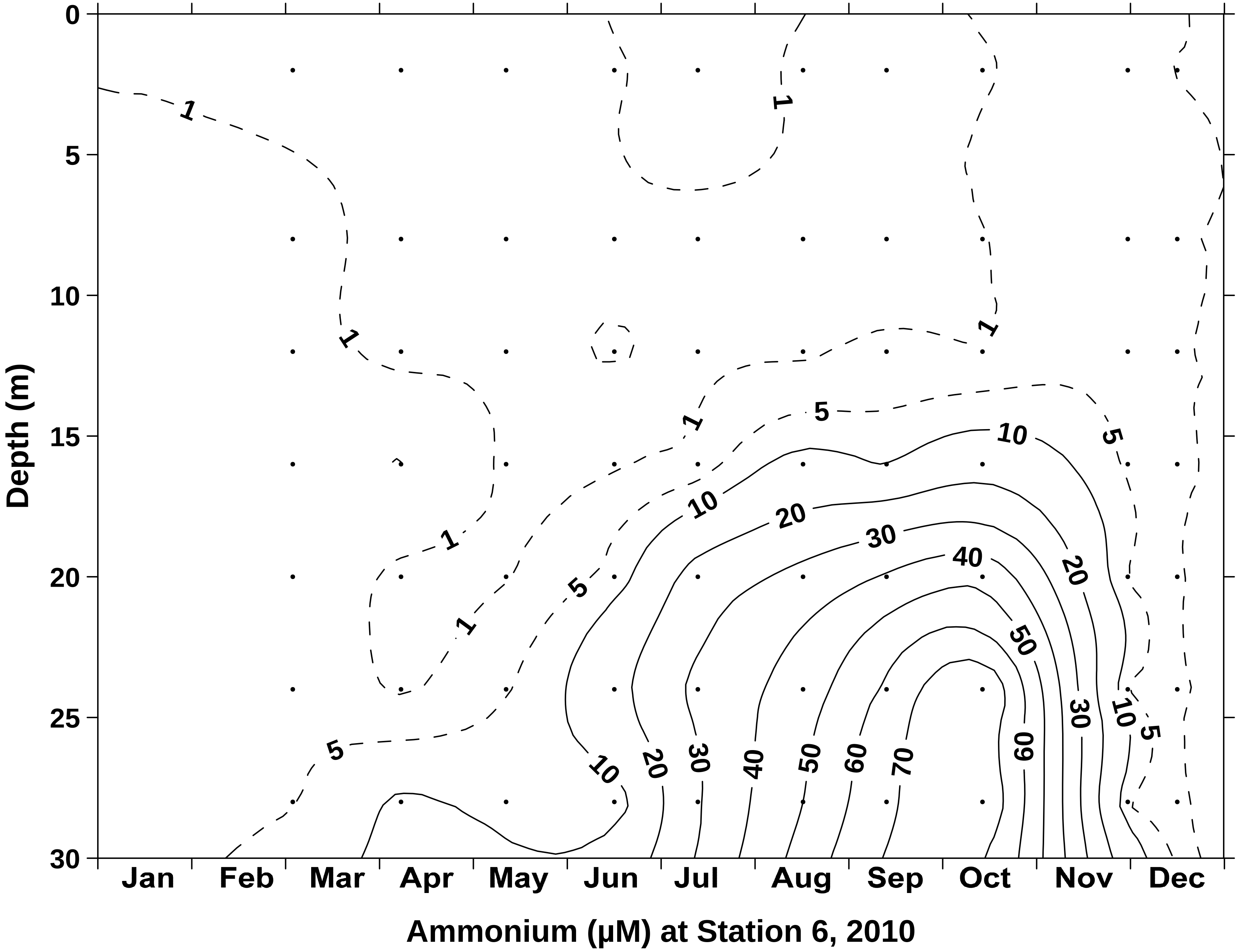

Depth (m)
0
5
10
15
20
25
30
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
1
5
10
20
30
40
50
60
70
Ammonium (μM) at Station 6, 2010

Figure 15

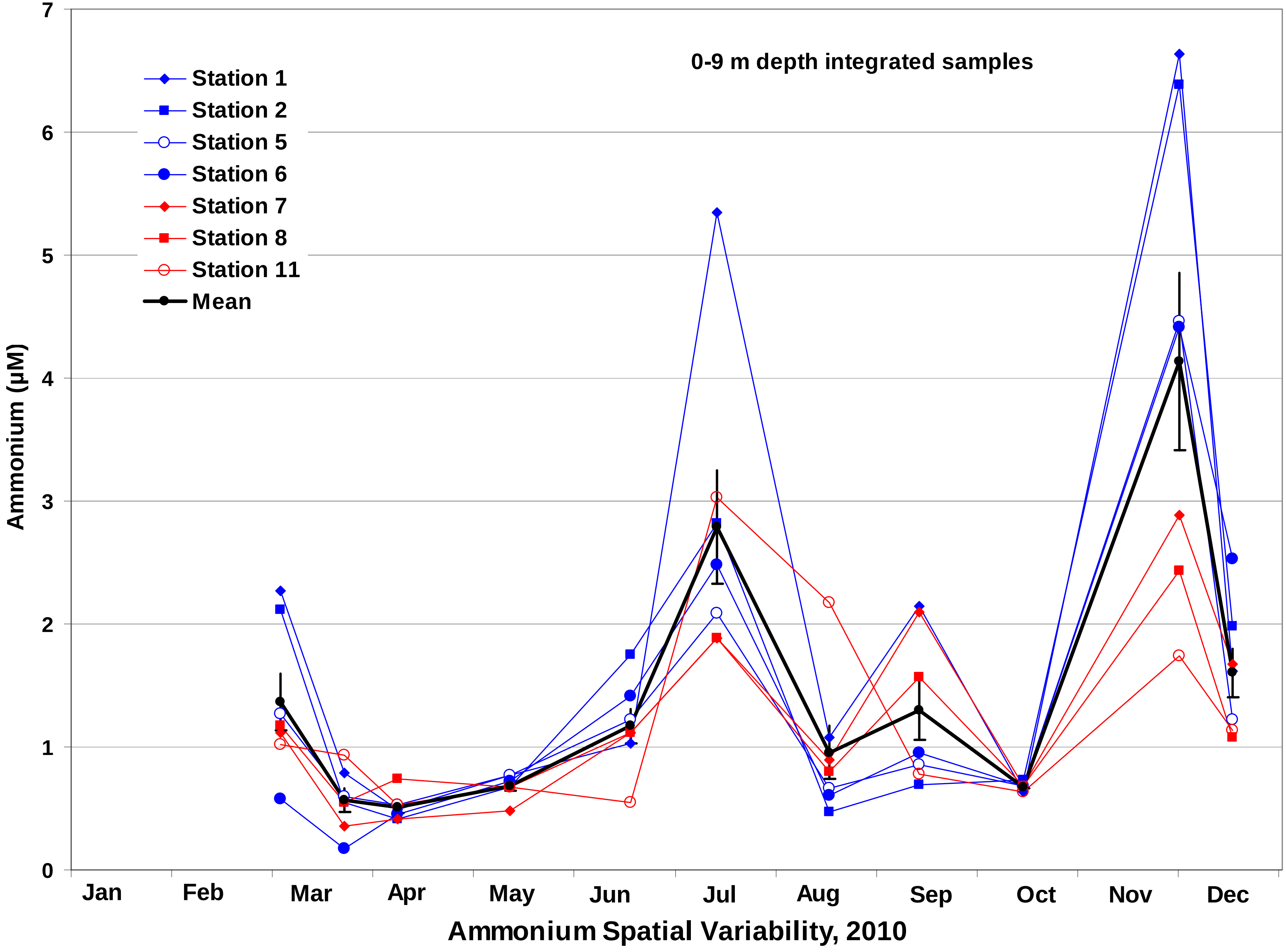
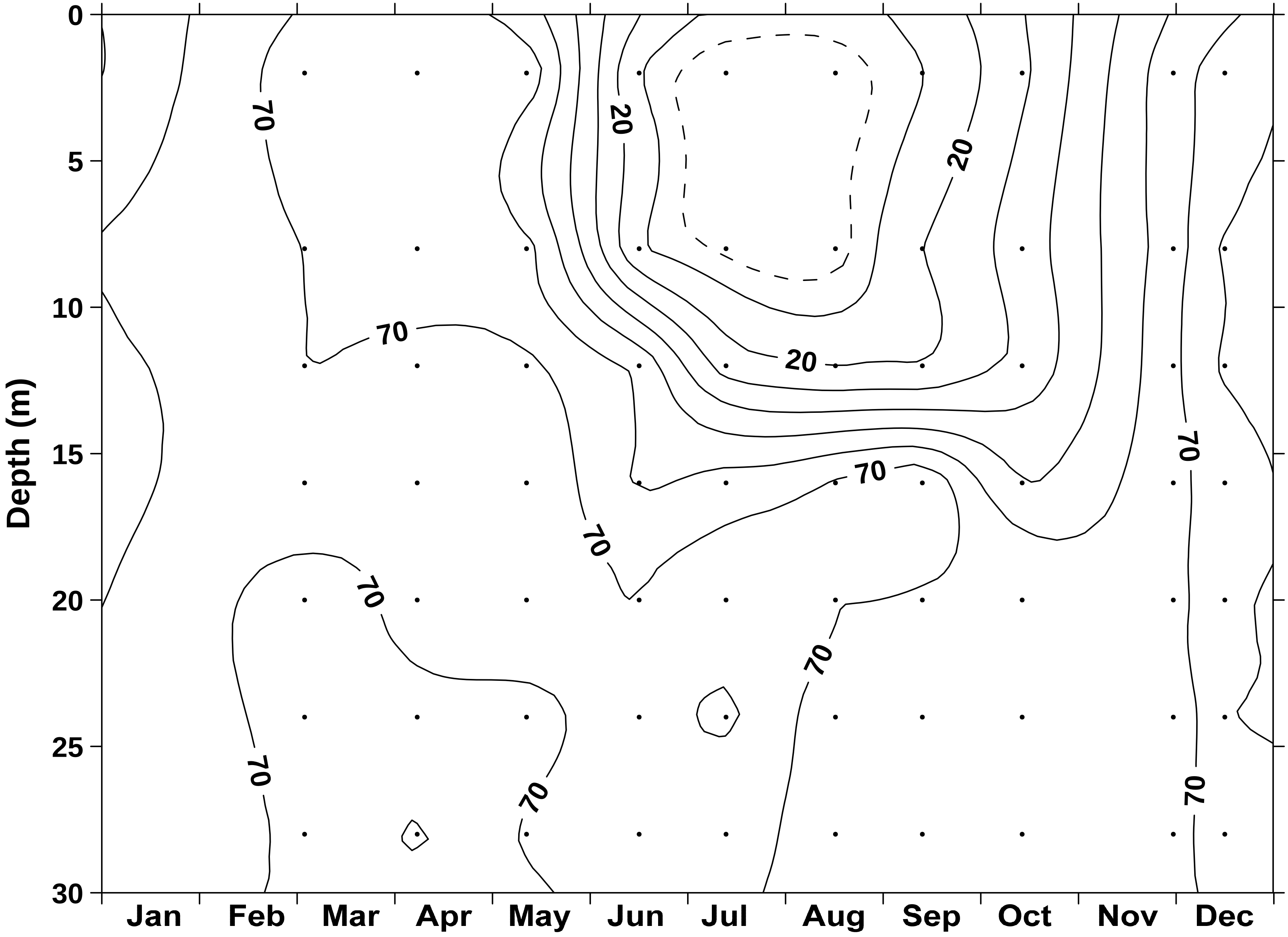

0-9 m depth integrated samples
Station 1
Station 2
Station 5
Station 6
Station 7
Station 8
Station 11
Mean
Ammonium (µM)
0
1
2
3
4
5
6
7
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Ammonium Spatial Variability, 2010

Figure 16



Chlorophyll a (µg/l) at Station 6, 2010

Figure 17

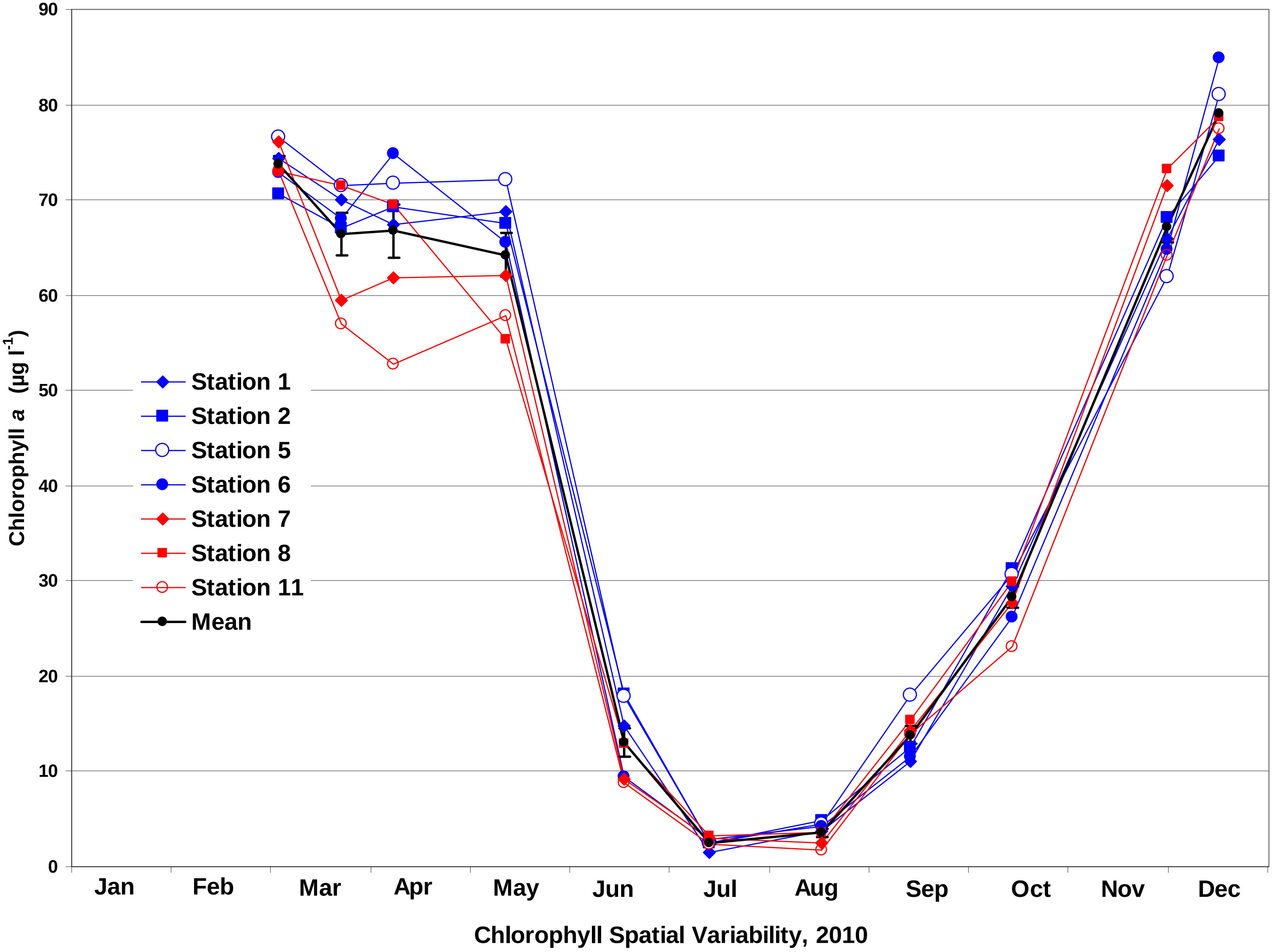
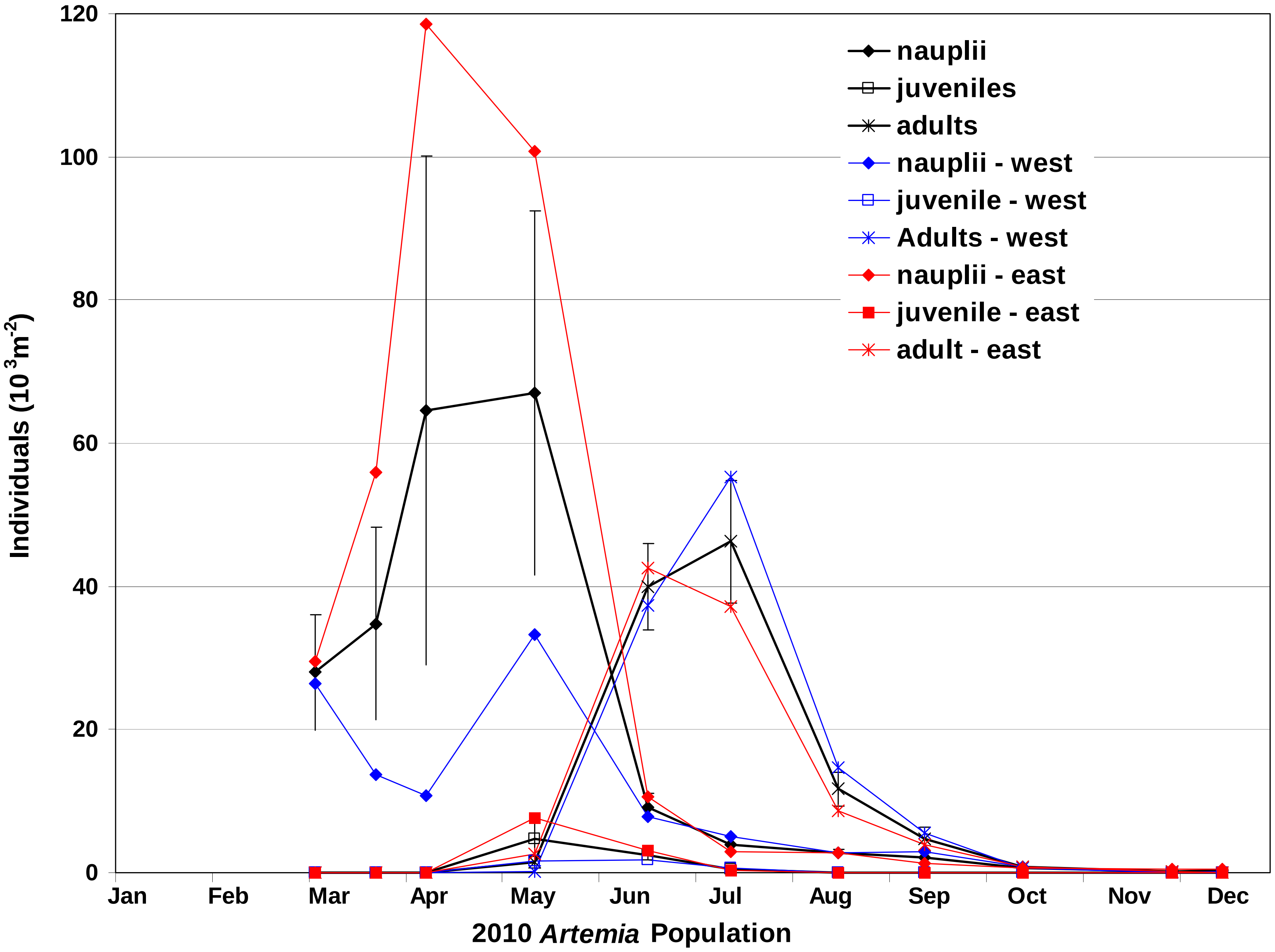

90
80
70
60
50
40
30
20
10
0
Chlorophyll a (µg l^{-1})
Station 1
Station 2
Station 5
Station 6
Station 7
Station 8
Station 11
Mean
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Chlorophyll Spatial Variability, 2010

Figure 18



120
100
80
60
40
20
0
Individuals ($10^3 m^{-2}$)
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
2010 *Artemia* Population
nauplii
juveniles
adults
nauplii - west
juvenile - west
Adults - west
nauplii - east
juvenile - east
adult - east

Figure 19

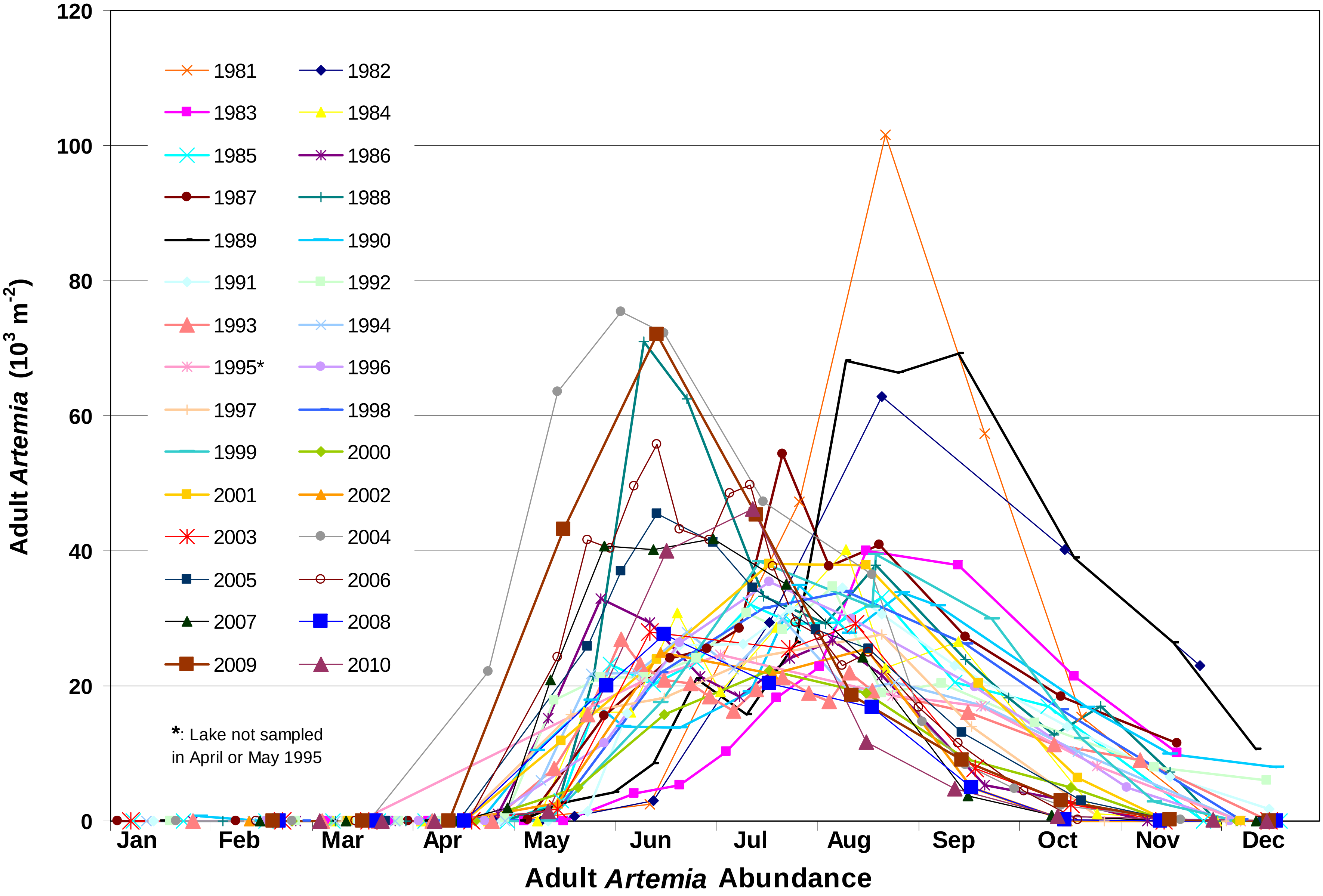
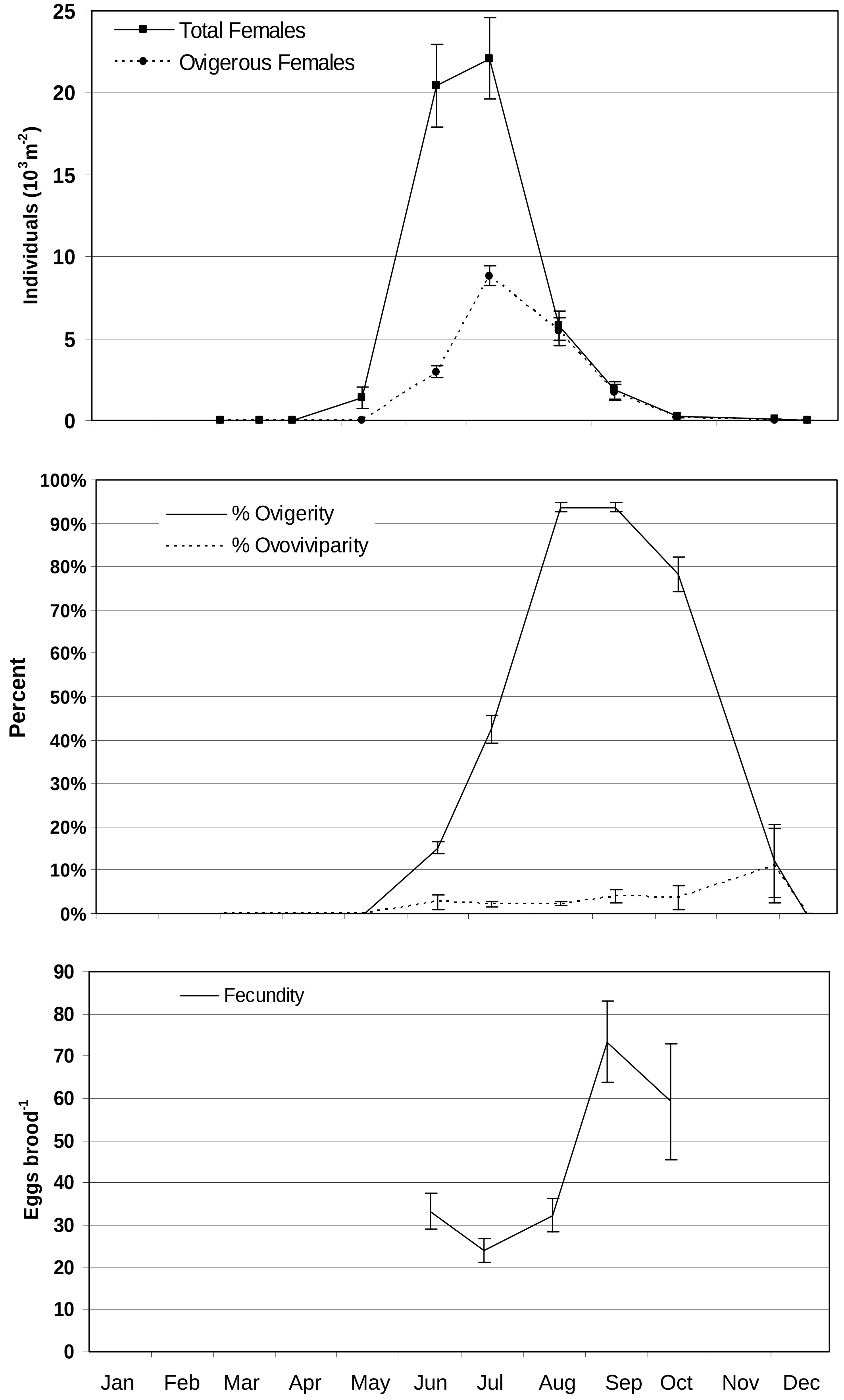
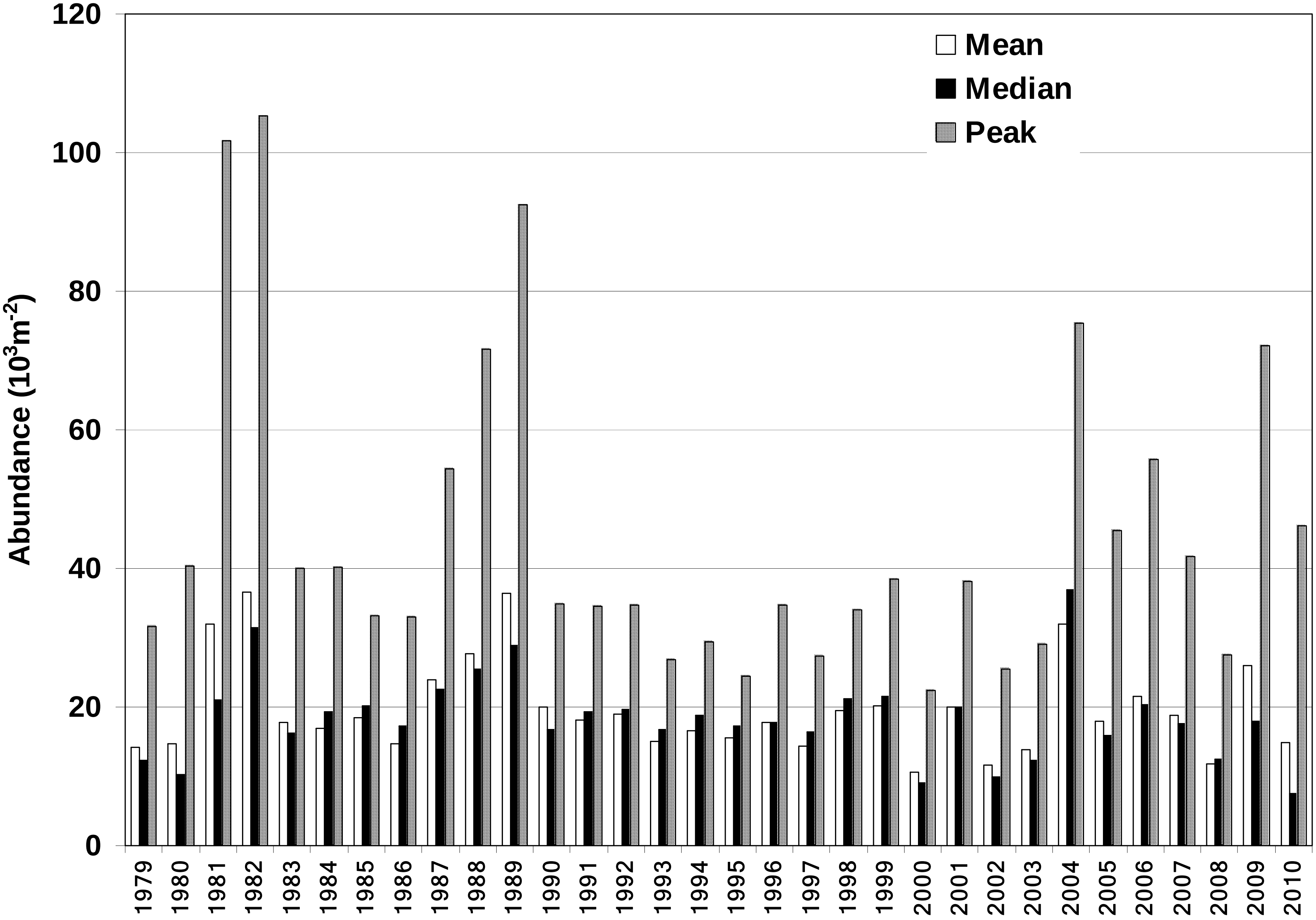

120
100
80
60
40
20
0
Adult Artemia (10^3 m^{-2})
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Adult Artemia Abundance
1981
1982
1983
1984
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995*
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
*: Lake not sampled
in April or May 1995

Figure 20

Figure 21



***Artemia* Reproductive Parameters**



Adult *Artemia* Summary

Figure 22

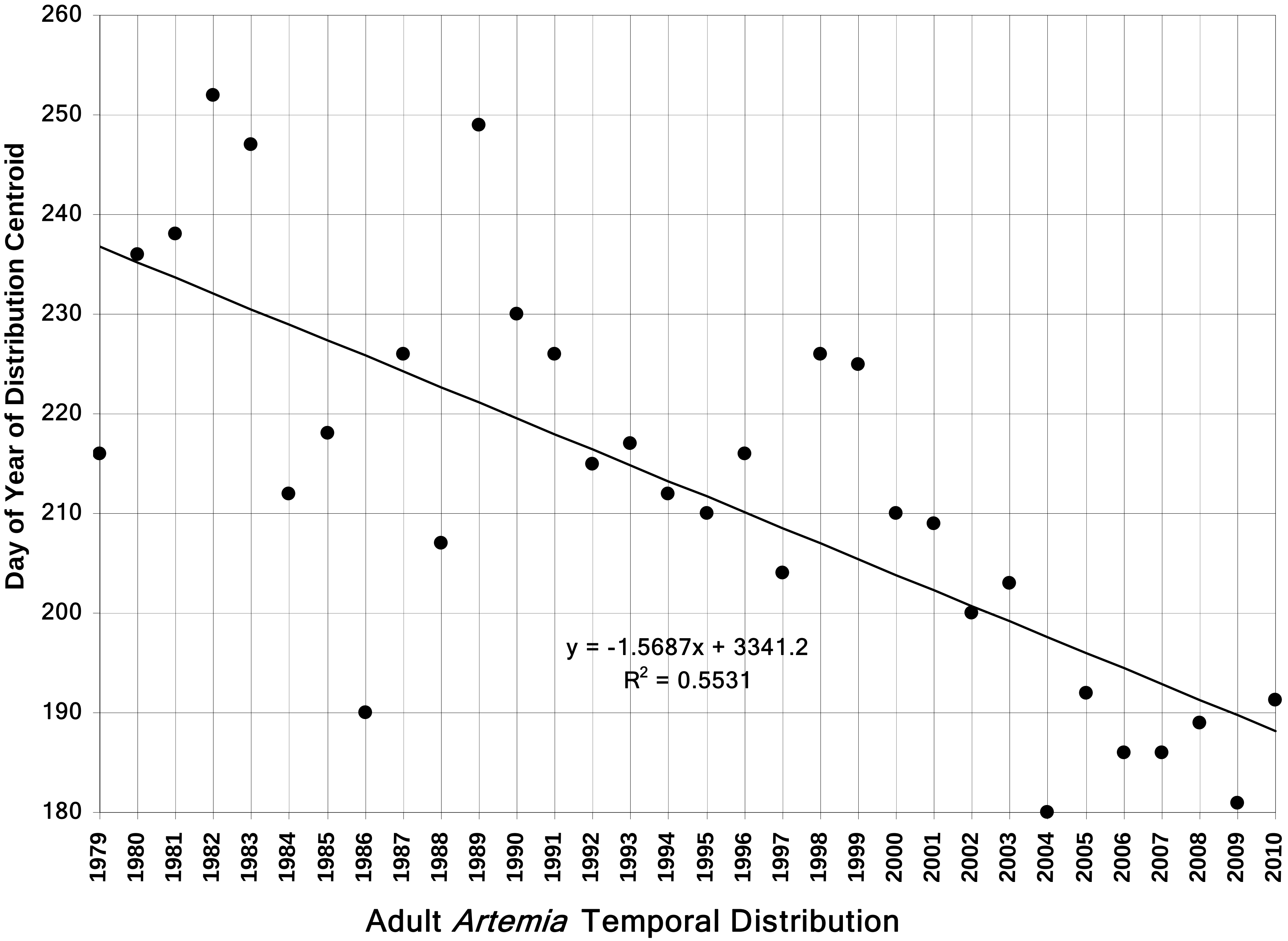
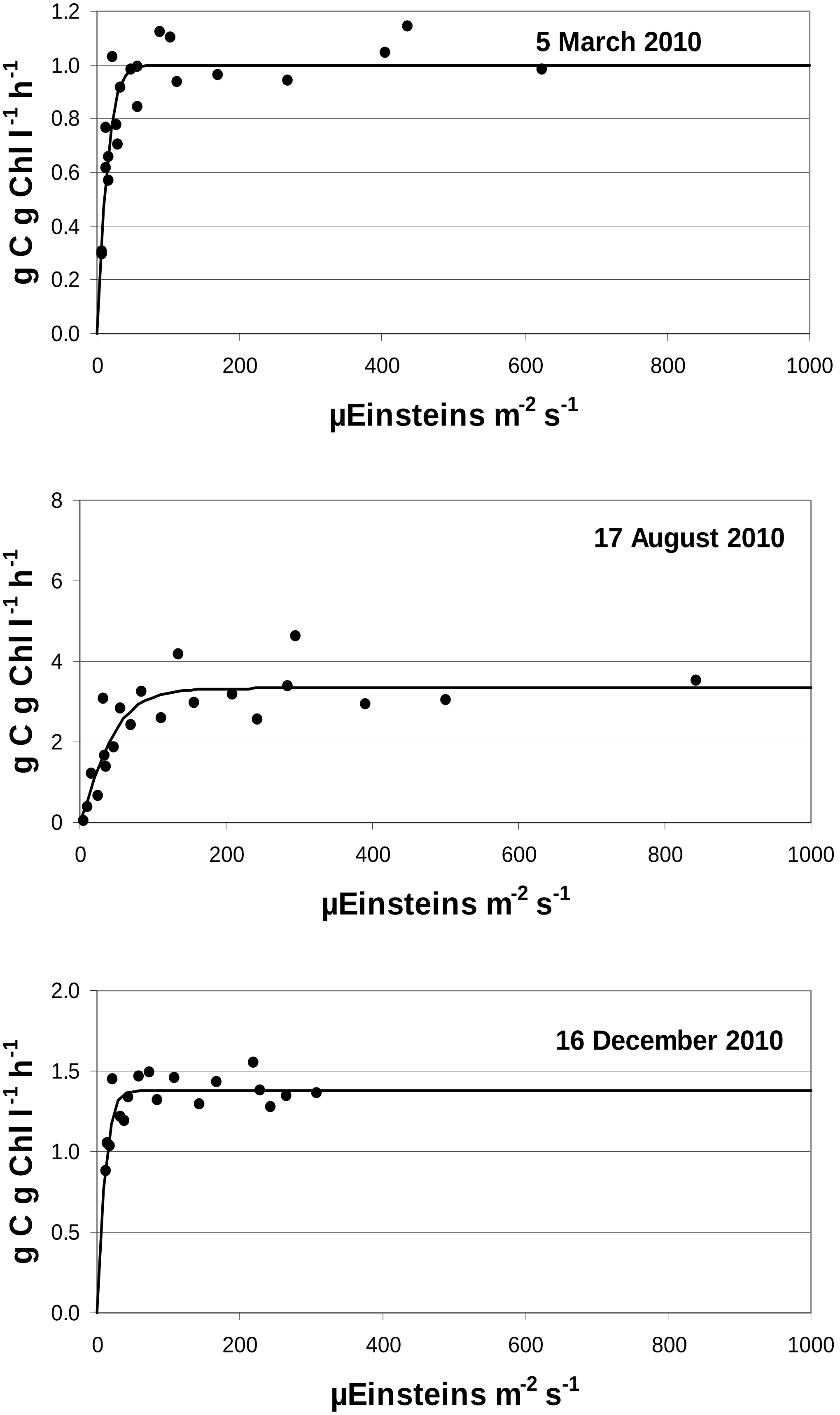

Day of Year of Distribution Centroid
260
250
240
230
220
210
200
190
180
1979
1980
1981
1982
1983
1984
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
y = -1.5687x + 3341.2
R2 = 0.5531
Adult Artemia Temporal Distribution

Figure 23

Figure 24



Photosynthetic Rates

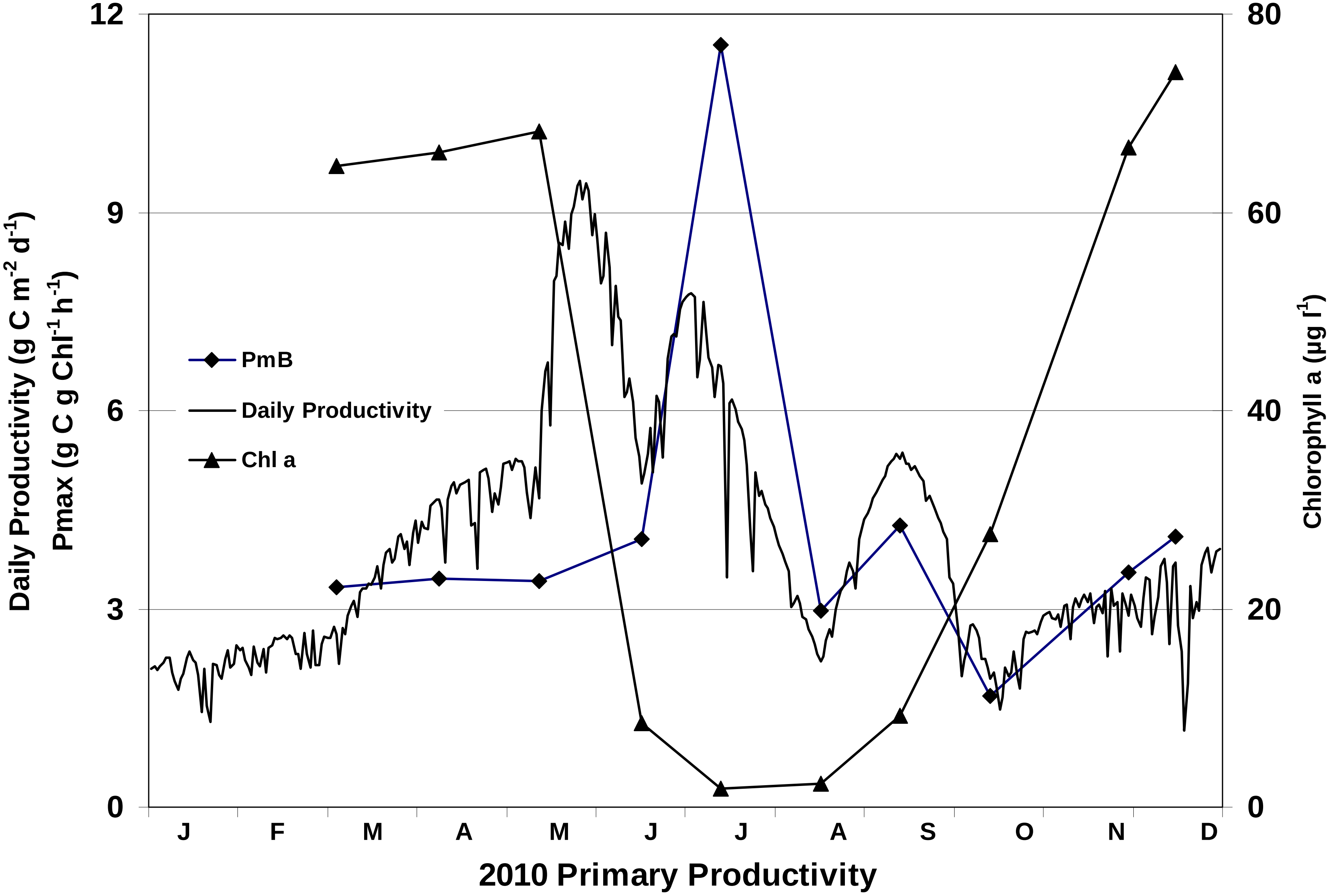
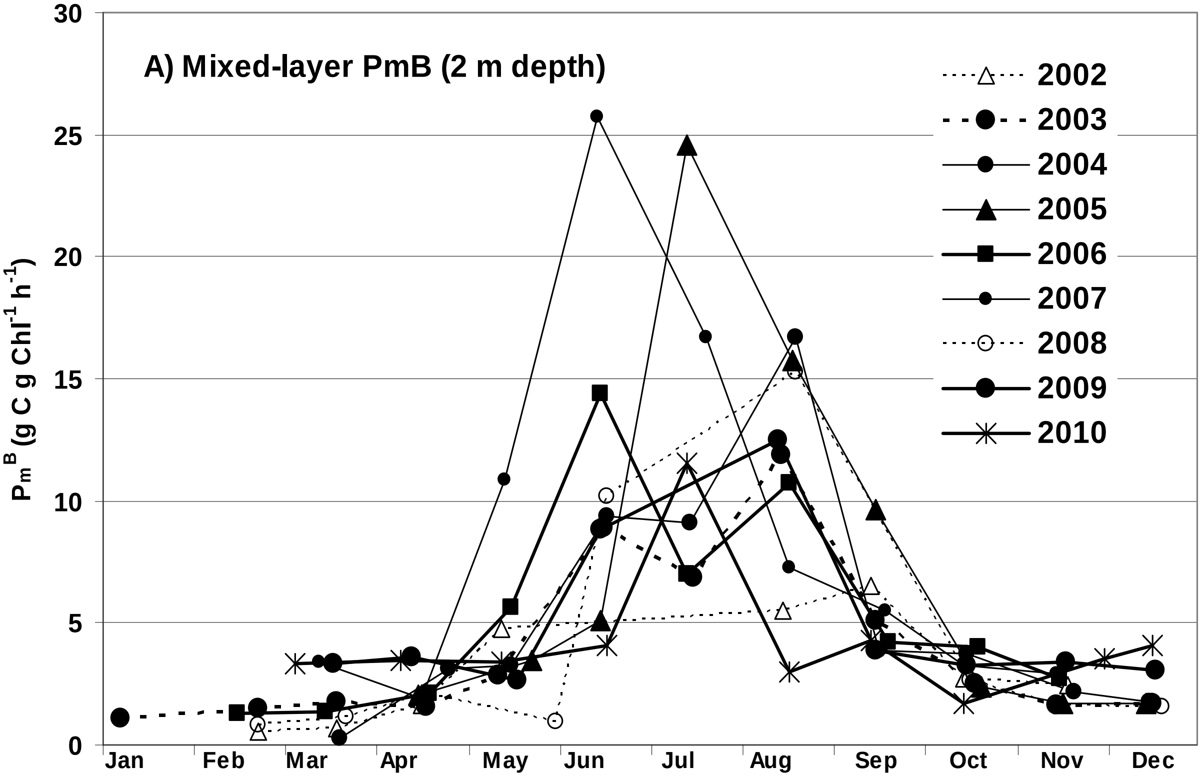
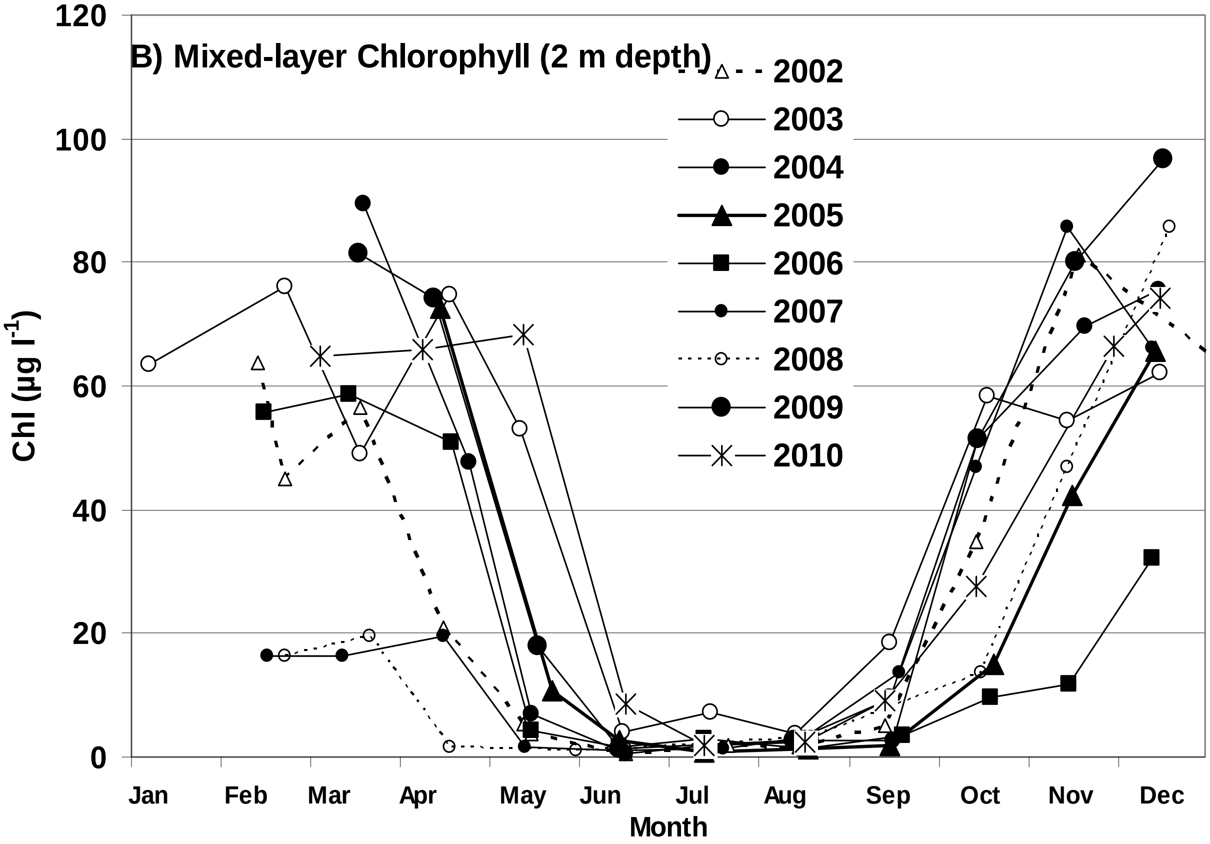
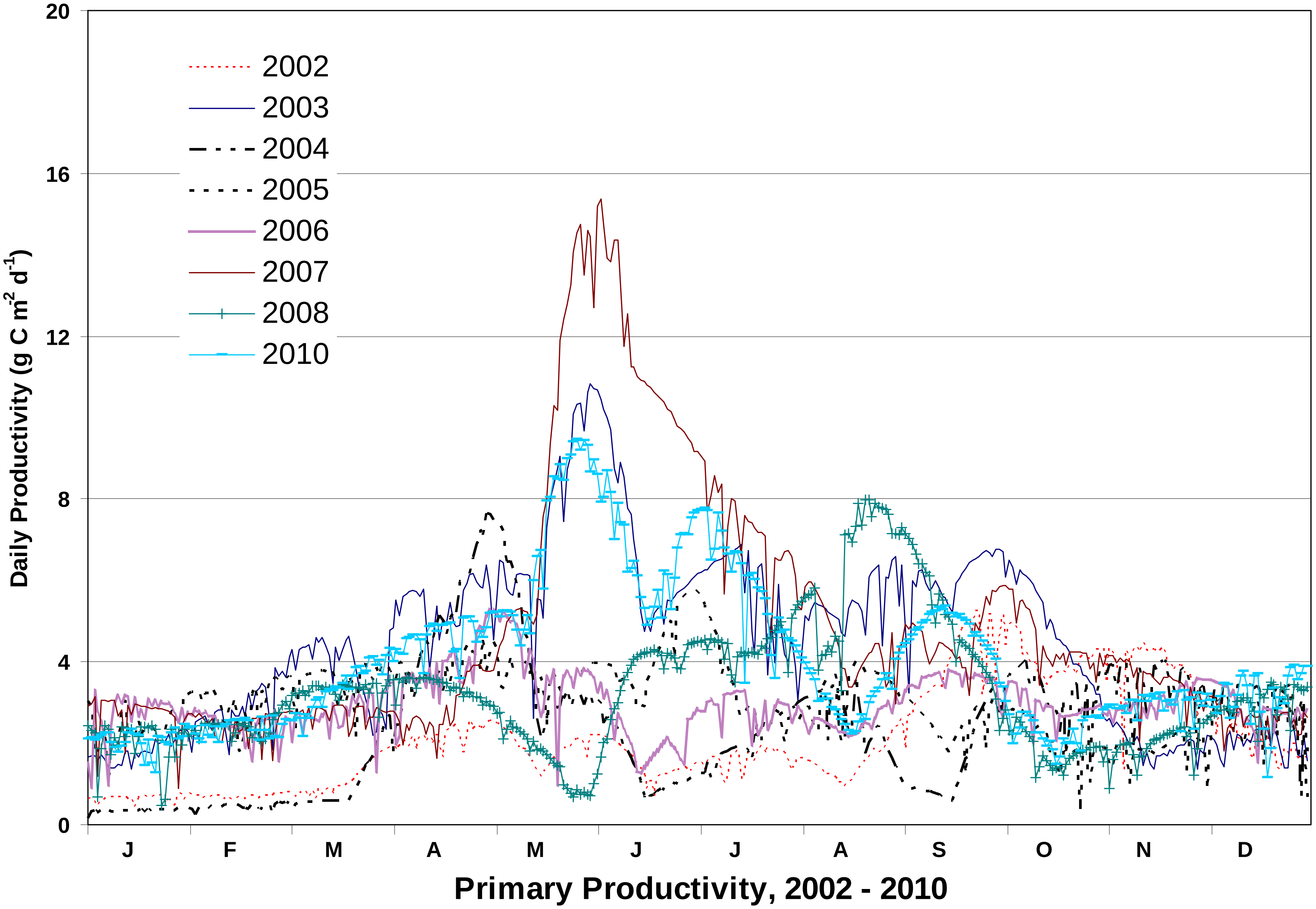

12
9
6
3
0
80
60
40
20
0
Daily Productivity (g C m^{-2} d^{-1})
Pmax (g C g Chl^{-1} h^{-1})
Chlorophyll a (µg l^{-1})
PmB
Daily Productivity
Chl a
J
F
M
A
M
J
J
A
S
O
N
D
2010 Primary Productivity

Figure 25

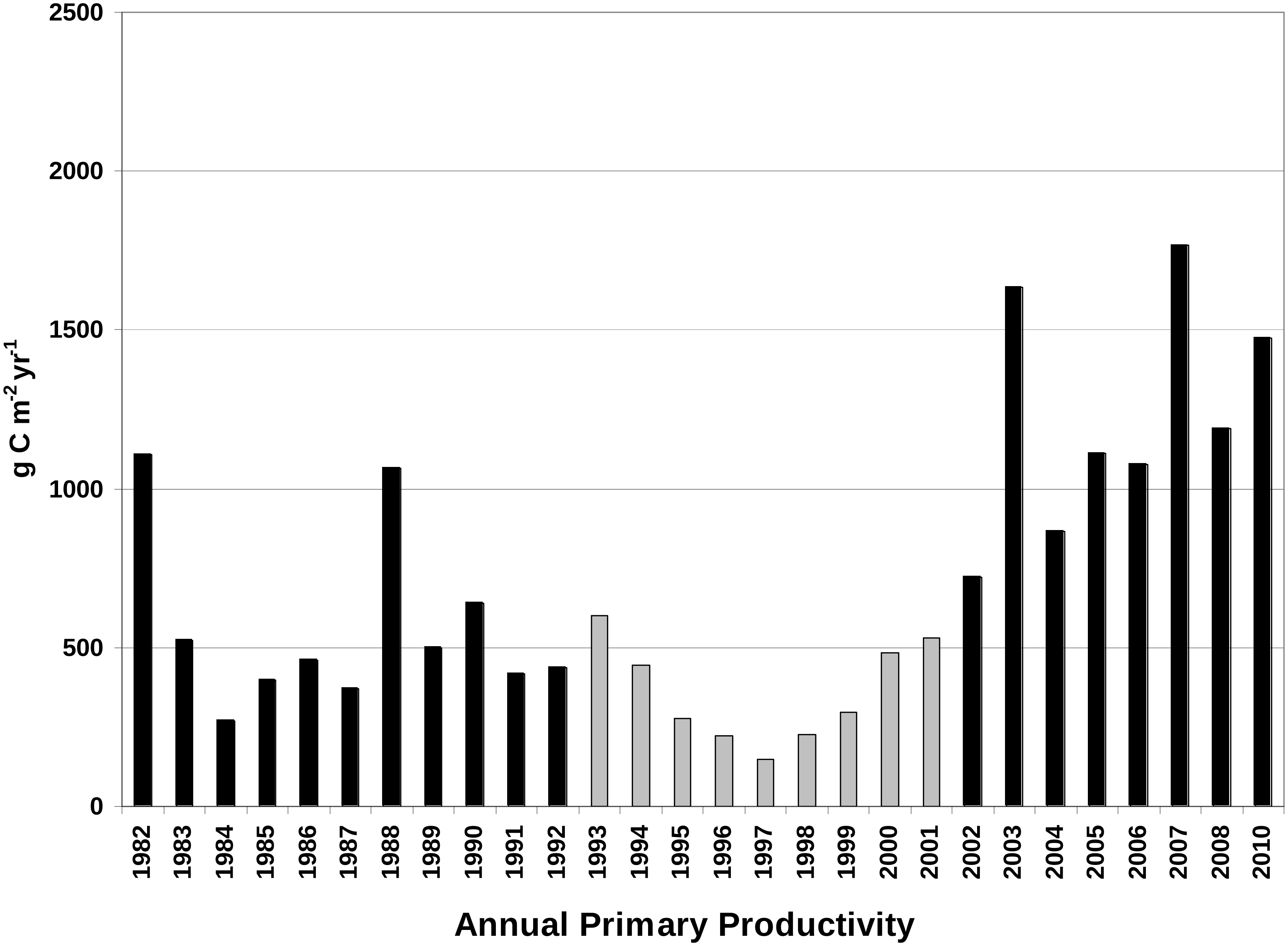

A) Mixed-layer PmB (2 m depth)
P_m^B (g C g Chl^{-1} h^{-1})
0
5
10
15
20
25
30
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
2002
2003
2004
2005
2006
2007
2008
2009
2010


B) Mixed-layer Chlorophyll (2 m depth)
Chl (µg l^{-1})
0
20
40
60
80
100
120
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Month
2002
2003
2004
2005
2006
2007
2008
2009
2010



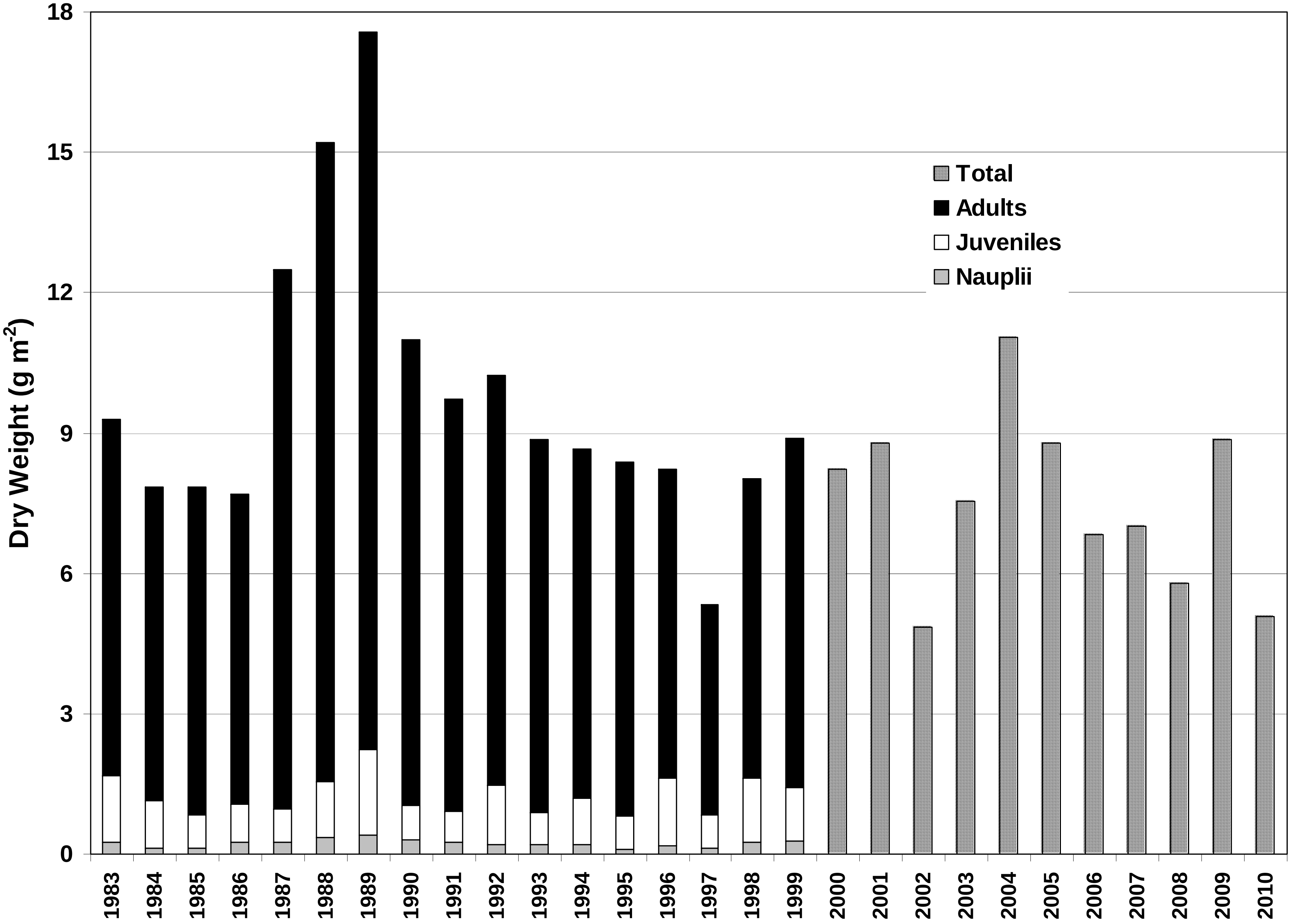
2002
2003
2004
2005
2006
2007
2008
2010
Daily Productivity (g C m^{-2} d^{-1})
20
16
12
8
4
0
J
F
M
A
M
J
J
A
S
O
N
D
Primary Productivity, 2002 - 2010

Figure 27



2500
2000
1500
1000
500
0
g C m^{-2} yr^{-1}
1982
1983
1984
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2010
Annual Primary Productivity

Figure 28



Mean Annual *Artemia* Biomass

Figure 29

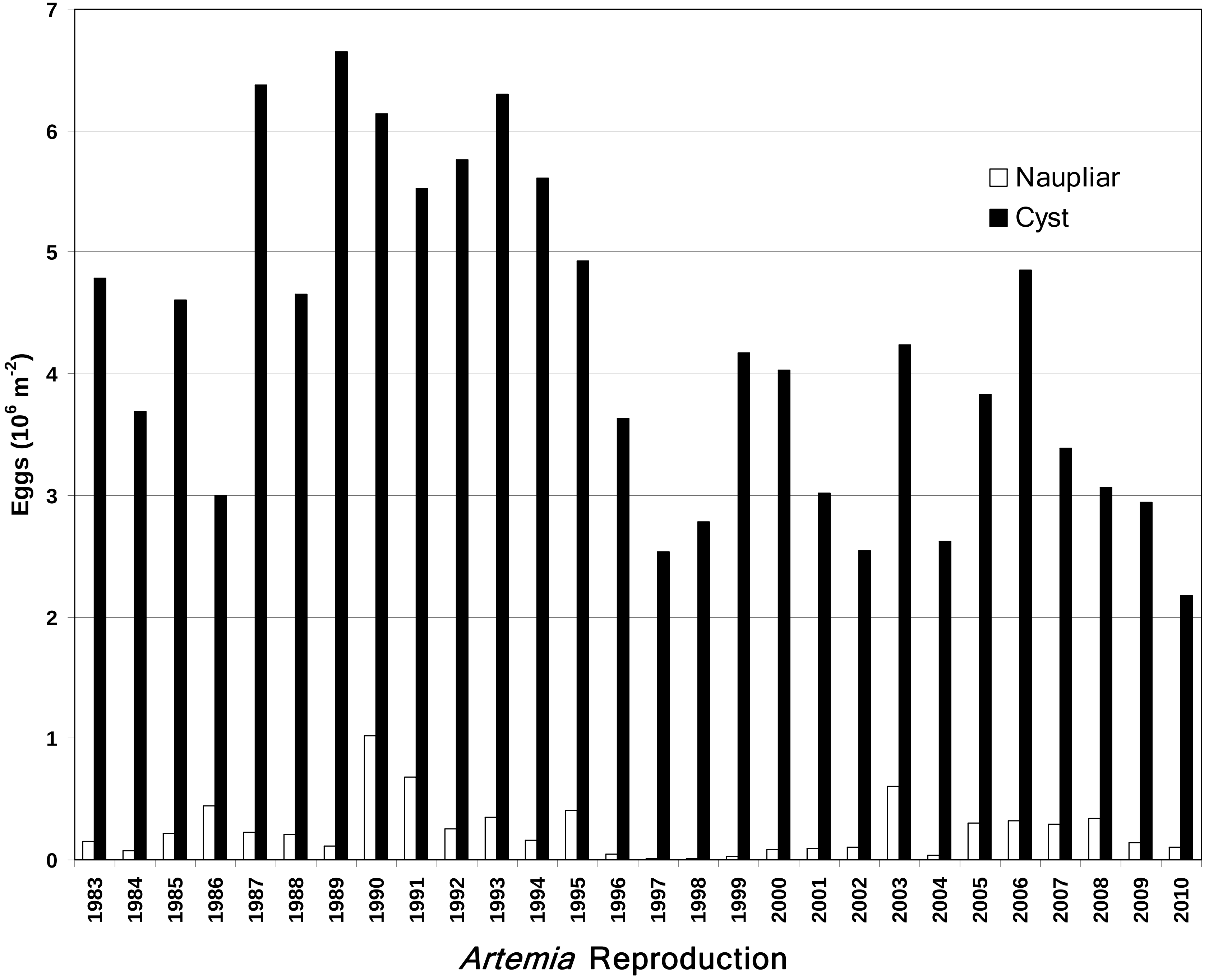

Eggs (10^6 m^{-2})
0
1
2
3
4
5
6
7
☐ Naupliar
■ Cyst
1983
1984
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
Artemia Reproduction

Figure 30

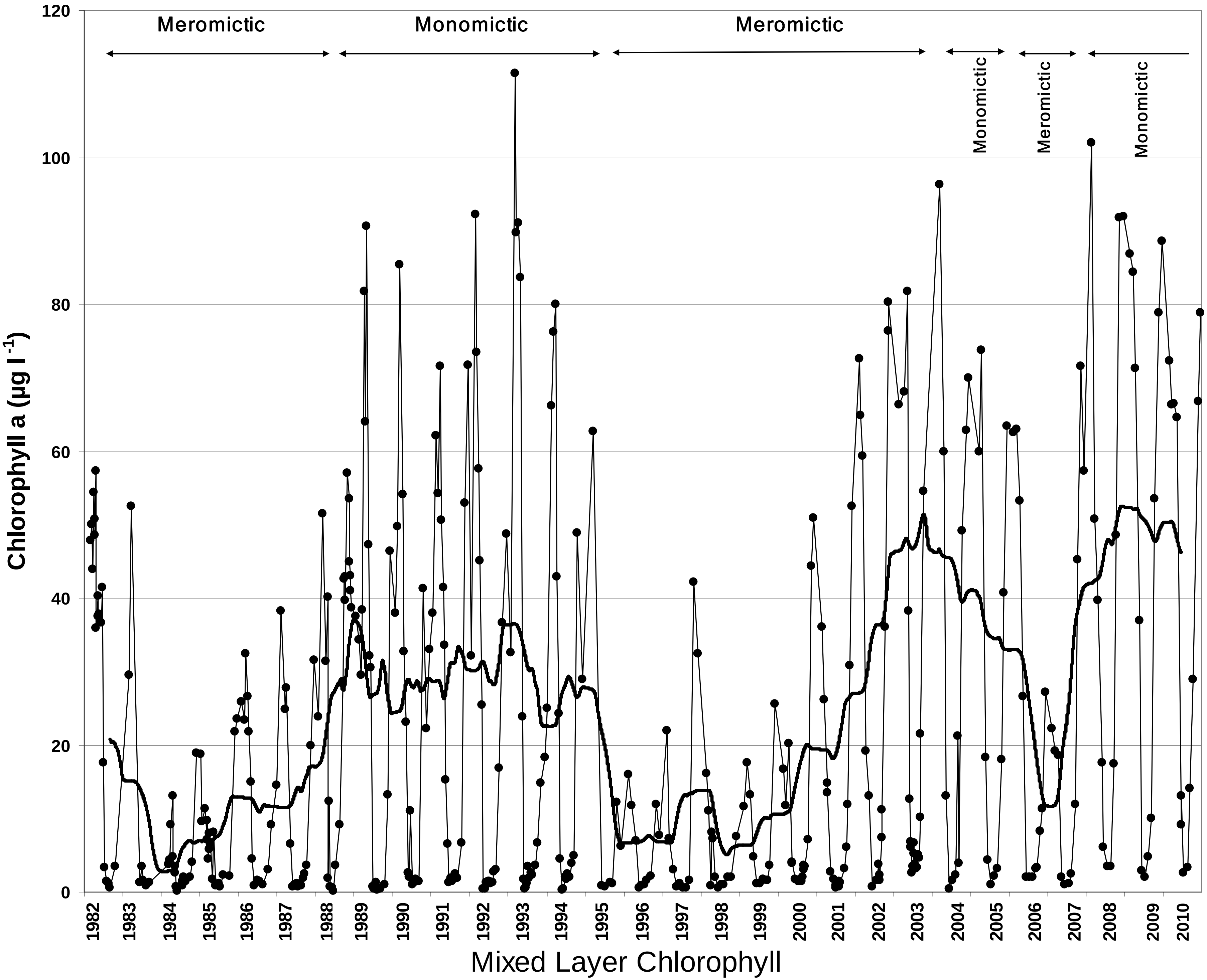

Meromictic
Monomictic
Meromictic
Monomictic
Meromictic
Monomictic
Chlorophyll a (µg l -1)
120
100
80
60
40
20
0
1982
1983
1984
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
Mixed Layer Chlorophyll

Figure 31

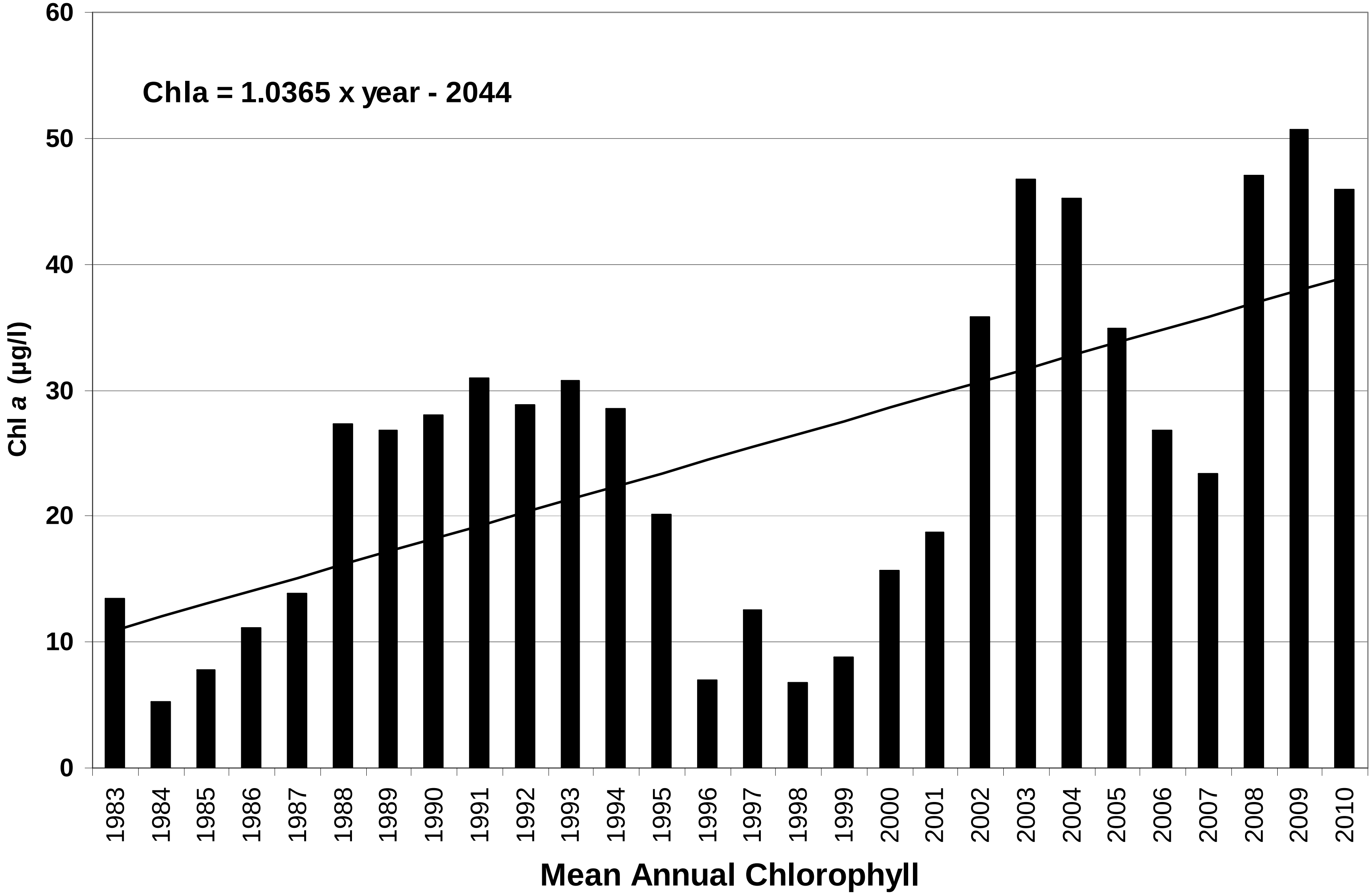
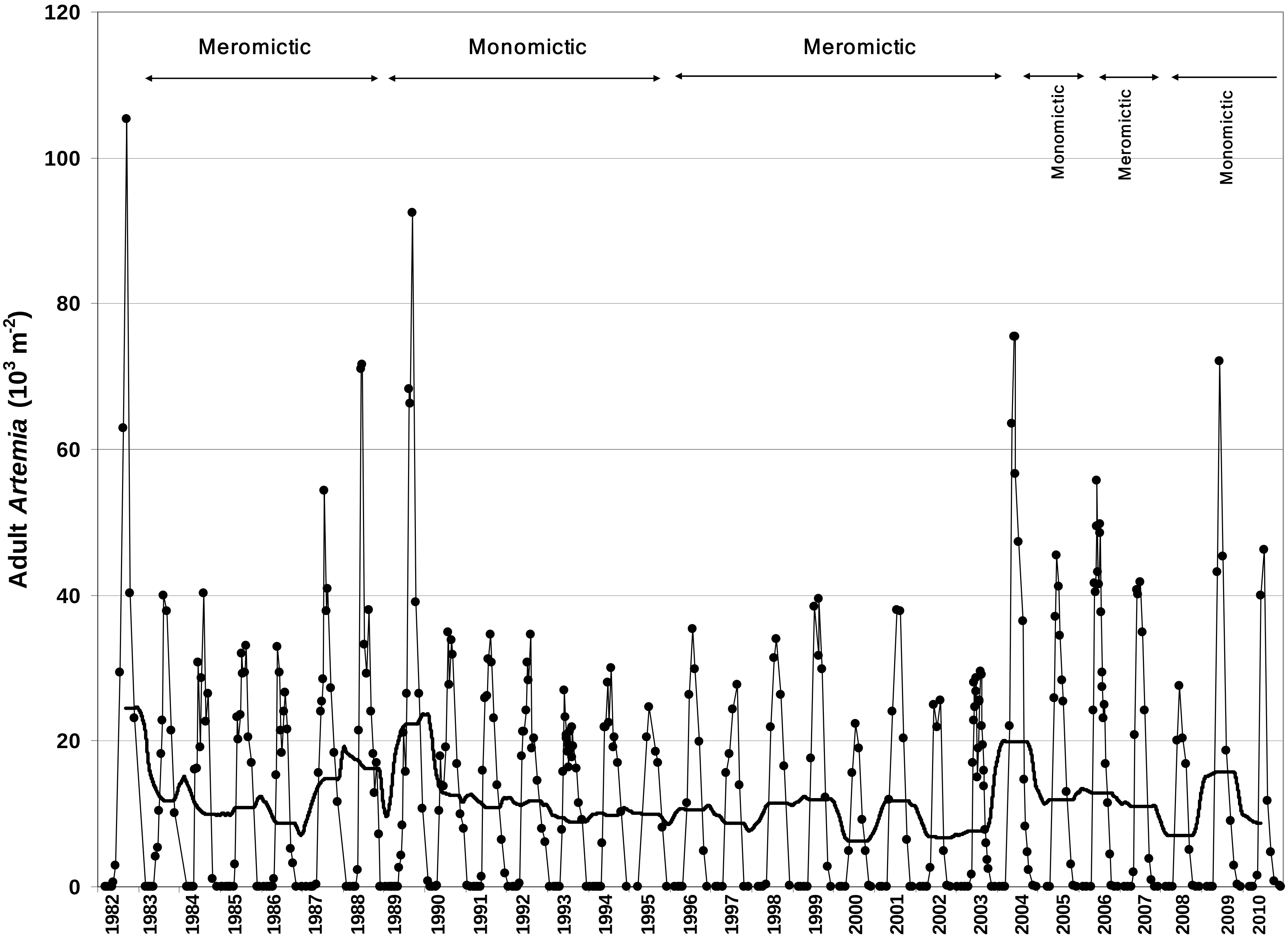

Chla = 1.0365 x year - 2044
Chl *a* (µg/l)
60
50
40
30
20
10
0
1983
1984
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
Mean Annual Chlorophyll

Figure 32



Adult *Artemia* Abundance

Figure 33

APPENDIX 2

Ornithology

MONO LAKE WATERFOWL POPULATION MONITORING

2010 Annual Report

10/26/2010

LOS ANGELES DEPARTMENT OF WATER AND POWER
PREPARED BY DEBBIE HOUSE
WATERSHED RESOURCES SPECIALIST
BISHOP, CA 93514
May 2011

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EXECUTIVE SUMMARY

Waterfowl populations were monitored in 2010 at Mono Lake, Bridgeport Reservoir, and Crowley Reservoir, as a component of the 1996 Mono Basin Waterfowl Habitat Restoration Plan. At Mono Lake, three summer ground surveys were conducted, documenting species composition, habitat use and brood production. Six fall aerial surveys were conducted at Mono Lake, Bridgeport Reservoir and Crowley Reservoir, providing an index of waterfowl numbers using each body of water during fall migration. The fall aerial surveys of Bridgeport and Crowley Reservoirs are being conducted in order to determine whether or not long-term trends observed at Mono Lake are mirrored at other Eastern Sierra water bodies or are specific to Mono Lake.

The elevation of Mono Lake has undergone annual variations in response to runoff conditions and precipitation regimes. The 2009-2010 water year in the Mono Basin was a “normal” year type and the elevation of Mono Lake declined as compared to 2009. In 2010, the region experienced a cold, wet spring, with a wetter than usual April and May and delayed snowmelt. When snowmelt commenced, larger than normal snowmelt flows occurred on the tributaries. Localized changes to lake-fringing waterfowl habitats were noted.

The four species that used the Mono Lake shoreline habitats for brooding in 2010 were Canada Goose, Gadwall, Green-winged Teal and Mallard. The number of broods detected along shoreline habitats at Mono Lake in 2010 (43) was the lowest observed since 2002, as brood counts continue to decline coincident with declining lake levels. The primary lake-fringing habitats used in 2010 were ria, unvegetated areas, and brackish lagoons. A total of nine broods of two species (Gadwall and Ruddy Duck) were observed at the Restoration Ponds in 2010.

Fall aerial surveys of Mono Lake recorded a total of 11,856 individuals and nine waterfowl species. Ruddy Ducks and Northern Shovelers were the dominant species during fall migration with Ruddy Ducks accounting for 51 % (6,049) of all detections, and Northern Shovelers accounting for 40% (4,733) of all detections. The peak one-day count of 3,293 waterfowl occurred on September 16 survey.

A total of 35,788 individuals and thirteen waterfowl species were recorded at Bridgeport Reservoir during fall aerial surveys. The most abundant species were Gadwall, Northern Shoveler and Northern Pintail. The peak number of waterfowl detected at Bridgeport Reservoir was 8,140, and occurred on September 16.

A total of 47,558 individuals and 14 waterfowl species were recorded at Crowley Reservoir during the six fall surveys. The most abundant species were Northern Shoveler, Gadwall and Ruddy Duck. The peak number detected at Crowley Reservoir was 9,802 and occurred during the September 29 survey.

Data from the past nine years indicate that brood production and waterfowl diversity have been significantly positively correlated with the surface elevation of Mono Lake. Total summer waterfowl use has tracked changes in lake elevation also, but the relationship is not statistically significant. The use of Mono Lake by waterfowl during fall migration has shown no direct relationship to lake level since regular waterfowl surveys were initiated in 1996. There has been no trend in the peak number of waterfowl using Mono Lake during fall migration since 1996.

WATERFOWL MONITORING COMPLIANCE

This report fulfills the Mono Lake waterfowl population survey and study requirement set forth in compliance with the State Water Resources Control Board (SWRCB) Order No. 98-05. The waterfowl monitoring program consists of summer ground counts at Mono Lake, fall migration counts at Mono Lake, fall comparative counts at Bridgeport and Crowley Reservoirs, and photos of waterfowl habitats taken from the air. Three summer grounds counts and six fall aerial surveys were conducted at Mono Lake in 2010. Six comparative fall aerial counts were completed at Bridgeport and Crowley Reservoirs. Photos of shoreline habitats were taken from a helicopter on October 26, 2010.

2010 Mono Lake Waterfowl Population Monitoring
Los Angeles Department of Water and Power
Prepared by Debbie House
Watershed Resources Specialist
Bishop, CA

INTRODUCTION

In 1996, the Mono Basin Waterfowl Habitat Restoration Plan (Plan) was prepared by the Los Angeles Department of Water and Power (LADWP) for the SWRCB (LADWP 1996). This plan identified restoration objectives and potential projects in addition to land management efforts designed to mitigate for the loss of waterfowl habitat due to the lowered elevation of Mono Lake. The key components of the Plan are:

a) increasing the water surface elevation of Mono Lake to 6,392 feet,
b) rewatering Mill Creek,
c) rewatering specific distributaries in the Rush Creek bottomlands,
d) implementation of the DeChambeau Pond and County Pond Restoration Project,
e) development and implementation of a prescribed burn program, and
f) control of saltcedar in lake-fringing wetlands.

The item identified as being the restoration measure of highest importance and priority was to increase the water surface elevation of Mono Lake to 6,392 feet.

The SWRCB Order WR 98-05 directed LADWP to implement the above restoration measures in the Plan and conduct monitoring to assess the success of waterfowl habitat restoration efforts. Components of the waterfowl habitat monitoring plan include the monitoring of lake levels, lake limnology and secondary producers, the mapping of riparian and lake-fringing wetland habitats, and waterfowl population surveys. The purpose of the waterfowl population survey component of the Plan is to provide information to track changes in population levels of waterfowl and assess waterfowl use of the various wetland habitats.

This report describes and discusses monitoring efforts related to evaluating waterfowl population responses to increases in Mono Lake water surface elevations. Survey data for the DeChambeau and County Restoration Ponds are also presented.

Summer ground surveys were conducted in order to determine the size of the breeding and/or summering population, species composition, spatial distribution and habitat use of waterfowl during the summer. Fall aerial surveys were conducted to provide an index of waterfowl numbers using Mono Lake during fall migration, as well as provide information on species composition and spatial distribution. Fall waterfowl surveys are also conducted at Bridgeport and Crowley Reservoirs in an effort to determine whether long-term trends observed at Mono Lake are mirrored at other Eastern Sierra water bodies or are specific to Mono Lake.

The monitoring of waterfowl populations in the Mono Basin is expected to continue until at least the year 2014, or until the targeted lake level (6,392 foot elevation) is reached and the lake cycles through a complete wet/dry cycle (LADWP 2000a).

All summer surveys were conducted by the author. Fall surveys were conducted by the author with assistance from Mr. Chris Allen, LADWP Watershed Resources Specialist.

METHODS

Summer Ground Surveys

Three ground-count surveys were conducted at Mono Lake at three-week intervals beginning in early June. All surveys were conducted as area counts, and locations were surveyed either by walking along the shoreline, along creek corridors or by making observations from a stationary point. Ground surveys were completed over three or four day periods.

Shoreline locations surveyed were those identified in the Plan as current or historic waterfowl concentration areas (Figure 1), namely: South Tufa (SOTU); South Shore Lagoons (SSLA); Sammann's Spring (SASP); Warm Springs (WASP); Wilson Creek (WICR); Mill Creek (MICR); DeChambeau Creek Delta (DECR); Rush Creek Delta (RUCR); and Lee Vining Creek bottomlands and delta (LVCR). Surveys were also conducted at the restoration ponds in the northwest: DeChambeau Ponds (DEPO) and County Ponds (COPO).

Shoreline areas including SOTU, SSLA, SASP, WASP, DECR, WICR, and MICR were surveyed by traversing the entire shoreline segment on foot, following the shoreline. In RUCR and LVCR, the creeks were surveyed from the County Road to the deltas. Surveys along lower Rush Creek were conducted by walking along the southern bluff above the creek, and traversing the delta along existing sandbars. This route offered a good view of the creek while limiting wildlife disturbance and flushing of waterfowl ahead of the observer. In Lee Vining Creek, surveys of the creek channel were conducted by walking along the north bank of the main channel, which offered the best view of the channel. At the mouth of the creek, the main channel splits in two and forms two delta areas separated by a tall earthen berm-like formation. In order to obtain good views of both delta areas, it was necessary to cross the main channel and walk on top of this berm. After viewing both delta areas from the berm, the delta areas were also traversed. In both areas, birds were observed and recorded within 100 meters on either side of the deltas.

At the Restoration Ponds, observations were taken from stationary points that allowed full viewing of each pond. A minimum of five minutes was spent at each observation point at the DeChambeau and County Ponds.

All summer ground surveys began within one hour of sunrise and were completed within approximately six hours. The order in which the various sites were visited was varied in order to minimize the effect of time-of-day on survey results. Total survey time was recorded for each area. The date and time of day for each survey during 2010 are provided in Appendix 1. The common names and scientific names for species referenced in the document can be found in Appendix 2.

Surveys along the shoreline and in Rush and Lee Vining Creeks were conducted by walking at an average rate of approximately 1.5 km/hr, depending on conditions, and recording waterfowl species as they were encountered. Because waterfowl are easily flushed, and females with broods are especially wary, the shoreline was frequently scanned well ahead of the observer in order to increase the probability of detecting broods. The following was recorded for each waterfowl observation: time of the observation; habitat type the individual or group was using; and an activity code indicating how the bird; or birds were using the habitat. The activity codes used were resting, foraging, flying over, nesting, brooding, sleeping, swimming, and “other”. Shorebirds were censused in the same manner, however shorebird data will not be presented in this document.

When a waterfowl brood was detected, the size of the brood was recorded, a GPS reading was taken (UTM, NAD 27, Zone 11, CONUS), and the location of each brood was marked on an aerial photograph while in the field. Each brood was also assigned to an age class based on its plumage and body size (Gollop and Marshall 1954). Since the summer surveys were conducted at three-week intervals, any brood assigned to Class I using the Gollop and Marshall age classification scheme (which includes subclasses Ia, Ib, and Ic), would be a brood that had hatched since the previous visit. Assigning an age class to broods allowed for the determination of the minimum number of “unique broods” using the Mono Lake wetland and shoreline habitats.

The habitat categories used generally follow the classification system found in the report entitled 1999 Mono Basin Vegetation and Habitat Mapping (LADWP 2000b). The habitat classification system defined in that report is being used for the mapping of lakeshore vegetation and the identification of changes in lake-fringing wetlands associated with changes in lake level. The specific habitat categories used in that mapping effort (and in this project) include: marsh, wet meadow, alkaline wet meadow, dry meadow/forb, riparian scrub, Great Basin scrub, riparian forest, freshwater stream, ria, freshwater pond, brackish lagoon, hypersaline lagoon, and unvegetated. Salinity measurements of ponds and lagoons were taken using an Extech EC400 Conductivity/TDS/Salinity probe in order to aid in the proper classification of fresh vs. brackish lagoons and ponds when recording habitat use. Ponds with a salinity of less than 500 ppm were classified as fresh. Lagoons with vegetation present and a salinity of greater than 500 ppm were classified as brackish. Lagoons which lacked vegetation and freshwater inflow were classified as hypersaline. For reference, the definition of each of these habitat types is provided in Appendix 3. Representative photos of these habitats can be found in the report entitled Mono Lake Waterfowl Population Monitoring 2002 Annual Report (LADWP 2003).

Two additional habitat types: open-water near-shore (within 50 meters of shore), and open-water offshore (>50 meters offshore), were added to the existing classification system in order to more completely represent areas used by waterfowl. Although a ">50 meter" category was used at the time of data collection, these observations will not be included in the final calculations unless the presence of waterfowl in the open-water offshore zone was determined to be due to observer influence (e.g., the observer sees that a female duck is leading her brood offshore and is continuing to swim away from shore).

Fall Aerial Surveys

Overview of Methodology

Aerial surveys were conducted in the fall at Mono Lake, Bridgeport Reservoir, and Crowley Reservoir using a small high-winged airplane. A total of six surveys were conducted at two-week intervals, with the first survey beginning during the first week of September, and the final fall survey occurring in the middle of November. A summary of the fall survey schedule has been provided as Appendix 4.

Each aerial survey began at Mono Lake at approximately 0900 hours. Mono Lake was surveyed in approximately one and one-half hours. Bridgeport Reservoir was surveyed next, and Crowley Reservoir was surveyed last. Fog covered Mono Lake early in the morning on November 16, delaying the survey until after the surveys at Bridgeport and Crowley Reservoirs had been completed that morning. In all cases, surveys of all three waterbodies were completed in a single flight by 1200 hours on the day of the survey.

At Mono Lake, waterfowl and shorebirds were censused, with the primary emphasis on the censusing of waterfowl. The greater concentration and diversity of waterfowl at Bridgeport and Crowley Reservoirs prevents censusing of shorebirds at these locations. This report will only present waterfowl data. Observations were verbally recorded onto a handheld digital audio recorder and later transcribed by the observer.

A second observer was present on all six flights. At Mono Lake, the second observer sat on the same side of the plane as the primary observer during the perimeter flight and censused shorebirds. During the cross-lake transect counts, observers sat on the opposite sides of the plane and counted Ruddy Ducks and other waterfowl, and phalaropes. At Bridgeport and Crowley, the second observer sat on the same side of the plane as the primary observer during the entire survey, and assisted in waterfowl counts.

Mono Lake Aerial Surveys

Aerial surveys of Mono Lake consisted of a perimeter flight of the shoreline and a set of fixed cross-lake transects. The shoreline was divided into 15 lakeshore segments (Figure 2) in order to document the spatial use patterns of fall migrant waterfowl. Coordinates forming the beginning of each segment were derived from the 2002 aerial photo of Mono Lake (2002 aerial image taken by I. K. Curtis, and processed by Air Photo, USA) and can be found in Appendix 5, along with the four-letter code for each lakeshore segment. The segment boundaries are the same as those used by Jehl (2002), except for minor adjustments made in order to provide the observer with obvious landmarks that are easily seen from the air.

The cross-lake transects covered open water areas of Mono Lake. The eight transects are spaced at one-minute (1/60 of a degree, approximately one nautical mile) intervals and correspond to those used by Boyd and Jehl (1998) for the monitoring of Eared Grebes during fall migration. The latitudinal alignment of each transect is provided in Appendix 6.

Each of the eight transects is further divided into two to four sub-segments of approximately equal length (Figure 2). The total length of each cross-lake transect was first determined from the 2002 aerial photo. These lengths were then sub-divided into the appropriate number of subsections to a total of twenty-five sub-segments, each approximately 2-km in length. This approach creates a grid-like sampling system that allows for the evaluation of the spatial distribution of species occurring offshore. The beginning and ending points for each subsection were determined using landscape features, or, when over open water, by using a stopwatch, since the survey aircraft's airspeed was carefully controlled and the approximate length of each subsection was known.

LADWP contracted with Black Mountain Air Service to conduct fixed-winged aerial counts. Black Mountain Air Service has obtained a low-altitude flight waiver from the Federal Aviation Administration in order to conduct these flights. Aerial surveys were conducted in a Cessna 180 at a speed of approximately 130 kilometers per hour, and at a height of approximately 60 meters above ground. Perimeter surveys were conducted over water while maintaining a distance of approximately 250 meters from the shoreline. When conducting aerial surveys, the perimeter flight was conducted first, and in a counterclockwise direction, starting in the Ranch Cove area. Cross-lake transects were flown immediately afterward, starting with the southernmost transect and working northwards.

In order to reduce the possibility of double-counting, only birds seen from or originating from the observer's side of the aircraft were recorded. Even though the flight path of the aircraft along the latitudinal transects effectively alternated the observer's hemisphere of observation in a North-South fashion due to the aircraft's heading on successive transects, the one-nautical-mile spacing between the transects worked in conjunction with the limited detection distance of the waterfowl (<< 0.5 nautical mile) to effectively prevent double-counting of birds on two adjacent transects.

Bridgeport Reservoir Aerial Surveys

The shoreline of Bridgeport was divided into three segments (Figure 3). Appendix 5 contains the four-letter code for each lakeshore segment and the coordinates of the beginning of each section. Survey flights started at the dam at the north end of the reservoir and proceeded counterclockwise. The distance from shore, flight speed, and height above ground were the same as employed at Mono Lake. Adjustments were made as necessary depending on lighting, lake level and waterfowl distribution. The reservoir was circumnavigated twice during each survey to allow for a second count of often large concentrations of mixed species flocks.

Crowley Reservoir Aerial Surveys

The shoreline of Crowley Reservoir was divided into seven segments (Figure 4). Coordinates forming the beginning of each segment were generated from the 2000 aerial photo of Crowley

Reservoir (2000 aerial image taken by I. K. Curtis, and processed by Air Photo, USA) and can be found in Appendix 5, as well as the four-letter code used for each segment. Each survey began at the mouth of the Owens River (UPOW) and proceeded over water in a counterclockwise direction along the shoreline. The distance from shore, flight speed, and height above the water were the same as at Mono Lake during most of each flight. Temporary diversions of distance from shore or height above ground were made by the pilot as necessary to avoid direct or low flight over float-tubers or boats. Adjustments were also made as necessary depending on lighting, lake level and waterfowl distribution. The reservoir was circumnavigated twice during each survey to allow for a second count of often large concentrations of mixed species flocks.

Ground Verification Counts

Ground verification counts were conducted whenever flight conditions (e.g., lighting, background water color, etc.) did not allow the positive identification of a significant percentage of the waterfowl encountered, or to confirm the species or number of individuals present. During a ground validation count, the total number of waterfowl present in an area was recorded first, followed by a count of the number of individuals of each species present.

Photo Documentation

As required by the Order 98-05, photo documentation of lake-fringing waterfowl habitats was completed in 2010. Photos were taken from a helicopter at all bodies of water on October 26, 2010. In 2010, shoreline conditions were also documented using a helicopter-mounted, geo-referenced video camera. Photos depicting the condition and available habitats for each shoreline segment are described under Data Summary below.

Data Summary and Analysis

2010 Summer Ground Count Data

Total detections of each species were summed by lakeshore segment for each survey. Total detections were also summed over the entire summer survey period, and the percent of total detections per lakeshore segment was calculated. Total numbers of broods per species, survey and lakeshore segment were also summed.

Chi-square goodness-of-fit analysis was used to determine if individual waterfowl species used any of the various habitats in a disproportionate manner. This analysis was done for the most abundant summering species, provided that the behavior of at least 30 individuals had been recorded. All habitat use observations except those of flyovers were included in this analysis. The waterfowl species for which habitat use data were analyzed were Canada Goose, Gadwall, and Mallard. For all significant goodness-of-fit tests, Bonferonni confidence intervals were calculated for each category, following Byers and Steinhorst (1984), to determine which specific habitats were used out of proportion with respect to the others.

2010 Fall Aerial Count Data

The total number of waterfowl of each species was summed by lakeshore segment and survey for each survey and water body. The spatial distribution of waterfowl at each body of water was determined by calculating the proportion of all fall detections that occurred in each lakeshore segment or offshore.

Evaluation of Trend in Waterfowl Populations

Simple linear regression analysis was used to evaluate trends in summer waterfowl detections, waterfowl diversity, the number of broods and total fall detections as a function of lake elevation. The reference elevations used for analyses were June for summer data, and September for fall data. Elevation data was obtained from the Mono Basin Clearinghouse (http://www.monobasinresearch.org/data/levelmonthly.htm) maintained by the Mono Lake Committee. Simple linear regression analysis was used to evaluate the trend in total fall detections and in peak one-day waterfowl numbers at Mono Lake since 1996. The analysis of peak one-day counts was done excluding Ruddy Duck numbers due to the difference in survey methods employed for this species from 1996 to 2001 versus 2002 to present. Regression equations were tested using ANOVA to determine the significance of the regression, (i.e. “Is the slope significantly different from zero?” Zar 1996).

RESULTS

Description of Shoreline Conditions in 2010

Mono Lake

The 2009-2010 water year in the Mono Basin was “Normal” year type with a predicted runoff of 104% of the 1941-1990 average runoff (see Order WR 98-05). The region experienced a cold, wet spring, with a wetter than usual April and May and delayed snowmelt. When snowmelt commenced, larger than normal snowmelt flows occurred on the tributaries. During the early June survey, snowmelt had not yet commenced, and many areas appeared much drier than during subsequent surveys. At 6381.9 feet, the lake level was 0.6 feet lower in early summer (June) than it had been during the same time in 2009. The lake level rose slightly (0.2 feet) through the summer survey period, and then decreased to an elevation of 6381.8 feet by the start of fall surveys in September. A cold front in October brought more than one inch of rain to the Mono Basin, causing a noticeable increase to the water level in most of the lake-fringing lagoons. Photos of shoreline habitats were taken after this precipitation event, and the increase in water levels in some lake-fringing lagoons as compared to conditions noted during summer and early fall is apparent. The overall decrease in lake elevation as compared to 2009 resulted in qualitative differences in lake-fringing habitats for waterfowl during the 2010 monitoring period, some of which are discussed below.

South Shoreline Areas (South Tufa, South Shore Lagoons, and Sammann’s Spring)

The western portion (near the South Tufa visitor area) continued to support mudflats due to spring outflow, while the shoreline area east of Navy Beach was dominated by exposed dry playa (Figure 5). Erosion was evident as the shoreline was unusually steep for this area. In early June, very small areas supporting hypersaline and brackish lagoons existed in the eastern portion of South Tufa. The slight rise in lake elevation through the summer resulted in a small increases in the extent of the existing lagoons.

The numerous isolated lagoons along the length of the South Shore Lagoons area continued to contract with decreasing lake elevation. The brackish lagoon at the west end of the South Shore Lagoons area, which receives much use when full, remained quite contracted, and few waterfowl were observed using the lagoon (Figure 6). The fresh water pond approximately 1.2 km farther east (Figure 7), no longer had standing water. At Sand Flat Spring some outflow to the lake had been re-established in early summer, however by fall, outflow was once again isolated from the lake (Figure 8). The main area of waterfowl use in 2010 along the South

Shore Lagoons area was the Goose Springs outflow area (Figure 9). Significant changes were noted in the Goose Springs area resulting in localized increases in the area of freshwater and brackish lagoons. Since 2002, the outflow from the Goose Springs complex has flowed west, filling a series of three shallow fresh water ponds. A spring channel then either carried the flow directly to the lakeshore, or, since 2008, been diverted westward and retained by a sand bar, forming an extensive brackish lagoon which received much use by waterfowl, especially in fall. In 2010, outflow from Goose Springs had shifted eastward, causing a decline in the level of freshwater ponds west of the springhead. These ponds to the west now had extensive algae growth on their surfaces. Based on field observations, it was deduced that perhaps some slumping had occurred due to the decline in lake level, and water was now spilling toward the east, resulting in the initiation of flooding of new areas of meadow habitat. More shoreward, a brackish lagoon formed in the immediate vicinity of Goose Springs.

In the Sammann's Spring shoreline segment, west of Sammann's Spring faultline, a littoral bar had formed along much of the shoreline area (Figure 10). The ponds that formed behind this berm were primarily shallow fresh water ponds due to the abundance of spring flow in this region. Small freshwater ponds continued to persist up gradient of littoral bars. More broods were seen in the Sammann's Spring area in 2010 than have been observed since 2002, possibly due to the shoreline configuration this year. East of the tufa grove, brackish lagoons continued to persist (Figure 11).

Warm Springs and Northeast Shore

There were no notable changes in the Warm Springs area as compared to 2009. Some of the flooding shown in Figure 12 is the result of the October rain event mentioned previously. The "north lagoon" which is supported by the outflow of Pebble and Twin Warm Springs, continued to be the primary area of waterfowl use on the east side of the lake. The south lagoon, supported by outflow from Warm Springs Marsh Channel, Warm B, and Bug Warm springs, was essentially dry throughout much of 2010. Since 2002, this south lagoon has been much smaller than the northern lagoon and less attractive to ducks and other waterbirds. In 2010 the Northeast Shore area was dominated by barren playa and did not support lagoons (Figure 13).

Bridgeport Creek, DeChambeau Embayment and Black Point

This area of the shoreline typically consists of several small lagoons with alkali meadow and or small areas of wet alkali meadow adjacent. Small isolated lagoons continued to persist in the shoreline area between Bridgeport Creek and Black Point (Figures 14 - 16) although the lagoons have contracted as the lake elevation has declined. These lagoons typically attract small numbers of waterfowl in the fall.

Northwest Shore (Wilson, Mill Creek and DeChambeau Creeks)

Qualitative changes were also noted along the northwest shore of the lake, from the Wilson Creek area to the DeChambeau Creek area. During the early June survey, there was extensive exposed shoreline in the Wilson Creek area. As runoff increased and the lake level increased slightly, the entire Wilson Creek delta area became quite wet. Figure 17 shows the condition of Wilson Creek in late fall. Head cuts persisted along the numerous outflow channels from Wilson Creek and are visible in Figure 18. At Mill Creek (Figure 18), the fresh water pond perched behind a gravel bar along the shoreline that formed in 2007 was now drained due to headcutting. In the DeChambeau Creek area (Figure 19), there were slight increases in the amount of exposed shoreline as compared to 2010. Due to the numerous springs in the area, the fresh water outflow creates extensive mudflats along the exposed shoreline areas. Very small fresh water ponds existed near shore where spring outflow was retained behind small sandbars.

West Shoreline (West Shore, Lee Vining Creek, Ranch Cove and Rush Creek)

The West Shore area (Figure 20) supports primarily meadow and riparian scrub habitats, but lacks lagoons. No significant changes were noted in 2010. In 2010 Lee Vining Creek experienced a large magnitude snowmelt flood that peaked on June 7. This resulted in a breach in the sand bar in the north arm of the delta and extensive flooding over the entire delta in the south arm. By early July, after a return to base flows, the amount of water going to the north arm decreased notably. Figure 21 shows conditions at the Lee Vining Creek delta in late fall. The Ranch Cove area (Figure 22) has limited fresh water input, and does not support lagoons due to the gradient. The area continued to be dominated by sandy beach and upland vegetation. Rush Creek received a higher than expected peak flow, given the overall runoff prediction. The peak flows in Rush Creek occurred in early July, however flows above the normal, prescribed base flow continued through much of July. Sandbars at the delta were breached resulting in numerous outflow areas to the lake (Figure 23).

Restoration Ponds

Both County Ponds were flooded in 2010. There was little open water visible at County Pond West due to the extensive growth of emergent vegetation. All of the DeChambeau Ponds were flooded except DeChambeau Pond five, which remained dry all year.

Bridgeport Reservoir

In September, the reservoir held 17,610 acre-feet (Department of Water Resources, California Data Exchange Center, http://cdec.water.ca.gov/cgi-progs/queryMonthly?s=BDP&d=today), approximately twice as much as at the same time 2009. As a point of reference, the storage capacity of Bridgeport Reservoir is 42,600 acre-feet. Figure 24 shows an overview of the reservoir as viewed from the south end looking north toward the dam. The south end of the reservoir, which includes the area referred to as "West Bay", and part of the "East Arm" area, receives fresh water inflows from Buckeye and Robinson Creeks and the East Walker River, creating extensive mudflat areas adjacent to these creek inflow areas. The northern arm of the reservoir includes primarily sandy beaches bordered by upland vegetation. The increase in elevation since 2009 resulted in the flooding of shoreline vegetation, especially the outflow of the East Walker River, and reduced area of exposed bare reservoir bottom.

Crowley Reservoir

In early September, Crowley Reservoir held 89,700 acre-feet (Department of Water Resources, California Data Exchange Center, http://cdec.water.ca.gov/cgi-progs/queryMonthly?s=crw&d=today). The elevation of Crowley Reservoir thus was lower than at the same time in 2009. As a point of reference, the storage capacity of Crowley Reservoir is 183,465 acre-feet. In September there was evidence of heavy algal growth, however the water appeared much clearer by the end of September. Figures 25-31 depict habitat conditions of each shoreline segment at Crowley Reservoir. The Upper Owens River delta area (Figure 25) includes large areas of exposed mudflats and reservoir bottom adjacent to the mouth of the Upper Owens River. Most of the length of Sandy Point area (Figure 26) is adjacent to elevated areas and upland vegetation. Small areas of meadow habitat occur in this area also. North Landing is largely bordered by meadows (Figure 27). The McGee Bay area (Figure 28) supports vast mudflat areas immediately adjacent to wet meadow habitats, and receives inflow from McGee Creek. Hilton Bay (Figure 29) is surrounded by meadow habitats, and receives some fresh water input from Hilton Creek. The Chalk Cliffs area (Figure 30) lacks fresh water inflow areas and wetland habitats, and is dominated by sandy beaches adjacent to steep, sagebrush-covered slopes. Layton Springs provides spring flow at the southern border of this lakeshore segment. The remainder of the area is bordered by upland vegetation and a large area of sandy beach in 2010 (Figure 31).

2010 Summer Ground Counts

The number of waterfowl detected in each shoreline area during each survey can be found in Table 1. Table 2 summarizes the summer survey data in terms of the number of detections of each species, total waterfowl detections, and the percent of total detections for each shoreline area. A total of 8 species of waterfowl were encountered during summer surveys. The total number of waterfowl using the shoreline (exclusive of dependent young) detected during summer surveys was highest (290) during the early June count and lowest (198) on the late July survey. The highest proportion of detections was in the northwest shore, including Wilson, Mill and DeChambeau Creek areas and at Sammann's Spring. Large numbers of waterfowl were present in Lee Vining Creek only on the early June survey. The fewest number of waterfowl were at the South Tufa area.

The waterfowl species that brooded in the lake-fringing wetlands and creeks at Mono Lake in 2010 were Canada Goose, Gadwall, Green-winged Teal and Mallard. The number of broods of each species in each shoreline area can be found in Table 3. Figure 32 shows the locations of all of the broods detected in 2010. The number of broods detected in lake-fringing habitats (43) was the lowest observed since 2002. The south shoreline, primarily Sammann's Spring and the Goose Springs area of South Shore Lagoons, was the area most heavily used for brooding as 11 and 7 broods were detected in these areas respectively. Wilson Creek was the next most heavily used, as eight broods were observed here.

Habitat Use

All three waterfowl species analyzed showed a disproportionate use of the various shoreline habitats in 2010. Table 4 provides the tabulated habitat use data, the chi-squared goodness-of-fit results, and the Bonferonni test results for the three species for which an adequate number of observations were obtained: Canada Goose, Gadwall, and Mallard. Figure 33 is a bar graph depicting the proportional use of habitats by each of these species. Canada Geese were observed using primarily unvegetated areas, meadow habitats, and open water areas near shore, with unvegetated areas used disproportionally more than other habitats. Gadwall were observed most frequently using ria, unvegetated areas, and brackish lagoons. Ria was used significantly more than other habitats. Mallard used brackish lagoons disproportionally, but were also seen observed using fresh water ponds and ria among other habitat types.

2010 Fall Aerial Surveys

Fall Aerial Survey Weather Conditions

The weather was fairly mild throughout the fall count period. In early-October, a wet system passed through resulting in more than one inch of rain in the Mono Basin, filling shore-fringing lagoons and depressions.

Mono Lake

A total of nine waterfowl species and 11,856 individuals were recorded at Mono Lake during fall aerial surveys (Table 5). The peak number of waterfowl detected at Mono Lake on any single count was 3,293 and occurred on the September 16 survey (Table 5, Figure 34). Compared to the 2009 counts, the total number of detections was 57% lower than 2009 (11,856 vs. 27,861 in 2009) while the one-day peak count in 2010 was approximately 58% less than that observed in 2009 (3,293 vs. 7,920 in 2009). The peak number of Northern Shoveler (2,803) occurred on September 16, and the peak number of Ruddy Ducks (2,658) occurred on October 27.

In terms of total detections, Ruddy Ducks and Northern Shovelers were the dominant species during fall migration with Ruddy Ducks accounting for 51 % (6,049) of all detections, and Northern Shovelers accounting for 40% (4,733) of all detections. Use of Mono Lake by Northern Shoveler was approximately one-third that observed in 2009 as evidenced by a comparison of the total detections. Use of Mono Lake by Ruddy Ducks in 2010 was roughly half that observed in 2009. Ruddy Duck numbers were unusually low in early September.

Tables 6 through 11 provide the results of each of the six fall surveys in terms of the number of individuals of each species detected in each lakeshore segment. The main areas of waterfowl use during fall 2010 were Wilson Creek and Sammann's Spring (Figure 35).

Bridgeport Reservoir

A total of 13 waterfowl species and 35,788 individuals were recorded at Bridgeport Reservoir during the 2010 fall aerial surveys (Table 12). The peak number of waterfowl detected on any single count at Bridgeport Reservoir was 8,140 individuals, which occurred on September 16 (Table 12, Figure 34). The most abundant species, in terms of total detections, were Gadwall, Northern Shoveler, and Northern Pintail. Tables 13-18 provide the results of each of the six fall surveys in terms of number of each species detected by lakeshore segment. The most heavily used area of the lake was the West Bay, accounting for 94% of all detections (Figure 37).

Crowley Reservoir

A total of 14 waterfowl species and 47,558 individuals were detected at Crowley Reservoir during the 2010 fall aerial surveys (Table 19). The peak number of waterfowl detected on any single count at Crowley Reservoir was 9,802 individuals and occurred on September 29 (Table 19, Figure 34). The most abundant species, in terms of total detections, were Northern Shoveler, Gadwall and Ruddy Duck. Tables 20-25 provide the results of each of the six fall surveys in terms of number of each species detected by lakeshore segment. The primary area of waterfowl use was McGee Bay (Figure 37).

Mono Lake Restoration Ponds

A total of seven species and 74 waterfowl were detected at the Restoration Ponds during summer surveys (Table 26). The most abundant species were Gadwall, Cinnamon Teal and Ruddy Duck. A total of nine broods were seen, including four Gadwall and five Ruddy Duck broods (Table 27).

A total of 160 individuals were detected at the DeChambeau and County Pond complexes during fall surveys (Table 28).

Trend Analysis – Mono Lake

Although the total number of summer waterfowl detections appears to have tracked changes in lake elevation (Figure 38), the data do not indicate a statistically significant relationship ($r = 0.636$, $p = 0.066$). Summer waterfowl diversity however has been significantly positively correlated to changes in lake elevation (Figure 39), ($r = 0.672$, $p = 0.048$) as has the number of broods ($r = 0.87$, $p<0.05$) (Figure 40). In addition, the distribution of broods has varied as a function of lake elevation since 2002 (see Figure 41). From 2002-2005, the lake elevation was declining, and during this period, the northwest shoreline areas supported the bulk of the broods, and the proportion of broods detected in this region increased through this period. From 2006-2007 the lake experienced an increase in elevation, and the proportion of broods in the northwest shore area decreased while the proportion increased along the south shore. Following declines in lake elevation starting in 2008, breeding waterfowl have in general shifted activity back towards the northwest shore area. In 2010, the south shoreline area saw an increase in use despite a drop in lake elevation, likely due to localized changes in shoreline configuration that created favorable conditions for brooding in the Goose Springs and west Sammann's Spring area.

Based on waterfowl counts conducted since 1996, the total number of fall detections has varied independently of lake elevation ($r = -0.38$, $p = 0.098$) Figure 42. Figure 43 illustrates the trend in the peak number of waterfowl detected at Mono Lake from 1996-2010. There has been no trend in the peak number of waterfowl, exclusive of Ruddy Ducks ($r = 0.391$, $p = 0.149$, $F = 2.348$ $df = 14$).

DISCUSSION

Response of Waterfowl Populations to Restoration Efforts

Data from the summer surveys indicate that fluctuations in the elevation of Mono Lake have influenced the breeding waterfowl population. Brood production and waterfowl diversity have been significantly positively correlated with the level of Mono Lake for the time period 2002-2010. Variations in lake elevation also explain 63% of the variability in the total number of waterfowl using the lake in summer.

In most shoreline areas, increases in lake elevation have been associated with changes to lake-fringing habitats that increase quality and quantity of potential breeding habitat for waterfowl. Between 2002 and 2004, Mono Lake experienced a drop in elevation followed by a subsequent rise in elevation from 2004 to 2006, and then a decline from 2007 thru 2010. Increases in elevation, (at least within the elevation ranges observed), result in increases in the number and extent of lake-fringing lagoons, especially the South Shore Lagoons area. Based on field observations, these lagoons enlarge due either to increases in the groundwater table or as a result of increased spring flow. Direct precipitation likely has less effect on these areas during June and July. The breeding population of waterfowl at Mono Lake appears to respond positively to these changes as increases in brood production, species diversity and size of the breeding population have been associated with increases in lake elevation.

Breeding waterfowl have also responded to lakeshore changes with a shift in distribution. From 2002-2005, the lake elevation was declining. During this period, the Northwest Shore supported the bulk of the broods, and the proportion of broods detected in this region increased through this period. From 2006-2007 the lake experienced an increase in elevation, and the proportion of broods in the northwest shore area subsequently decreased while the proportion detected along in the South Shoreline increased. Brooding waterfowl were observed using many of the ephemeral lagoons that had developed at the elevated lake level. As the lake declined further in 2008-2009, and lagoons along the south shore have continued to retract, breeding waterfowl have again shifted back towards the Northwest Shore areas. In 2010, localized changes in the Goose Springs area created newly flooded fresh water ponds and brackish lagoons that attracted breeding waterfowl to this area.

Summering and breeding waterfowl have shown a great deal of annual variability with regard to the proportional use of the various lake-fringing habitats. The dabbling ducks have generally been encountered in brackish lagoons, fresh water ponds, using “ria” or areas of freshwater outflow at the mouths of creeks and spring outflow onto the lake, and in unvegetated areas along the shoreline. Canada Geese have typically been encountered in unvegetated areas or meadow habitats. The habitats in which waterfowl at Mono Lake are encountered are ephemeral or highly variable in nature and extent on a yearly basis. The availability of the more ephemeral habitat types on a yearly or seasonal basis are being documented through field observations of conditions during the summer and annual photography of shoreline areas in the fall, but habitat conditions that may explain waterfowl use and the spatial distribution of waterfowl at Mono Lake are not readily quantified during existing vegetation mapping efforts being conducted every five years.

The use of Mono Lake by waterfowl during fall migration in terms of the total number of detections has shown no direct relationship to lake level. There has been no significant trend in the peak number of waterfowl during fall migration (exclusive of Ruddy Ducks) for the time period of 1996-2010. The relationship between trends in waterfowl use and lake limnology at Mono Lake, and comparison with fall counts at Bridgeport and Crowley Reservoirs will be presented in a future document.

REFERENCES

Boyd, W. S. and J. R. Jehl, Jr. 1998. *Estimating the Abundance of Eared Grebes on Mono Lake, California by Aerial Photography*. Colonial Waterbirds 21(2): 236-241.

Gollop, J. B. and W. H. Marshall. 1954. *A Guide to Aging Duck Broods in the Field.* Mississippi Flyway Council Technical Section. 14 pp. Northern Prairie Wildlife Research Center Home Page.

Jehl, J. R. Jr. 2002. *Waterfowl Populations at Mono Lake, California, 2001.* Hubbs-Sea World Research Institute. Technical Report 2002-330.

Los Angeles Department of Water and Power (LADWP). 1996. *Mono Basin Waterfowl Habitat Restoration Plan.* Prepared for the State Water Resources Control Board. In response to Mono Lake Basin Water Right Decision 1631.

Los Angeles Department of Water and Power (LADWP). 2000a. *Mono Basin Implementation Plan*. To comply with State Water Resources Control Board Decision 1631 and Order No. 98-05 and 98-07.

Los Angeles Department of Water and Power (LADWP). 2000b. 1999 *Mono Basin Vegetation and Habitat Mapping.*

Los Angeles Department of Water and Power (LADWP). 2003. *Mono Lake Waterfowl Population Monitoring – 2002 Annual Report.* Prepared by Debbie House. April 2003.

Zar, J. 1996. *Biostatistical Analysis.* Third Edition. Prentice Hall. New Jersey.

Table 1. 2010 Summer Ground Count Data

Survey 1	DECR	LVCR	MICR	RUCR	SASP	SOTU	SSLA	WASP	WICR	Total
Canada Goose	4					2	2		2	10
Cinnamon Teal							2	7		9
Gadwall	22	100	14	7	15	2	6	26	14	206
Green-winged Teal		1		14	1					16
Mallard	3	6		6	10		6	13	1	45
Northern Pintail					2			2		4
Total Waterfowl by Area	**29**	**107**	**14**	**27**	**28**	**4**	**16**	**48**	**17**	**290**

Survey 2	DECR	LVCR	MICR	RUCR	SASP	SOTU	SSLA	WASP	WICR	Total
Brant	1							1		2
Canada Goose	15				12	8			14	49
Cinnamon Teal					2					2
Gadwall	6	2	40	2	23		13	1	106	193
Green-winged Teal			1	1						2
Mallard					2		1			3
Ruddy Duck			6							6
Total Waterfowl by Area	**22**	**2**	**47**	**3**	**39**	**8**	**14**	**2**	**120**	**257**

Survey 3	DECR	LVCR	MICR	RUCR	SASP	SOTU	SSLA	WASP	WICR	Total
Canada Goose	27				21				22	70
Cinnamon Teal					2					2
Gadwall	4	5	45	4	9	1	1		26	95
Green-winged Teal		4		1						5
Mallard		5		2	2		3	5		17
Ruddy Duck			9							9
Total Waterfowl by Area	**31**	**14**	**54**	**7**	**34**	**1**	**4**	**5**	**48**	**198**

Table 2. Summary of 2010 Summer Ground Count Data
Table shows the total detections of each species in each shoreline area, total waterfowl detections by area, and the percent of total detections by area.

Species	DECR	LVCR	MICR	RUCR	SASP	SOTU	SSLA	WASP	WICR	**Total**
Brant	1							1		2
Canada Goose	46				33	10	2		38	129
Cinnamon Teal					4		2	7		13
Gadwall	32	107	99	13	47	3	20	27	146	494
Green-winged Teal		5	1	16	1					23
Mallard	3	11		8	14		10	18	1	65
Northern Pintail					2			2		4
Ruddy Duck			15							15
Total Detections	**82**	**123**	**115**	**37**	**101**	**13**	**34**	**55**	**185**	**745**
% of Detections	11.0%	16.5%	15.4%	5.0%	13.6%	1.7%	4.6%	7.4%	24.8%	

Table 3. 2010 Brood Data

Table shows the number of broods by species per visit in shoreline survey area.

	Shoreline Segment	DECR	LVCR	MICR	RUCR	SASP	SOTU	SSLA	WASP	WICR	**Total**
Survey 1	Canada Goose	2					1	1		1	**5**
	Gadwall										**0**
	Green-winged Teal										**0**
	Mallard				1			1			**2**
	Total Broods	2	0	0	1	0	1	2	0	1	**7**
Survey 2	Canada Goose	1									**1**
	Gadwall				1	3		2			**6**
	Green-winged Teal										**0**
	Mallard										**0**
	Total Broods	1	0	0	1	3	0	2	0	0	**7**
Survey 3	Canada Goose					2					**2**
	Gadwall	2	2	3	3	6		1		7	**24**
	Green-winged Teal				1						**1**
	Mallard							2			**2**
	Total Broods	2	2	3	4	8	0	2	0	7	**28**
Total	Shoreline Segment	DECR	LVCR	MICR	RUCR	SASP	SOTU	SSLA	WASP	WICR	**Total**
	Canada Goose	3				2	1	1		1	**8**
	Gadwall	2	2	3	4	9		3		7	**30**
	Green-winged Teal				1						**1**
	Mallard				1			3			**4**
	Total broods per area	5	2	3	6	11	1	7	0	8	**43**

Table 4. Chi Square Goodness-of-Fit Results for Waterfowl Habitat Use Data
Grayed categories were excluded from analysis. The results of the Bonferroni Test are indicated in the "Sign" (= significance) column. NS indicates that there was no significant difference between expected and observed use of a habitat type at the $p < 0.05$ level.

	Canada Goose				Gadwall				Mallard			
Habitat	Obs	Exp	χ^2	Sign	Obs	Exp	χ^2	Sign	Obs	Exp	χ^2	Sign
Marsh					4	48.8	41.1	-	3	9.28	4.3	-
Dry Meadow					2	48.8	44.8	-				
Wet Meadow	19	23.6	0.9	NS	2	48.8	44.9	-				
Alkali Wet Meadow	7	23.6	11.7	-								
Freshwater Stream					12	48.8	27.8	-	8	9.28	0.2	NS
Ria	11	23.6	6.727	-	279	48.8	1085.9	+	13	9.28	1.5	NS
Fresh Water Pond					28	48.8	8.9	-	15	9.28	3.5	NS
Brackish Lagoon					62	48.8	3.6	NS	22	9.28	17.4	+
Hypersaline Lagoon					4	48.8	41.1	-				
Unvegetated	45	23.6	19.4	+	68	48.8	7.6	NS	3	9.28	4.3	-
Open Water	36	23.6	6.5	NS	27	48.8	9.7	-	1	9.28	7.4	-
Total	118		45.2		488		1315.4		65		38.5	

Table 5. Summary of 2010 Mono Lake Fall Aerial Survey Count Data

Species	1-Sep	16-Sep	29-Sep	14-Oct	27-Oct	16-Nov	Total detections	% Total
Canada Goose				52	77	25	154	1.3%
Gadwall	27	10	49	43	27	18	174	1.5%
Green-winged Teal		27	12	5	14		58	0.5%
Lesser Scaup					2		2	<0.1%
Mallard	56	35	6	104	22	109	332	2.8%
Northern Pintail		6	220	4	10		240	2.0%
Northern Shoveler	742	2803	833	238	112	5	4733	39.9%
Ruddy Duck	25	412	912	1001	2658	1041	6049	51.0%
Snow Goose						15	15	0.1%
Unidentified diving duck			1				1	<0.1%
Unidentified Teal	10			28	20	40	98	0.8%
Total Waterfowl	860	3293	2033	1475	2942	1253	11856	

Table 6. Mono Lake - Fall Aerial Survey, September 1, 2010

	Lakeshore Segment															**Shoreline**	**Offshore**	**Lakewide**
Species	RUCR	SOTU	SSLA	SASP	WASP	NESH	BRCR	DEEM	BLPO	WICR	MICR	DECR	WESH	LVCR	RACO	**Total**	**Total**	**Total**
Gadwall	7		2		12									5		26	1	27
Mallard	6		12	15	3					20						56		56
Northern Shoveler	10			65				1		568	85	5	6	2		742		742
Ruddy Duck											25					25		25
Unidentified Teal											10					10		10
Total Waterfowl	23	0	12	80	15	0		1	0	588	120	5	6	7	0	**859**	**1**	**860**

Table 7. Mono Lake - Fall Aerial Survey, September 16, 2010

	Lakeshore Segment															**Shoreline**	**Offshore**	**Lakewide**
Species	RUCR	SOTU	SSLA	SASP	WASP	NESH	BRCR	DEEM	BLPO	WICR	MICR	DECR	WESH	LVCR	RACO	**Total**	**Total**	**Total**
Gadwall														10		10		10
Green -winged Teal			12	3							10	2				27		27
Mallard			5	25							5					35		35
Northern Pintail													5	1		6		6
Northern Shoveler	8			403			5	7		2200	120	50	5		5	2803		2803
Ruddy Duck				5							92	60	7	7	2	173	239	412
Total Waterfowl	8	0	5	436	0	0	5	7	0	2200	217	112	17	18	7	**3054**	**239**	**3293**

Table 8. Mono Lake - Fall Aerial Survey, September 29, 2010

Species	Lakeshore segment															**Shoreline**	**Offshore**	**Lakewide**
	RUCR	SOTU	SSLA	SASP	WASP	NESH	BRCR	DEEM	BLPO	WICR	MICR	DECR	WESH	LVCR	RACO	**Total**	**Total**	**Total**
Gadwall				8									5	4	4	21	28	49
Green-winged Teal														12		12		12
Mallard					6											6		6
Northern Pintail										220						220		220
Northern Shoveler	4		5	227				2		400	60	120		15		833		833
Ruddy Duck	22	1									79	65	97		23	287	625	912
Unidentified Diving Duck																0	1	1
Total Waterfowl	**26**	**1**	**5**	**235**	**6**			**2**		**620**	**139**	**185**	**102**	**31**	**27**	**1379**	**654**	**2033**

Table 9. Mono Lake - Fall Aerial Survey, October 14, 2010

	Lakeshore Segment															**Shoreline**	**Offshore**	**Lakewide**
Species	RUCR	SOTU	SSLA	SASP	WASP	NESH	BRCR	DEEM	BLPO	WICR	MICR	DECR	WESH	LVCR	RACO	**Total**	**Total**	**Total**
Canada Goose			15	12				25								52		52
Gadwall			3	5	15			2			5	5				35	8	43
Green -winged Teal										5						5		5
Mallard			4		75					25						104		104
Northern Pintail								4								4		4
Northern Shoveler				180				5		30		23				238		238
Ruddy Duck	2	52	7	25		5		2		5	12	15	74	16	70	285	716	1001
Unidentified Teal		3		10	5					10						28		28
Total Waterfowl	2	55	29	232	95	5	0	38	0	75	12	43	74	16	70	**751**	**724**	**1475**

Table 10. Mono Lake - Fall Aerial Survey, October 27, 2010

Species	Lakeshore segment															**Shoreline**	**Offshore**	**Lakewide**
	RUCR	SOTU	SSLA	SASP	WASP	NESH	BRCR	DEEM	BLPO	WICR	MICR	DECR	WESH	LVCR	RACO	**Total**	**Total**	**Total**
Canada Goose				33				44								77		77
Gadwall				16								6		1		23	4	27
Green-winged Teal										12		2				14		14
Lesser Scaup	2															2		2
Mallard			12		6					4						22		22
Northern Pintail												10				10		10
Northern Shoveler	8			45						55						108	4	112
Ruddy Duck	9	6		3		10		3	2		1	2	56	10	6	108	2550	2658
Unidentified Teal			15		5											20		20
Total Waterfowl	**19**	**6**	**27**	**97**	**11**	**10**		**47**	**2**	**71**	**1**	**20**	**56**	**11**	**6**	**384**	**2558**	**2942**

Table 11. Mono Lake - Fall Aerial Survey, November 16, 2010

Species	Lakeshore segment															**Shoreline Total**	**Offshore Total**	**Lakewide Total**
	RUCR	SOTU	SSLA	SASP	WASP	NESH	BRCR	DEEM	BLPO	WICR	MICR	DECR	WESH	LVCR	RACO			
Canada Goose							6	19								25		25
Gadwall		7	3									8				18		18
Mallard	3			5	2			4		65						79	30	109
Northern Shoveler												1				1	4	5
Ruddy Duck	6	8				2			54	2	23	1	97	24	37	254	787	1041
Snow Goose																	15	15
Unidentified Teal										5	30		5			40		40
Total Waterfowl	**9**	**15**	**3**	**5**	**2**	**2**	**6**	**23**	**54**	**72**	**53**	**10**	**102**	**24**	**37**	**417**	**836**	**1253**

Table 12. Summary of 2010 Bridgeport Reservoir Fall Aerial Survey Count Data

Species	1-Sep	16-Sep	29-Sep	14-Oct	27-Oct	16-Nov	Total detections	% Total
American Wigeon		10				3	13	<0.1%
Bufflehead				4	44	109	157	0.4%
Canada Goose	37	45	60	80	110	298	630	1.8%
Cinnamon Teal	103	11					114	0.3%
Common Goldeneye						6	6	<0.1%
Common Merganser	12	20	25	23	1	7	88	0.2%
Gadwall	1210	2812	3019	1627	731	1667	11066	30.9%
Green-winged Teal	250	5	759	500	928	1570	4012	11.2%
Mallard	145	255	637	445	962	935	3379	9.4%
Northern Pintail	200	193	1411	2504	516	725	5549	15.5%
Northern Shoveler	1516	4609	306	420	202		7053	19.7%
Ruddy Duck		120		650	118	63	951	2.7%
Tundra Swan						25	25	0.1%
Unidentified Teal	130	60	1265	1082	208		2745	7.7%
Total Waterfowl	3603	8140	7482	7335	3820	5408	35788	

Table 13. Bridgeport Reservoir Fall Survey, September 1, 2010

Species	Lakeshore Segment			Total
	NOAR	WEBA	EASH	
Canada Goose		37		37
Cinnamon Teal	3	50	50	103
Common Merganser	12			12
Gadwall	5	1200	5	1210
Green-winged Teal		250		250
Mallard		120	25	145
Northern Pintail		200		200
Northern Shoveler	16	1500		1516
Unidentified Teal	10		120	130
Total Waterfowl	46	3357	200	3603

Table 14. Bridgeport Reservoir Fall Aerial Survey, September 16, 2010

Species	Lakeshore Segment			Total
	NOAR	WEBA	EASH	
American Wigeon	10			10
Canada Goose		45		45
Cinnamon Teal	11			11
Common Merganser	20			20
Gadwall	7	2800	5	2812
Green-winged Teal			5	5
Mallard	5	250		255
Northern Pintail	2	191		193
Northern Shoveler	10	4583	16	4609
Ruddy Duck		120		120
Unidentified Teal			60	60
Total Waterfowl	65	7989	86	8140

Table 15. Bridgeport Reservoir Fall Aerial Survey , September 29, 2010

Species	Lakeshore Segment			Total
	NOAR	WEBA	EASH	
Canada Goose		60		60
Common Merganser	25			25
Gadwall	12	3000	7	3019
Green-winged Teal	14	700	45	759
Mallard	25	600	12	637
Northern Pintail	15	1390	6	1411
Northern Shoveler	36	200	70	306
Unidentified Teal	5	1120	140	1265
Total Waterfowl	132	7070	280	7482

Table 16. Bridgeport Reservoir Fall Aerial Survey, October 14, 2010

Species	Lakeshore Segment			Total
	NOAR	WEBA	EASH	
Bufflehead		4		4
Canada Goose		80		80
Common Merganser	15	8		23
Gadwall		1600	27	1627
Green-winged Teal		500		500
Mallard		400	45	445
Northern Pintail	4	2500		2504
Northern Shoveler	10	400	10	420
Ruddy Duck		650		650
Unidentified Teal		1060	22	1082
Total Waterfowl	29	7202	104	7335

Table 17. Bridgeport Reservoir Fall Aerial Survey, October 27, 2010

Common Name	Lakeshore Segment			Total
	NOAR	WEBA	EASH	
Bufflehead		34	10	44
Canada Goose		110		110
Common Merganser	1			1
Gadwall	1	700	30	731
Green-winged Teal		900	28	928
Mallard	6	900	56	962
Northern Pintail	1	495	20	516
Northern Shoveler		202		202
Ruddy Duck	12	100	6	118
Unidentified Teal		200	8	208
Total Waterfowl	21	3641	158	3820

Table 18. Bridgeport Reservoir Fall Aerial Survey, November 16, 2010

Species	Lakeshore Segment			Total
	NOAR	WEBA	EASH	
American Wigeon	3			3
Bufflehead	14	30	65	109
Canada Goose		285	13	298
Common Goldeneye			6	6
Common Merganser	7			7
Gadwall	202	1425	40	1667
Green-winged Teal	380	1190		1570
Mallard	60	800	75	935
Northern Pintail		700	25	725
Ruddy Duck	1	50	12	63
Tundra Swan		25		25
Total Waterfowl	667	4505	236	5408

Table 19. Summary of 2010 Crowley Reservoir Fall Aerial Survey Count Data

Species	1-Sep	16-Sep	29-Sep	14-Oct	27-Oct	16-Nov	Total Detections	% Total
American Wigeon			402		2	54	458	1.0%
Bufflehead					270	167	437	0.9%
Canada Goose	133	132	77	14	15	25	396	0.8%
Cinnamon Teal	84	7					91	0.2%
Common Goldeneye						2	2	<0.1%
Gadwall	332	2390	2620	1272	1050	435	8099	17.0%
Green-winged Teal	177	335	2071	542	632	182	3939	8.3%
Lesser Scaup					6	4	10	<0.1%
Mallard	20	305	765	1093	1958	1179	5320	11.2%
Northern Pintail	302	700	300	2120	385	594	4401	9.3%
Northern Shoveler	3538	4685	2062	2170	160	212	12827	27.0%
Ruddy Duck	25	20	70	691	3621	3259	7686	16.2%
Snow Goose						1	1	<0.1%
Tundra Swan						33	33	0.1%
Unidentified Teal	670	50	1435	1510	193		3858	8.1%
Total Waterfowl	5281	8624	9802	9412	8292	6147	47558	

Table 20. Crowley Reservoir Fall Aerial Survey, September 1, 2010

Species	Lakeshore Segment							Total
	UPOW	SAPO	NOLA	MCBA	HIBA	CHCL	LASP	
Canada Goose	8			80			45	133
Cinnamon Teal	20		12	30	22			84
Gadwall	20	10	2	300				332
Green-winged Teal	27			150				177
Mallard	20							20
Northern Pintail	2			300				302
Northern Shoveler	180			3300			58	3538
Ruddy Duck	25							25
Unidentified Teal				650			20	670
Total Waterfowl	302	10	14	4810	22		123	5281

Table 21. Crowley Reservoir Fall Aerial Survey, September 16, 2010

Species	Lakeshore Segment							Total
	UPOW	SAPO	NOLA	MCBA	HIBA	CHCL	LASP	
Canada Goose	4			65	18	8	37	132
Cinnamon Teal			2		5			7
Gadwall	20			2370				2390
Green-winged Teal				325	10			335
Mallard				300	5			305
Northern Pintail				700				700
Northern Shoveler	600			4000	45		40	4685
Ruddy Duck	20							20
Unidentified Teal					30		20	50
Total Waterfowl	644		2	7760	113	8	97	8624

Table 22. Crowley Reservoir Fall Aerial Survey, September 29, 2010

Species	Lakeshore Segment							Total
	UPOW	SAPO	NOLA	MCBA	HIBA	CHCL	LASP	
American Wigeon	2			400				402
Canada Goose				77				77
Gadwall				2500	120			2620
Green-winged Teal	6			2000	40		25	2071
Mallard				700	65			765
Northern Pintail				300				300
Northern Shoveler	238	4		1800			20	2062
Ruddy Duck	65		5					70
Unidentified Teal				1400	35			1435
Total Waterfowl	311	4	5	9177	260		45	9802

Table 23. Crowley Reservoir Fall Aerial Survey, October 14, 2010

Species	Lakeshore Segment							Total
	UPOW	SAPO	NOLA	MCBA	HIBA	CHCL	LASP	
Canada Goose				14				14
Gadwall	80		2	1125	20	45		1272
Green-winged Teal	65			375	100		2	542
Mallard	75		4	900	110	4		1093
Northern Pintail	160			1800	160			2120
Northern Shoveler	120			1800	250			2170
Ruddy Duck	150			500		41		691
Unidentified Teal				1500		10		1510
Total Waterfowl	650		6	8014	640	100	2	9412

Table 24. Crowley Reservoir Fall Aerial Survey, October 27, 2010

Species	Lakeshore Segment							Total
	UPOW	SAPO	NOLA	MCBA	HIBA	CHCL	LASP	
American Wigeon						2		2
Bufflehead	80	3	16	61	9	69	32	270
Canada Goose	15							15
Gadwall	120	50		700	60	60	60	1050
Green-winged Teal	20			600	12			632
Lesser Scaup				6				6
Mallard	110	60	55	1500	40	153	40	1958
Northern Pintail	20			350		15		385
Northern Shoveler				160				160
Ruddy Duck	147	50	7	3125	40	242	10	3621
Unidentified Teal			3	190				193
Total Waterfowl	512	163	81	6692	161	541	142	8292

Table 25. Crowley Reservoir Fall Aerial Survey, November 16, 2010

Species	Lakeshore Segment							Total
	UPOW	SAPO	NOLA	MCBA	HIBA	CHCL	LASP	
American Wigeon	45					9		54
Bufflehead	32	8	55	20	21	10	21	167
Canada Goose		25						25
Common Goldeneye				1			1	2
Gadwall	35	50		300		50		435
Green-winged Teal	74			100			8	182
Lesser Scaup	4							4
Mallard	16	27	55	850	36	170	25	1179
Northern Pintail	46	10	33	500	4	1		594
Northern Shoveler				200		12		212
Ruddy Duck	720	126	43	2000	98	142	130	3259
Snow Goose	1							1
Tundra Swan				33				33
Total Waterfowl	973	246	186	4004	159	394	185	6147

Table 26. Mono Lake Restoration Ponds - Total Summer Detections

Species	COPOE	COPOW	DEPO_1	DEPO_2	DEPO_3	DEPO_4	DEPO_5	Total
Blue-winged Teal			1					1
Cinnamon Teal	4		17	2				23
Gadwall	18	3	1			2		24
Green-winged Teal			1					1
Mallard	3			2				5
Northern Pintail	1							1
Ruddy Duck	2	1	1	6		9		19
Pond Totals	28	4	21	10	0	11	0	74

Table 27. Mono Lake Restoration Ponds - Total Waterfowl Broods

Species	County Ponds	DeChambeau Ponds
Gadwall	4	
Ruddy Duck	1	4
Total Broods	5	4

Table 28. Mono Lake Restoration Ponds - 2010 Fall Survey Counts

County Ponds	1-Sep	16-Sep	29-Sep	14-Oct	27-Oct	16-Nov	Total Fall Detections
Gadwall	15				1		16
Mallard		3				2	5
Total Waterfowl	15	3	0	0	1	2	21

DeChambeau Ponds	1-Sep	16-Sep	29-Sep	14-Oct	27-Oct	16-Nov	Total Fall Detections
Gadwall	4				30		34
Mallard					20	7	27
Unidentified Teal	15	38	4	19		2	78
Total Waterfowl	19	38	4	19	50	9	139

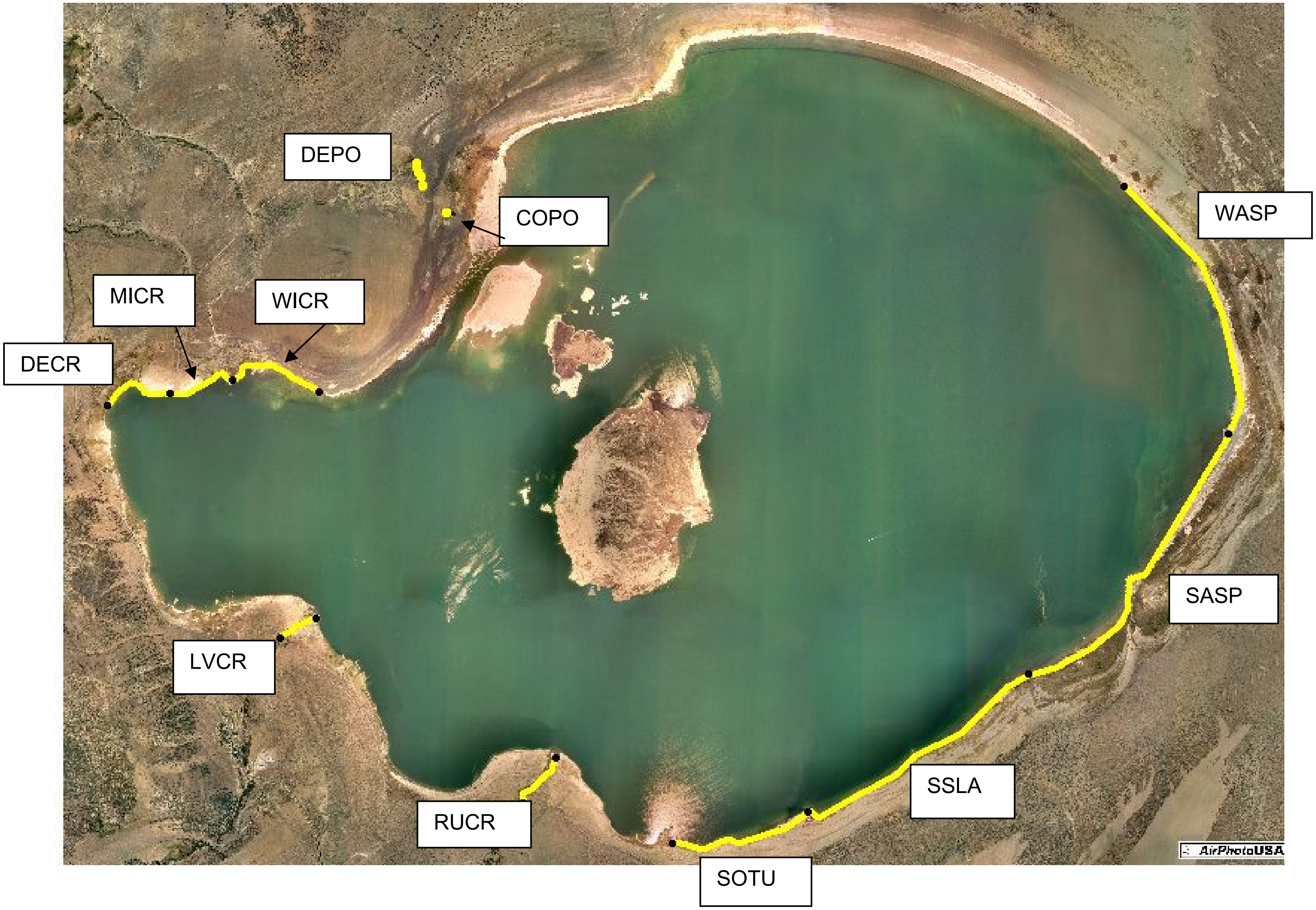


Figure 1. Summer Ground Count Survey Areas

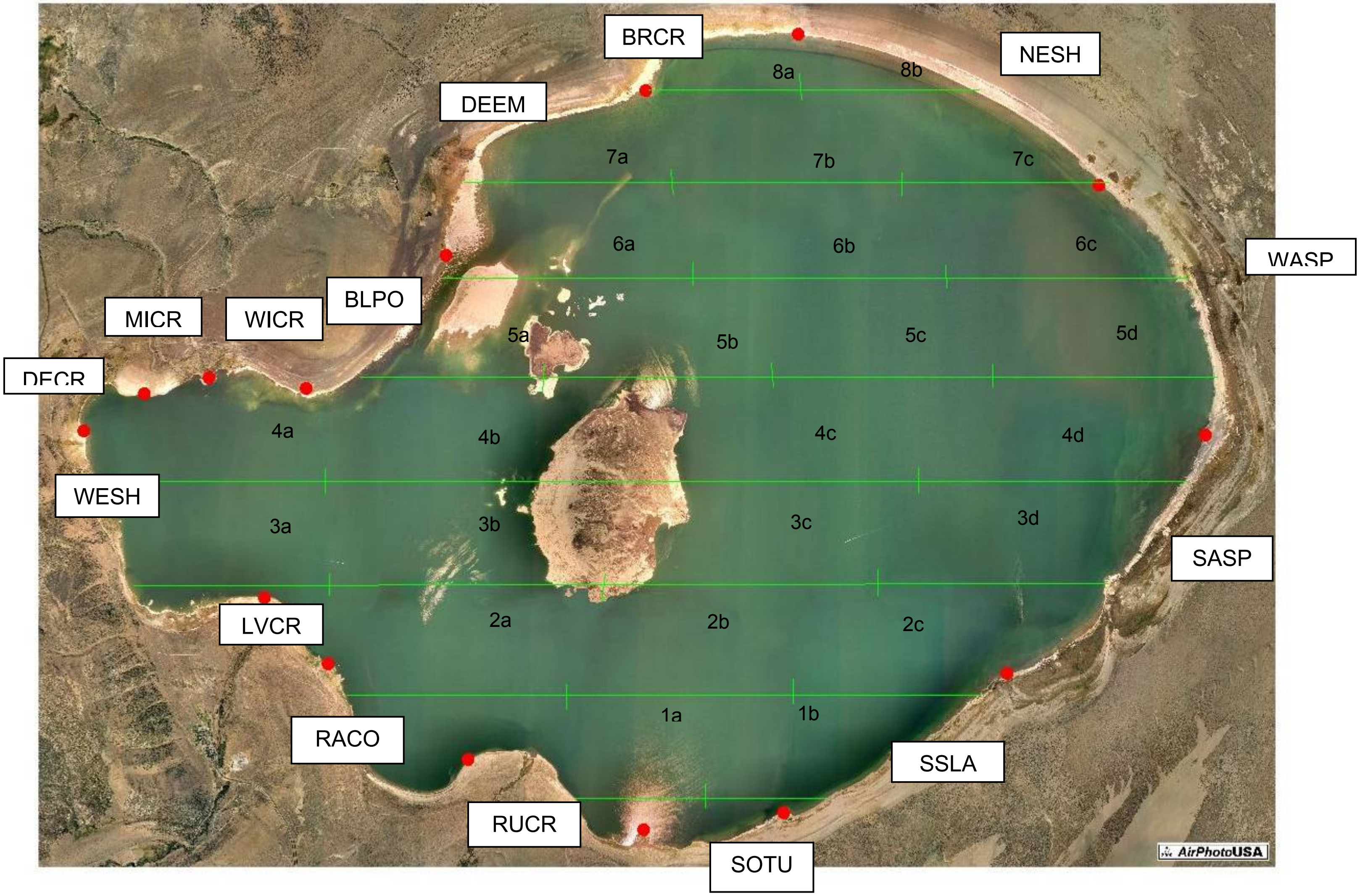


Figure 2. Mono Lake Fall Aerial Survey Lakeshore Segments, Boundaries, and Cross-Lake Transects

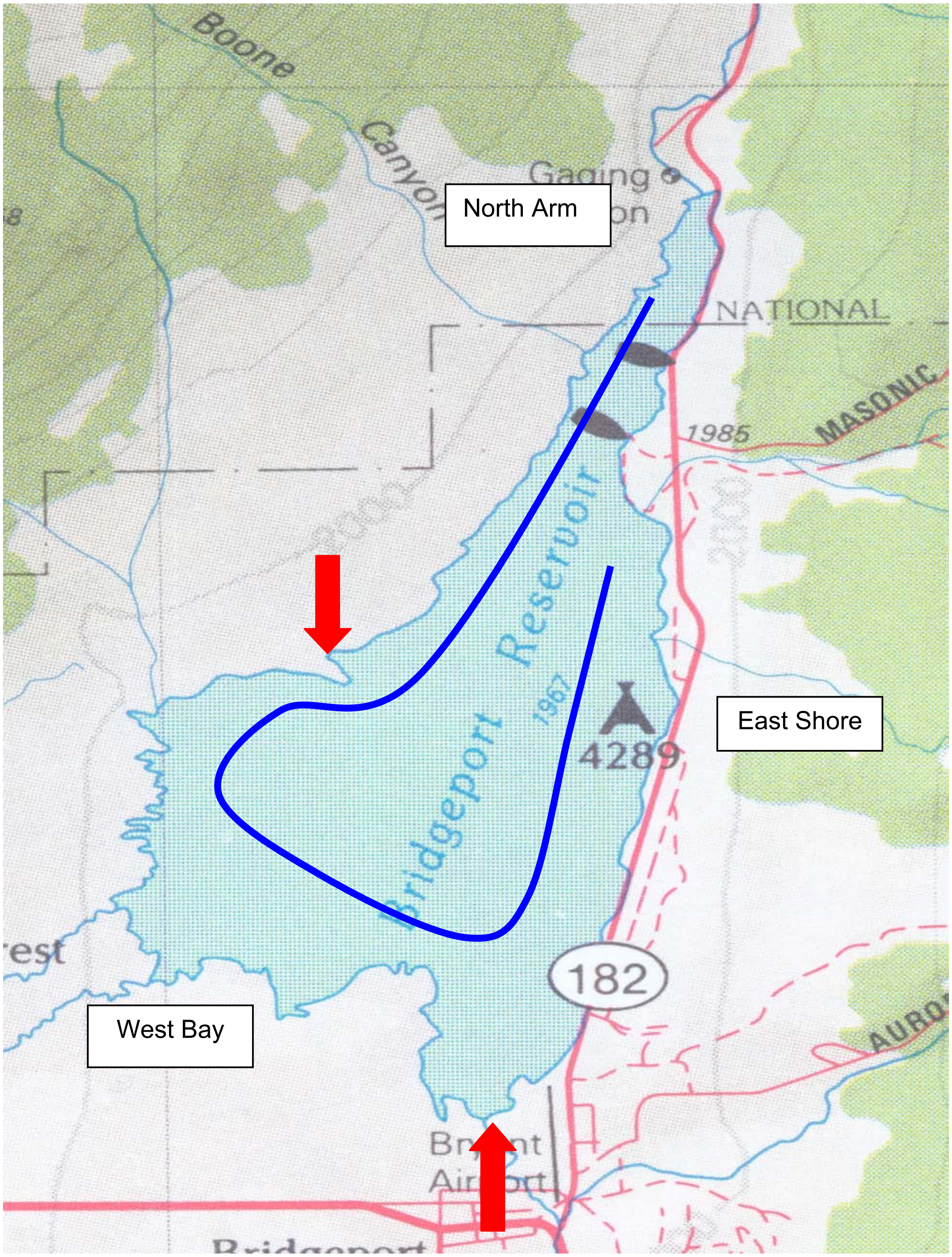


Figure 3. Bridgeport Reservoir Lakeshore Segments and Segment Boundaries

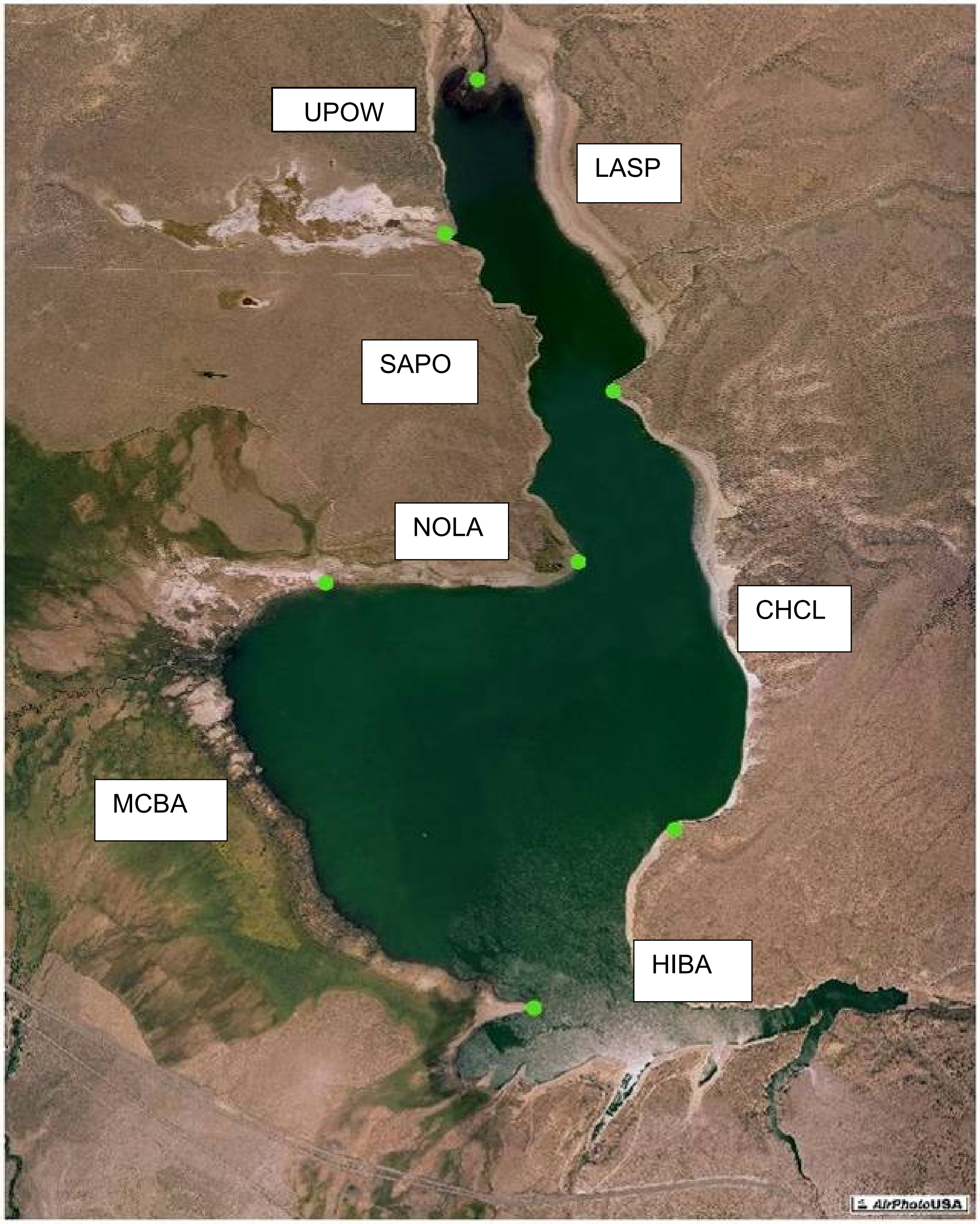


Figure 4. Crowley Reservoir Lakeshore Segments and Segment Boundaries

Figure 5. South Tufa, East of Navy Beach

Figure 6. South Shore Lagoons Area – First Lagoon

Figure 7. South Shoreline – Freshwater Pond

Figure 8. South Shore Lagoons – Sand Flat Spring


10/26/2010

Figure 9. South Shore Lagoons Goose Springs Outflow Area


10/26/2010

Figure 10. Sammann's Spring West of Tufa Grove


10/26/2010

Figure 11. Sammann's Spring, east of Tufa grove


10/26/2010

Figure 12. Warm Springs – North Lagoon

Figure 13. Northeast Shore

Figure 14. Bridgeport Creek Shoreline Area

Figure 15. DeChambeau Embayment

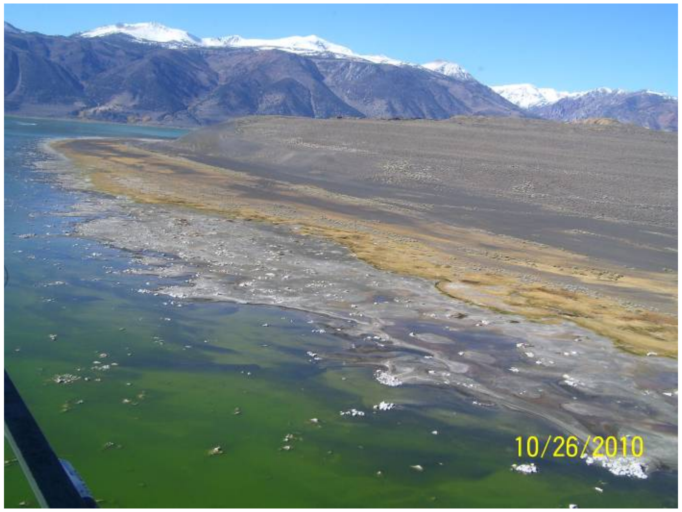


Figure 16. Black Point

Figure 17. Wilson Creek Shoreline Area

Figure 18. Mill Creek Delta

Figure 19. DeChambeau Creek Shoreline Area


10/26/2010

Figure 20. West Shore


10/26/2010

Figure 21. Lee Vining Creek Delta


10/26/2010

Figure 22. Ranch Cove Shoreline Area


10/26/2010

Figure 23. Rush Creek Delta

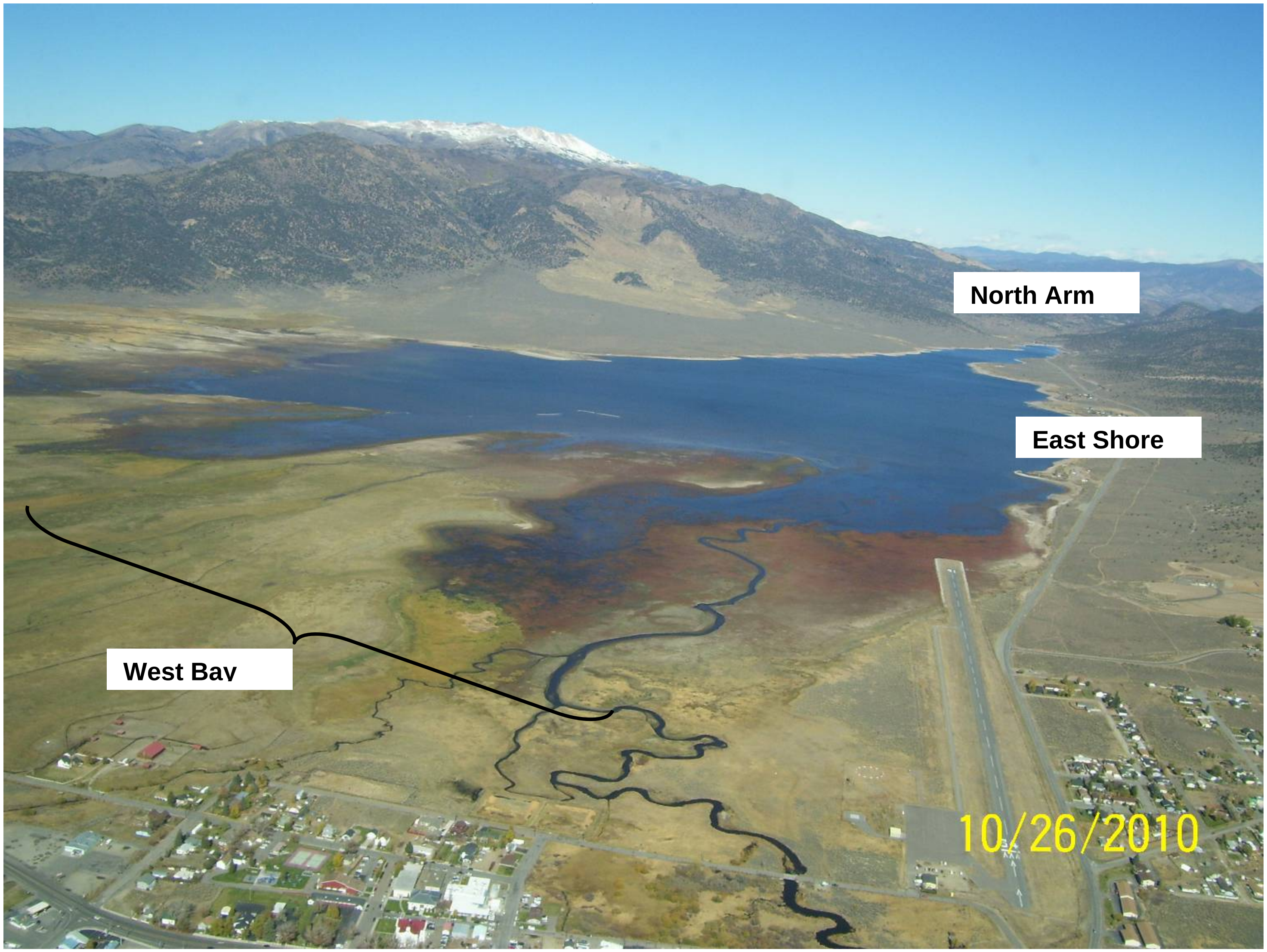


Figure 24 Photo of Bridgeport Reservoir, Looking North
Photo shows the West Bay area and the south end of the East Shore area. The majority of waterfowl that use Bridgeport Reservoir in the fall congregate in this southern end of the reservoir.

Figure 25. Upper Owens River Delta

Figure 26. Sandy Point Shoreline Area

Figure 27. North Landing Shoreline Area

Figure 28. McGee Bay

Figure 29. Hilton Bay

Figure 30. Chalk Cliffs

Figure 31. Layton Springs

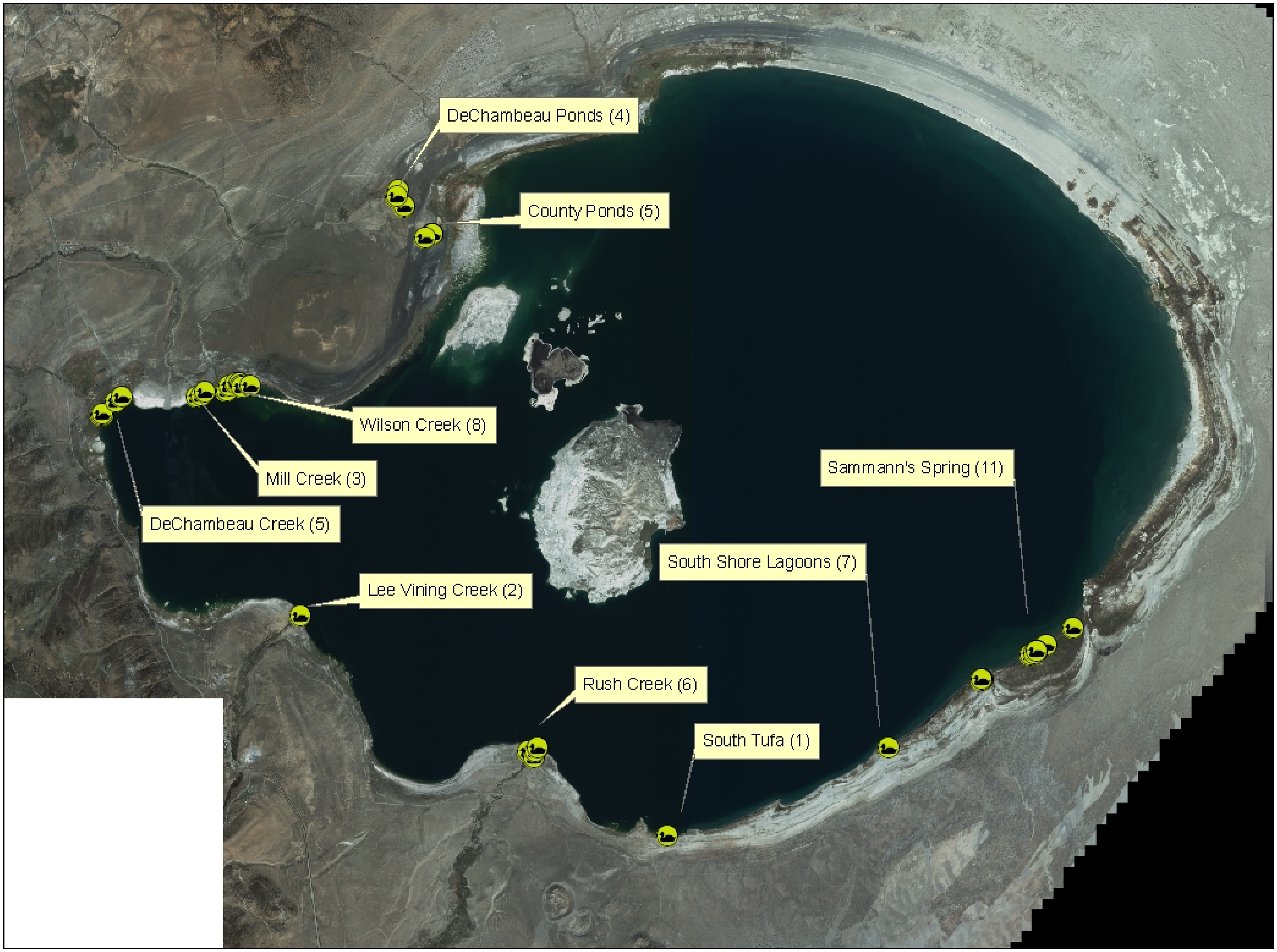


Figure 32. 2010 Brood Locations
The number in parentheses indicates the number of broods found in each area.

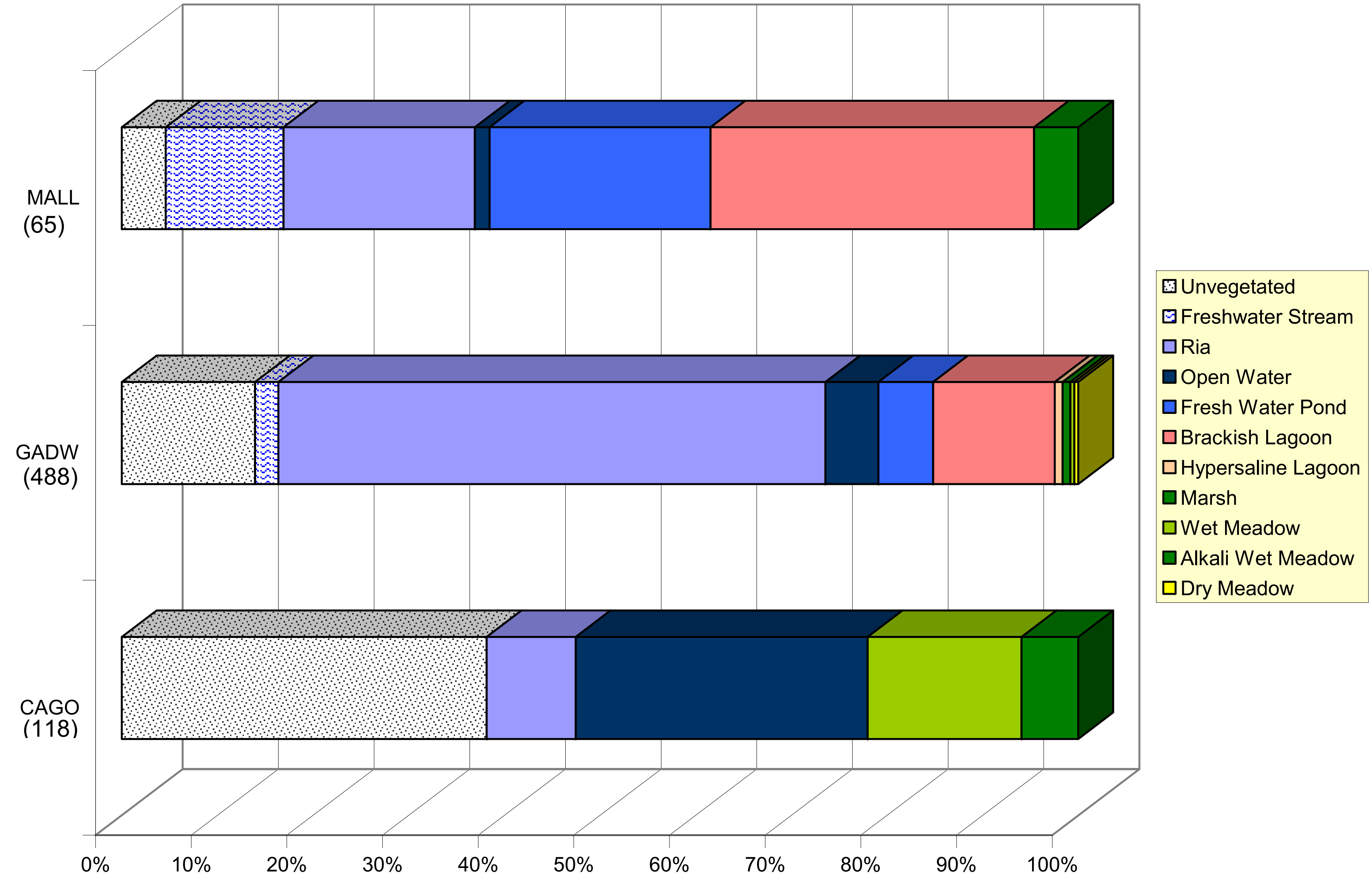


Figure 33. Waterfowl Habitat Use
The numbers in parentheses indicate sample size. The bars represent the percent of the total observations.

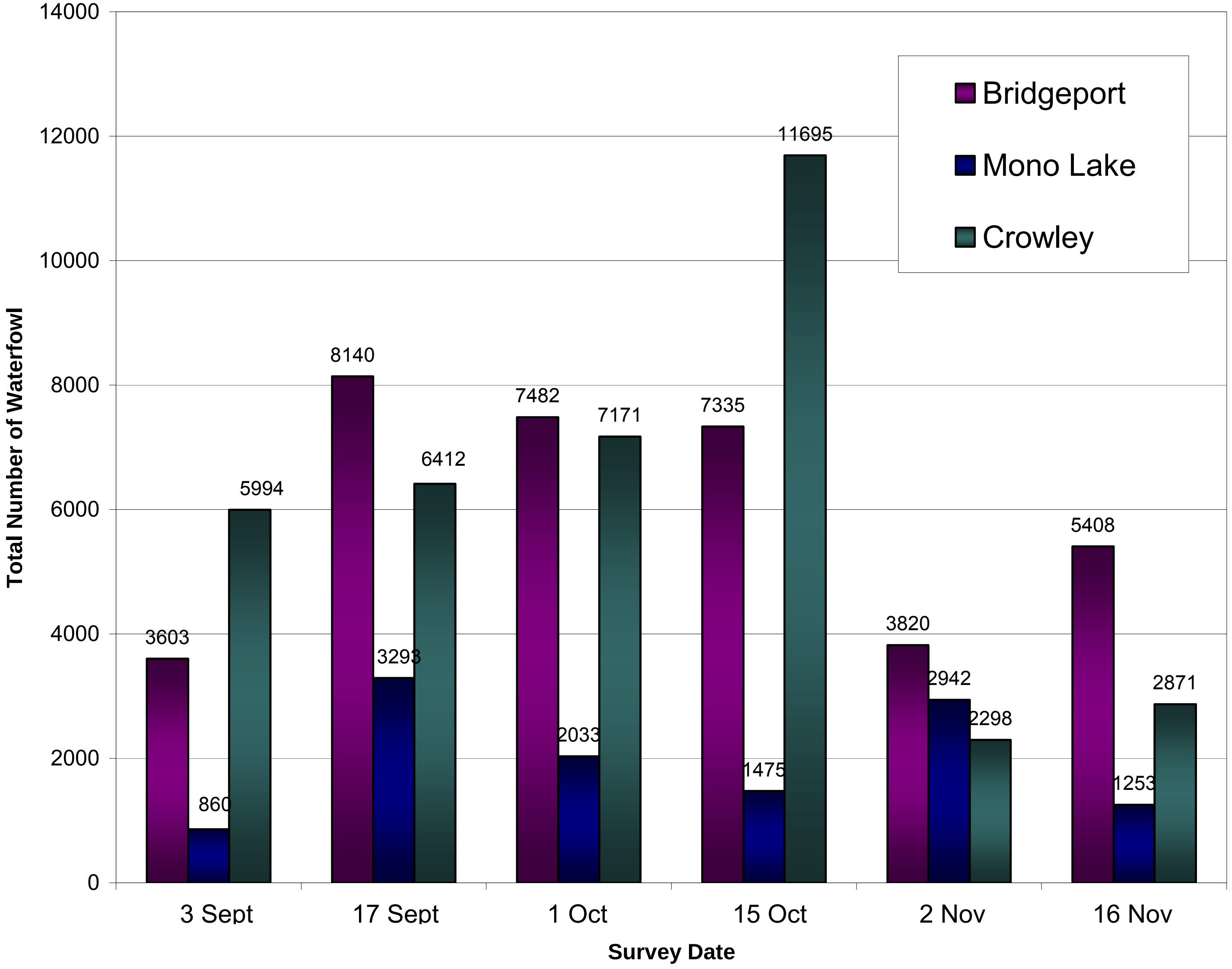


Figure 34. Total Fall Detections by Waterbody

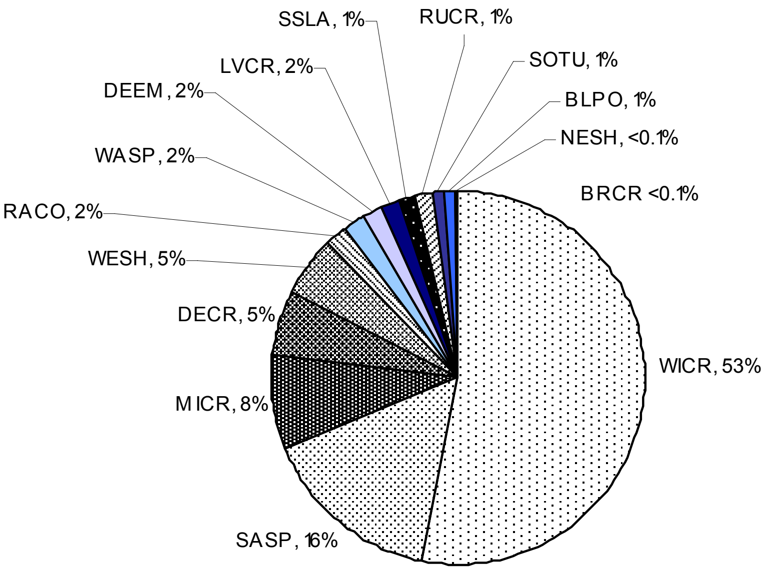


Figure 35. Spatial Distribution – Mono Lake

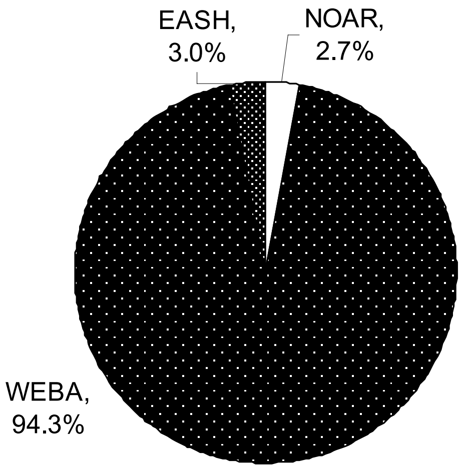


Figure 36. Spatial Distribution – Bridgeport Reservoir

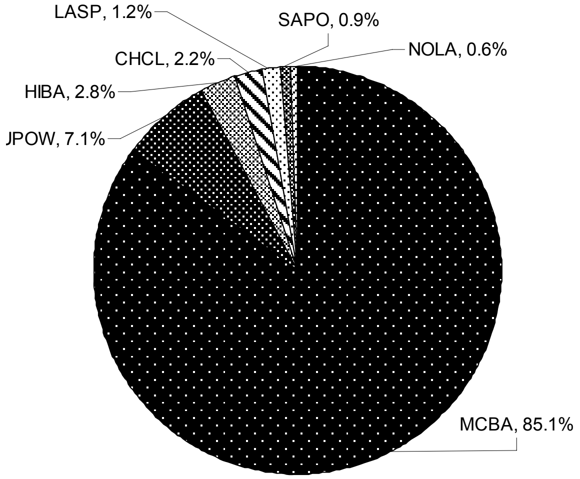


Figure 37. Spatial Distribution – Crowley Reservoir

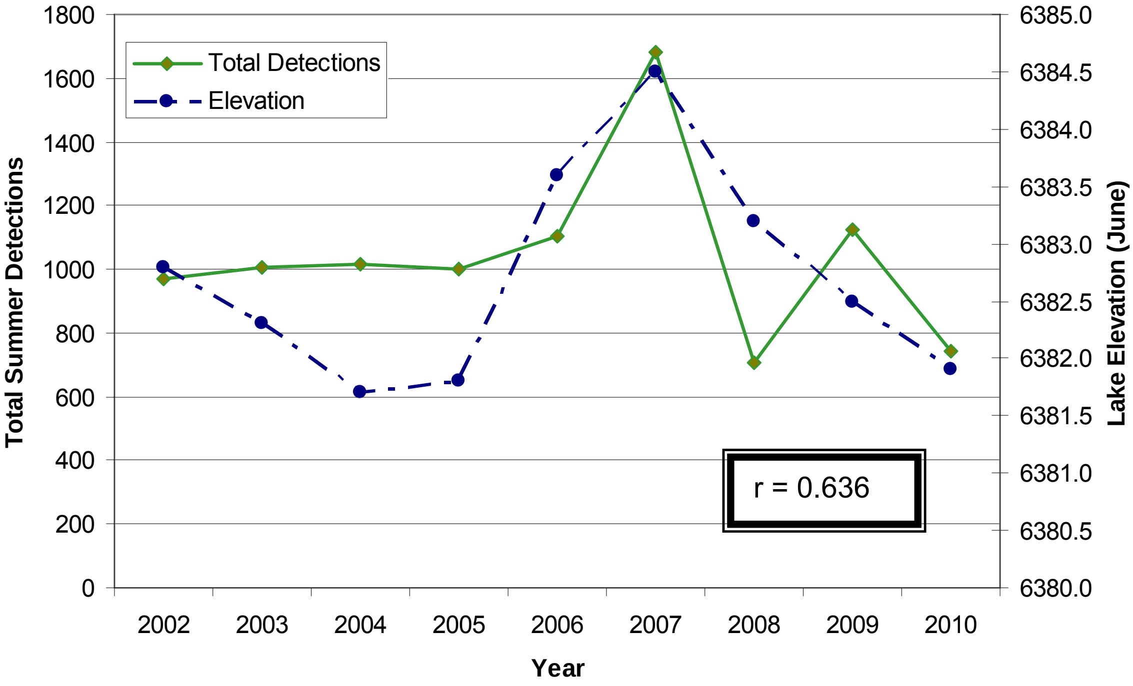


Figure 38. Total Summer Waterfowl Detections vs. Lake Elevation in June (2002-2010)

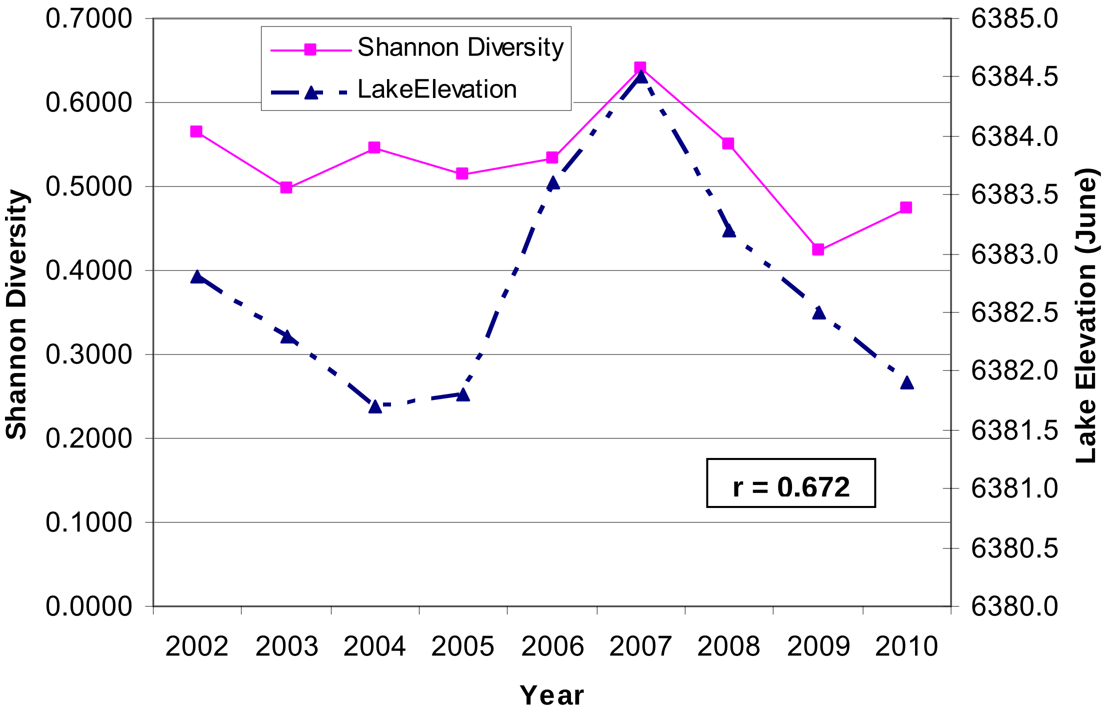


Figure 39. Summer Waterfowl Diversity vs. Lake Elevation (2002-2010)

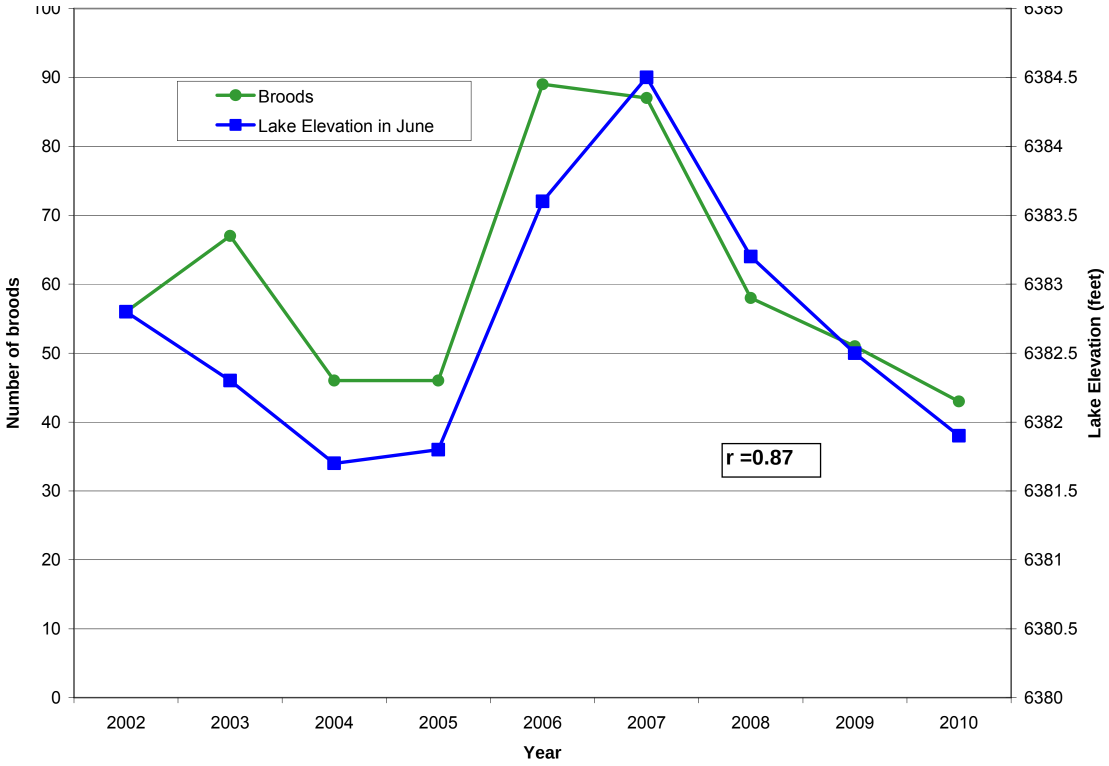


Figure 40. Number of Broods at Mono Lake vs. Lake Elevation 2002-2010

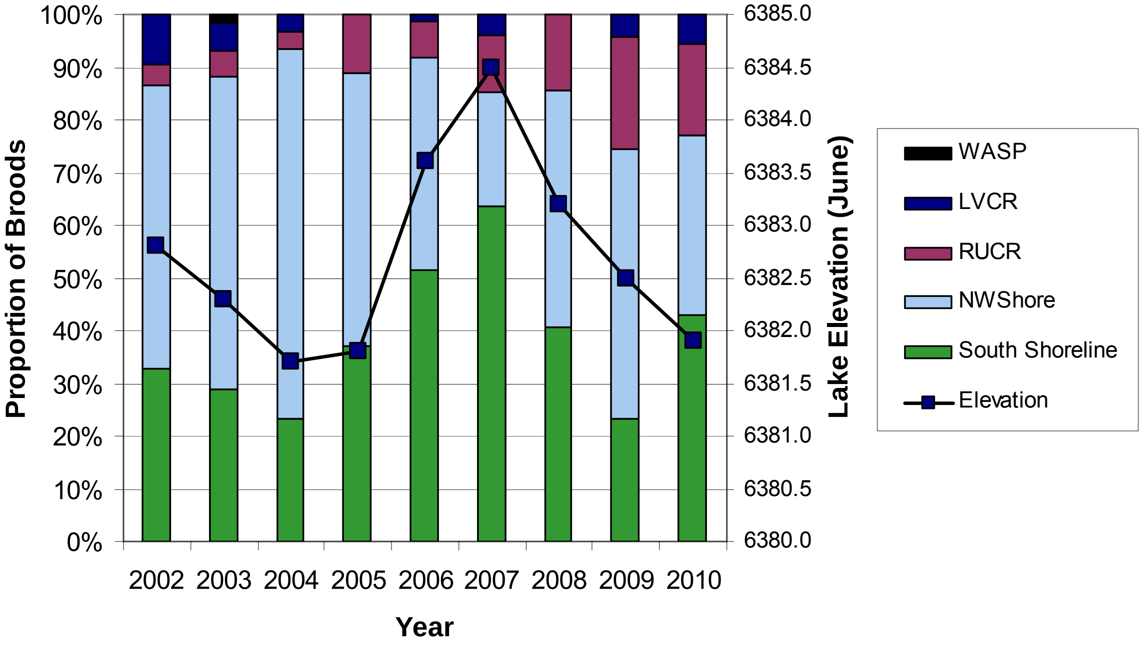
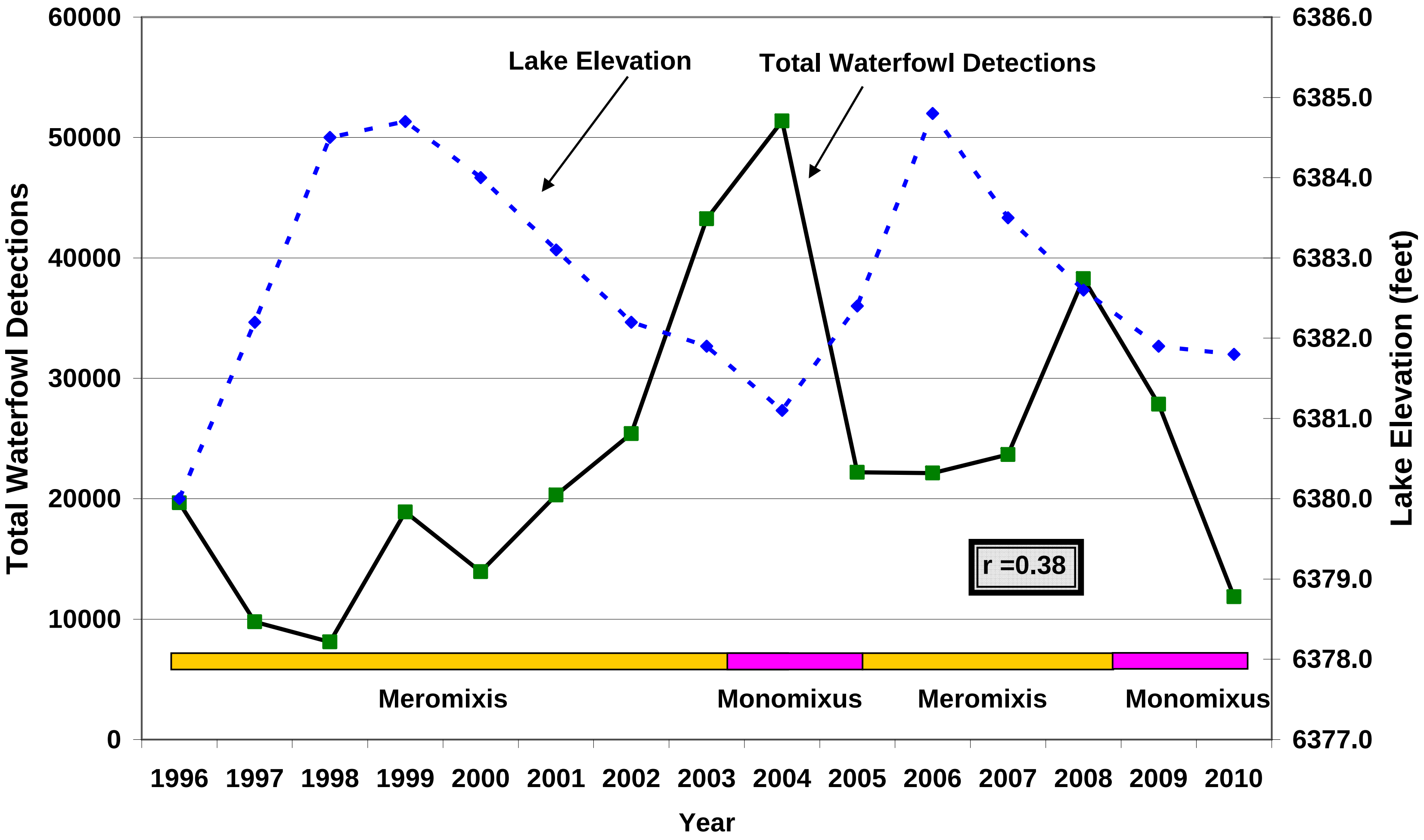


Figure 41. Proportional Use of Mono Lake Shoreline Areas for Brooding 2002-2010

Figure 42. Total Fall Waterfowl Detections vs. Mono Lake Elevation 2002-2010



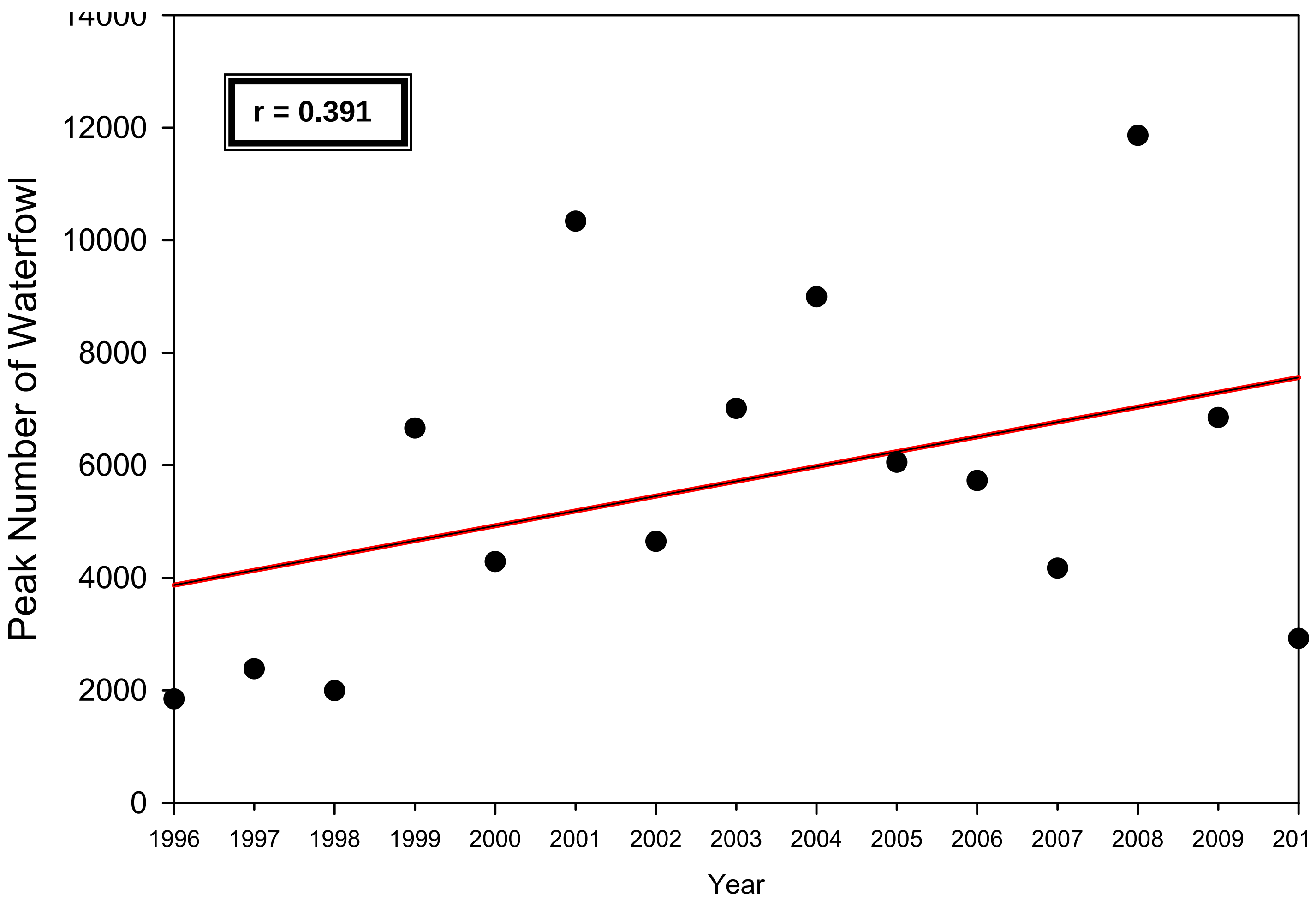


Figure 43. Trend in Peak Waterfowl Numbers (not including Ruddy Ducks) - Mono Lake 1996-2010

APPENDICES

Appendix 1. 2010 Ground Count Survey Dates and Times

Survey 1

Survey Area	Survey Date and Time		
	8-Jun	9-Jun	10-Jun
RUCR	0537 - 0630 hrs		
SOTU	0708 - 0725 hrs		
SSLA	0758 - 1005 hrs		
DECR		0540 - 0627 hrs	
MICR		0627 - 0700 hrs	
WICR		0700 - 0728 hrs	
LVCR		0907 - 0955 hrs	
DEPO		1037 - 1102 hrs	
COPO		1110 - 1125 hrs	
SASP			0549 - 0841 hrs
WASP			0850 - 1012 hrs

Survey 2

Survey Area	Survey Date and Time		
	6-Jul	7-Jul	8-Jul
RUCR	1136 - 1235 hrs		
SOTU	0556 - 0652 hrs		
SSLA	0652 - 0910 hrs		
DECR		0550 - 0641 hrs	
MICR		0641 - 0730 hrs	
WICR		0730 - 0806 hrs	
LVCR		1108 - 1215 hrs	
DEPO		0946 - 1015 hrs	
COPO		1032 - 1045 hrs	
SASP			0845 - 1115 hrs
WASP			0621 - 0845 hrs

Appendix 1. Continued. 2010 Ground Count Survey Dates and Times

Survey 3

Survey Area	Survey Date and Time		
	26-Jul	28-Jul	29-Jul
RUCR	0552 - 0700 hrs		
SOTU	0730 - 0822 hrs		
SSLA	0822 - 1035 hrs		
DECR		0805 - 0856 hrs	
MICR		0856 - 0945 hrs	
WICR		0945 - 1037 hrs	
LVCR		0543 - 0635 hrs	
DEPO		1241 - 1300 hrs	
COPO		1217 - 1240 hrs	
SASP			0634 - 1025 hrs
WASP			1035 - 1158 hrs

Appendix 2. Common and Scientific Names for Species Referenced in the Document.

Common Name	Scientific Name
Snow Goose	*Chen caerulescens*
Canada Goose	*Branta canadensis*
Brant	*Branta bernicla*
Tundra Swan	*Cygnus columbianus*
Gadwall	*Anas strepera*
American Wigeon	*Anas americana*
Mallard	*Anas platyrhynchos*
Blue-winged Teal	*Anas discors*
Cinnamon Teal	*Anas cyanoptera*
Northern Shoveler	*Anas clypeata*
Northern Pintail	*Anas acuta*
Green-winged Teal	*Anas crecca*
Lesser Scaup	*Aythya affinis*
Bufflehead	*Bucephala albeola*
Common Goldeneye	*Bucephala clangula*
Common Merganser	*Mergus merganser*
Ruddy Duck	*Oxyura jamaicensis*
Unidentified Teal	*Anas* spp.
Unidentified diving duck	*Aythya* spp.

Appendix 3. Habitat Categories Used for Documenting Use by Waterfowl Species (from 1999 Mono Basin Habitat and Vegetation Mapping, Los Angeles Department of Water and Power 2000).

Marsh

Areas with surface water usually present all year and dominated by tall emergent species such as hard-stem bulrush (*Scirpus acutus*), cattail (*Typhus latifolia*), three-square (*Scirpus pungens*), alkali bulrush (*Scirpus maritimus*) and beaked sedge (*Carex utriculata*).

Wet Meadow

Vegetation with seasonally or permanently wet ground dominated by lower stature herbaceous plant species, such as sedges (*Carex* spp.), rushes (*Juncus* spp.), spikerushes (*Eleocharis* spp.), and some forbs (e.g. monkey flower [*Mimulus* spp.], paintbrush [*Castilleja exilis*]). Wet meadow vegetation was in areas where alkaline or saline soils did not appear to be present. This class included the “mixed marsh” series from Jones and Stokes 1993 mapping.

Alkaline Wet Meadow

This type was similar in stature to the wet meadow class but occurred in areas clearly affected by saline or alkaline soils. Vegetation was typically dominated by dense stands of Nevada bulrush (*Scirpus nevadensis*), Baltic rush (*Juncus balticus*), and/or saltgrass (*Distichlis spicata*). The high density and lushness of the vegetation indicated that it had a relatively high water table with at least seasonal inundation and distinguished it from the dry meadow vegetation class.

Dry meadow/forb

This vegetation class included moderately dense to sparse (at least 15 percent) cover of herbaceous species, including a variety of grasses and forbs and some sedges (e.g. *Carex douglasii*). As with the alkaline wet meadow type above, comparison to vegetation series in Jones and Stokes (1993) was sometimes problematic due to difficulty in distinguishing dry meadow from wet meadow types.

Riparian and wetland scrub

Areas dominated by willows (*Salix* spp.) comprised most of the vegetation classified as riparian.wetlands scrub. Small amounts of buffalo berry (*Shepardia argentea*) and Wood’s rose (*Rosa woodsii*) usually mixed with willow also were included in this class.

Great Basin scrub

Scattered to dense stands of sagebrush (*Artemisia tridentata*), rabbitbrush (*Chrysothamnus nauseosus*), and/or bitterbrush (*Purshia tridentata*) were classified as Great Basin scrub. This vegetation type included a range of soil moisture conditions, as rabbitbrush was often found in moist areas close to the lakeshore and sagebrush was typically in arid upland areas.

Riparian forest and woodland

Aspen (*Populus tremuloides*) and black cottonwood (*Populus trichocarpa*) were the two tree species most common in the riparian forest/woodland vegetation type.

Freshwater-stream

Freshwater-stream habitats are watered; freshwater channels such as exist in Rush Creek and Lee Vining Creeks.

Freshwater-ria

Freshwater-ria areas were surface water areas at the mouths of streams that likely have some salt/freshwater stratification.

Freshwater-pond

This type included ponds fed by springs within marsh areas or artificially by diversions from streams (e.g. DeChambeau/County ponds).

Ephemeral Brackish Lagoon

Lagoons along the shoreline created by the formation of littoral bars with an extensive area of marsh or wet meadow indicating the presence of springs was present landward, were identified as ephemeral brackish lagoons. In some cases, lagoons were not completely cut off from lake water, but were judged to still have brackish water due to freshwater input and reduced mixing.

Ephemeral Hypersaline Lagoon

Lagoons along the shoreline created by the formation of littoral bars, but without an extensive area of marsh or wet meadow present landward, were identified as ephemeral hypersaline lagoons. These were presumed to contain concentrated brine due to evaporation.

Unvegetated

Unvegetated areas were defined as those that were barren to sparsely vegetated (<15 percent cover). This class included sandy areas, alkaline flats, tufa, and delta outwash deposits.

Appendix 4. 2010 Fall Aerial Survey Dates

Survey Number	1	2	3	4	5	6
Mono Lake	3 Sept	17 Sept	1 Oct	15 Oct	2 Nov	16 Nov
Bridgeport Reservoir	3 Sept	17 Sept	1 Oct	15 Oct	2 Nov	16 Nov
Crowley Reservoir	3 Sept	17 Sept	1 Oct	15 Oct	2 Nov	16 Nov

Appendix 5. Lakeshore Segment Boundaries

(UTM, Zone 11, NAD 27, CONUS)

Mono Lake	Lakeshore Segment	Code	Easting	Northing
	South Tufa	SOTU	321920	4201319
	South Shore Lagoons	SSLA	324499	4201644
	Sammann's Spring	SASP	328636	4204167
	Warm Springs	WASP	332313	4208498
	Northeast Shore	NESH	330338	4213051
	Bridgeport Creek	BRCR	324773	4215794
	DeChambeau Embayment	DEEM	321956	4214761
	Black Point	BLPT	318252	4211772
	Wilson Creek	WICR	315680	4209358
	Mill Creek	MICR	313873	4209544
	DeChambeau Creek	DECR	312681	4209246
	West Shore	WESH	315547	4208581
	Lee Vining Creek	LVCR	314901	4205535
	Ranch Cove	RACO	316077	4204337
	Rush Creek	RUCR	318664	4202603
Crowley Reservoir				
	Upper Owens	UPOW	346150	4168245
	Sandy Point	SAPO	345916	4167064
	North Landing	NOLA	346911	4164577
	McGee Bay	MCBA	345016	4164414
	Hilton Bay	HIBA	346580	4161189
	Chalk Cliff	CHCL	347632	4162545
	Layton Springs	LASP	347177	4165868
Bridgeport Reservoir				
	North Arm	NOAR	306400	4244150
	West Bay	WEBA	304100	4240600
	East Shore	EASH	305600	4237600

Appendix 6. Mono Lake Cross-Lake Transect Positions

Cross-Lake Transect Number	Latitude
1	37º 57’00”
2	37º 58’00”
3	37º 59’00”
4	38º 00’00”
5	38º 01’00”
6	38º 02’00”
7	38º 03’00”
8	38º 04’00”