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Assessment of Hydrologic and Water Quality Data Collected in Abbotts Lagoon Watershed, Point Reyes National Seashore, California, during Water Years 1999 and 2000

Scientific Investigations Report 2005–5261

U.S. Department of the Interior
U.S. Geological Survey

Front cover: Looking west at lower Abbotts Lagoon and the Pacific Ocean from a hill above the footbridge on the National Park Service trail. The hill is created by an outcropping of the Monterey Formation. (Photograph by Charles R. Kratzer, U.S. Geological Survey).

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Tables

Abbreviations, Acronyms and Initialisms

NAVD 88, North American Vertical Datum of 1988
Fe, Iron
HPLC, high-pressure liquid chromatography
ID, identification
ICP, inductively coupled plasma
N, nitrogen
NA, not analyzed
NPS, National Park Service
NWIS, National Water Information System
NWQL, National Water Quality Laboratory
P, phosphorus
PST, Pacific Standard Time
PVC, polyvinyl chloride
TN, Total Nitrogen
TP, Total Phosphorus
USGS, U.S. Geological Survey

Units of measurement

acre-ft, acre foot
cm, centimeter
ft, foot
ft^3/s, cubic foot per second
h, hour
in., inch
L, liter
m, meter
mi, mile
mi^2, square mile
mi/h, mile per hour
mg/L, milligram per liter
mm, millimeter
µg/L, microgram per liter
µg/g, microgram per gram
µm, micrometer
µS/cm, microsiemens per centimeter

Notes

MSL, mean sea level. (In this report, “mean sea level” refers to the National Geodetic Vertical Datum of 1929 (NGVD 29)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called the “Sea Level Datum of 1929.” All references to mean sea level in this report are based on surveys of water levels in Abbotts Lagoon relative to the NGVD 29 elevation of 51.2 feet for the National Geodetic Survey benchmark H 477 located at 38°07’38” latitude and 122°56’12” longitude (NAD 83).

Assessment of Hydrologic and Water Quality Data Collected in Abbotts Lagoon Watershed, Point Reyes National Seashore, California, during Water Years 1999 and 2000

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Abstract

Abbotts Lagoon is part of Point Reyes National Seashore, located about 40 miles northwest of San Francisco and about 20 miles south of Bodega Bay. Water-quality samples were collected quarterly during water year 1999 at a site in each of three connected lagoons that make up Abbotts Lagoon and at a site in its most significant tributary. The quarterly samples were analyzed for major ions, nutrients, and chlorophyll-*a*. A bed-sediment sample was collected in each lagoon during August 1999 and was analyzed for organic carbon, iron, and total phosphorus. Seven tributaries were sampled during a February 1999 storm and four during an April 1999 storm. These samples were analyzed only for nutrients. One storm sample collected in April 1999 from a tributary downstream of the I Ranch dairy was analyzed for a suite of 47 compounds indicative of wastewater. Continuous water-level recorders were installed in the most significant tributary and the two largest lagoons for portions of the study.

A water budget analysis for an April 2000 storm indicated that the main tributary accounted for 85 percent of surface inflows to Abbotts Lagoon. The portion of the surface inflow from the main tributary was lower in the February 1999 storms and is a function of upstream storage and vegetative growth in the tributary basins. Another water budget analysis for a period of no surface inflow (June and July 2000) indicated that the net ground-water contribution was an outflow (seepage) from Abbotts Lagoon of about 0.3 ft^3/s.

Salinity increased and nutrient concentrations decreased from upstream to downstream in the chain of lagoons. The lower lagoon, nearest the ocean, had less organic carbon and total phosphorus in the bed sediment than the upper lagoons. The two tributaries originating in the I Ranch dairy had the highest concentrations of nutrients in storm runoff, and the highest loading rates and yields of ammonia and phosphorus. These tributaries account for only 10.3 percent of the area drained by the sampled tributaries, but contributed 83 percent of the ammonia load and 79 percent of the orthophosphate load. The basins with the highest nutrient loading rates and yields had the highest percentage of dairy and (or) ranching impacted land use and, to a lesser extent, grazing land use. The ratios of inorganic nitrogen to phosphorus in the lagoons ranged from 0.1 to 9.5 in the upper lagoon, 0.10 to 0.15 in the middle lagoon, and 0.05 to 0.10 in the lower lagoon. Thus, there is an abundance of phosphorus in the lagoons, and nitrogen appears to be limiting the growth of phytoplankton. Two sterols indicative of fecal material were among 11 compounds detected in the sample collected for analysis of wastewater indicators from a tributary downstream of the I Ranch dairy.

Introduction

Abbotts Lagoon is part of Point Reyes National Seashore, located about 40 mi northwest of San Francisco and about 20 mi south of Bodega Bay (*fig. 1*). The land was originally part of the Rancho Punta de los Reyes Sobrante land grant and was used extensively for grazing dairy and beef cattle. The National Park Service (NPS) acquired the land following park establishment in 1962. The area is now managed by the NPS, to preserve the natural and cultural resources of the area. As part of the pastoral zone, several historical dairy and beef cattle ranches from the mid-1800s are still in operation. Four ranches are partially or completely in the Abbotts Lagoon watershed. The I Ranch dairy and the H Ranch beef cattle ranch are completely in the watershed. The L Ranch dairy and the G Ranch beef cattle ranch are only partially in the watershed.

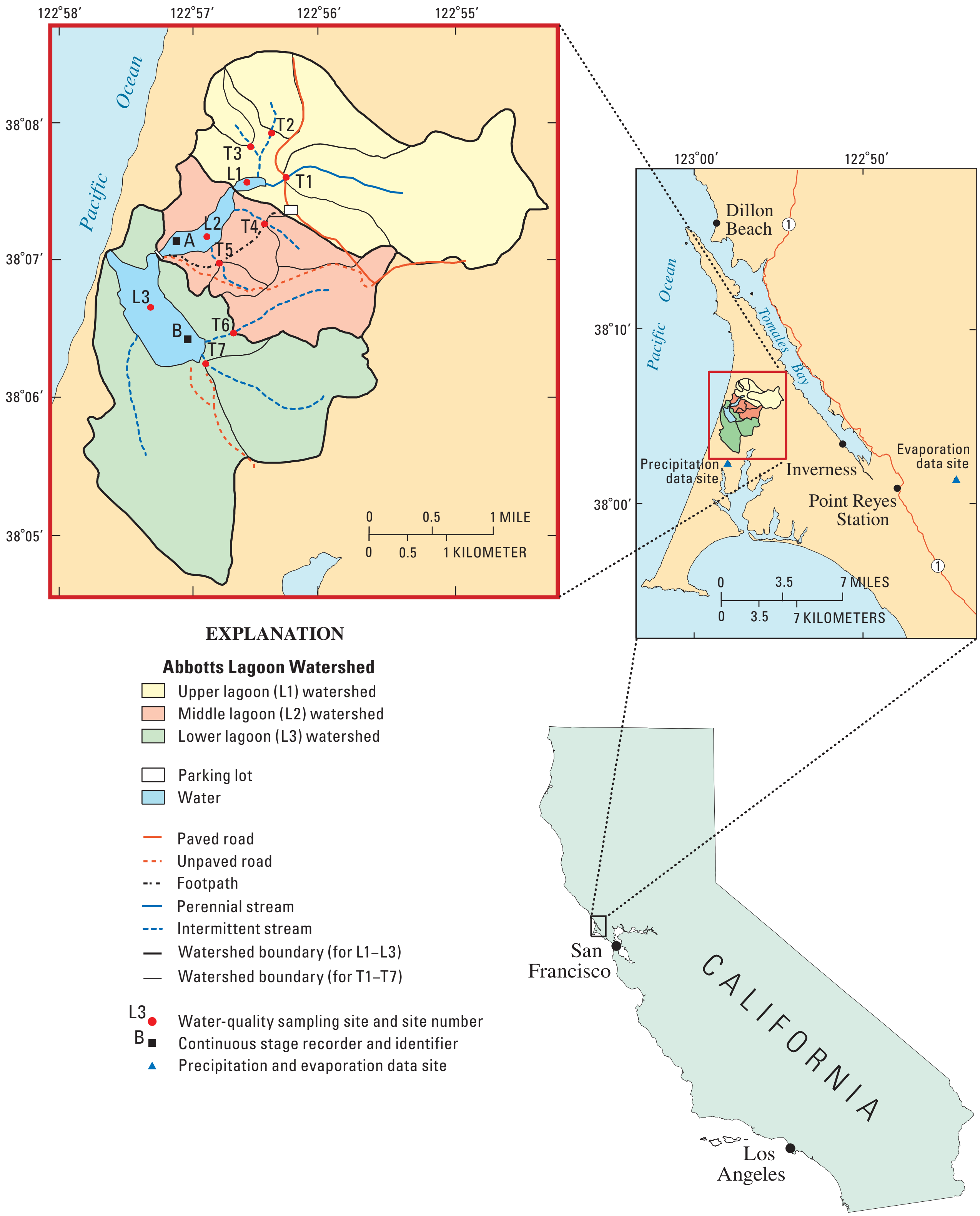

Figure 1. Location of sampling sites, sites for precipitation and evaporation data, sites for continuous stage recorders, and watersheds in Abbotts Lagoon watershed.

The most extensive evaluation of water-quality conditions in Abbotts Lagoon was conducted in the late-1980s (Anima, 1991). The study concluded that the upper portion of Abbotts Lagoon was especially susceptible to eutrophic conditions, as evidenced by relatively high nutrient and chlorophyll levels (Steve Hagar, U.S. Geological Survey, written commun., 1991). However, the lack of either streamflow information or sufficient monitoring of inflows made it impossible to conclude anything about the significance of nutrient sources. Using Pb210 radioactive isotope analysis of sediments in middle and lower Abbotts Lagoon, Anima (1991) estimated a sedimentation rate between 8 and 19 cm for every 100 years. This rate was slower than neighboring Drakes Estero. Anima (1991) attributed this slower rate to less sediment input from cliff erosion in Abbotts Lagoon from the Monterey Formation that is more resistant to erosion than the Purisima Formation at Drakes Estero. Anima (1991) concluded that the main sources of sediment supply to Abbotts Lagoon is from Aeolian dune encroachment, open-coast processes (berm overwash and wave erosion), and stream input.

The objective of this report is to provide a comprehensive summary of the work done in this study. The primary objectives of this study were to compare the water quality of storm runoff from subbasins with contrasting land uses and to evaluate seasonal variations in water quality in the most significant tributary stream and the lagoon. This study was funded by the U.S. Geological Survey (USGS) under a competitive grant from the NPS–USGS Water-Quality Monitoring and Assessment Partnership. The other half of this study was an assessment of the fishery resources in Abbotts Lagoon, carried out by Michael Saiki of the USGS, Biological Resources Discipline (Saiki and Martin, 2001).

Environmental Setting

Study Area

Abbotts Lagoon and its watershed is a unique hydrologic system in Point Reyes National Seashore, combining rare wilderness dune habitat with active ranching operations (Brannon Ketcham, National Park Service, oral commun., 2005). The lagoon is easily accessible by way of a walking trail maintained by the NPS from the parking lot (*fig. 1*). It is a favorite hike for many visitors to Point Reyes National Seashore, especially among bird-watching enthusiasts (Salcedo-Chourre, 2003). Four historic ranches are located within the 5.3-mi^2 watershed area: two are operated as dairies and two as beef cattle ranches. The lagoon is actually three separate, yet usually surficially connected, waterbodies. These will be referred to in this report as the upper lagoon, middle lagoon, and lower lagoon (*fig. 1*). The small, shallow upper lagoon is separated from the much larger and deeper middle lagoon by an earthen berm. The middle lagoon is separated from the largest and deepest lower lagoon just below the footbridge on the NPS trail by an outcropping of the Monterey Formation. The lowest lagoon is usually separated from the ocean by the sandy beach. However, the beach berm occasionally breaches for short periods, allowing the direct exchange of seawater with the lagoon(s). Data collection sites and drainage basin boundaries for each water-quality site are shown on *figure 1*.

Land Use

Land use information for the Abbotts Lagoon basin was provided by NPS staff (Brannon Ketcham, National Park Service, written commun., 2001). The general land use categories provided by NPS staff are native vegetation, sand dunes, silage, grazing (permanent, seasonal, and general), and dairy- and (or) ranching-impacted. The grazing categories distinguish between dairy and beef cattle grazing and the level of grazing impact. The general grazing category is used for beef cattle grazing where the animals are able to graze year round, but they are spread out over a relatively large area. The seasonal grazing category is for dairy cattle, where the animals are able to graze on a relatively small area and for a limited number of months each year. The permanent grazing category is for dairy cattle where the animals are able to graze on a relatively small area for the entire year. The dairy- and (or) ranching-impacted category is where there are permanent feeding and (or) milking structures associated with the dairy and (or) ranching operations. The land use categories and information was provided by NPS staff and digitized into an ArcInfo Geographical Informational System coverage (*fig. 2*). Overlaying the basin boundaries made it possible to summarize the percentage of each land use in each sampled water-quality basin (*table 1*).

Land use in the basin of the upper lagoon is 42.0 percent grazing, 29.1 percent silage, 22.1 percent native vegetation, and 6.1 percent dairy- and (or) ranching-impacted operations. Because the upper lagoon flows into the middle lagoon, it is part of the middle lagoon basin; in fact, it accounts for about 78 percent of the basin area for the middle lagoon. The drainage directly to the middle lagoon—that is not part of the basin for the upper lagoon—has relatively more grazing, less silage, and no dairy and (or) ranching impacted operations. Likewise, the basin area for the lower lagoon includes the basin areas of the upper and middle lagoons. Relative to the upper and middle lagoons, the drainage directly to the lower lagoon has more grazing and sand dunes, and less native vegetation, silage, and dairy and (or) ranching impacted operations.

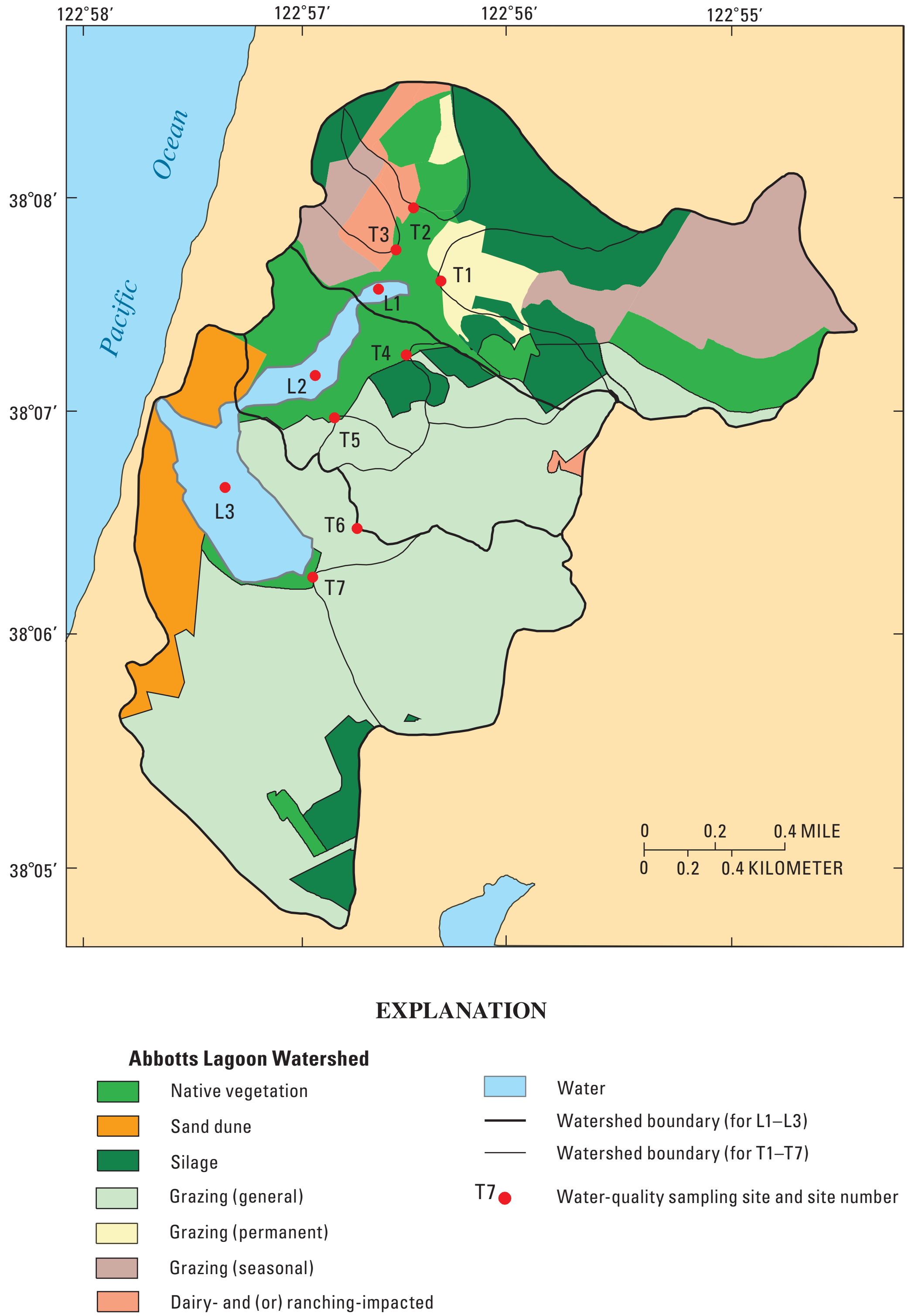

Figure 2. Location of sampling sites, watersheds, and land use in Abbotts Lagoon watershed.

Table 1. Sampling sites, drainage areas, and land use in Abbotts Lagoon watershed.

[ID, identification; NA, not applicable; mi^2, square mile]

Site no. (see fig. 1)	Site name	Site ID	Basin area (mi^2)	Land use, percentage of basin area							
				Native vegetation	Sand dunes	Water	Silage	Grazing (general)	Grazing (permanent)	Grazing (seasonal)	Dairy/ ranching (impacted)
L1	Abbotts Lagoon, upper small lagoon	380736122562401	1.92	22.1	0.0	0.7	29.1	5.0	7.3	29.7	6.1
L2	Abbotts Lagoon, middle lagoon	380717122564101	2.47	22.4	0.4	3.2	21.4	24.2	4.7	19.3	4.3
L3	Abbotts Lagoon, lower lagoon	380652122570501	5.29	13.5	5.9	6.2	14.1	44.5	2.7	10.8	2.4
T1	Unnamed tributary 1 to Upper Abbotts Lagoon	380738122560701	0.98	18.2	0.0	0.0	17.9	8.7	8.2	46.9	0.0
T2	Unnamed tributary 2 to Upper Abbotts Lagoon	380753122561501	0.18	49.0	0.0	0.0	14.0	0.0	11.3	0.0	25.6
T3	Unnamed tributary 3 to Upper Abbotts Lagoon	380752122562501	0.07	2.0	0.0	0.0	26.7	0.0	0.0	34.0	37.3
T4	Unnamed tributary 4 to Middle Abbotts Lagoon	380722122561601	0.12	4.2	0.0	0.0	31.2	64.6	0.0	0.0	0.0
T5	Unnamed tributary 5 to Middle Abbotts Lagoon	380708122563501	0.05	0.7	0.0	0.0	0.0	99.3	0.0	0.0	0.0
T6	Unnamed tributary 6 to Lower Abbotts Lagoon	380642122563601	0.42	0.0	0.0	0.0	0.0	97.6	0.0	0.0	2.4
T7	Unnamed tributary 7 to Lower Abbotts Lagoon	380633122564001	0.62	0.0	0.0	0.0	0.2	99.8	0.0	0.0	0.0
T1–T7	Total drainage area for tributaries T1—T7	NA	2.44	11.2	0.0	0.0	10.6	50.9	4.1	19.8	3.4
L3 minus water and tributaries T1–T7	Abbotts basin land area not in tributary basins	NA	2.52	17.5	12.4	0.0	19.3	44.1	1.7	3.5	1.8

The drainage basin for the perennial stream at site T1 is the largest (0.98 mi^2) of the sampled tributaries (*table 1*). It is dominated by grazing (63.8 percent), with about 18 percent each in silage and native vegetation. Tributaries T2 and T3 drain the I Ranch dairy area and 25.6 and 37.3 percent of their drainage basins, respectively, are dairy-impacted operations. The rest of the drainage basin for T2 is primarily native vegetation (49.0 percent), and about 14 percent silage and 11 percent grazing. The rest of the drainage basin for T3 is primarily grazing (34.0 percent) and silage (26.7 percent). Tributaries T1, T2, and T3 drain into the small upper lagoon. Tributaries T4 and T5 were sampled along the NPS footpath leading from the Abbotts Lagoon parking area to the footbridge between the middle and lower lagoons. They drain directly to the middle lagoon and have relatively small drainage basins that are dominated by grazing—64.6 and 99.3 percent, respectively. The T4 drainage basin has 31.2 percent silage. Tributaries T6 and T7 drain directly to the lower lagoon, and their drainage basins are dominated by grazing, with 97.6 and 99.8 percent, respectively. The T6 drainage basin also includes a ranching-impacted operation (H Ranch) at the upper end of the watershed.

The area drained by sampled tributaries (T1–T7) is 2.44 mi^2, 49.2 percent of the total drainage-basin land area of 4.96 mi^2 (*table 1*). The land not in the sampled tributary basins has relatively more native vegetation, sand dunes, and silage, and relatively less grazing and dairy- and (or) ranching-impacted land use than the land in the sampled tributary basins (*table 1*). The most intensive animal land uses (permanent and seasonal grazing, and dairy- and [or] ranching-impacted) account for 16.9 percent of the Abbotts basin land area. These land uses represent 27.3 percent of the land drained by the sampled tributaries, but only 7.0 percent of the other land in the Abbotts basin. The only intermittent stream of significance enters the lower lagoon from the south (*fig. 1*) and was virtually inaccessible during storm events.

Methods

Sample Collection

The sampling strategy for the water-quality assessment included quarterly sampling at the three lagoon sites and the perennial tributary T1, plus sampling two storm events at several tributary sites. The quarterly water-quality sampling occurred on November 24, 1998, January 27, 1999, May 19, 1999, and August 26, 1999. Storm sampling occurred on February 6–7, 1999, and April 10–11, 1999. A continuous water-level recorder was installed at T1 in February 1999, just prior to the storm sampling. A streamflow rating was developed by the USGS for this tributary and was used to develop a continuous streamflow record for water years 1999 and 2000. Streamflow in T1 is mainly a function of rainfall; the stream becomes almost dry during extended periods without rain. Four samples were collected at T1 during the storm hydrograph on February 6–7, 1999, and two samples were collected during the storm hydrograph on April 10–11, 1999. Seven tributaries (T1–T7) and the middle lagoon (L2) were sampled from one to four times during the February 6–7, 1999, storm runoff. During the April 10–11, 1999, storm runoff, two samples were collected at T1, and single samples were collected at T2, T3, T5, and the middle lagoon.

During November, January, and May, the lagoon sites (L1, L2, and L3) were sampled from a canoe. During August, a larger boat was used because of the one-time collection of bed-sediment samples. The quarterly water-quality samples from the lagoon were collected with a Van Dorn sampler. Samples collected for laboratory parameters were obtained about one foot below the water surface. Field parameters were also measured near the lagoon bottom at each site. The bed-sediment samples collected at the lagoon sites in August were collected with an Ekman Dredge. Quarterly samples at T1 were collected as midpoint grabs with a 3-L Teflon bottle. Storm samples were collected as midpoint grabs directly into 1-L amber glass bottles at all sites.

Sample Processing and Laboratory Methods

The water samples collected quarterly at the lagoon sites and T1 were analyzed for field parameters, major ions, nutrients, chlorophyll, and suspended sediment. Only samples collected at L1 were analyzed for dissolved organic carbon. The bed-sediment samples collected in August at the lagoon sites were analyzed for percentage of inorganic and organic carbon, iron, and phosphorus. Field parameters measured at each site during quarterly sampling included temperature, specific conductance, pH, dissolved oxygen, alkalinity, and Secchi disk transparency (lagoon sites only). Storm samples were analyzed only for field parameters (temperature, specific conductance, and pH), nutrients, and suspended sediment. The April 1999 storm sample collected at T3 was also analyzed for a suite of 47 indicators of wastewater as part of a USGS national reconnaissance on “emerging contaminants” (Kolpin and others, 2002). Except for suspended sediment and chlorophyll, all laboratory samples were stored on ice and shipped overnight to the USGS’s National Water Quality Laboratory (NWQL) in Denver, Colorado, within two days of collection. Suspended sediment samples were sent to the USGS’s California Water Science Center Sediment Laboratory in Salinas, California. Chlorophyll samples were stored on dry ice and shipped separately to the NWQL.

Samples collected for major-ion analyses (schedule 2701 at NWQL) were filtered through a 0.45-μm capsule filter and were analyzed by the inductively coupled plasma (ICP) method at the NWQL (Fishman and Friedman, 1989). Samples collected for analyses of dissolved nutrient species (schedule 2702 at NWQL) were filtered through a 0.45-μm capsule filter. Both dissolved and total nutrient species were analyzed by the colorimetry method at the NWQL (Fishman and Friedman, 1989). Chlorophyll samples (labcode 586 at NWQL) were filtered through a 0.7-μm glass fiber filter in the field, then the filter was folded and put in a petri dish, wrapped in aluminum foil and stored on dry ice until shipped to the NWQL. At the NWQL, chlorophyll samples were ruptured mechanically by centrifuge, and the pigments were separated from each other and degradation products by high-pressure liquid chromatography (HPLC). The chlorophyll-*a* concentrations were then determined by fluorescence spectroscopy (Britton and Greeson, 1987). The dissolved organic carbon samples (labcode 113 at NWQL) were filtered through a 0.45-μm silver filter in the field. At the NWQL, the dissolved organic carbon was determined by ultraviolet-promoted persulfate oxidation and infrared spectrometry (Brenton and Arnett, 1993). The bed-sediment samples were sieved through a 2-mm sieve in the field. Thus, the bed sediment samples analyzed for percent carbon, total phosphorus, and iron represent material less than 2 mm in diameter. The percentage of inorganic and organic carbon in bed material (labcodes 1458 and 1459, respectively at NWQL) were determined by wet-chemical oxidation and infrared spectrometry (Burkhardt and others, 1997). The total phosphorus in bed material (labcode 515 at NWQL) was determined by colorimetry (Fishman and Friedman, 1989). The iron in bed material (labcode 2566 at NWQL) was determined by ICP (Garbarino and Struzeski, 1998). The samples for wastewater indicators (custom labcode 8033 at NWQL) were analyzed by gas chromatography/mass spectrometry on unfiltered water (Barber and others, 2000).

Quality Control Samples

The quality control sampling was limited in this study because of the limited budget available for additional analytical samples. During the storm sampling, one replicate and one field blank were collected for nutrients only. The field blank collected at T4 on February 7, 1999, at 1008 had no detections of nitrogen species, and low-level detections of dissolved phosphorus species (0.006 mg/L dissolved phosphorus as P; 0.019 mg/L dissolved orthophosphate as P). The reporting levels for these constituents were 0.006 and 0.018 mg/L as P, respectively. The corresponding values in the environmental sample collected at T4 were 0.070 and 0.052 mg/L as P, respectively. Because the storm samples were collected directly in 1-L glass bottles, there was no cleaning of a sample collection bottle. Thus, phosphorus contamination of the blank was probably introduced either during filtering or in the blank water itself.

A replicate was collected at T2 on February 7, 1999, at 1441. All dissolved nutrient measurements had relative percent differences of less than 10 percent. For whole-water constituents—total Kjeldahl nitrogen and total phosphorus—the relative percent differences were 50 and 17 percent, respectively. These replicates were collected as sequential replicates into separate 1-L glass bottles. This illustrates the problem with representing (and reproducing) suspended material with sequential mid-point grabs (Martin and others, 1992). The environmental sample had a suspended sediment concentration of 88 mg/L, with 36 percent of this being material coarser than clay or silt (that is, with diameter greater than 0.062 mm). The flow at this site was mostly runoff from a dairy operation, and the proper splitting of solids between replicates greatly affects suspended nutrient levels. Sequential grab samples are not a good way to reproduce suspended-nutrient concentration results.

Hydrology

The hydrology of Abbotts Lagoon watershed has a big effect on the water quality in the three lagoons. To improve our understanding of water quality in the lagoons, we first present an estimated water budget. As part of this exercise, we instrumented the two lower lagoons (L2 and L3) with water-level recorders and the perennial tributary (T1) with a streamflow gage (*fig. 1*). We also obtained precipitation and evaporation data for nearby sites operated by the National Weather Service and the Marin Municipal Water District, respectively (*fig. 1*).

Abbotts Lagoon is normally a freshwater lagoon, separated from the Pacific Ocean by a narrow strip of beach. However, this sand berm is occasionally breached during winter or early spring following several precipitation-runoff events in the watershed or during times of high tides and waves in the ocean. Since 1982, breaches occurred in February 1986, January and March of 1995, and twice in 1998 (Michael Lighthiser, 1998, unpub. term paper, University of California, Berkeley). During this study, a breach was reported to the lead author by a frequent visitor to the Abbotts Lagoon foot trail. The visitor reported that a breach occurred at the end of March 1999 during a period of high waves. The visitor observed a wave of seawater moving through the breach into L3 and past the footbridge separating L3 and L2. The visitor noted that the wave eroded some of the sand dunes along L2 that are directly north of the footbridge. The visitor estimated that the breach closed within about a week. The breach probably occurred early in a storm on March 24 that had sustained northwest winds of over 30 mi/h for 10 h and peak gusts up to 53 mi/h at the National Weather Service weather station just south of Abbotts Lagoon (see precipitation site on *figure 1*; data from the California Data Exchange Center website at *http://cdec.water.ca.gov* for the site coded as "PTR" accessed on February 3, 2004). The breach closed before April 1, when the lead author visited Abbotts Lagoon. We know that water levels were high in the lagoons during this period, and the strong northwest winds probably created big ocean waves that could erode the sand berm at the ocean end of L3.

Although our information is incomplete to adequately define a water budget for Abbotts Lagoon for the entire study period, some components were measured for parts of the study period. An attempt will be made here to estimate what is known about the water budget for specific periods of time. The most basic expression of a water budget is:

$$\text{Inflow} - \text{Outflow} = \text{Change in Storage} \qquad (1)$$

A completely unknown component of either inflow or outflow is ground water. To avoid the unknown of surface flows between the three lagoons (that is, from L1 to L2 and from L2 to L3), the water budget was performed on all three lagoons as if they were one lagoon. An essential part of the water budget is the development of suitable stage versus volume relations for the lagoons to directly measure change in storage in equation 1. This task required revising the bathymetric map produced by Anima (1991).

Change in Storage

Because the Anima (1991) bathymetric map does not have a water-surface elevation (mean sea level, MSL) reference point, we used observations and a survey to estimate a MSL for the map. This MSL is relative to the North American Vertical Datum of 1988 (NAVD 88). The lead author was at Abbotts Lagoon on April 1, 1999, after the breach had closed and observed a high-water line near the footbridge that was 5 in. above the water surface level on April 1. The water level in L2 (and L3 since they were at the same level) on April 1 was 6 in. below the bottom of the footbridge that was surveyed by transit on February 13, 2004, by the USGS as 14.94 ft MSL. Thus, the breach on March 24, 1999, occurred at a water surface elevation of close to 15.0 ft MSL. This was considered to be the full condition for L1, L2, and L3 for development of a bathymetric map and stage versus volume relations.

Water depths at the time of sampling are included in Saiki (2000). On February 27, 1999, maximum depths in L1 of 10.1 ft and in L2 of 24.0 ft were reported (Saiki, 2000). No maximum depths were reported for L3 because of high winds. The transects used to develop the bathymetric map are shown in Anima (1991). The maximum depths shown in the transects are 6.0 ft in L1, 19.0 ft in L2, and 31.5 ft in L3. However, in the bathymetric map, Anima (1991) shows a maximum depth in L1 of 2 m (6.5 ft) and in L3 of 10 m (32.5 ft). We assumed that Anima (1991) used some additional information (for example, scuba diving observations for L3) to revise the maximum depths for L1 and L3. Thus, at the elevation of his bathymetric map, Anima (1991) had the following maximum depths: L1 (6.5 ft), L2 (19.0 ft), and L3 (32.5 ft).

Although Saiki (2000) noted that water levels in the lagoons were very high on February 27, 1999, there was no indication of how high relative to the MSL. Also, it is not clear if the three lagoons were at the same elevation at the time. With reference to a breach early in the March 24, 1999, storm, a water budget for February 28 to March 23, 1999, indicates that the lagoons (in total) increased in storage by at least 363 acre-ft. This is based on an average flow of 6.9 ft^3/s in T1, a total evaporation of 0.82 in., and precipitation of 2.88 in. (not including the March 24–25, 1999, storm) for the 24 days. This increase in storage of 363 acre-ft would raise the elevation of Abbotts Lagoon by 1.73 ft overall. Assuming that L3 was still slightly lower than L1 and L2 at the beginning of the February 28, 1999, to March 23, 1999, period, L1 and L2 would be raised by 1.5 ft and L3 by about 1.8 ft. The depth readings by Saiki (2000) on February 27, 1999, indicate the relationship to Anima depths for L1 and L2, although they are not very exact because they only represent one point on the lagoon, whereas Anima (1991) used transects across the lagoons. Also, Saiki (2000) was not able to measure a depth for L3 on February 27, 1999. So, assuming that L1 and L2 rose by 1.5 ft from February 27 to March 24, 1999, the depths on March 24 at the time of the breach would be about 11.6 ft for L1 and about 25.5 ft for L2.

Because we assume that all three lagoons are at the same elevation in Anima (1991) and also on March 24, 1999, before the breach, we increased the depth data from Anima (1991) for all lagoons by 6.0 ft. This means maximum depths at a water elevation of 15.0 ft MSL of 12.5 ft in L1, 25.0 ft in L2, and 38.5 ft in L3. This means that the Anima (1991) bathymetric map represents depths for a water elevation of 9.0 ft MSL. Thus, we adjusted the Anima (1991) bathymetric map to show water depths at full (15.0 MSL) and these are 6.0 ft (1.85 m) deeper than shown on the original map. We added 6.0 ft to the original contours and added a 25.0-ft contour for L2 to account for a deeper spot in the lower portion of L2 that was identified in Anima (1991) transect K-K' and in the February 26, 1999, sampling by Saiki (2000) (*fig. 3*). We then used the revised bathymetric map to define a complete stage versus volume relationship for L1, L2, and L3 (*fig. 4*). The new maximum depths (at 15.0 MSL) for the lagoons are as follows: L1 (3.85 m, 12.5 ft), L2 (7.69 m, 25.0 ft), and L3 (11.85 m, 38.5 ft). The range of stages for the lagoons are: L1 (2.5 to 15.0 ft MSL), L2 (–10.0 to 15.0 ft MSL), and L3 (–23.5 to 15.0 ft MSL).

On the Anima (1991) transect K-K' at a MSL of 9.0 ft, it appears that the connections between L1 and L2 and between L2 and L3 are severed at any water-surface elevation below 9.0 ft (that is, the lowest point on the berms between the lagoons are about 9.0 ft MSL). This explains why the water depth in L1 was consistently around 6 ft during our sampling. When the water level in L2 drops below the water level of L1, water from L1 flows to L2, thus keeping the water level in L1 at around 9.0 ft MSL. The depth in L1 does not drop much below this because of the inflow from T1 into L1 offsetting some evaporation losses. When the water surface elevation of L2 drops below 9.0 ft MSL, it will stop spilling into L3 at the footbridge.

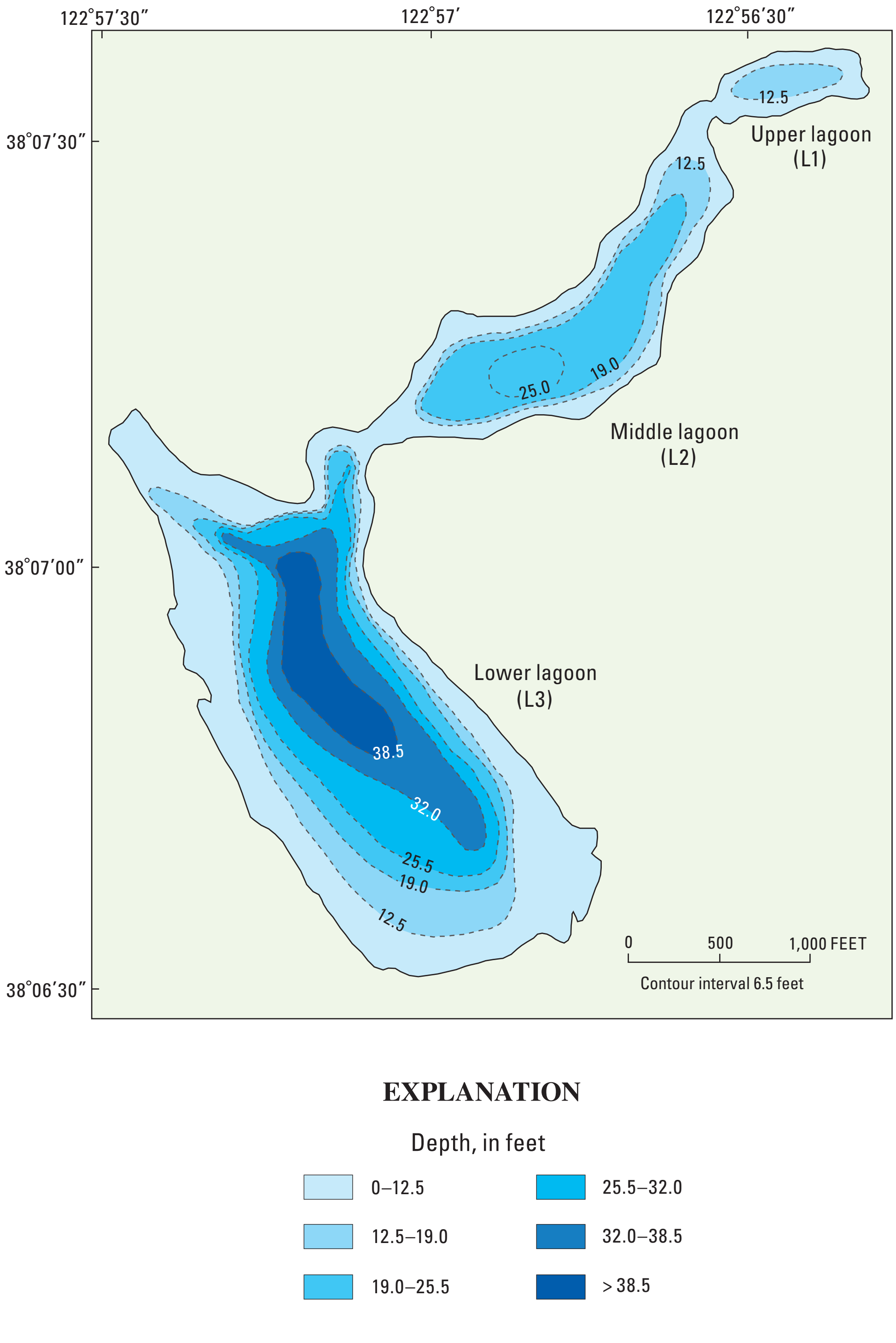

Figure 3. Bathymetry of upper, middle, and lower lagoons in Abbotts Lagoon at water surface elevation of 15.0 feet mean sea level (MSL). Revised from Anima, 1991.

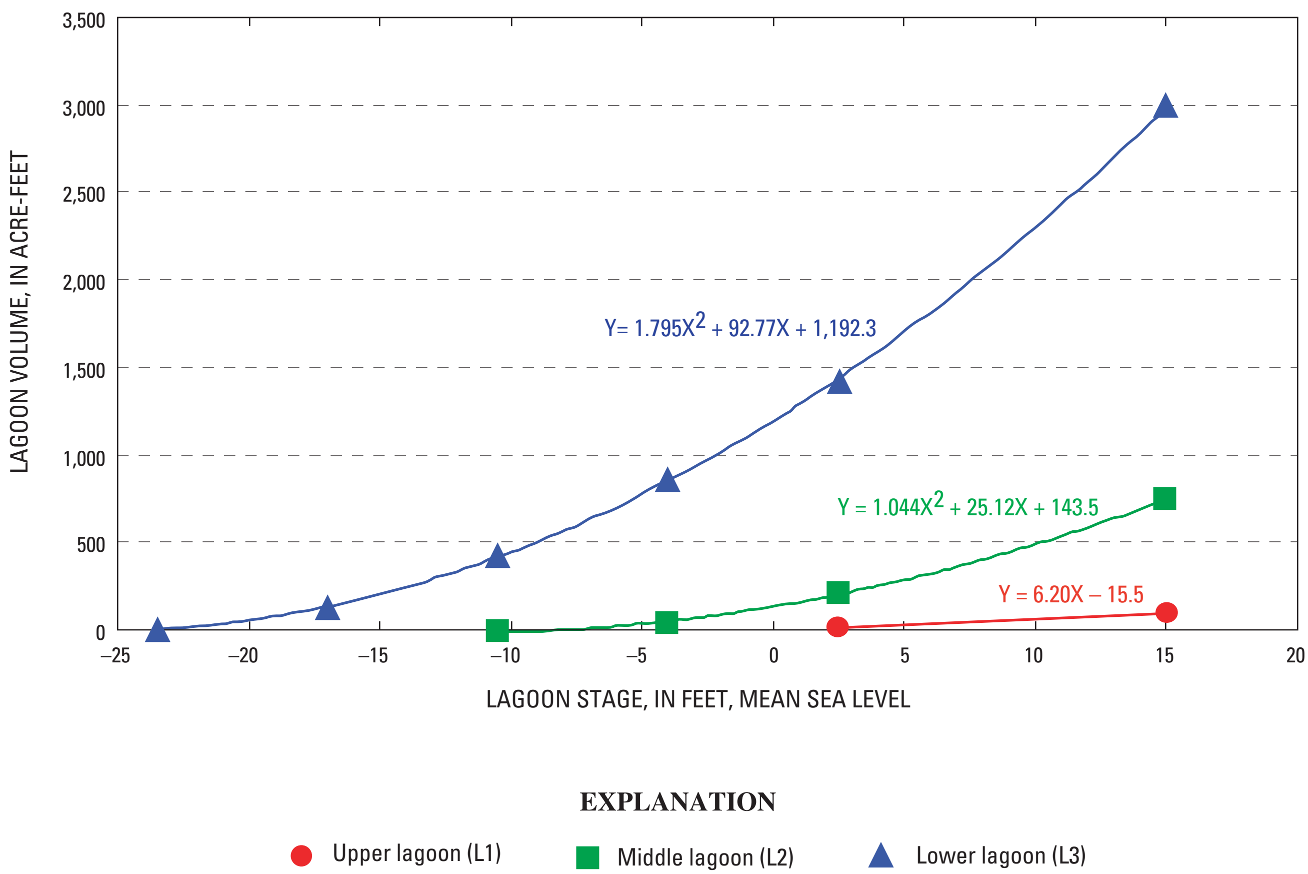

Figure 4. Volume versus stage relationships for the upper, middle, and lower lagoons in Abbotts Lagoon.

Continuous water-level recorders (Global Water WL-14 model) were initially installed in 2.5-in. polyvinyl chloride (PVC) pipe at sites A and B on March 2, 2000. With reference to results from a February 13, 2004, USGS survey of the PVC pipes (and tapedown measurements on the pipes and on a staff pipe at L2), the initial water levels at sites A and B were 11.87 and 11.40 ft MSL, respectively. However, the recorder at site A became buried in sediment by March 8 and started giving unreliable measurements. The recorder was raised out of the sediment on March 29 at 1300 and the data became reliable. At the start of a reliable record of stage at sites A and B (*fig. 1*) on March 29 at 1300, the water levels at the sites were 12.41 and 12.09 ft MSL, respectively. Using these starting water levels, continuous stage and volumes for L1, L2, and L3 for March 29 to July 27, 2000, were measured (*fig. 5*).

Inflows

Inflows to Abbotts Lagoon include several small tributaries and drainages, precipitation on the surface of the lagoon, and possibly ground-water contributions. Total precipitation at the National Weather Service precipitation site just south of the Abbotts Lagoon drainage basin (*fig. 1*) during water years 1999 and 2000 was 47.17 in.; 27.31 in. in water year 1999, and 19.86 in. in water year 2000 (*fig. 6*; data from the California Data Exchange Center website at *http://cdec.water.ca.gov* for the site coded as “PTR” accessed on January 23, 2003). Missing precipitation data for October 1–29, 1998, at the National Weather Service site was filled in with precipitation data from the NPS Point Reyes National Seashore Headquarters about 2 mi south of Point Reyes Station (*fig. 1*), adjusted by the ratio of annual precipitation for water year 1999 of 0.64 (with the National Weather Service site having lower precipitation) (Brannon Ketcham, National Park Service, written commun., 2001). Streamflow in T1 is strongly controlled by precipitation and it is essentially zero during much of the summer and fall months (*fig. 6*). The storm runoff response of T1 is very quick (within a few hours) and streamflow generally returns to close to prestorm levels within a couple of days (*fig. 7*). Except for T7, streamflows at T1 during the two sampled storms were at least five times greater than at the other tributary sites (*fig. 7*). The streamflows at T7 during the February 1999 storm were about half to two-thirds the streamflows at T1. This is consistent with drainage basin size; T7 has the second largest drainage basin after T1.

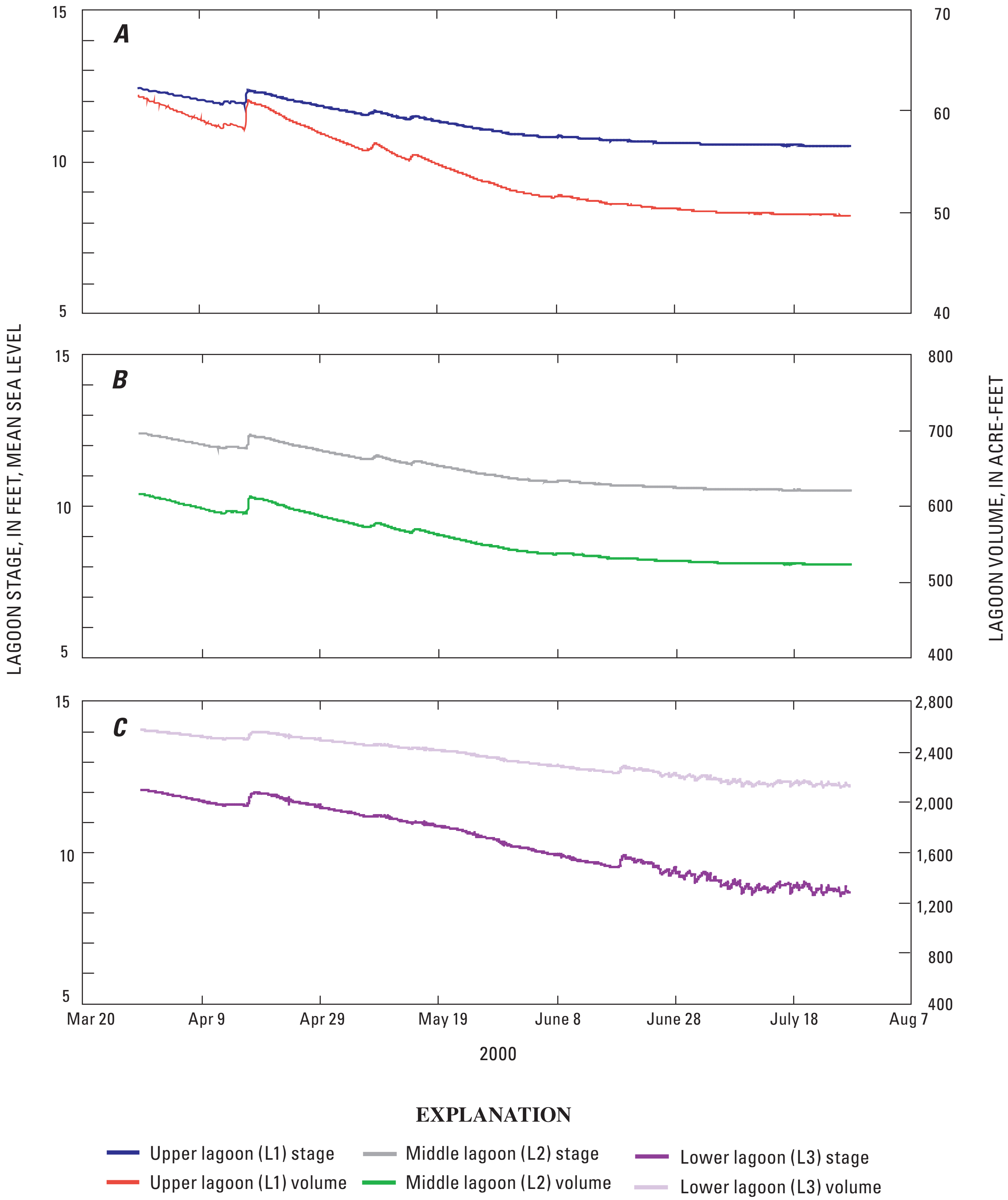

Figure 5. Hourly stage and volume for the upper, middle, and lower lagoons in Abbotts Lagoon from March 29 to July 27, 2000.

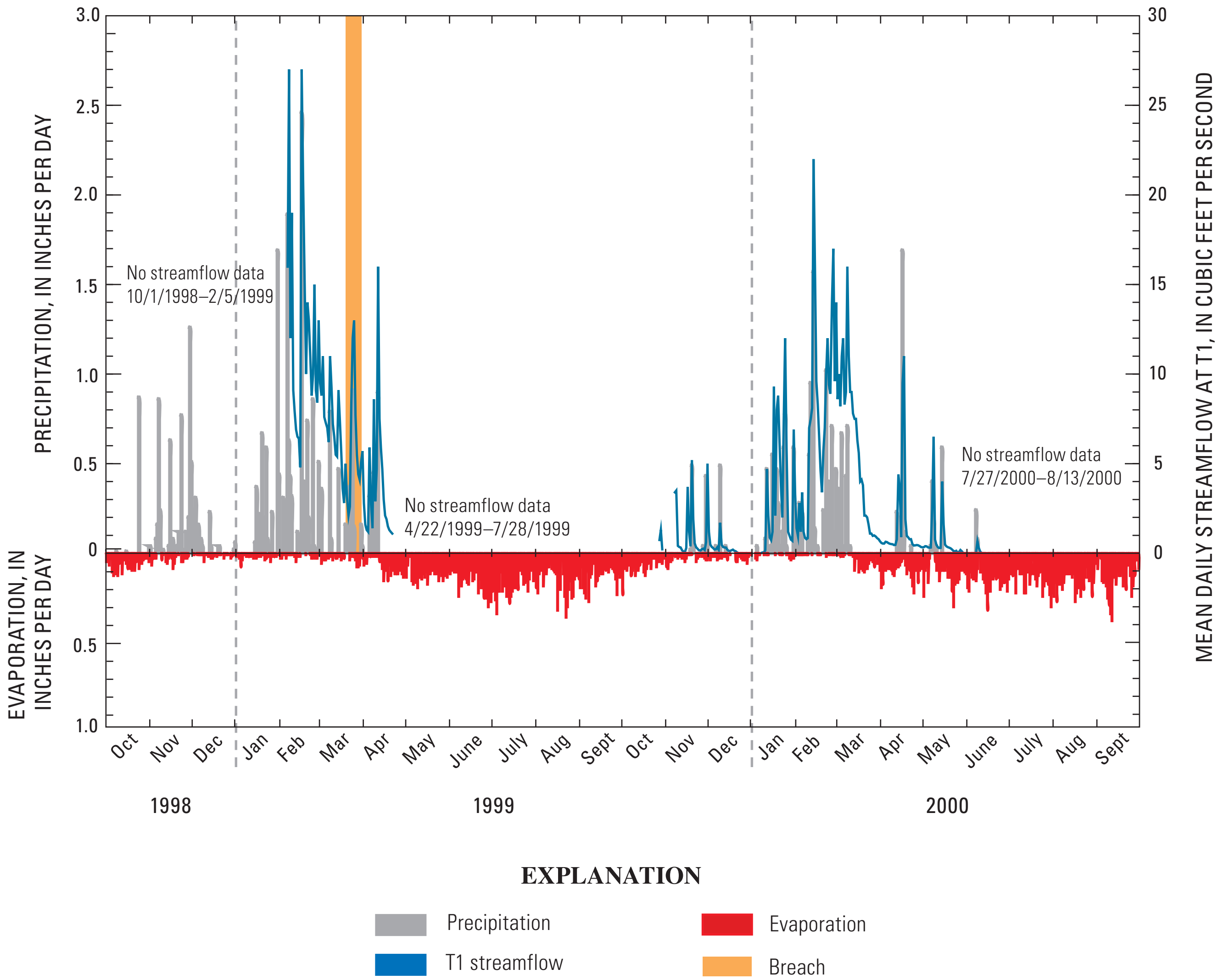

Figure 6. Mean daily streamflow in tributary T1 in Abbotts Lagoon watershed, and daily precipitation and evaporation, for water years 1999 and 2000.

The relationship of T1 flows to total surface inflows to Abbotts Lagoon can be estimated over the time period of a storm and the resulting change in storage if we assume that ground water inflow–outflow over this short time period is insignificant compared with surface flows. The best storm for this purpose was the 1.81 in. of rain that fell on April 16–17, 2000, and the resulting runoff in T1 with a peak instantaneous streamflow of 29 ft^3/s on April 16 at 11 p.m. The total surface inflow can be solved for using equation (2), developed as follows:

$$\text{Inflow} - \text{Outflow} = \text{Change in Storage} \quad (1)$$

Where,
Inflow ≡ Surface inflow + Precipitation
Outflow ≡ Evaporation

$$\text{Surface Inflow} = \text{Change in Storage} + \text{Evaporation} - \text{Precipitation} \quad (2)$$

Streamflows in T1 and storage in L2 and L3 increased on April 16 at 10 a.m. and stabilized by 3 a.m. on April 18. Thus, equation 2 will be solved for this 41-h period. The total inflow in T1 during this period was 40.8 acre-ft. The precipitation (1.81 in.) and evaporation (0.06 in.) from the 210-acre surface of Abbotts Lagoon amounts to 31.7 and 1.1 acre-ft, respectively. The change in storage over the time period was 2.4 acre-ft in L1, 19.7 acre-ft in L2, and 56.7 acre-ft in L3 (*fig. 5*). Using equation (2), this would mean a total surface inflow of 48.2 acre-ft. Thus, the T1 inflow during this storm was 85 percent of the total surface inflow to Abbotts Lagoon.

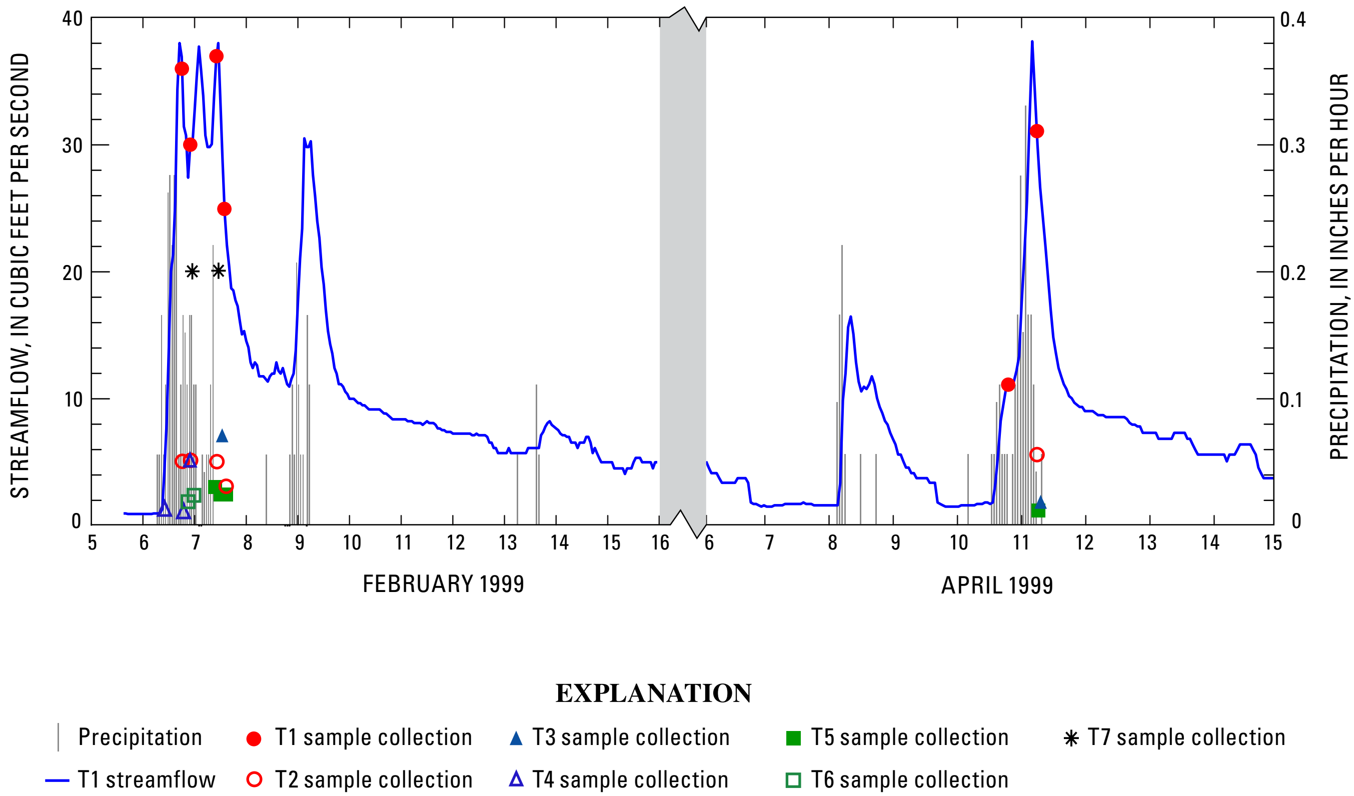

Figure 7. Hourly streamflow in tributary T1 in Abbotts Lagoon watershed and instantaneous streamflows at time of sampling for other tributary sites, and sample collection times and hourly precipitation for February 5–16, 1999, and April 6–15, 1999. The vertical gray bar in the center of the graph represents a break in the graph.

Although this method shows that T1 is the most significant surface inflow to Abbotts Lagoon, it is not the only significant source of surface inflows during winter storms. The flows in T7 during the February 1999 storm sampling were more than half the flows in T1 (*fig. 7*). Many of the flows during storms depend on the freeboard in upstream storage ponds and the stage of growth of vegetation upstream of the site. Flows in T2, T4, T6, and T7 are dependent upon the freeboard in stock watering ponds in the drainage upstream prior to the storm. The flows in T5 during the February 1999 storm sampling were much greater when the vegetative growth in the drainage was dormant, compared with the April 1999 storm sampling when vegetative growth was very active.

Outflows

Outflows from Abbotts Lagoon include evaporation from the lagoon surface and, possibly, ground-water seepage. Evaporation from the surface of Abbotts Lagoon was estimated from pan evaporation data from Marin Municipal Water District (Randy Arena, Marin Municipal Water District, written commun., 2001) for Nicasio Reservoir, about 10 mi to the southeast (*fig. 1*). The data at the pan evaporation site was assumed to represent Abbotts Lagoon. In reality, there are two offsetting effects on the conversion of evaporation rates from Nicasio Reservoir to Abbotts Lagoon: (1) more fog at Abbotts Lagoon that would decrease evaporation relative to Nicasio Reservoir and (2) higher winds at Abbotts Lagoon that would increase evaporation relative to Nicasio Reservoir. Annual evaporation rates at Nicasio Reservoir were 32.7 in. in water year 1999 and 32.4 in. in water year 2000. Summer evaporation rates at Nicasio Reservoir averaged about 0.17 in. per day (June through August) and winter rates about 0.02 in. per day (December through February; *fig. 6*). Missing and questionable data for 156 days at the Nicasio Reservoir site were filled in with interpolated data that accounted for the ratio of Nicasio Reservoir data to evapotranspiration data from a California Department of Water Resources weather station near Novato (about 20 mi east of Abbotts Lagoon, *fig. 1*; data from a Center for Irrigation Technology website accessed on November 22, 2003, at *http://www.wateright.org/site2/reference/cimisdist.asp* for Novato site).

Ground Water

Ground-water interactions with Abbotts Lagoon could be inflows, outflows, or both. The best opportunity to evaluate net ground-water flow would be when no surface inflows occur. At this time, the net ground-water flow is a function of only the change in storage and evaporation:

$$\text{Inflow} - \text{Outflow} = \text{Change in Storage} \qquad (1)$$

Where,
Inflow ≡ Ground-water inflow
Outflow ≡ Ground-water outflow + Evaporation

$$\text{Ground-water Inflow} - \text{Ground-water Outflow} = \text{Change in Storage} + \text{Evaporation} \qquad (3)$$

The best time period during our study to estimate net ground-water flow is from June 11 through July 27, 2000. We have data on change in storage in L1, L2, and L3, and there was no precipitation and no surface flows to Abbotts Lagoon according to recorded flows of T1. With this information we can estimate the net ground-water flow using equation (3).

Evaporation from Abbotts Lagoon (using the data for Nicasio Reservoir) during the June 11 through July 27, 2000, period was 7.16 in. For the 210-acre surface area of Abbotts Lagoon, this amounts to 125.2 acre-ft. Change in storage over this time period in L1 (–1.7 acre-ft), L2 (–13.3 acre-ft), and L3 (–135.9 acre-ft) was a decrease of 150.9 acre-ft. Thus, the net ground-water contribution to the water budget would be an outflow from Abbotts Lagoon to the ground water (seepage) of 25.7 acre-ft. This amounts to an average outflow (seepage) rate for the ground water of about 0.3 ft^3/s.

Water Quality

Quarterly Sampling

The non-nutrient quarterly sampling data collected at T1, L1, L2, and L3 are shown in *table 2* (Freeman and others, 2000). Field parameters did not vary much between surface and bottom at the lagoon sites during the quarterly sampling. The lagoons became increasingly brackish from L1 to L3; mean quarterly specific conductivities were 352 in L1, 1,000 in L2, and 9,580 µS/cm in L3. This seawater influence is observed in the ions of most significance in seawater, namely chloride, sodium, sulfate, magnesium, calcium, and potassium (*table 2*). The reported breach in the sand berm in late March 1999 and the subsequent movement of seawater into L2 is confirmed by the water-quality data (*fig. 8*).

The quarterly nutrient data at these sites is shown, along with the storm sampling data at the seven tributary sites plus L2, in *table 3* (Freeman and others, 2000). Nitrogen concentrations in the lagoons decrease from L1 to L3 (*fig. 9*). This is due to both greater direct tributary inputs to L1 than to L2 or L3, and uptake by macrophytes and phytoplankton as the water moves from L1 to L3. Nitrate and ammonia concentrations were especially high in L1 during the winter sampling, probably because of inputs from runoff in the tributaries that were influenced by the dairies. Ammonia concentrations were also high in L1 in the August sampling. Phosphorus concentrations also decreased from L1 to L3 (*fig. 10*). Concentrations were especially high in the August sampling. The high ammonia and phosphorus concentrations in L1 during August appear to indicate that runoff from the dairy was affecting the lagoon.

Chlorophyll-*a* concentrations decreased at all three lagoons during the study, except for a big increase in L1 in spring (*fig. 11*). The increase in L1 appears to be directly linked to high nitrogen inputs in winter (*fig. 12*). The decrease in chlorophyll-*a* in L2 and L3 from winter to spring is probably related to breaching of the sand berm and flushing of the two lower lagoons with seawater. A reduction in algal growth in August (lower chlorophyll-*a*) at all lagoons probably could be an explanation for some of the higher nutrient concentrations, because of less nutrient uptake by algae. Chlorophyll-*a* and Secchi disk water transparency did not appear to be related in L2 and L3 and slightly inversely related in L1. A major effect on the Secchi disk water transparency in the larger lagoons, L2 and L3, probably is due to disturbance from the wind.

A commonly used criterion for determining the limiting nutrient in lakes is the ratio of dissolved inorganic nitrogen (nitrite, nitrate, and ammonia) to dissolved orthophosphate. If this ratio is above 10 (by weight), the lake is assumed to be phosphorus limited (Sas, 1989). Conversely, if this ratio is below 10, the lake is assumed to be nitrogen limited. Additionally, if dissolved inorganic nitrogen concentration is above 0.1 mg/L as N or if dissolved orthophosphate concentration is above 0.01 mg/L as P, these nutrients are not considered to be limiting (Sas, 1989). These criteria are also dependent on hydraulic residence time and other potentially limiting factors such as light. With reference to the nitrogen to phosphorus ratio criteria, the lagoons were nitrogen limited (*fig. 13*). Dissolved orthophosphate concentrations in the lagoons were always well above the 0.01 mg/L as P criterion. The dissolved inorganic nitrogen concentrations in L1 were also usually above the 0.1 mg/L as N criterion. However, the input of nitrogen in winter storm runoff appears to have directly stimulated spring algal growth in L1. Also, the nitrogen appears to have been completely incorporated into this algal growth (*fig. 12*).

Table 2. Quarterly sampling data collected at sites T1, L1, L2, and L3 for all water-quality constituents except nutrients in the water column.

[In the headers, the numbers in parentheses denote the National Water Information System (NWIS) parameter code; a blank cell indicates the constituent was not analyzed for; C, Celsius; chromo fluorom, chromatographic-fluorometric method; diam., diameter; e, estimated; fm, from; mg/L, milligram per liter; mm/dd/yyyy, month/day/year; recov, recoverable; —, no data; <, actual value is known to be less than the value shown; µg/L, microgram per liter; µS/cm, microsiemens per centimeter; %, percent]

Site ID	Site name (no.)	Date (mm/dd/yyyy)	Time	Sampling depth (ft)	Specific Conductance (µS/cm)	pH water whole field (standard units)	Temperature water (deg C)	Oxygen, dissolved (mg/L)	Transparency, Secchi disk (ft)
				(00003)	(00095)	(00400)	(00010)	(00300)	(49701)
380738122560701	Unnamed tributary 1 to Upper Abbotts Lagoon (T1)	11/24/1998	1010	—	339	7.5	10.6	9.5	—
		1/27/1999	1430	—	261	7.3	8.7	10.7	—
		5/19/1999	1220	—	212	7.7	14.1	9.3	—
		8/26/1999	1040	—	219	7.3	14.9	—	—
380736122562401	Abbotts Lagoon, upper small lagoon (L1)	11/24/1998	1030	1	362	8.0	12.9	7.2	—
		11/24/1998	1040	5	—	—	12.5	5.3	
		1/27/1999	1600	1	360	7.3	9.8	6.8	1.8
		1/27/1999	1610	6	363	7.3	9.3	6.2	
		5/19/1999	1530	1	310	9.1	18.8	12.4	1.3
		5/19/1999	1540	6	310	9.2	—	12.7	
		8/26/1999	1320	1	377	7.3	21.0	—	2.0
		8/26/1999	1330	6	382	7.3	20.4	—	
380717122564101	Abbotts Lagoon, middle lagoon (L2)	11/24/1998	1130	1	651	7.9	13.2	8.5	—
		11/24/1998	1140	15	—	—	13.0	7.8	
		1/27/1999	1530	1	588	7.8	10.6	10.1	4.0
		1/27/1999	1540	18	588	7.9	10.3	9.5	
		5/19/1999	1500	1	1,420	7.6	17.8	9.9	2.3
		5/19/1999	1510	16	1,430	7.5	—	9.6	
		8/26/1999	1240	1	1,350	8.1	20.9	—	2.8
		8/26/1999	1250	16	1,350	8.1	20.0	—	
380652122570501	Abbotts Lagoon, lower lagoon (L3)	11/24/1998	1230	1	11,000	8.8	13.2	11.0	—
		11/24/1998	1240	30	—	—	12.9	8.4	
		1/27/1999	1510	1	10,200	8.0	10.0	10.7	6.9
		1/27/1999	1510	34	10,200	8.0	9.8	10.4	
		5/19/1999	1420	1	8,030	7.8	15.5	9.4	6.0
		5/19/1999	1430	30	8,040	7.8	—	9.4	
		8/26/1999	1130	1	9,070	8.4	19.8	—	3.5
		8/26/1999	1140	29	9,080	8.3	18.7	—	

Table 2. Quarterly sampling data collected at sites T1, L1, L2, and L3 for all water-quality constituents except nutrients in the water column—Continued.

[In the headers, the numbers in parentheses denote the National Water Information System (NWIS) parameter code; a blank cell indicates the constituent was not analyzed for; C, Celsius; chromo fluorom, chromatographic-fluorometric method; diam., diameter; e, estimated; fm, from; mg/L, milligram per liter; mm/dd/yyyy, month/day/year; recov, recoverable; —, no data; <, actual value is known to be less than the value shown; µg/L, microgram per liter; µS/cm, microsiemens per centimeter; %, percent]

Site ID	Site name (no.)	Date (mm/dd/yyyy)	Time	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)	Sodium, dissolved (mg/L as Na)	Potassium, dissolved (mg/L as K)	Alkalinity, wat. dis. gran t. field $CaCO_3$ (mg/L)	Sulfate, dissolved (mg/L as SO_4)	Chloride, dissolved (mg/L as Cl)
				(00915)	(00925)	(00930)	(00935)	(29802)	(00945)	(00940)
380738122560701	Unnamed tributary 1 to Upper Abbotts Lagoon (T1)	11/24/1998	1010	17.1	10.3	32.8	3.75	46	31.0	50.5
		1/27/1999	1430	12.7	7.18	23.1	1.34	28	17.3	39.4
		5/19/1999	1220	12.6	7.24	20.7	0.53	62	7.5	19.8
		8/26/1999	1040	9.12	5.8	25.5	0.48	46	13.7	21.1
380736122562401	Abbotts Lagoon, upper small lagoon (L1)	11/24/1998	1030	15.7	12.1	35.7	5.66	83	19.2	49.0
		11/24/1998	1040							
		1/27/1999	1600	13.5	10.3	30.4	8.52	59	25.8	48.0
		1/27/1999	1610							
		5/19/1999	1530	11.3	9.64	33.0	3.29	65	15.2	41.4
		5/19/1999	1540							
		8/26/1999	1320	17.8	13.4	35.4	4.33	109	9.7	41.7
		8/26/1999	1330							
380717122564101	Abbotts Lagoon, middle lagoon (L2)	11/24/1998	1130	12.2	15.3	87.9	6.71	70	21.4	146
		11/24/1998	1140							
		1/27/1999	1530	10.8	13.4	72.5	5.79	61	28.1	121
		1/27/1999	1540							
		5/19/1999	1500	17.0	28.0	200	11.5	50	—	—
		5/19/1999	1510							
		8/26/1999	1240	17.7	27.1	181	11.0	65	51.2	338
		8/26/1999	1250							
380652122570501	Abbotts Lagoon, lower lagoon (L3)	11/24/1998	1230	83.8	241	2,010	89.1	70	499	3,840
		11/24/1998	1240							
		1/27/1999	1510	80.2	237	1,920	66.7	70	439	3,260
		1/27/1999	1510							
		5/19/1999	1420	60.4	166	1,410	54.0	—	336	2,440
		5/19/1999	1430					63		
		8/26/1999	1130	58.1	165	1,340	65.7	66	352	2,830
		8/26/1999	1140							

Table 2. Quarterly sampling data collected at sites T1, L1, L2, and L3 for all water-quality constituents except nutrients in the water column.—Continued

[In the headers, the numbers in parentheses denote the National Water Information System (NWIS) parameter code; a blank cell indicates the constituent was not analyzed for; C, Celsius; chromo fluorom, chromatographic-fluorometric method; diam., diameter; e, estimated; fm, from; mg/L, milligram per liter; mm/dd/yyyy, month/day/year; recov, recoverable; —, no data; <, actual value is known to be less than the value shown; µg/L, microgram per liter; µS/cm, microsiemens per centimeter; %, percent]

Site ID	Site name (no.)	Date (mm/dd/yyyy)	Time	Fluoride, dissolved (mg/L as F)	Silica, dissolved (mg/L as SiO_2)	Solids, residue at 180 deg C, dissolved (mg/L)	Iron, dissolved (µg/L as Fe)	Manganese, dissolved (µg/L as Mn)	Sediment, suspended (mg/L)	Sediment suspended, sieve diameter % finer than 0.062 mm
				(00950)	(00955)	(70300)	(01046)	(01056)	(80154)	(70331)
380738122560701	Unnamed tributary 1 to Upper Abbotts Lagoon (T1)	11/24/1998	1010	<0.1	16.7	242	553	161	33	97
		1/27/1999	1430	0.1	16.3	174	511	91.7	19	91
		5/19/1999	1220	0.1	15.9	157	1,070	54.8	28	97
		8/26/1999	1040	0.1	22.8	139	798	48.8	12	95
380736122562401	Abbotts Lagoon, upper small lagoon (L1)	11/24/1998	1030	<0.1	21.1	250	178	80.6	13	99
		11/24/1998	1040							
		1/27/1999	1600	<0.1	17.9	238	326	95.6	—	—
		1/27/1999	1610							
		5/19/1999	1530	0.1	6.37	196	375	e1.5	—	—
		5/19/1999	1540							
		8/26/1999	1320	0.1	11.8	215	375	155	—	—
		8/26/1999	1330							
380717122564101	Abbotts Lagoon, middle lagoon (L2)	11/24/1998	1130	<0.1	13.5	389	27	3.9	6	97
		11/24/1998	1140							
		1/27/1999	1530	0.1	15.2	340	36	3.1	—	—
		1/27/1999	1540							
		5/19/1999	1500	0.1	10.2	802	51	<15.0	—	—
		5/19/1999	1510							
		8/26/1999	1240	0.1	13.5	706	14	e1.6	—	—
		8/26/1999	1250							
380652122570501	Abbotts Lagoon, lower lagoon (L3)	11/24/1998	1230	0.2	2.84	7,310	<200	<60.0	3	100
		11/24/1998	1240							
		1/27/1999	1510	0.2	5.47	6,170	<100	<30.0	—	—
		1/27/1999	1510							
		5/19/1999	1420	0.2	5.45	4,580	<50	e8.9	—	—
		5/19/1999	1430							
		8/26/1999	1130	0.2	4.00	5,130	<50	<11.0	—	—
		8/26/1999	1140							

Table 2. Quarterly sampling data collected at sites T1, L1, L2, and L3 for all water-quality constituents except nutrients in the water column.—Continued

[In the headers, the numbers in parentheses denote the National Water Information System (NWIS) parameter code; a blank cell indicates the constituent was not analyzed for; C, Celsius; chromo fluorom, chromatographic-fluorometric method; diam., diameter; e, estimated; fm, from; mg/L, milligram per liter; mm/dd/yyyy, month/day/year; recov, recoverable; —, no data; <, actual value is known to be less than the value shown; µg/L, microgram per liter; µS/cm, microsiemens per centimeter; %, percent]

Site ID	Site name (no.)	Date (mm/dd/yyyy)	Time	Carbon, organic dissolved (mg/L as C)	Carbon, inorganic sediment bed materal (percent)	Carbon, organic sediment bed material (percent)	Phosphorus, recov from bottom material (µg/g as P)	Iron, recov from bottom material (µg/g as Fe)	Chlor-*a* phytoplankton chromo fluorom (µg/L)
				(00681)	(30241)	(30243)	[1](00668)	(01170)	(70953)
380738122560701	Unnamed tributary 1 to Upper Abbotts Lagoon (T1)	11/24/1998	1010	—	—	—	—	—	—
		1/27/1999	1430	—	—	—	—	—	—
		5/19/1999	1220	—	—	—	—	—	—
		8/26/1999	1040	—	—	—	—	—	—
380736122562401	Abbotts Lagoon, upper small lagoon (L1)	11/24/1998	1030	10	—	—	—	—	23.0
		11/24/1998	1040						
		1/27/1999	1600	14	—	—	—	—	8.1
		1/27/1999	1610						
		5/19/1999	1530	17	—	—	—	—	22.7
		5/19/1999	1540						
		8/26/1999	1320	14	0.05	12	e6,000	28,000	6.8
		8/26/1999	1330						
380717122564101	Abbotts Lagoon, middle lagoon (L2)	11/24/1998	1130	—	—	—	—	—	—
		11/24/1998	1140						16.5
		1/27/1999	1530	—	—	—	—	—	12.1
		1/27/1999	1540						
		5/19/1999	1500	—	—	—	—	—	2.9
		5/19/1999	1510						
		8/26/1999	1240	—	0.03	11	e6,700	29,000	2.3
		8/26/1999	1250						
380652122570501	Abbotts Lagoon, lower lagoon (L3)	11/24/1998	1230	—	—	—	—	—	—
		11/24/1998	1240						26.3
		1/27/1999	1510	—	—	—	—	—	16.5
		1/27/1999	1510						
		5/19/1999	1420	—	—	—	—	—	1.9
		5/19/1999	1430						
		8/26/1999	1130	—	0.02	8.4	e2,400	26,000	2.0
		8/26/1999	1140						

[1]Samples analyzed after NWQL holding period.

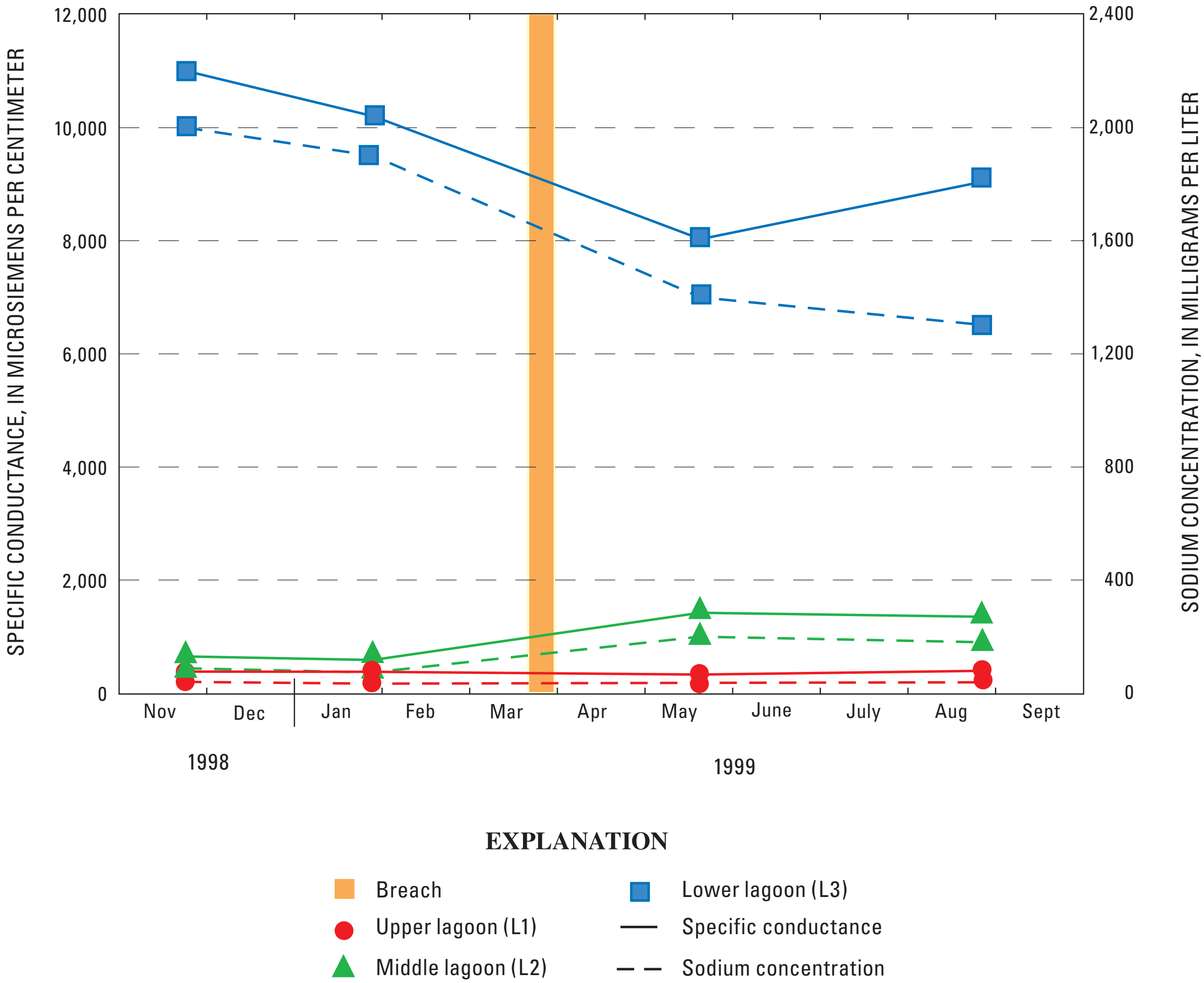

Figure 8. Specific conductance and sodium concentrations in the upper, middle, and lower lagoons in Abbotts Lagoon for water year 1999.

The bed sediment samples collected at L1, L2, and L3 in August 1999 had organic carbon percentages of 12, 11, and 8.4, respectively (*table 2*). Phosphorus concentrations on the bed material were higher in L1 and L2 (6,000 and 6,700 µg/g as P) than in L3 (2,400 µg/g as P). Thus, the bed sediment in L3 contained less organic carbon and phosphorus than in L1 and L2. Iron concentrations on the bed material were nearly the same at the three lagoons (28,000, 29,000, and 26,000 µg/g as Fe in L1–L3). Dissolved iron concentrations in the input tributary T1 (mean of 740 µg/L as Fe) and the upper lagoon L1 (mean of 315 µg/L as Fe) were considerably higher than in L2 and L3 (means of 32 and <100 µg/L as Fe, respectively). These concentrations imply higher levels of organic material and bacteria in the water column at L1, but similar levels in the sediment in all three lagoons.

Storm Sampling

The water-quality data collected during the February and April 1999 storms are shown in *table 3*. Concentrations of nitrogen and phosphorus species in the tributaries, plus storm flows at T1, are shown in *figures 14* and *15*, respectively. The tributaries T2 and T3, originating at the I Ranch dairy, had the highest concentrations of nitrogen and phosphorus during both storms. Tributary T5 had high concentrations of nitrate in the first storm, but not in the second. Between the February 1999 and the April 1999 storms, vegetation in the T5 basin grew from short and dormant to much taller and actively growing. This growth resulted in lower flows and much reduced nutrient concentrations. Suspended sediment and attached nutrients (that is, total nitrogen and total phosphorus) were generally higher in storm samples collected at T1 and T2 on the rising limb of the storm hydrographs.

Table 3. Storm and quarterly sampling data for field parameters, nutrients in the water column, and suspended sediment at all sites in Abbotts Lagoon watershed.

[In the headers, the numbers in parentheses denote the National Water Information System (NWIS) parameter code; a blank cell indicates the constituent was not analyzed for; diam., diameter; e, estimated; ft^3/s, cubic feet per second; inst., instantaneous; mm/dd/yyyy, month/day/year; mg/L, milligram per liter; mm, millimeter; Sed., sediment; susp., suspended; —, no data; <, actual value is known to be less than the value shown; µS/cm, microsiemens per centimeter]

Site ID	Site name (no.)	Date (mm/dd/yyyy)	Time	Discharge, inst. (ft^3/s)	Specific conductance (µS/cm)	pH water whole field (standard units)	Temperature water (deg C)	Nitrogen, nitrite dissolved (mg/L as N)	Nitrogen, nitrite + nitrate, dissolved (mg/L as N)	Nitrogen, ammonia dissolved (mg/L as N)	Nitrogen, ammonia + organic total (mg/L as N)	Nitrogen, ammonia + organic dissolved (mg/L as N)	Phosphorus, total (mg/L as P)	Phosphorus, dissolved (mg/L as P)	Phosphorus ortho, dissolved (mg/L as P)	Sediment, suspended (mg/L)	Sediment, suspended sieve diam. % finer than 0.062 mm
				(00061)	(00095)	(00400)	(00010)	(00613)	(00631)	(00608)	(00625)	(00623)	(00665)	(00666)	(00671)	(80154)	(70331)
380738122560701	Unnamed tributary 1 to Upper Abbotts Lagoon (T1)	11/24/1998	1010	0.01	339	7.5	10.6	0.01	0.26	0.10	1.8	1.5	0.13	0.06	0.03	33	97
		1/27/1999	1430	—	261	7.3	8.7	0.01	0.26	0.08	0.87	0.73	0.079	0.032	0.02	19	91
		2/6/1999	1810	36	148	6.9	10.2	<.01	0.17	0.03	1.9	0.69	0.33	0.043	0.02	242	92
		2/6/1999	2200	30	141	7.0	9.9	<.01	0.18	0.03	1.3	0.67	0.21	0.051	0.03	171	75
		2/7/1999	1000	37	132	7.0	12.2	<.01	0.37	0.04	1.0	0.66	0.157	0.186	0.06	121	90
		2/7/1999	1420	25	132	7.0	10.8	<.01	0.41	0.02	1.2	0.74	0.172	0.052	0.05	99	89
		4/10/1999	1840	10	173	7.4	9.3	<.01	0.14	0.02	1.3	0.71	0.12	0.041	0.02	—	—
		4/11/1999	0545	28	118	7.1	8.6	<.01	0.10	<.02	1.7	0.75	0.29	0.29	0.23	—	—
		5/19/1999	1220	0.49	212	7.7	14.1	<.01	0.39	0.05	1.0	0.75	0.120	0.063	0.06	28	97
		8/26/1999	1040	0.03	219	7.3	14.9	0.01	1.64	0.06	0.69	0.51	0.13	0.064	0.05	12	95
380753122561501	Unnamed tributary 2 to Upper Abbotts Lagoon (T2)	2/6/1999	1850	e5	386	7.0	10.5	0.076	3.41	1.00	5.2	3.3	2.06	1.56	1.46	118	78
		2/6/1999	2150	e5	388	7.2	9.3	0.058	2.93	1.27	6.4	3.7	3.22	2.19	2.05	163	82
		2/7/1999	1030	e5	321	7.0	10.4	0.067	3.32	0.83	4.5	2.8	1.79	1.76	2.21	96	83
		2/7/1999	1440	e3	372	7.0	11.3	0.085	4.61	0.72	3.0	2.6	1.34	1.02	1.08	88	64
		4/11/1999	0600	e5	330	7.4	9.1	0.096	5.01	0.79	7.8	3.0	2.67	1.47	1.53	—	—
380752122562501	Unnamed tributary 3 to Upper Abbotts Lagoon (T3)	2/7/1999	1300	e.7	636	7.2	13.6	0.223	8.66	3.46	9.9	7.2	5.22	3.68	4.44	148	87
		4/11/1999	0715	e1.5	506	7.5	8.1	0.085	3.48	1.68	13	5.1	5.19	2.27	2.48	—	—
380722122561601	Unnamed tributary 4 to Middle Abbotts Lagoon (T4)	2/6/1999	1850	e.1	172	7.1	9.9	<.010	0.10	0.06	0.64	0.60	0.082	0.047	0.02	5	100
		2/6/1999	2150	e.5	192	7.0	9.8	<.010	0.10	0.07	0.71	0.62	0.082	0.052	0.03	4	91
		2/7/1999	1000	e1.2	183	6.8	10.6	<.010	0.14	0.06	0.94	0.67	0.133	0.070	0.05	14	73
380708122563501	Unnamed tributary 5 to Middle Abbotts Lagoon (T5)	2/7/1999	1020	e3.0	202	6.4	11.4	0.011	4.41	0.10	1.6	1.1	0.28	0.183	0.17	34	91
		2/7/1999	1430	e2.5	235	6.4	—	0.013	4.97	0.06	1.6	1.2	0.26	0.171	0.16	22	92
		4/11/1999	0630	e1.0	141	6.8	8.6	<.010	0.07	<.02	0.98	0.74	0.078	0.036	0.02	—	—

Table 3. Storm and quarterly sampling data for field parameters, nutrients in the water column, and suspended sediment at all sites in Abbotts Lagoon watershed—Continued.

[In the headers, the numbers in parentheses denote the National Water Information System (NWIS) parameter code; a blank cell indicates the constituent was not analyzed for; diam., diameter; e, estimated; ft^3/s, cubic feet per second; inst., instantaneous; mm/dd/yyyy, month/day/year; mg/L, milligram per liter; mm, millimeter; Sed., sediment; susp., suspended; —, no data; <, actual value is known to be less than the value shown; µS/cm, microsiemens per centimeter]

Site ID	Site name (no.)	Date (mm/dd/yyyy)	Time	Discharge, inst. (ft³/s) (00061)	Specific conductance (µS/cm) (00095)	pH water whole field (standard units) (00400)	Temperature water (deg C) (00010)	Nitrogen, nitrite dissolved (mg/L as N) (00613)	Nitrogen, nitrite + nitrate, dissolved (mg/L as N) (00631)	Nitrogen, ammonia dissolved (mg/L as N) (00608)	Nitrogen, ammonia + organic total (mg/L as N) (00625)	Nitrogen, ammonia + organic dissolved (mg/L as N) (00623)	Phosphorus, total (mg/L as P) (00665)	Phosphorus, dissolved (mg/L as P) (00666)	Phosphorus ortho, dissolved (mg/L as P) (00671)	Sediment, suspended (mg/L) (80154)	Sediment, suspended sieve diam. % finer than 0.062 mm (70331)
380642122563601	Unnamed tributary 6 to Lower Abbotts Lagoon (T6)	2/6/1999	2100	e2.0	159	6.5	9.5	<.010	1.23	0.04	1.2	0.71	0.133	0.042	0.02	143	67
		2/6/1999	2320	e2.5	151	6.5	11.7	<.010	1.24	0.04	1.0	0.76	0.141	0.050	0.03	67	82
		2/7/1999	1210	e2.5	189	6.5	12.7	0.011	3.74	0.06	0.98	0.93	0.154	0.104	0.10	28	96
380633122564001	Unnamed tributary 7 to Lower Abbotts Lagoon (T7)	2/6/1999	2300	e20	164	6.6	10.5	<.010	0.07	<.02	0.89	0.79	0.088	0.043	0.02	23	98
		2/7/1999	1150	e20	139	6.6	11.3	<.010	0.45	0.02	0.90	0.78	0.095	0.048	0.03	26	82
380736122562401	Abbotts Lagoon, upper small lagoon (L1)	11/24/1998	1030		362	8.0	12.9	0.021	0.33	0.27	2.0	1.3	0.57	0.34	0.27	13	99
		1/27/1999	1600		360	7.3	9.8	0.045	1.47	0.74	2.3	1.9	0.490	0.25	0.24		
		5/19/1999	1530		310	9.1	18.8	<.010	<.05	<.02	1.9	1.1	0.57	0.30	0.27		
		8/26/1999	1320		377	7.3	21.0	<.010	0.11	0.54	2.1	1.6	—	1.42	1.28		
380717122564101	Abbotts Lagoon, middle lagoon (L2)	11/24/1998	1130		651	7.9	13.2	<.010	<.05	0.03	1.3	0.74	0.38	0.31	0.27	6	97
		1/27/1999	1530		588	7.8	10.6	<.010	0.11	0.02	0.95	0.65	0.21	0.179	0.16		
		2/7/1999	1450		548	7.6	—	<.010	0.14	0.08	0.89	0.66	0.22	0.160	0.14		
		4/10/1999	1915		1,790	7.9	11.4	0.011	0.13	<.02	1.2	0.76	0.26	0.165	0.13		
		5/19/1999	1500		1,420	7.6	17.8	<.010	<.05	0.03	1.0	0.85	0.27	0.209	0.16		
		8/26/1999	1240		1,350	8.1	20.9	<.010	<.05	<.02	0.84	0.75	0.51	0.52	0.45		
380652122570501	Abbotts Lagoon, lower lagoon (L3)	11/24/1998	1230		11,000	8.8	13.2	<.010	<.05	0.03	1.9	0.56	0.44	0.29	0.25	3	100
		1/27/1999	1500		10,200	8.0	10.0	<.010	<.05	0.03	0.81	0.62	0.207	0.159	0.14		
		5/19/1999	1420		8,030	7.8	15.5	<.010	<.05	<.02	0.77	0.72	0.135	0.117	0.09		
		8/26/1999	1130		9,070	8.4	19.8	<.010	<.05	<.02	0.57	0.51	0.220	0.21	0.23		

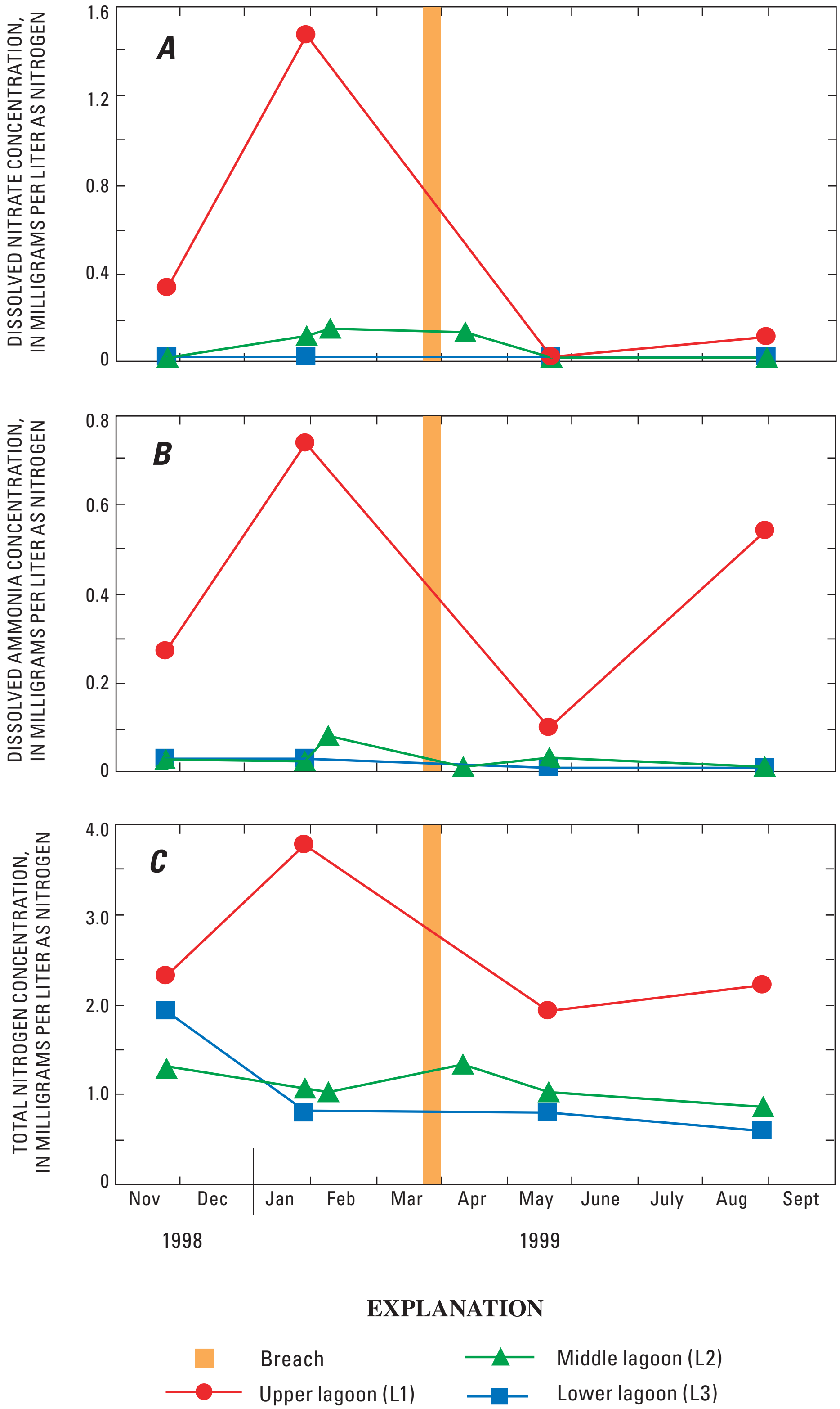

Figure 9. Dissolved nitrate, dissolved ammonia, and total nitrogen concentrations in the upper, middle, and lower lagoons in Abbotts Lagoon for water year 1999.

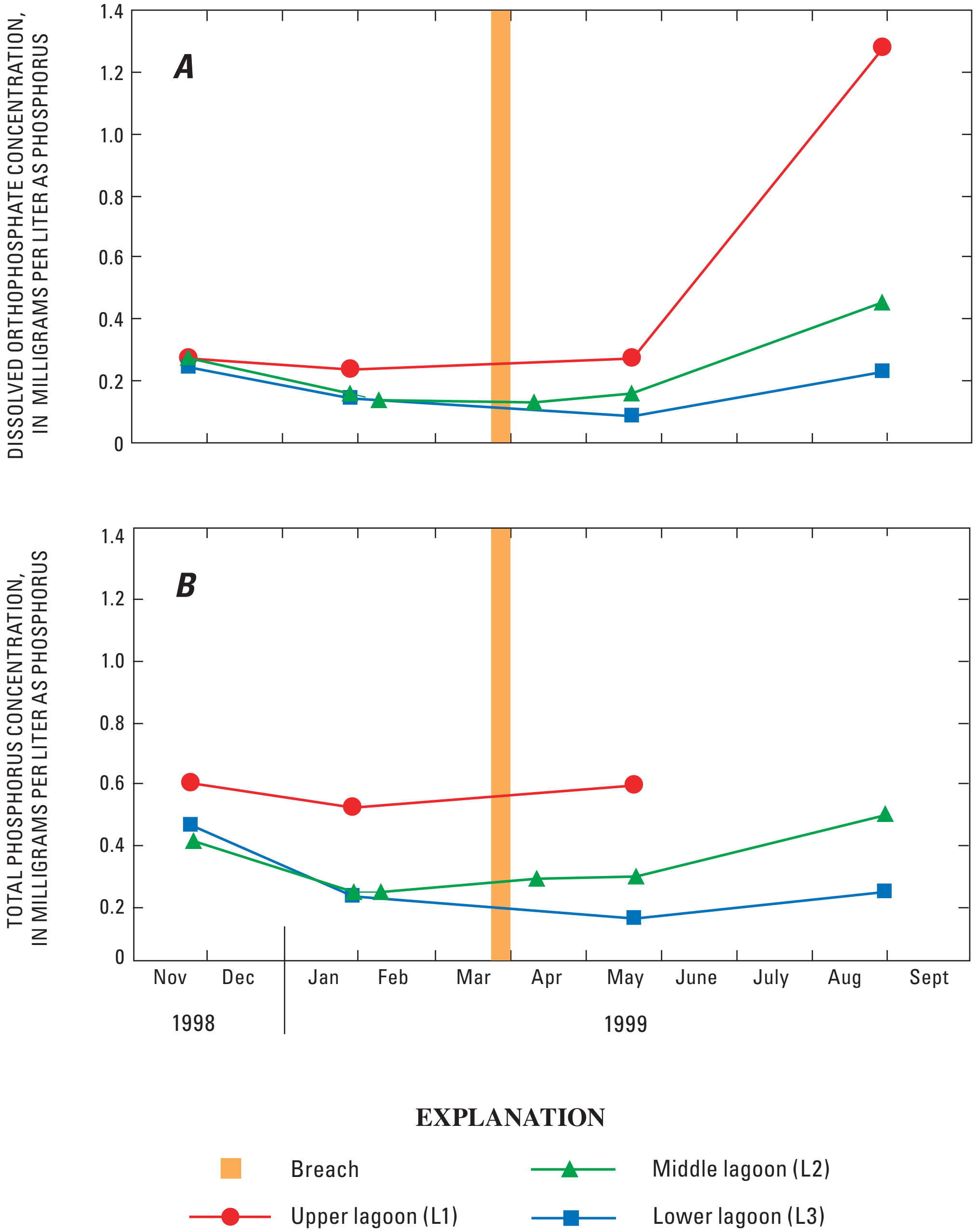

Figure 10. Dissolved orthophosphate and total phosphorus concentrations in the upper, middle, and lower lagoons in Abbotts Lagoon for water year 1999. No total phosphorus data is available for the upper lagoon in August 1999.

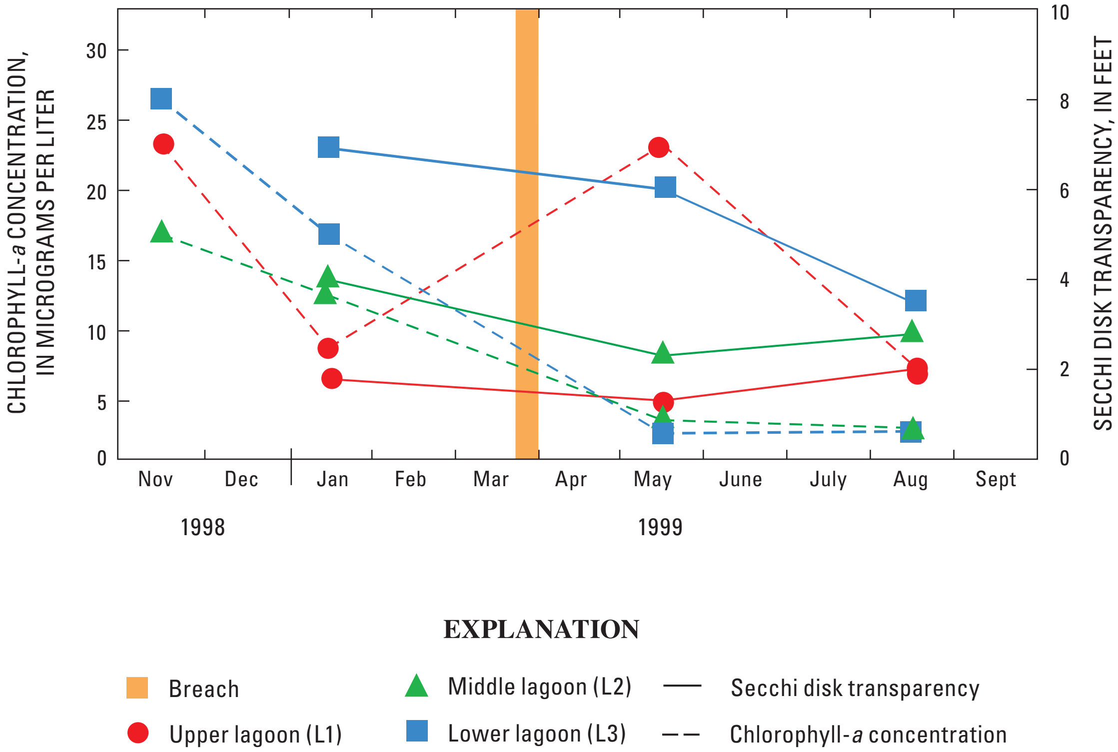

Figure 11. Chlorophyll-*a* concentrations and Secchi disk water transparency in the upper, middle, and lower lagoons in Abbotts Lagoon for water year 1999.

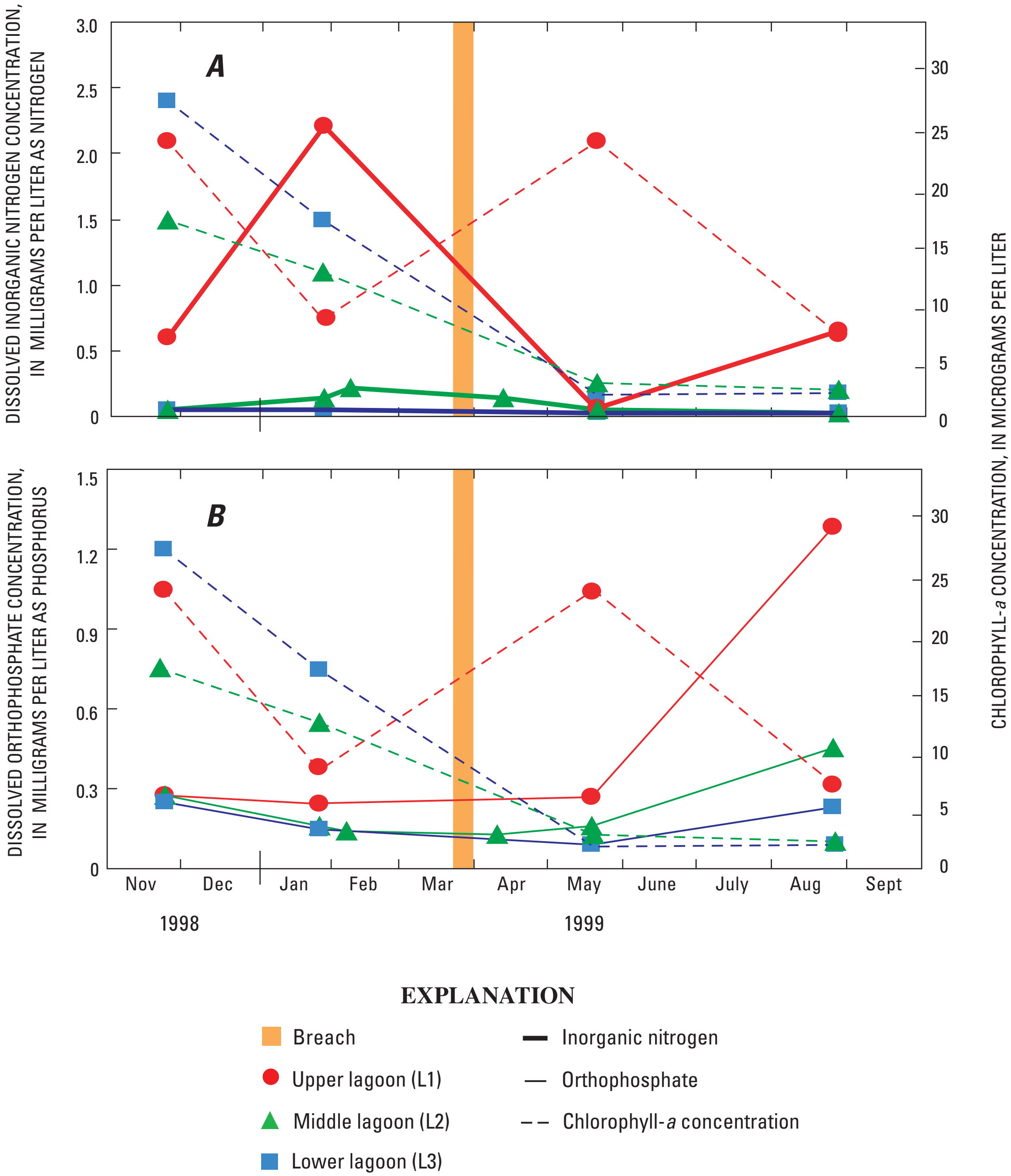

Figure 12. Dissolved inorganic nitrogen, dissolved orthophosphate, and chlorophyll-*a* concentrations in the upper, middle, and lower lagoons in Abbotts Lagoon for water year 1999.

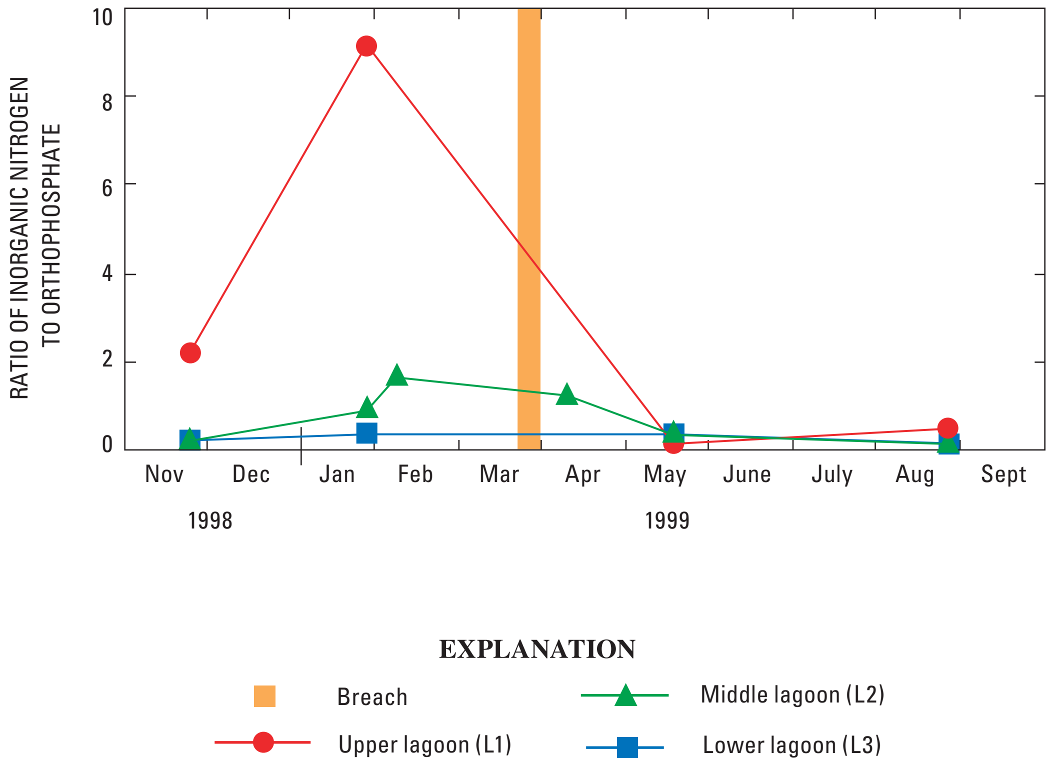

Figure 13. Ratios of inorganic nitrogen to orthophosphate in the upper, middle, and lower lagoons in Abbotts Lagoon for water year 1999.

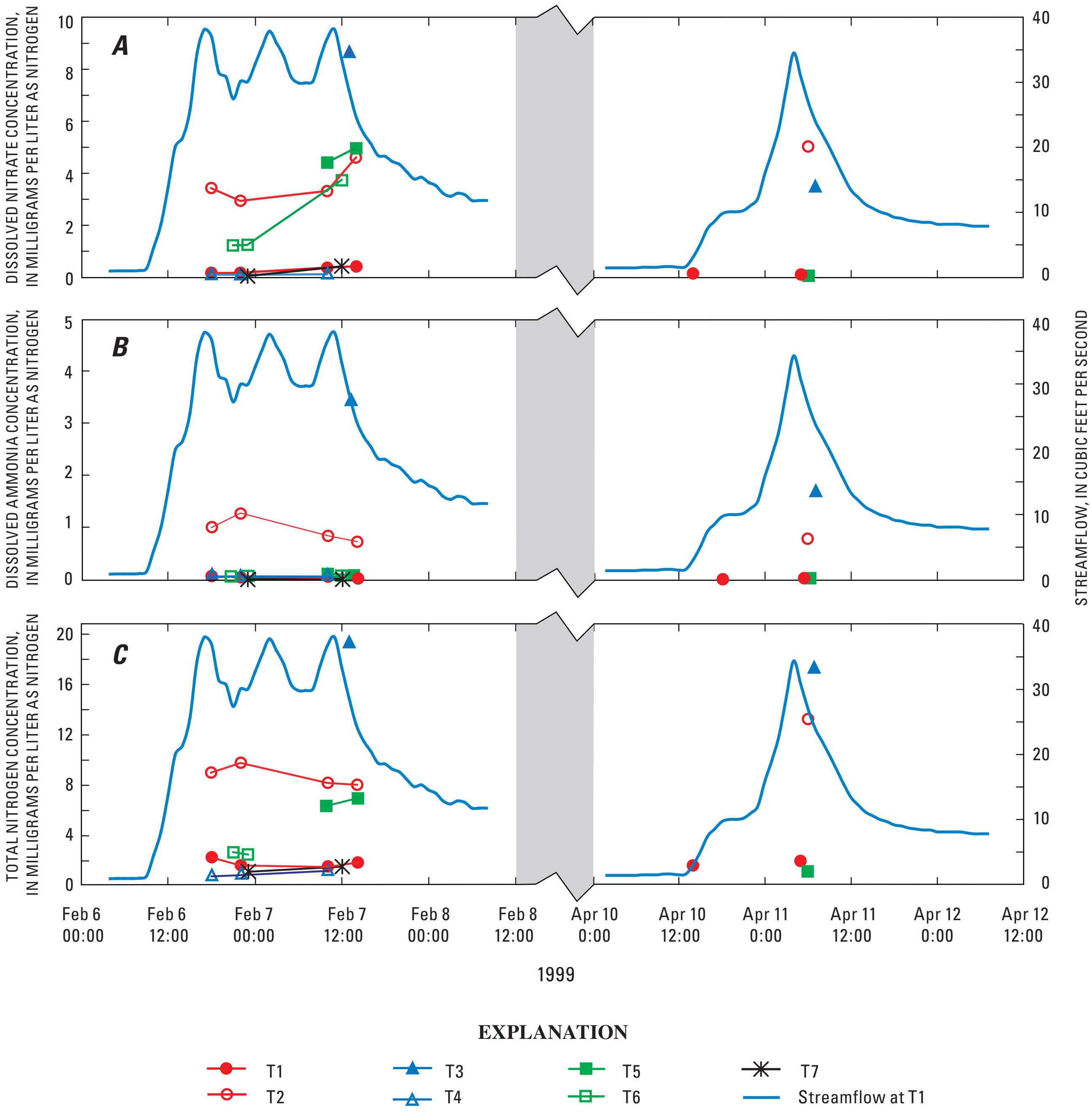

Figure 14. Dissolved nitrate, dissolved ammonia, and total nitrogen concentrations in Abbotts Lagoon watershed tributaries relative to streamflow in tributary T1 for February and April 1999 storms.The time zone reference is Pacific Standard Time (PST) in 24-hour format. The vertical gray bar in the center of the graph represents a break in the graph.

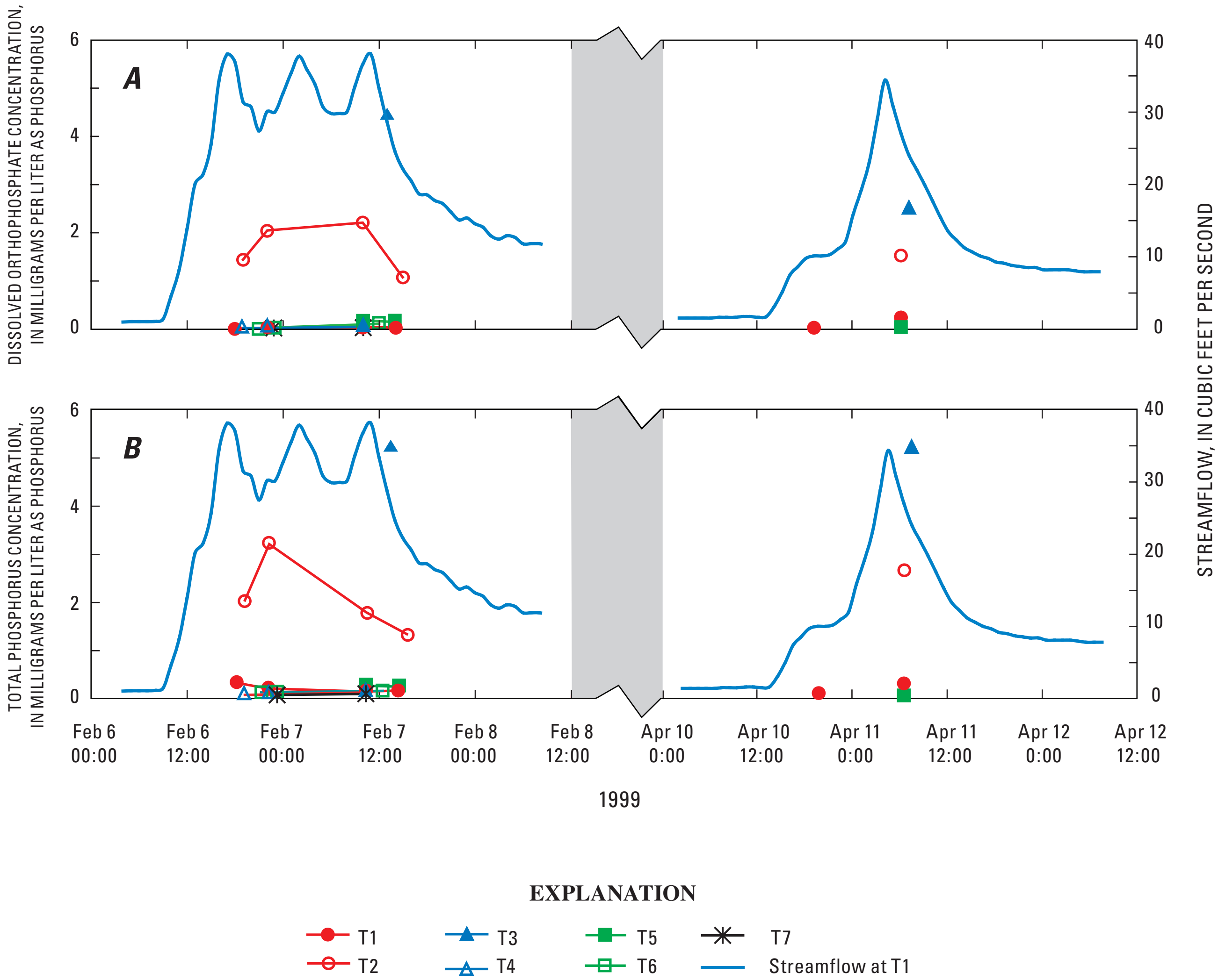

Figure 15. Dissolved orthophosphate and total phosphorus concentrations in Abbotts Lagoon watershed tributaries relative to streamflow in tributary T1 for February and April 1999 storms.The time zone reference is Pacific Standard Time (PST) in 24-hour format. The vertical gray bar in the center of the graph represents a break in the graph.

A sample was collected at T3 during the April 1999 storm and analyzed for 47 different indicators of wastewater (Barber and others, 2000). The analytical method focuses on the determination of nonionic surfactant compounds and their degradates that are persistent indicators of wastewater. Other compounds included in the method are representative of food additives, fragrances, antioxidants, flame retardants, plasticizers, industrial solvents, disinfectants, fecal sterols, polycyclic aromatic hydrocarbons, and high-use domestic pesticides. Eleven compounds were detected in the T3 sample. Although detected, only six of the detections were above 0.1 μg/L. These six compounds were two sterols that are also indicators of fecal material (3β-coprostanol, 4 μg/L; cholesterol, 9.3 μg/L), a plasticizer (bis[2-ethylhexyl] phthalate, 5.2 μg/L), a plastic (phthalic anhydride, 0.38 μg/L), a flame retardant (tri[2-butoxyethyl] phosphate, 0.24 μg/L), an antioxidant (bisphenol A, 0.19 μg/L), and a microbial disinfectant (triclosan, 0.12 μg/L).

Instantaneous loading rates of nitrogen and phosphorus species in the tributaries, plus streamflows at T1, are shown in *figures 16* and *17*, respectively. The comparison of loading rates in tributaries T1–T7 in *table 4* is based on the flow-weighted average of the instantaneous storm loading rates at each site. Tributaries T2 and T5 accounted for over half the nitrate loading rate. As mentioned earlier, loading rates in T5 were much higher in the February storm than the April storm. The two tributaries originating in the I Ranch dairy, T2 and T3, accounted for over 80 percent of the ammonia loading rate. Tributaries T1 and T2 were the main sources of total nitrogen loading rate. Tributary T1 is a significant source of loads largely because of its relatively high streamflow. The tributaries that discharge directly into the upper lagoon—T1, T2, and T3—accounted for over 85 percent of the phosphorus loading rate. Nitrogen and phosphorus loading rates in T4 were small relative to the other tributaries.

In terms of yield (loading rate per basin area), tributaries T2, T3, and T5 were most significant (*table 4*). Tributaries T2 and T3 had by far the greatest yields of ammonia and phosphorus. The basins for T2 and T3 have the highest percentage of intensive grazing (permanent and seasonal) and dairy- and (or) ranching-impacted land use. These basins have 36.9 and 71.3 percent of these land uses compared with 0.0–2.4 percent for basins T4–T7. Although the basin for T1 has 55.1 percent of these land uses, it does not have any dairy- and (or) ranching-impacted area. The yields in T1 were moderate compared with T2 and T3. The basin for T5 is almost all classified as general grazing. The nitrate yields in the February storm were especially high in this tributary. The April storm yields were an order of magnitude lower. This small basin is on a relatively steep grassy slope that was covered with low brush in April. The vegetation appeared to greatly reduce the runoff from the basin across the footpath and apparently reduced the nutrient loading rates as well. The dairy operation and, to a lesser extent, the intensive grazing of animals clearly contributes to higher nutrient loading rates to Abbotts Lagoon.

The two tributaries that contribute storm runoff from the I Ranch dairy (T2 and T3) account for only 10.3 percent of the 2.44 mi^2 drained by the seven tributaries, but contributed 44 percent of the nitrate load, 83 percent of the ammonia load, 40 percent of the total nitrogen load, 79 percent of the orthophosphate load, and 64 percent of the total phosphorus load to Abbotts Lagoon from the sampled tributaries during storm runoff (*table 4*). The perennial tributary (T1) contributed 31 percent of the total nitrogen load and 26 percent of the total phosphorus load, but also accounts for 40.2 percent of the area drained by the tributaries. The small tributary draining general grazing land to the middle lagoon (T5) contributed 21 percent of the nitrate load from a drainage area representing only 2.0 percent of the total area drained by the tributaries.

Possible Future Studies

This study was a preliminary assessment of the hydrology and water quality of the Abbotts Lagoon watershed. Our understanding of the hydrology and water quality could be improved considerably in future studies. The water budget for Abbotts Lagoon could be refined by installing continuous stage recorders in all three lagoons. A continuous stage recorder could be installed on T2 and a stage-discharge rating developed. A precipitation and evaporation site could be established within the Abbotts watershed. Although the water budget evaluation of net ground-water flow would also be improved considerably with these improvements, it would also be informative to directly measure ground-water flows with seepage meters at several points in the lagoons.

An understanding of water quality in the lagoons, and the impact from tributary sources, would benefit from more sampling. Sampling in the lagoons should be at least every other month, preferably monthly. Tributaries should be sampled throughout several storm events plus monthly at T1 and T2. The additional storm sampling would help to determine the significance of tributary sources, especially in the case of T5—a significant source of nitrate in one storm and a very small source in a later storm.

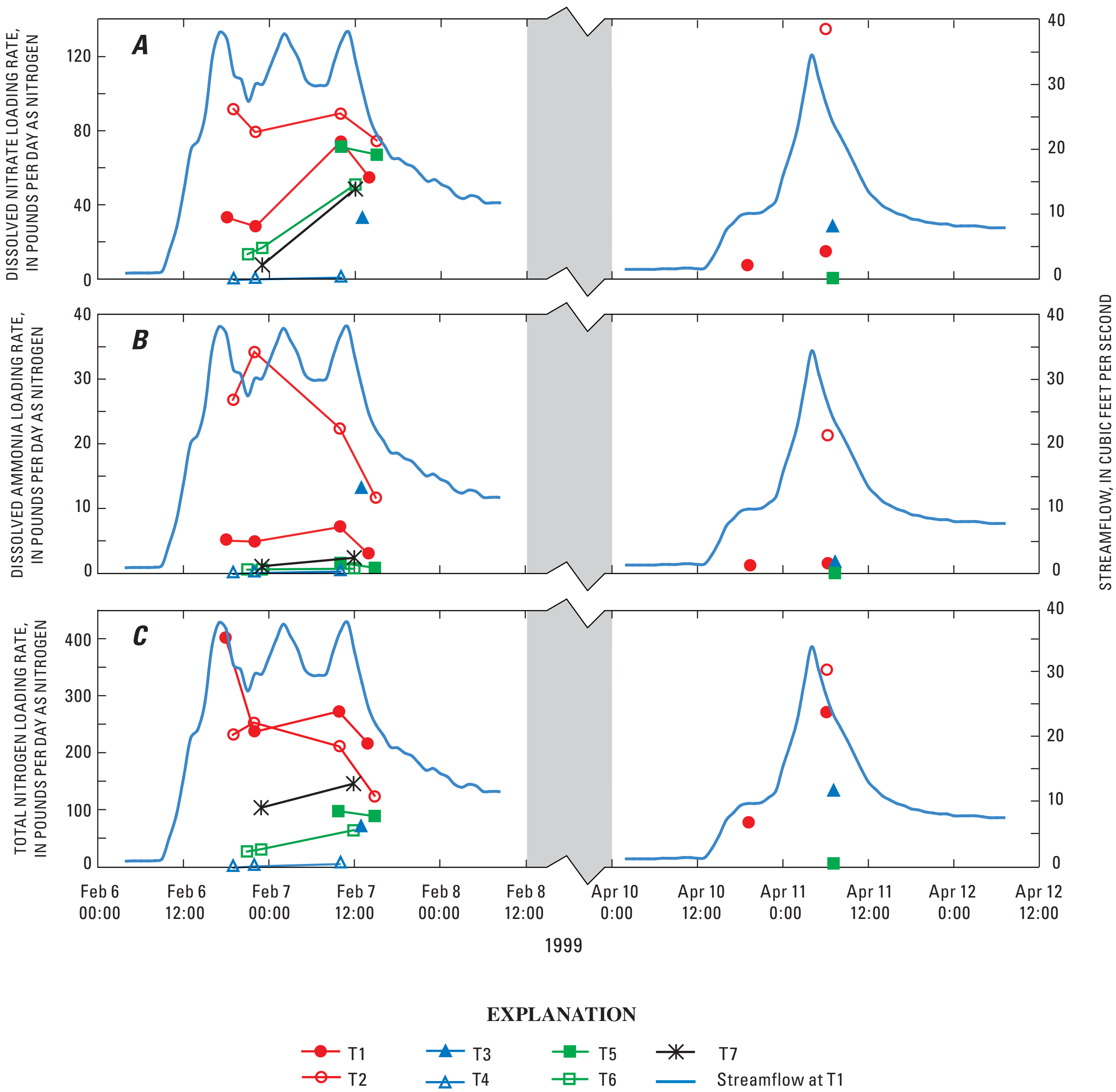

Figure 16. Instantaneous loading rates of dissolved nitrate, dissolved ammonia, and total nitrogen in Abbotts Lagoon tributaries relative to streamflow in tributary T1 for February and April 1999 storms.The time zone reference is Pacific Standard Time (PST) in 24-hour format. The vertical gray bar in the center of the graph represents a break in the graph.

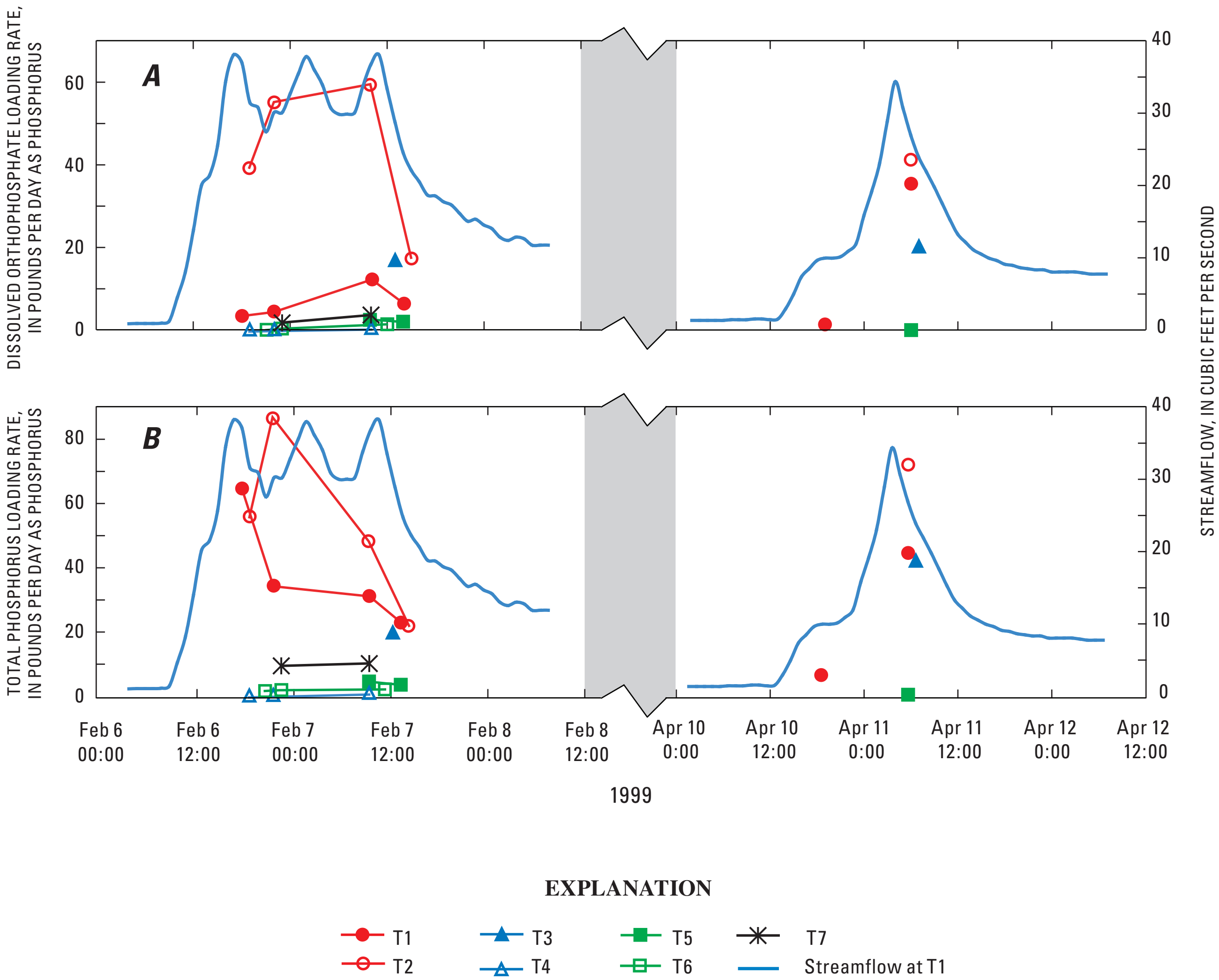

Figure 17. Instantaneous loading rates of dissolved orthophosphate and total phosphorus in Abbotts Lagoon tributaries relative to streamflow in tributary T1 for February and April 1999 storms.The time zone reference is Pacific Standard Time (PST) in 24-hour format. The vertical gray bar in the center of the graph represents a break in the graph.

Table 4. Comparison of nutrient loading rates and yields with land use in tributaries to Abbotts Lagoon.

[Loading rates are in pounds per day; yields are in pounds per day per square mile and are shown in parentheses; ID, identification; Ortho P, orthophosphate; mi^2, square mile; TN, total nitrogen; TP, total phosphorus]

					Land use, percentage of basin area				
Site no. (see fig. 1)	Site name	Site ID	Basin area (sq. mi.)	Percent of T1–T7 area (percent)	Silage	Grazing (general)	Grazing (permanent)	Grazing (seasonal)	Dairy/ ranching (impacted)
T1	Unnamed tributary 1 to Upper Abbotts Lagoon	380738122560701	0.98	40.2	17.9	8.7	8.2	46.9	0.0
T2	Unnamed tributary 2 to Upper Abbotts Lagoon	380753122561501	0.18	7.4	14.0	0.0	11.3	0.0	25.6
T3	Unnamed tributary 3 to Upper Abbotts Lagoon	380752122562501	0.07	2.9	26.7	0.0	0.0	34.0	37.3
T4	Unnamed tributary 4 to Middle Abbotts Lagoon	380722122561601	0.12	4.9	31.2	64.6	0.0	0.0	0.0
T5	Unnamed tributary 5 to Middle Abbotts Lagoon	380708122563501	0.05	2.0	0.0	99.3	0.0	0.0	0.0
T6	Unnamed tributary 6 to Lower Abbotts Lagoon	380642122563601	0.42	17.2	0.0	97.6	0.0	0.0	2.4
T7	Unnamed tributary 7 to Lower Abbotts Lagoon	380633122564001	0.62	25.4	0.2	99.8	0.0	0.0	0.0
Totals			2.44						
Average									

Table 4. Comparison of nutrient loading rates and yields with land use in tributaries to Abbotts Lagoon—Continued.

[Loading rates are in pounds per day; yields are in pounds per day per square mile and are shown in parentheses; ID, identification; Ortho P, orthophosphate; mi^2, square mile; TN, total nitrogen; TP, total phosphorus]

Site no. (see fig. 1)	Site name	Site ID	Basin area (sq. mi.)	Percent of T1–T7 area (percent)	Flow-weighted average instantaneous nutrient loading rates and yields					Percentage of loading rate from all tributaries				
					Nitrate loading rate (yield)	Ammonia loading rate (yield)	TN loading rate (yield)	Ortho P loading rate (yield)	TP loading rate (yield)	Nitrate	Ammonia	TN	Ortho P	TP
T1	Unnamed tributary 1 to Upper Abbotts Lagoon	380738122560701	0.98	40.2	39.3 (40.1)	4.4 (4.5)	274 (280)	11.4 (11.6)	38.6 (39.4)	14.2	9.6	31.2	14.1	25.9
T2	Unnamed tributary 2 to Upper Abbotts Lagoon	380753122561501	0.18	7.4	93.7 (521)	24.3 (135)	242 (1,345)	44.8 (249)	59.9 (333)	33.9	53.2	27.5	55.4	40.1
T3	Unnamed tributary 3 to Upper Abbotts Lagoon	380752122562501	0.07	2.9	28.8 (412)	13.4 (192)	113 (1,616)	19.0 (271)	34.9 (498)	10.4	29.3	12.9	23.5	23.4
T4	Unnamed tributary 4 to Middle Abbotts Lagoon	380722122561601	0.12	4.9	0.6 (5.4)	0.3 (2.6)	5.3 (43.9)	0.2 (2.0)	0.6 (5.3)	0.2	0.7	0.6	0.2	0.4
T5	Unnamed tributary 5 to Middle Abbotts Lagoon	380708122563501	0.05	2.0	58.6 (1,172)	1.0 (20.7)	79.8 (1,596)	2.1 (41.4)	3.5 (69.1)	21.2	2.2	9.1	2.6	2.3
T6	Unnamed tributary 6 to Lower Abbotts Lagoon	380642122563601	0.42	17.2	27.7 (65.9)	0.6 (1.5)	41.0 (97.6)	0.7 (1.7)	1.8 (4.4)	10.0	1.3	4.7	0.9	1.2
T7	Unnamed tributary 7 to Lower Abbotts Lagoon	380633122564001	0.62	25.4	27.5 (44.3)	1.7 (2.8)	125 (201)	2.7 (4.4)	9.9 (15.9)	10.0	3.7	14.1	2.3	6.6
Totals Average			2.44		276 (113)	45.7 (18.7)	880 (361)	80.9 (33.2)	149 (61.1)					

Summary and Conclusions

Abbotts Lagoon comprises three separate, yet normally connected, waterbodies, with the farthest downstream lagoon separated from the Pacific Ocean by a narrow strip of beach. However, a breach in the beach berm reportedly occurred during this study in late March 1999 for about a week, allowing seawater to move into the lower two lagoons. Water-quality samples were collected quarterly at sites in each of the three lagoons and at the most significant tributary during water year 1999. The quarterly samples were analyzed for major ions, nutrients, and chlorophyll-*a*. In addition to the main tributary, up to six other tributaries were sampled during two storm events in 1999. The storm samples were analyzed only for nutrients. A continuous water-level recorder was installed in the main tributary in February 1999, and a rating was developed to obtain continuous streamflow values. Continuous water-level recorders were also installed in the middle and lower lagoons to allow for the estimation of change in storage for March 29 to July 27, 2000.

The collection of continuous streamflow and change in storage data allowed us to estimate the water budget of Abbotts Lagoon for portions of the study period. During storm runoff from April 16, 2000, at 10 a.m. to April 18, 2000, at 3 a.m., the inflow at the main tributary was 85 percent of the total surface inflow. This percentage was lower in the February 1999 storms and is a function of upstream storage and vegetative growth in the tributary basins. Net ground-water interaction with Abbotts Lagoon during June 11 to July 27, 2000, was an outflow (seepage) of about 0.3 ft^3/s. This number is highly dependent upon the many assumptions made in the study.

The three lagoons were increasingly brackish from upstream to downstream, with mean specific conductivities of 352, 1,000, and 9,580 μS/cm. The reported late March 1999 breach was confirmed by the water-quality data. Nutrient concentrations decreased from upstream to downstream in the three lagoons. The lower lagoon had less organic carbon and total phosphorus in the bed sediment than the upper two lagoons.

Tributaries T2 and T3, originating in the I Ranch dairy, had the highest concentrations of nutrients during both storms. These tributaries also had the highest loading rates and yields of ammonia and phosphorus. Although these tributaries account for only 10.3 percent of the area drained by the sampled tributaries, they contributed 83 percent of the ammonia load and 79 percent of the orthophosphate load. The basins with the highest nutrient loading rates and yields had the highest percentage of dairy and (or) ranching land use and, to a lesser extent, intensive grazing (permanent and seasonal) land use. From the ratio of inorganic nitrogen to orthophosphate and the response of algae growth, nitrogen appears to be the limiting nutrient for algal growth in the lagoons. The April 1999 storm runoff in T3 contained several compounds indicative of wastewater, including two sterols indicative of fecal material (3β-coprostanol and cholesterol).

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